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Dynamics of the alluvial aquifer in the northern part of the dallol Bosso and assessment of water potential for small-scale irrigation: Departments of Balleyara and Filingué

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ABSTRACT

In the Departments of Balleyara and Filingué in Niger, the development of irrigated agriculture is a key factor in improving food security. Irrigation is considered as the best way to increase agricultural production and reduce its vulnerability to climate variability. The alluvial aquifer of the dallol Bosso, easily mobilized because of its shallow depth, is heavily used for this purpose. However, this groundwater resource is subjected to the effects of anthropogenic actions and climate change. The aims of this study, was to improve knowledge of the aquifer system and the dynamics of the alluvial aquifer in the context of climate change. The methodology adopted was based on the analysis of hydro-climatic and hydrodynamic parameters and their processing using various softwares. The results obtained showed a decrease in precipitation from south to north part in the area, with interannual averages of 440.3 mm in Balleyara and 408.73 mm in Filingué. The water balance estimated for the year 1952 showed an infiltration rate in the water table of 20.29% for an easily usable reserve (RFU) of 100 mm and 23.79% for an RFU of 50 mm and the annual recharge of the water table for the year 2018 is estimated at 1.4310^8 m^3. The dynamics of land use between 1972 and 2014 showed a deterioration of vegetation in favor of bare surfaces. The alluvial aquifer is mainly made up of sand of alluvial and aeolian origin, with thicknesses varying between 5 m and 27 m. The piezometry shows a main flow direction from south to north, at the alluvial water table scale. These results showed that the alluvial aquifer is favorable for irrigation.

Keywords: Dallol Bosso; Dynamics, Alluvial Table; Small Irrigation; Climate Change; Tillabery.

INTRODUCTION

In Niger, a Sahelian country, groundwater resources constitute a major concern for populations given the scarcity and quality of surface water (Saley, 2018; Yahouza et al., 2018; Maigary, 2018; Saley et al., 2019; Saidou Garba et al., 2019; Abdou Sani Oumarou, 2022; Saidou Garba et al., 2023).

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Therefore, groundwater constitutes a basis for socio-economic development for the population (Dambo, 2007; Sandao, 2013; Abdou Babaye et al., 2015; Sandao, 2018). Thus, the trend declines in rainfall (recurrent drought), observed from the 1970s to the present in the Sahel, coupled with strong demographic pressure, as well as the degradation of natural resources (decrease in soil fertility), have resulted in a reduction in rainfed agricultural production. These factors have strongly militated in favor of the adoption of irrigation as a priority strategy for agricultural development (Zakari et al., 2016). Thus, to achieve food self-sufficiency, the Niger Republic has made enormous efforts in the development of irrigated agriculture, although the country only has 11% of agricultural land out of its total area, i.e. 15 million hectares (MA, 2015). This development of irrigation coupled with the increase in population with a rate of 3.1% (PDC, 2011; PDC, 2017) induces a very strong demand on shallow alluvial water tables, therefore easily accessible, to satisfy their water needs. Thus, the alluvial aquifer of the dallol Bosso, (dallol: Peulh term, designates a humid valley where groundwater is found at shallow depth), fossil valley, located to the east of the Niamey region, is heavily used for the small irrigation. The general objective of this study aims to improve knowledge on the dynamics of the alluvial water table in the northern part of the dallol Bosso in the context of climate change. Specifically, this involves: (i) analyzing climatic parameters and establishing the hydrological balance; (ii) analyze land use dynamics; (iii) determine the geometry of the aquifer of the dallol Bosso alluvial table; (iv) establish periodic piezometric maps; (v) evaluate its potential in the face of the dynamics of the water table. The paper is structured into three main parts: an overview of the general framework of the study area; the materials and methods and the results and discussions.

MATERIAL AND METHODS

Presentation of the study area

The study area, is shared between the departments of Balleyara and Filingué, in Tillabery region of Niger. With an area of 911 km ^{2}, it is located between 13° 30' and 14° 00' north latitude and between 2° 50' and 3° 20' east longitude (Figure 1). It partially brings together from north to south, 3 municipalities, namely: the municipalities of Imanan and Tondikandia in the department of Filingué and the municipality of Tagazar, in the department of Balleyara. The relief of the study area is mainly characterized by a largely alluvial system, plateaus and dune complex.

The dallol Bosso is a fossilized stream, which flows into the Niger River, which constitutes its outlet. The hierarchy of its very well-developed hydrographic network (Figure 2), established from MNT images, Landsat 8, at 15 m resolution from the year 2003 of the area, gives the main watercourse an order 8.

At the dallol Bosso, agriculture constitutes the primary economic activity of populations composed (INS, 2020) of sedentary people (Zarma, Touareg and Kourfeyawa) and nomads (Touareg and Peulh). There are two (2) main types of crops: Rain fed crops mainly concern varieties such as millet, sorghum, cowpeas, corn, voandzou, peanuts, sesame and sorrel and irrigated crops, such as tomatoes, potato, pepper, onion, sweet potato, cassava, lettuce, squash (Mahamadou Ambarka, 2019).

The different types of soils encountered in the Balleyara Department are: sandy soils relatively enriched by alluvial and colluvial contributions; lateritic soils with a sandy-clayey veneer, generally not very fertile, and glacis and heavy formations rich in clay and humus.

The dallol Bosso was incised at the beginning of the Quaternary in the upper clay-sandstone series of the Continental Terminal (CT), then backfilled by essentially sandy alluvial and aeolian deposits. The CT formations are separated by sandstones and clays of the Continental Intercalaire (CI) underlying Paleocene marls, limestones and clays of the Terminal Cretaceous. The geological context of the study area makes it possible to distinguish, the following main geological formations from bottom to top (Figure 3):

- Band from Tégama, of Albian to Lower Cenomanian age, constituting the ultimate term of the CI;

- Continental Hamadian, characterized by medium to coarse, micaceous sandstones with variegated kaolinitic cement, the age of which is very controversial and which would be the Continental equivalent of the Cenomano -Turonian marine and marginalo -littoral series;
- Continental Terminal (CT), corresponds to vast detrital spreading with siderolithic facies, dating from the Tertiary and discordant with all the previous formations. The age of the Continental Terminal is between post-Eocene and ante-Quaternary. It contains three aquifers (CT1, CT2 and CT3) separated by layers of gray clay with lignites whose variations in lithological facies locally induce exchanges between the different units. CT1, formed of a succession of ferruginous sandstones, ferruginous clays, oolite sands or clays and ferruginous oolites. It does not exist to the west and is relayed by the clay-sand lignite series of CT2 (Favreau, 2000). CT2, represented by a complex comprising alternating sands, fine sandstones more or less clayey, gray clays or black laminated muds, characterized by the presence of plant debris and lignite. Their thickness increases from west to east to reach more than 80 m at the level of the dallol Bosso (Favreau, 2000) . CT3, its wall is made up of gray lignite clays and its roof of sandstone plateaus with a lateritic shell, covered with tiger bush and cut by erosion. These formations rest to the west on the crystalline base where its thickness is almost zero (beveling), and can reach more than 130 m towards the east.
- Quaternary alluvial deposits: made up of fluvial alluvium which fills the fossil valley of dallol and its main tributary of the Azgaret. The filling power varies greatly. The thickness varies from a few meters in the valleys of the river and its tributaries, to more than 20 m in the dallol Bosso and 15 m at most in the Azgaret.

The hydrogeology of the study area consists of the following aquifers from bottom to top:

- CT aquifers, composed of three (3) layers superimposed from bottom to top as follows:
  - CT1 aquifer, captive and gushing locally with low pressure (1 to 3 m) in the dallols. Drilling flow rates are generally greater than 20 m^3/h. The mineralization of water is less than 350 mg/L, in general, with a sodium bicarbonate facies (Guero, 2003);
  - CT2 aquifer, captive, non-spouting, have temperatures of 31 to 34°C and pH around 7. The mineralization is generally relatively high (conductivities of 1000 to 1500 µs /cm) and presents sulfated to sodium bicarbonate chemical facies (Favreau, 2000);
  - CT3 aquifer, phreatic, generally with a free surface (Barrat, 2016). Depths of 10 to 45 m in the fossil valleys and koris, with an exception in the Balleyara area where the water table merges with the Quaternary water table in the southern part, with a depth ranging from 0 to 10 m. In general, the waters are very lightly mineralized (<300 mg/L) but, in certain places they are (>500 mg/L) with calcic bicarbonate facies (Ibrahim, 2010).
- The alluvium layers, of shallow depth, relatively little mineralized and soft, remain very sensitive to chemical and/or bacteriological pollution. In the alluvium of the dallol Bosso, the electrical conductivity of the water has variable values from 50 to more than 1000 µS/cm, and is almost constant between 50 and 200 µS/cm, in certain areas. The waters present calcium and sodium bicarbonate type facies (Ibrahim, 2010).

MATERIALS AND METHODS

Data

Consisting of doctoral theses, study reports, scientific articles, climatic sheets and drilling techniques, piezometric surveys, chemical and bacteriological analysis sheets, lithological sections, geological and hydrogeological maps, digital terrain model (DTM), having a resolution of 15 meters and satellite imagery from 1972 and 2014.

Tools

Consisting of a Garmin type GPS (for taking geographic coordinates and moving around in the field), a 100 m light-sound

Rossignole probe (for measuring water levels in structures: wells and boreholes) and a HANNA brand portable multifunction conductivity meter with direct reading (for in-situ measurements of the physical parameters of water: T°, pH and Electrical Conductivity (EC)). These tools also include various software: Gesfor (for producing lithological logs), Zotero (for the bibliographic reference), Adobe Illustrator CS6 (for developing geological sections), ArcGis 10.2.2 (for cartography), and Statistica and R (for statistical analyses).

Data acquisition

- Data collection, the collection and synthesis of bibliographic data were carried out at the level of the documentary and archiving centers of the Ministry of Hydraulics, the regional and departmental technical services concerned, from projects, NGOs and research offices.
- Hydro-climatic data, measurements of hydro-climatic factors from the Balleyara station and that of Filingué for the period from 1981 to 2017 were collected at the level of the National Meteorology Direction of Niger (DMN).
- Satellite images, these are LANDSAT-1 satellite images with a resolution of 15 m taken in 1972, and LANDSAT-8 dated 2014, with 57 m resolution. This collected data comes from the AGRHYMET Regional Center.
- Field campaign, two field campaigns were carried out as part of this study, one in October 2017 and the other in October 2018. These campaigns focused on the inventory of hydraulic structures; measurement of static level and physical parameters in situ. The piezometric monitoring works are selected on the basis of the following criteria: belonging to the dallol Bosso; works capturing the alluvial water table and the good representativeness of water points. All the piezometric measurements were carried out on wells, due to the lack of a piezometer, numbering thirty (30) and all capturing the alluvial water table (Figure 4). For the measurement of physicochemical parameters, twenty-six (26) structures were involved, including twelve (12) wells (blue circle) and fourteen (14) boreholes (red square).

Data processing

Rainfall data

To assess the evolution of rainfall over the different years, the rainfall index method was applied. It makes it possible to highlight excess and deficit periods. The rainfall data collected for the two stations (Balleyara and Filingué) respectively for the periods from 1981 to 2017 and from 1950 to 2017 are processed on Excel software, by calculating the rainfall indices and applying the formula of NICHOLSON et al. (1988 in Mahamadou Ambarka, 2019), according to the following equation:

$$\text{Index} = \frac{Xi - \overline{X}}{\sigma}$$

With, Xi = rainfall height in mm of year i; $\overline{X}$ = average rainfall height for the period considered and σ= Standard deviation of rainfall over the period considered.

Negative values of the indices correspond to deficit years, and positive values to excess years. Climatic data (Precipitation, Temperature and ETP) are also used as part of this study for the calculation of the water balance and the processing of certain climatic parameters due to the lack of a synoptic station in the study area. These climate data are on a monthly scale spatialized in the form of half square degree grids available from Climatic Research Unit (CRU) at the University of East Anglia (New et al., 2000). These data were created by interpolating the monthly data available at the station level with a Spline function.

For the water balance, the Thornthwaite method was used, at monthly intervals, based on the following parameters and relationships: if P > ETP, then ETR = ETP and if P < ETP, then ETR = P. By bringing into play the useful reserve of the soil denoted RFU, two cases can arise: if P – RFU < ETP, then surplus = 0 and if P – ETP > RFU, then surplus = P – ETP.

With, P = rain, RFU = easily usable reserve, ETP = potential evapotranspiration, ETR = real evapotranspiration.

ETP and rainfall data were used to establish the hydrological balance and come from CRU data for the study area.

Preparation of geological sections

The lithological logs of the boreholes collected as part of this study were analyzed and allowed the development of litho-stratigraphic correlations between them. This correlation made it possible to determine the geometry of the alluvial aquifer of the dallol Bosso and to highlight the superposition of the different geological formations and the various aquifers. The direction of the correlation profile (Figure 5) is northeast at point A (Ichiwil) to southwest at point B (Djongo djerma).

piezometric maps

The piezometric coasts were calculated by the difference between the altitudes of the water points (extracted from the DEMs: on ArcMap: " Arctoolbox " => "3D analyst tools " => " functional surface" => " add surface info" => ok.) and the value of the static levels of the water points in relation to the ground. These coasts were used to draw up the piezometric map of the alluvial table of the dallol Bosso. The piezometric map aims to represent the configuration of the aquifer and the hydrodynamic behavior of the aquifer. It reflects the morphology of the water surface of the aquifer at a specific time, and makes it possible to define the direction, from the flow of water, to deduce the areas of supply and/or outlet of water from the groundwater.

Charging estimation

The annual recharge is estimated from this relationship: $Ra = D \times S \times ne$ and $D = Pb - Ph$

Where, *D: difference in the volume of water stored between the low water period and the high water period, corresponds to the replenishment of the aquifer;* P_{b}*: the depth of the lowest piezometric level, at the end of the dry season;* P_{h} *: the depth of the highest piezometric level, during high water periods; S : the surface area of the dallol Bosso and* n_{e} *: the effective porosity of the alluvium.*

Satellite imagery

The methodology adopted for the development of maps of land use dynamics includes the following operations: (i) preprocessing of satellite images, operations carried out on the images prior to any processing, they consist of mosaicking and visual improvement of images to facilitate their interpretations ; (ii) definitive processing, it consists of the synthesis of information on the different occupation classes and the colored composition of the image, which consists of combining information contained in three different bands by displaying them simultaneously in the three primary colors (red, green and blue). The goal is to have information allowing good land use discrimination. Color composition 543 was used for Landsat-8 images and 421 for Landsat-1 in this study. Thus, numbers were assigned to each type of class; the digitalization of each occupancy unit and the decoration of the cards. The nomenclature for the construction of databases on land use in Niger south of the 16th parallel was used. However, the different occupation classes retained are:

- Rupicolous cords: these are gallery forests constituting a narrow strip along the edge of the watercourse;
- Continuous rain fed crops: these are areas in which crops are grown during the rainy season;
- Rain fed crop areas under wooded parkland: these are areas where rain fed crops are grown on a cover of relatively high-density trees and/or shrubs;
- Fallows: these are cultivated lands left to rest in order to restore their fertility;
- Residential areas: it includes towns and villages;
- Bodies of water: these are temporary bodies of water;
- Koris: these are rivers with intermittent flow;
- Bare soils: these are land use units characterized by soils devoid of plant cover;
- Rocky terrain: these are plateaus devoid of plant cover

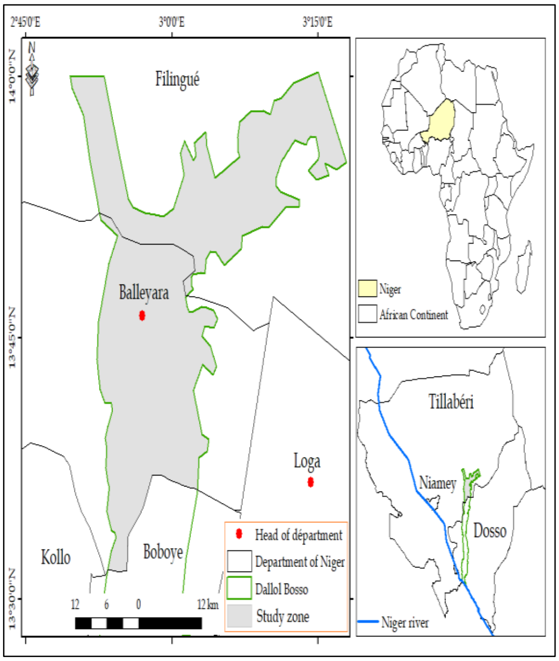

Figure 1: Location map of the study area.

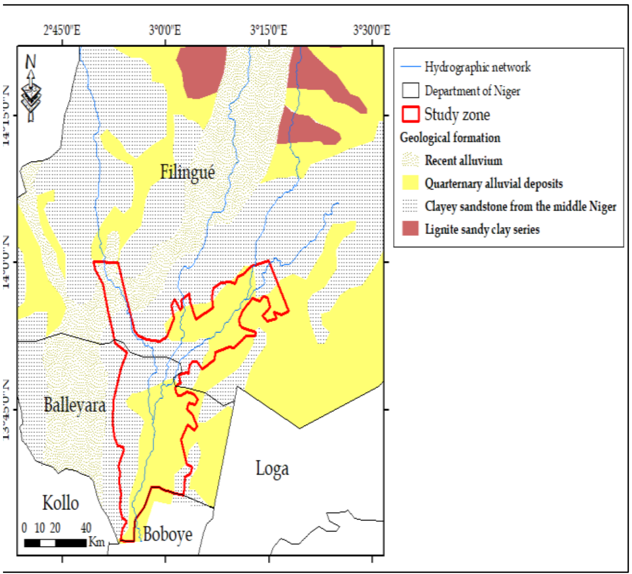

Figure 3: Geological map of the Iullemeden basin.

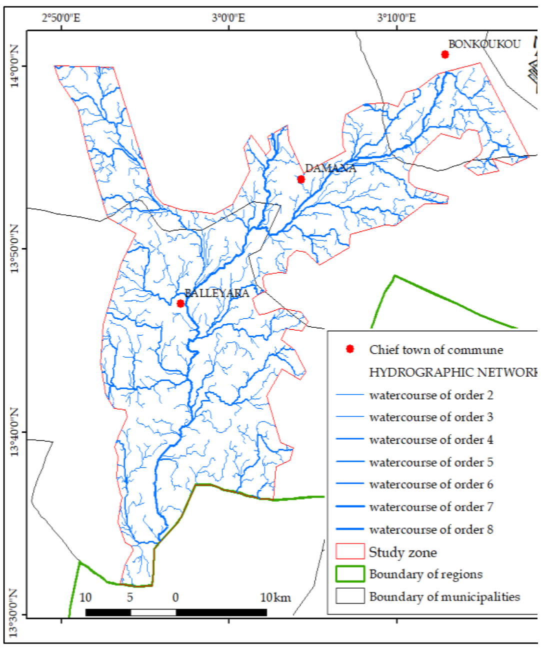

Figure 2: Map of the hydrographic network of dallol Bosso.

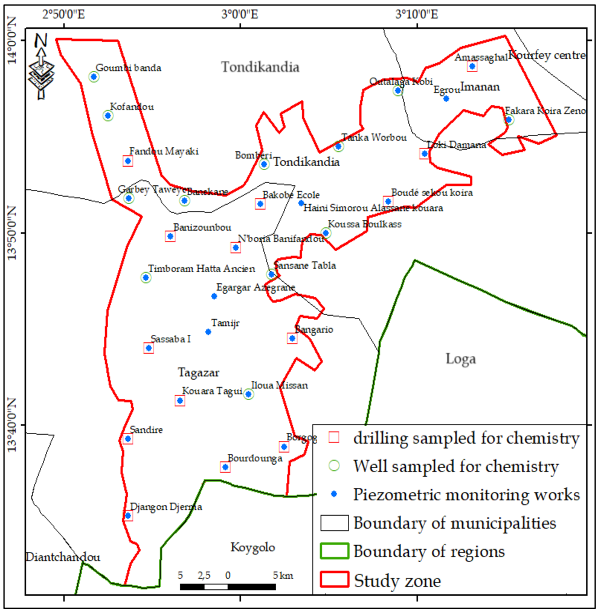

Figure 4: Piezometric monitoring and water sampling networks in dallol Bosso.

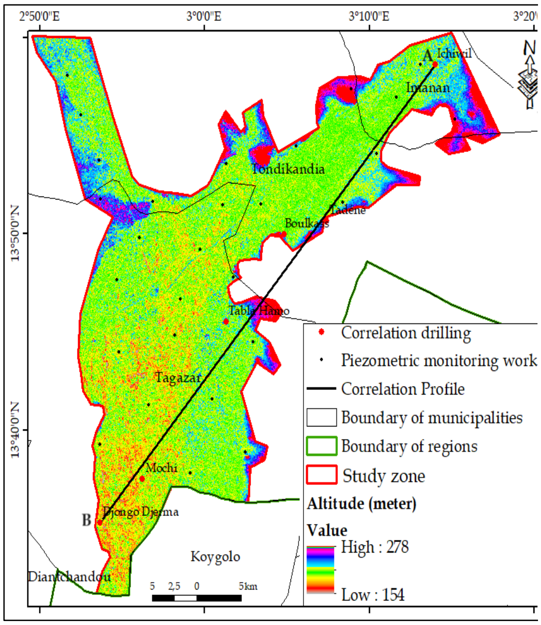

Figure 5 : Litho-stratigraphic correlation profile.

RESULTS

Interannual variations in precipitation

Annual rainfall values vary between 220.2 mm (1984) and 643.8 mm (2006), with an average of 440.3 mm for the Balleyara station (south) and between 795.5 mm (1953) and 135.1 mm (1987), with an average of 408.73 mm for that of Filingué (north) in the study area. This highlights a drop in annual rainfall from south to north in the area, linked to the movement of the Inter Tropical Front (FIT) to Niger in accordance with the results of previous studies (Maigary, 2018). The analysis of the spatio-temporal variability of annual rainfall indices and their average for the Balleyara station, calculated from data from 1981 to 2017, shows a heterogeneous distribution of precipitation, materialized by two (2) main periods (Figure 6). (i) A dry period, from 1981 to 1991, characterized by deficit years, with an exceptionally wet year (1983). The interannual rainfall average is 372.94 mm with a standard deviation of 63.43 mm and the rainfall deficit compared to the general average is 67.39 mm. (ii) A normal period marked by the alternation of excess and deficit years, which goes from 1992 to 2017, with an interannual rainfall average of 469.94 mm and a standard deviation of 66.90 mm.

The analysis of the spatio-temporal variability of annual rainfall indices and their average for the Filingué station, calculated from a longer series than that of balleyara, from 1950 to 2017 shows the succession of three periods (Figure 7). (i) A wet period from 1950 to 1968, corresponding to surplus years (positive rainfall index), with an interannual rainfall average of 527.80 mm and a standard deviation of 117.73 mm ; (ii) a dry period from 1969 to 1999, characterizing deficit years (negative rainfall index), with an interannual rainfall average of 331.80 mm and a standard deviation of 73.16 mm, the rainfall deficit compared to the general average is 76.94 mm ; (iii) a normal period which characterizes the alternation of wet and dry periods, ranging from 2000 to 2017, with an inter-annual rainfall average of 415.44 mm and a standard deviation of 70.80 mm. This succession of wet, dry and normal periods reflects the climatic variability of the area which has strong repercussions on surface and groundwater resources leading to: a reduction in precipitation, drying or a reduction in the rate of supply.

Water balance

The monthly values of ETP and rainfall for the years 1952 and 2004 were used to calculate the water balance. The choice of these years is based on the fact that 1952 is a wet year, with an annual rainfall of 922.5 mm and 2004 is a dry year, with a rainfall of 423.2 mm and the interannual average is 544.38 mm. The RFU corresponds to the quantity of water stored by the soil and which can be taken up by plant evapotranspiration. It depends on the structure and plant cover of the soil. According to Ousmane (1988), Daddy (1993) and Guéro (2003), there can only be infiltration towards the water table when the maximum capacity of this reserve is reached. The results of the hydrological balance are reported in tables 1 and 2.

Analysis of these results shows that for the year 1952 (Table 1), only the months of August and September are in excess, regardless of the value of the RFU used (100 mm or 50 mm). The excess rainfall which contributes to recharge is low. On the other hand, for the year 2004 (Table 2), considered as a dry year, whatever the value of the RFU used (100 or 50 mm), the excess rainfall which contributes to the supply of the dallol Bosso is zero. Thus, for the year 1952, the choice of RFU = 100 mm and RFU = 50 mm respectively shows an annual recharge of 187.2 mm, i.e. an infiltration rate of 20.29% compared to the annual rain and an annual recharge of 236.2 mm, i.e. an infiltration rate of 25.60% compared to the annual rainfall. It emerges from these results that the months of August and September, characterized by a considerable supply of rain, the drop-in temperature and the reduction in evapotranspiration, are the only excess months, where there can be infiltration towards the water table. The other months of the year are always in deficit. These results are close to those found by Oumarou (2016) and Hayo (2017).

Dynamics of land use in the study area

Analysis of the dynamics of land use in the study area, slightly enlarged towards the western part of this same area, for better observation of rocky terrain, with an area of approximately 120,813.31 ha is made from maps resulting from the processing of LANDSAT satellite imagery from 1972 and 2014 (Table 3). Thus, eight (8) classes of land use and occupation were identified for each of the two periods concerned (1972 and 2014) as follows (Figures 8 and 9):

- Continuous rain fed cultivation area;
- Cultivation zone under wooded park;
- Rocky terrain;
- Fallows;
- Riparian cord;
- Bare ground;
- Residential area;
- and Body of water.

The classifications and areas of the different land use units for the two (2) periods 1972 and, 2014 are indicated in Table 6 below. Thus, the evolution of land use units between 1972 and 2014 (Figure 10) shows that:

- the area occupied by continuous rainfed crops has experienced an expansion of approximately 6.43%, while the area of fallow fields and that of cultivation areas under tree parks has declined respectively by 5.27% and 4 .76%;
- barriers increase from 4.32% in 1972 to 7.86% in 2014, an increase of 3.54%, resulting in an increase in surface runoff and a development of the hydrographic network;
- areas experienced a considerable increase to reach 0.87% in 2014 compared to 0.27% in 1972, an increase of 0.6%. On the other hand, rocky terrain experienced a decrease of 2.44%;
- bodies of water show an increase in their surface area, which goes from 0.01% to 0.26%, or an extension of 0.25%;
- finally, bare soils increased from 666 ha (1.03%) to 4,189 ha (2.69%), an increase of 1.66%, thus accentuating water and wind erosion.

Hydrogeological parameters

Total drilling depths

The equipped depths of wells and boreholes capturing the alluvial water tables of the dallol Bosso, in the study area, vary between 1.90 m (Tamijr) and 32.5 meters (Haini Simorou Koira Tagui), with a mean of 10.10 m and a standard deviation of 8.28 m (n = 40). The depth coasts equipped with boreholes (Figure 11) decrease from east to west in the study area, from 190 m to 204 m altitude, reflecting an increase in the depths of water capture from east to west. This could be explained by the topography of the area. These shallow catchment depths of the alluvial aquifer, especially in the eastern part of the area, constitute an enormous risk of pollution of the aquifer waters, linked to anthropogenic activities. On the other hand, these shallow depths easily ensure the collection of water tables without problem, which could favor the development of the irrigation sector.

Lithology and geometry of the alluvial layer of the dallol Bosso

The analysis of the lithological sections of the boreholes carried out in the study area made it possible to reconstruct the lithology of the Dallol Bosso aquifer. These litho-stratigraphic logs show a lithology essentially composed of fine to coarse sands, very little clayey sands, little sandy clays and black peat at the base. Indeed, the Continental Terminal constitutes the bedrock of the dallol Bosso. The thickness varies depending on the topography of the land along the valley between less than 2 m (Tamijr) and 32.5 m (Haini Simorou Koira Tagui). This aquifer is easily accessible by wells and sumps, and is in great demand for the supply of drinking water to populations, watering animals and for small irrigation. The litho-stratigraphic correlation established between the different logs (Figure 12), following profile A (Ichiwil) – B (Djongo djerma) shows that the catchment depths of boreholes in the area increase from east to west.

Piezometry of dallol Bosso

Static levels

The piezometric monitoring campaigns carried out in the study area in October 2018 show that the aquifer is shallow (generally less than 10 meters), and is usable especially for small-scale irrigation. The depth of the water table decreases from north to south, and from the plateaus towards the valley, where they become zero locally, depending on the topography. The spatial distribution map of depths of static levels for the month of October 2018 (Figure 13) shows that static levels vary between 0.26 m in the south (Heyni Simorou Alassane kouara) and 24.7 m to the north (Outalaga Kobi).

Interannual variations of static levels of Dallol Bosso

The analysis of the interannual variation of static levels, in the northern part of the Dallol Bosso, based on the chronicles of the piezometric readings of the year 2017 and 2018, shows a low fluctuation of the piezometric level for the piezometers of Banékane, Boulkass, Sandiré and Borgo gorou. The water table is almost stable during these two years despite the withdrawals for different uses and its flow towards the outlet. On the other hand, for the Outalaga piezometer, the fluctuation of the piezometer level is well marked, with a rise in the static level in October 2017. A drop in the static level is noted at all piezometers for the month of May, with a tendency for the static level to rise from August. This rise (Figure 14) is explained by the direct and/or indirect replenishment of the water table by precipitation water.

Piezometric map

The piezometric maps (Figures 15 and 16) of the study area, established respectively from data from October 2017 campaign and that of October 2018, show that, the layers have simple and regular piezometric surfaces on the entire area and for the two campaigns. The two maps do not show a big difference because the two campaigns were carried out during the same period of high water (month of October). However, we note a small difference in the shape of the isopiezes between the October 2017 map and that of October 2018, due to the local presence of a few piezometric domes, favorable to recharge, around the village of Banizoumbou and Bangario. This presence of domes confirms the free nature of the aquifers of the alluvial table. The recharge zones of the alluvial aquifer are present almost everywhere on the surface of the aquifer. These are the highest parts of the piezometric surface, where the isopiezes are closed, causing a divergence of the current lines. The isopiez curves (Figures 15 and 16) generally decrease in altitude, on the scale of the Dallol, from north to south, except in areas of overexploitation or recharge of the aquifer, locally defining particular flow directions waters. Thus, the general flow axis is from north – south. This is in accordance with the results found by Oumarou (2016).

Water potential

Estimated total water reserve of the Dallol Bosso alluvial aquifer

The parameters used to calculate the water reserve are: (i) the surface area of the study area (911 km ^{2}); (ii) the effective porosity estimated from the lithological nature of the sediments (20%) and (iii) the thickness of the Quaternary aquifers with renewable groundwater resources of Dallol Bosso (between 10 and 20 m). Thus, the useful volume of the alluvial aquifer horizon estimated from the above parameters is equal to $3{,}644.10^9$ m ^{3}.

Annual potential for irrigation

The piezometric surface of the alluvial aquifer of the Dallol Bosso is influenced by the contributions of precipitation, withdrawals intended for human consumption, irrigation, animal watering, drainage and flow towards the outlet. It could have positive as well as negative consequences on the fluctuation of the water table. The difference in the volume stored between the low water period and the high-water period corresponds to the replenishment of the alluvial aquifer. The average annual recharge is 0.79 m in the year 2018 (Table 4). The surface area of the aquifer is estimated at approximately 911 km ^{2} and the storage coefficient being assumed uniform is equal to 2.10^{-1}, we can estimate that the annual recharge of the water table is equal to $1.43.10^8$ m^3 in 2018.

Physico-chemical characteristics of alluvial water

The water conductivity values of the study area vary between 1560 µs/Cm and 90 µs/Cm, with a mean of 410 µs /Cm and a standard deviation of 339.42 µs/Cm. The spatial distribution of conductivity (Figure 17) in the northern part of the Dallol Bosso indicates that 80% of the samples have contents less than or equal to 500 µs/Cm and 20% have contents greater than this value. These high values of conductivities at the northern end and in the center of the Dallol Bosso could be due to water pollution, either by infiltration of water having washed away livestock droppings or by the risks of point pollution (water intrusion deep, precisely those artesian of the CT).

The pH values measured on 26 groundwater samples are between 5.41 and 7.87, with an average of 6.61 and a standard deviation of 0.65. Overall, the waters are acidic to slightly basic, similar to those found for alluvial aquifers in the Tahoua region (Amadou et al., 2014). Indeed, according to Beauchamp (2006), the pH is acidic in the waters of sandy or granitic aquifers. This acidic character of the waters can be linked to the lithological and free nature of the aquifer, in accordance with the results of Oumarou (2016).

The water temperature of Dallol Bosso varies between 29.5°C and 34.5°C, with an average of 32.24°C and a standard deviation of 1.22°C. These low temperature values are mainly linked to the shallow depths of the water table, consequently the water is subject to the influence of atmospheric temperatures. The mean and median values are close to those found by Guero (2003), respectively 31.6 °C and 31.7°C in the boreholes of the free aquifer of the CT of the southwest edge of the Iullemenden basin. They are also close to the atmospheric average (32.9°C) recorded in October 2016 at the Niamey airport station (Maigary, 2018).

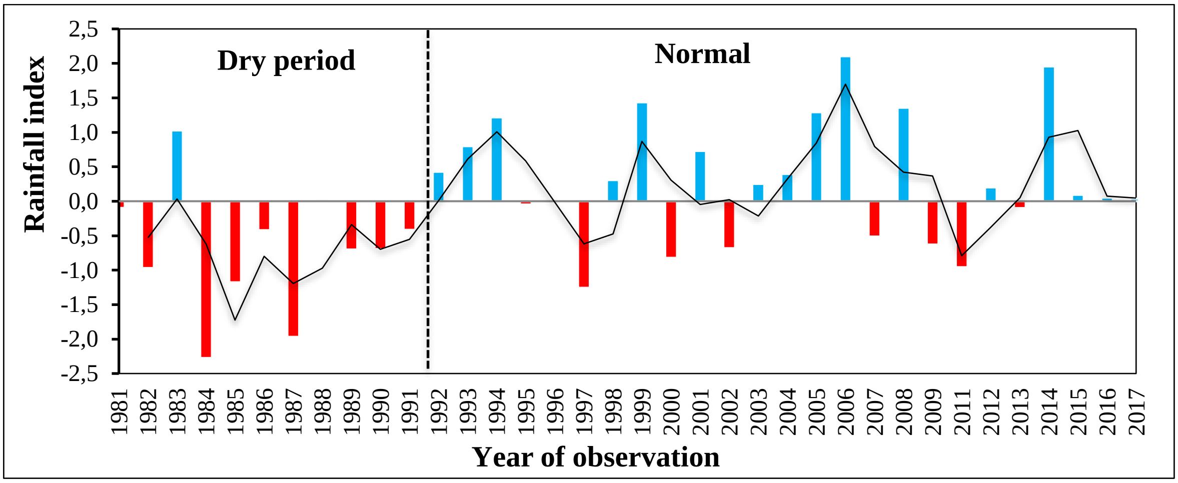

Figure 6 : Evolution of the rainfall index at the Balleyara station (1981 to 2017).

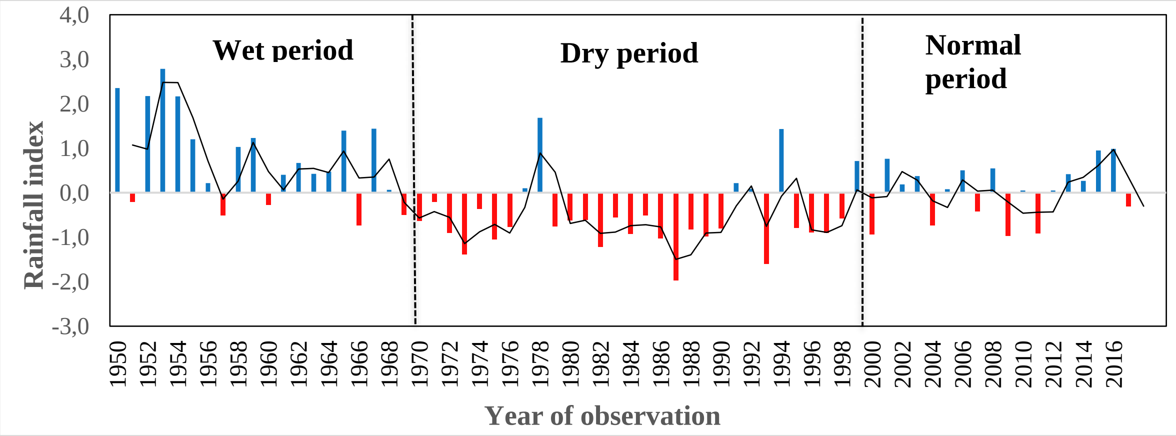

Figure 7 : Evolution of the rainfall index at the Filingué station (1950 to 2017)

Table 1: Water balance for the year 1952, with RFU = 100mm and RFU = 50 mm.

Settings	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly FTE	198.4	201.6	232.5	237	235.6	210	173.6	142.6	150	176.7	180	182.9
Rush (1952)	0	0.2	0	12.8	38.7	114.6	149	368.7	211.1	27.4	0	0
Monthly ETR	0	0.2	0	12.8	38.7	114.6	149	142.6	150	27.4	0	0
Useful reserve (RFU= 100mm)	0	0	0	0	0	0	0	100	100	0	0	0
Rainfall deficit	198.4	201.4	232.5	224.2	196.9	95.4	24.6	0	0	149.3	180	182.9

Excess rainfall								**126.1**	**61.1**			
Useful reserve (RFU= 50mm)	0	0	0	0	0	0	0	50	50	0	0	0
Rainfall deficit	198.4	201.4	232.5	224.2	196.9	95.4	24.6	0	0	149.3	180	182.9
Excess rainfall								**176.1**	**60.1**			

Table 2: Water balance for the year 2004, with RFU = 100mm and RFU = 50 mm.

Settings	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly FTE	195.3	190.4	220.1	228	223.2	195.0	173.6	151.9	165	189.1	177	186
Rush (2004)	0	0.2	0.1	14.9	33.2	47.10	113.70	149.3	63.5	1.20	0	0
Monthly ETR	0	0.2	0	12.8	38.7	114.6	149	142.6	150	27.4	0	0
Useful reserve (RFU= 100mm)	0	0	0	0	0	0	0	100	0	0	0	0
Rainfall deficit	195.3	190.4	220	213.1	190	147.9	59.9	2.6	1.5	187.9	177	186
Excess rainfall								**0**				
Useful reserve (RFU= 50mm)	0	0	0	0	0	0	0	50	0	0	0	0
Rainfall deficit	195.3	190.4	220	213.1	190	147.9	59.9	2.6	51.5	187.9	177	186
Excess rainfall								**0**				

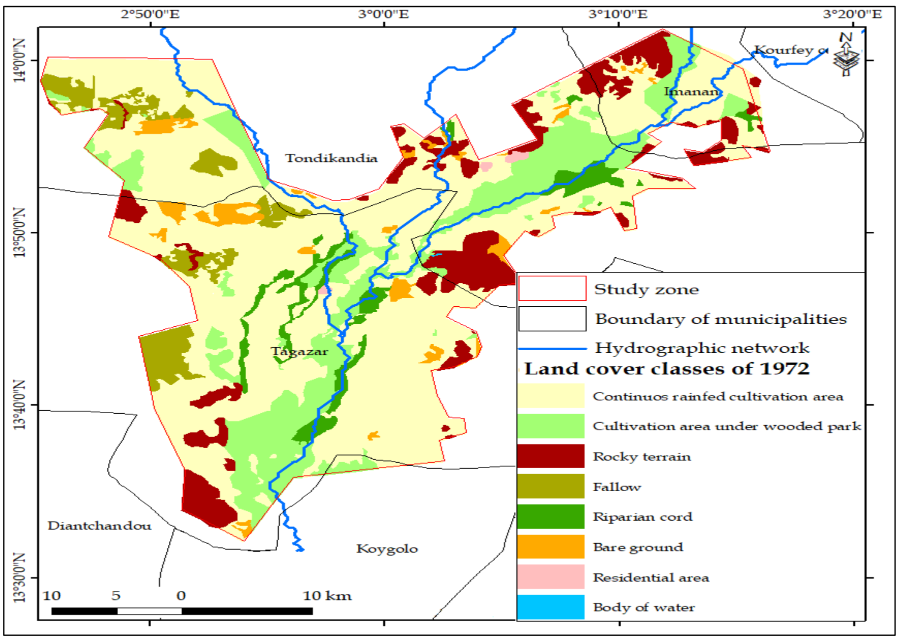

Figure 8: Land occupation and use map in 1972.

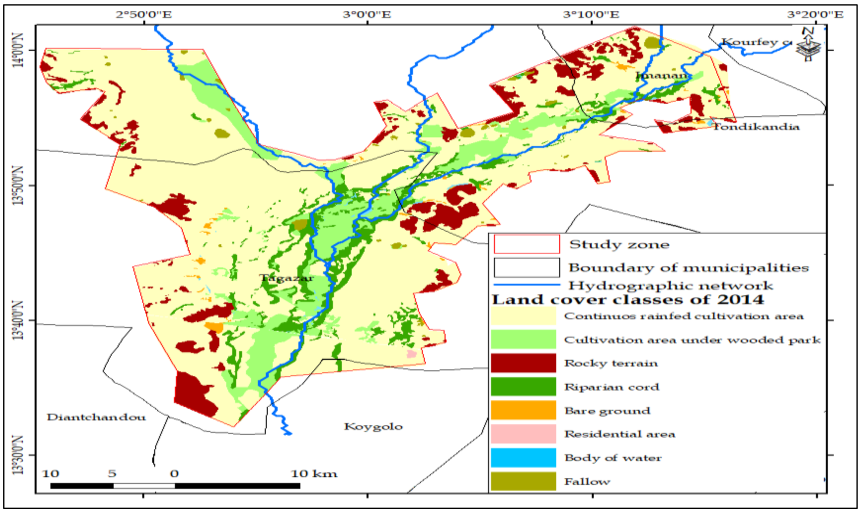

Figure 9: Land occupation and use map in 2014.

Table 1: Area of land use classes and occupation in 1972 and 2014.

Land cover and use classes	In 1972		In 2014		% difference between 2014 and 1972	Area
	Area in ha	%	Area in ha	%		
Continuous rainfed cultivation area	75226.8	62.27	88279.62	68.7	6.43	Increase
Cultivation area under wooded park	19694.9	16.3	14828.5	11.5	-4.76	Decrease
Rocky terrain	12617.9	10.44	10280.9	8	-2.44	Decrease
Fallo w	6468.84	5.35	108.26	0.08	-5.27	Decrease
Riparian cord	5221.36	4.32	10094.6	7.86	3.54	Increase
Bare group of	1244.45	1.03	3456.43	2.69	1.66	Increase
Resident in the area	323.99	0.27	1113.42	0.87	0.6	Increase
Plane of water	15.07	0.01	333.73	0.26	0.25	Increase
Total	**120813.31**	**100**	**128495.46**	**100**	0	

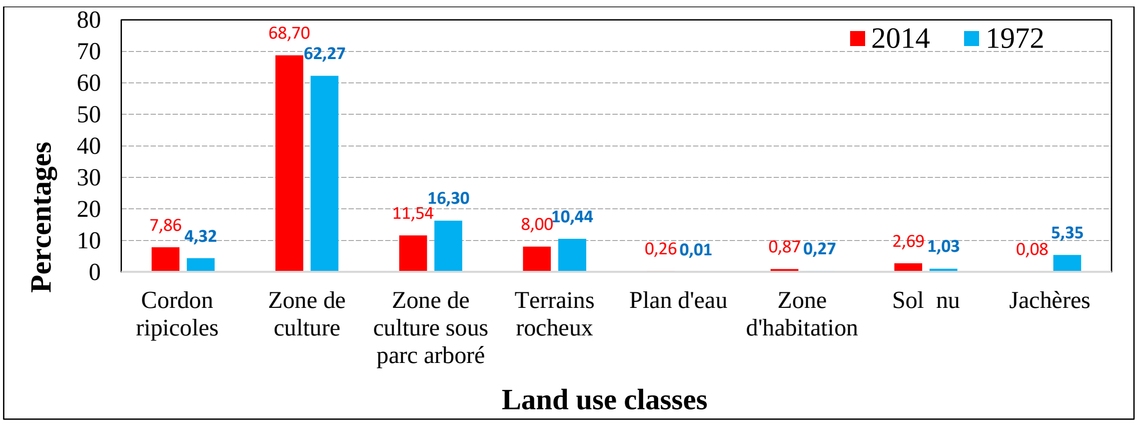

Figure 10: Evolution of land use between 1972 and 2014 in dallol Bosso.

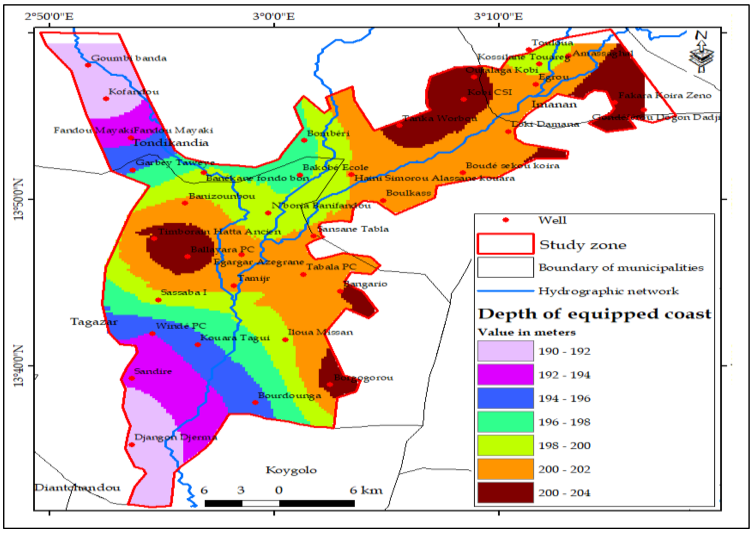

Figure 11: Map of depths equipped with boreholes capturing the alluvial water table.

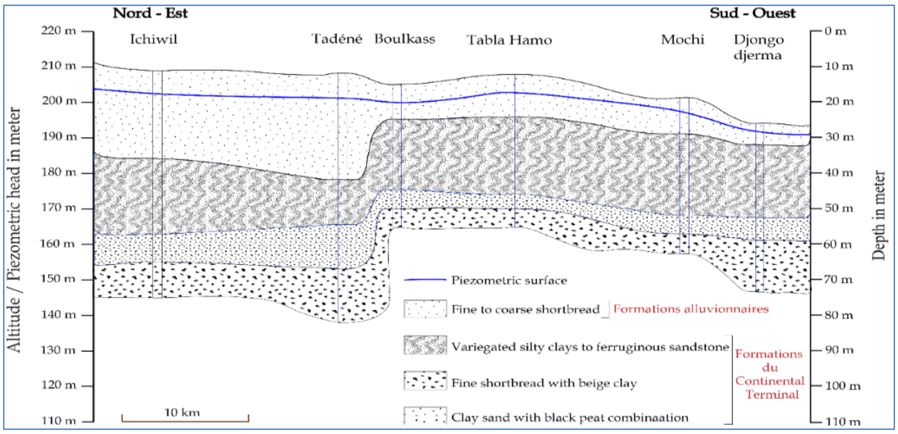

Figure 12: Lithological sections of drilling with litho-stratigraphic correlations in the study area.

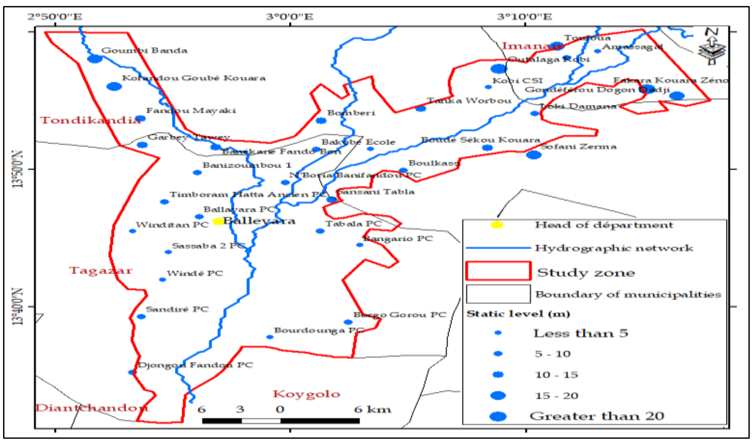

Figure 13 : Spatial distribution of static levels in the study area (October, 2018).

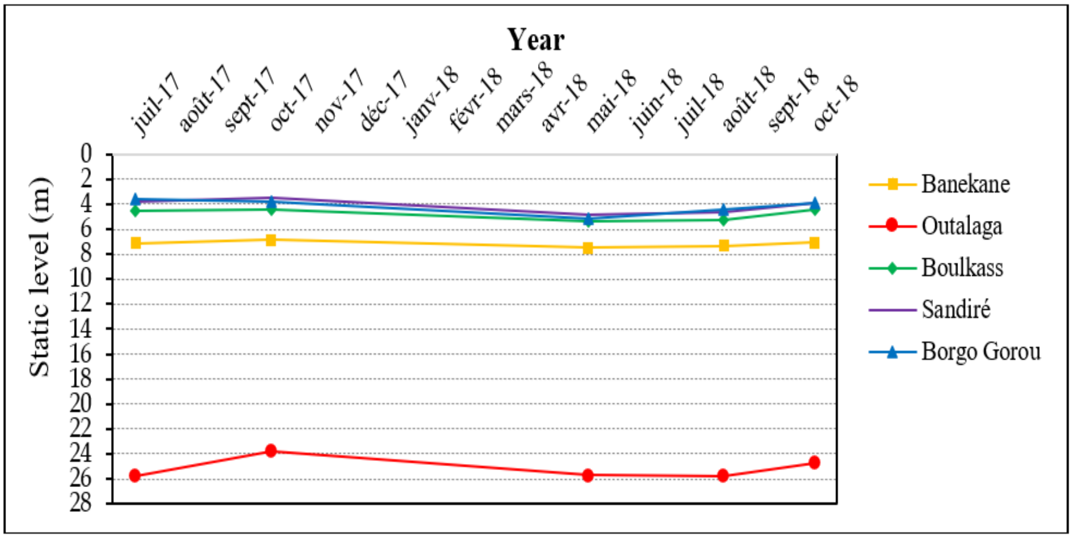

Figure 14 : Fluctuation of the static level of the alluvial table of dallol Bosso.

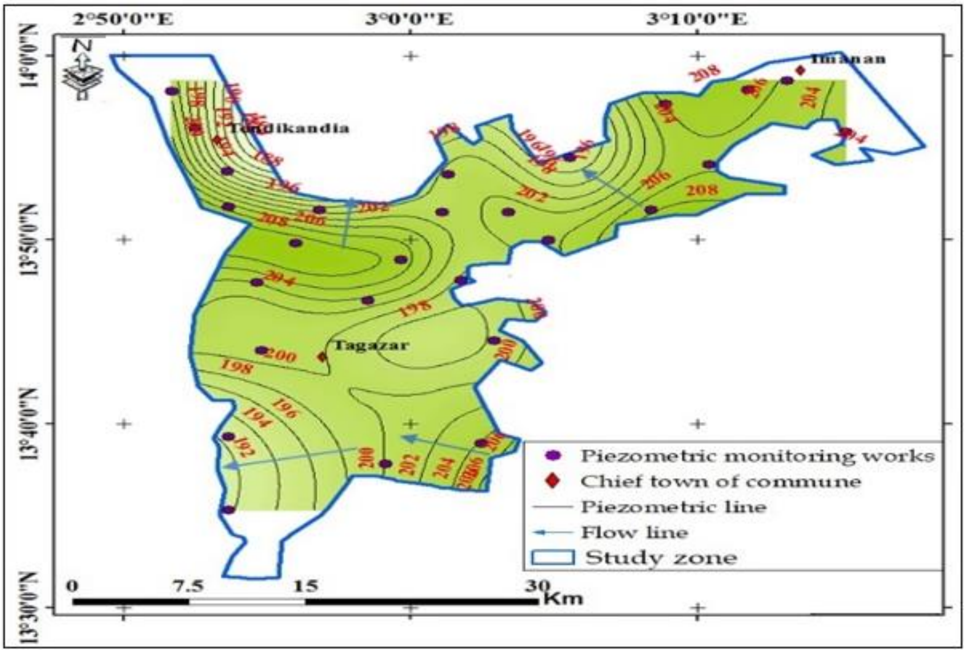

Figure 15 : Piezometric map of dallol Bosso during the high-water period (October, 2017).

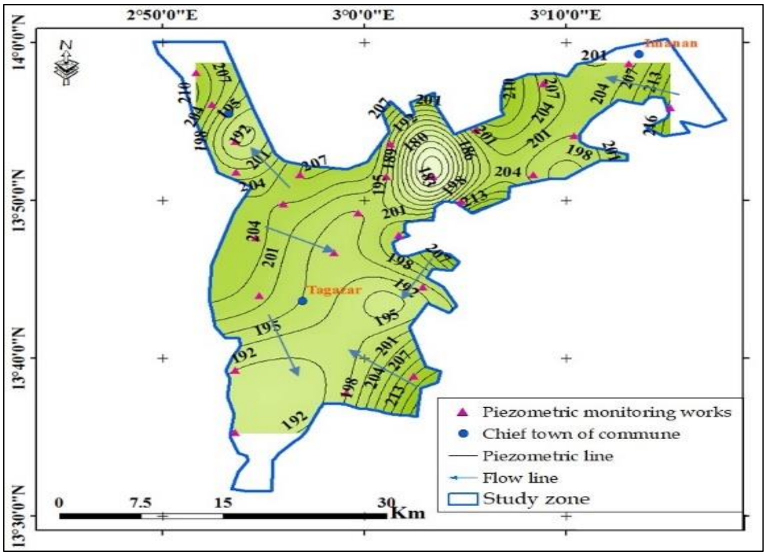

Figure 16 : Piezometric map of dallol Bosso during the high-water period (October, 2018).

Table 2: Values of Pb, Ph and D in dallol Bosso.

Piezometers (wells)	**Year**		**D**
	May-18	**Oct-18**	
	Pb (m)	**pH (m)**	
Banekane	7.46	7.05	0.41
Bomberi	9.15	8.6	0.55
Bangario	3.75	3.03	0.72
Tanka Warbou	7.62	6.93	0.69
Sofani Djerma	19.7	19.07	0.63
Borgo Gorou	5.18	3.88	1.3
Outalaga kobi	25.73	24.72	1.01
Boulkass	5.35	4.45	0.9
Sandire	4.8	3.86	0.94
Average			**0.79**

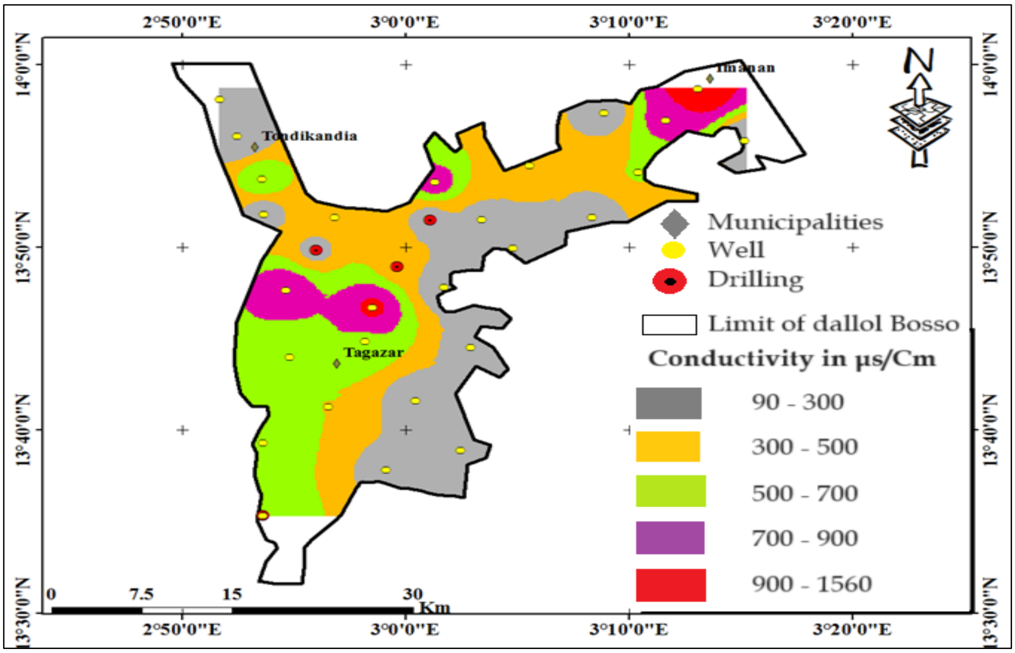

Figure 17 : Spatial distribution of water conductivities in the study area, October 2018 campaign.

DISCUSSION

The average annual rainfall for the period from 1981 to 2017 being estimated at 440.3 mm at the Baleyara station, it is 408.73 mm at that of Filingue for the period from 1950 to 2017, hence a drop in this last from south to north in the study area, linked to the movement of the FIT in Niger in accordance with the results of previous studies (Favreau, 2000; Maigary, 2018). The estimation of the water balance using the Thornthwaite method showed that from the month of August, a considerable contribution of rain, the drop-in temperature and the reduction in evapotranspiration allow the recharge of the aquifer. in accordance with previous studies on samples in Niger (Guéro, 2003; Favreau, 2000; Hassane Saley, 2018; Maigary 2018). However, August and September are the only surplus months. The other months of the year are always in deficit. These results are close to those found by (Oumarou, 2016 and Hayo, 2017).

The water temperature values in the study area are all above 25°C. The mean and median values are close to those found by (Guéro, 2003), respectively 31.6°C and 31.7°C in the boreholes of the free aquifer of the CT of the southwest edge of the Iullemenden basin. They are also close to the atmospheric average (32.9°C) recorded in October 2016 at the Niamey airport station, or even to the atmospheric averages of arid zones in the Sahel (Abdou Babaye et al., 2015; Abdou Babaye et al., 2016; Hassane Saley, 2018; Djahadi et al., 2021). The pH results show that the waters of the northern part of the Bosso dallol have an acidic to basic character. The basic pH values are close to those found by (Amadou et al., 2014; Maigary, 2018) in the Dallol Bosso wells, respectively in Sandiré and Bonkoukou. The acidic pH values found are similar to those of (Oumarou, 2016; Abdou Sani Oumarou, 2022; Seki et al., 2024), which showed acidic waters in the southern part. The acidic character of this water is due to their origin (rainwater by direct infiltration and runoff) on the one hand, but also to the free nature of the reservoir. Indeed, according to (Beauchamp, 2006), the pH is acidic in the waters of free sandy or granite aquifers and becomes more and more basic at depth or in a confined environment (Hassane Saley et al., 2019). The conductivity values of the waters of the alluvial aquifer of Dallol Bosso indicate that 80% of the samples measured have contents less than or equal to 500 µs/cm and 20% have contents greater than this value. These values are very close to those found by Maigary (2018) in the same area of the Bosso dallol.

The dynamics of land use observed in the area have negative effects on the hydrological regime. The analysis of the evolution of the state of land use from 1972 to 2014 made it possible to highlight a generalized degradation of the dallol Bosso ecosystem, the main factors of which in accordance with previous studies (Maigary, 2018) are demographic pressure (expansion of residential areas); new cultivation practices (destructive to the environment) and climate change. This degradation results in a regression of cultivation areas under tree parks and fallows in favor of areas of continuous rainfed cultivation, residential areas and bare soils. This is why actions to restore and recover the soil in this valley and raise awareness among populations about the consequences of certain practices seem essential.

Mineralization is low with an average of 200 mg/L in most of the valley, with the exception of the center and the extreme north of Dallol Bosso. These results are close to those found by (Maigary, 2018; Laoualy et al., 2018; Konate et al., 2018) in the study area. This strong mineralization may be due to high levels of certain chemical elements (nitrate, potassium, iron) exceeding the standards set by the WHO.

The interpretation of the piezometric map shows a general flow direction along the North valley towards the south, this is in accordance with the results found by (Maigary, 2018 and Oumarou, 2016). These flow directions are also consistent with those found by (Favreau, 2000; Guéro, 2003; Maigary, 2018; Hassane Saley et al., 2019) for the aquifers of the Continental Terminal and those of the Continental Intercalaire/Hamadien in the basin of Iullemeden, whose outlet is the Niger River.

The shallow catchment depths of the alluvial aquifer in the study area constitute an enormous risk of pollution of the aquifer waters, linked to anthropogenic activities. This has already been demonstrated by (Maigary, 2018). On the other hand, these shallow depths easily ensure the capture of said aquifers without major difficulties (Ibrahim, 2010; Maigary, 2018), which could favor the development of small-scale irrigation.

The average annual recharge is 0.79 m in the year 2018. The surface area of the aquifer is estimated at approximately 911 km2 and the storage coefficient being assumed uniform is equal to 2.10‾1, we can estimate that the annual recharge of the water table is equal to 1.43.108 m3 in 2018, these results are similar to those found by (Maigary, 2018) in the study area.

Conclusion

At the end of this study, the main results obtained show that the study area is subject to a Sahelian type climate, with strong monthly and annual precipitation irregularities. The interannual evolution of precipitation from the years 1981 to 2017 at the Baleyara station and from 1950 to 2017 for the Filingué station, showed that the climate is characterized by a succession of wet, dry and normal periods. Thus, the calculation of the hydrological balance using the Thornthwaite method shows that from August onwards, precipitation is greater, thus leading to a predominance over evapotranspiration allowing the recharge of the alluvial aquifer. The aquifer is recharged only from precipitation water. Land use has changed significantly in the dallol Bosso area. The diachronic analysis of satellite images from 1972 to 2014 made it possible to highlight changes in this occupation. The expansion of human habitation areas, peri-urbanization and poor agricultural practices, combined with climatic factors, has caused soil degradation. The alluvial aquifer reservoir consists of medium to coarse sand, with an average depth of 14.66 m. It is covered by aeolian or fluvial deposits. The depths of the static level are variable, and vary according to the topography of the land. The interpretation of the piezometric map of the alluvial aquifer of dallol Bosso shows that the axis of the general flow is mainly directed from north to south with the presence of piezometric domes favorable to recharge locally. The waters are acidic to slightly basic, with temperatures similar to those of ambient air. In this area of dallol Bosso, we can estimate a significant annual recharge of the water table, favorable to the development of irrigation. Finally, it remains necessary to continue investigations into this aquifer, in order to better assess its potential for sustainable management of these groundwater resources.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

AKHS: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing - original draft, Writing - review and editing. IS: Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Writing - review and editing. **ISG**: Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Writing - review & editing. BMA: Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Writing - review and editing. MI: Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Writing - review and editing.

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