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**ARTICLE**

# Inventory and Characterization of the Artesian Boreholes of Dallol Maouri in the Dosso Region in Niger

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## ABSTRACT

This study aims to list and characterize the artesian boreholes of the Dallol Maouri valley, in the Dosso Region (Niger), and to assess their water potential with a view to their development for irrigation. The Dallol Maouri is one of the country's most dynamic agricultural areas, where groundwater is the main source of supply for drinking water, irrigation and pastoral activities. Despite the drilling of many artesian boreholes over several decades, their contribution to agricultural development remains limited due to insufficient knowledge of their hydrogeological characteristics and their operational condition. The methodology is based on an integrated approach combining the analysis of bibliographic and technical data, an exhaustive inventory of artesian boreholes supported by field surveys and in situ measurements (condition of the structures, flows and uses), as well as statistical, hydrogeological and spatial analyses under GIS. Forty-one artesian boreholes were inventoried, 93% of which are still flowing. The structures mainly exploit the aquifers of the Intercalary Continental/Hamadien (CI/H) and the lower Continental terminal ($Ct^1$). Boreholes tapping the CI/H show high flows, reaching up to 257 $m^3/h$, while those of the $Ct^1$ display flows below 40 $m^3/h$. The results highlight a significant and easily mobilizable water potential for irrigation, contrasted with an advanced deterioration of the structures, 78% of which are in poor condition and require urgent rehabilitation actions. The demonstration of the morpho-structural control of artesian-ism constitutes a decision-support tool for the siting of hydraulic structures and the integrated management of water resources

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in the Dallol Maouri sub-basin.

***Keywords:*** Dallol Maouri; Artesian Aquifer; Irrigation; Inventory

# 1. Introduction

The Dallol Maouri valley, located in the north in the Sahelian zone and in the south in the Sudanian zone of Niger[1], suffers the negative and persistent impacts of climate variability, leading to recurrent agricultural production deficits[2]. This area is also characterized by sustained population growth, from 1,012,056 inhabitants in 2012 the population is 1,578,359 inhabitants in 2024[3]. This increases pressure on natural resources and particularly on water potential. In this area, which constitutes the syncline of the Iullemmeden Basin[4,5], the Meso-Cenozoic fill is more than 1,000 m thick and is composed of the Continental Intercalary/Hamadien formations of Upper Cretaceous age, overlain by levels 1, 2 and 3 of the Terminal Continental formations[4,6]. The whole is covered by the valley's alluvial deposits of Quaternary age. The deepest aquifer levels, beyond 300 m, are confined and most often artesian, which has allowed the drilling of several artesian boreholes intended for drinking water supply or irrigation over the decades. Despite the existence of a significant groundwater potential, the lack of knowledge of the real condition and performance of the artesian boreholes limits their development and raises the question of the sustainability of the resource in a context of increasing pressures. The inventory of artesian boreholes, therefore, constitutes a fundamental step in understanding the aquifer systems and in the sustainable management of groundwater resources, particularly in a Sahelian and semi-arid context[7,8]. This study is also justified by the decrease in artesian pressure currently observed in the study area, with extinction of artesianism on some structures, reducing access to water for the different uses (drinking water supply, irrigation, livestock), and increasing the socioeconomic vulnerability of the populations[9]. This drop in artesian pressure is interpreted by some authors as the consequence of overexploitation of the aquifers that caused depletion of the resource[1,10], or the deterioration of structures that led to a decrease in their initial performance[1]. In this context, the absence of reliable data on the location, condition, hydraulic performance and uses of the boreholes constitutes a major obstacle to the rational and sustainable management of the resource[11]. Hence, the need to carry out an inventory and characterization of the artesian boreholes in order to better assess the exploitable potential and to guide actions for the development of irrigation[12]. The present study reports the results of this inventory, the analysis of the data collected and proposes recommendations for a sustainable and rational management of these fossil water resources. To do this, the article is structured into three (3) main parts. (i) the materials and methods section, (ii) the results obtained section and (iii) the discussion of the results section.

The study is fundamentally based on a conceptual hydrogeological model describing the functioning of artesian aquifers and the processes controlling artesian discharge decline[13,14]. In such systems, artesian flow is governed by regional piezometric conditions, aquifer transmissivity, and borehole characteristics. Based on existing hydrogeological knowledge of artesian aquifers, a conceptual model was developed to guide the methodological approach and data interpretation in this study (**Figure 1**).

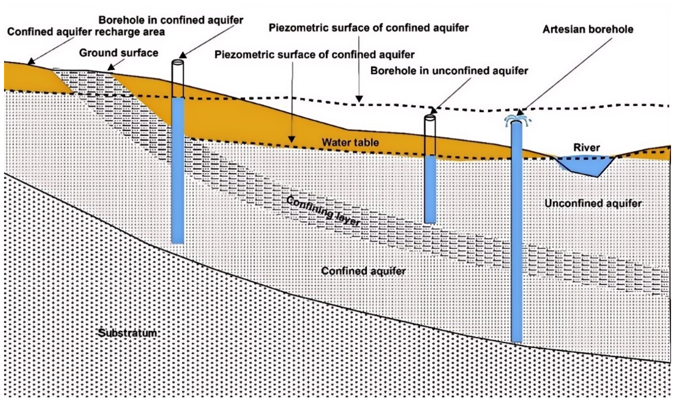


**Figure 1.** Conceptual model illustrating the main natural and structural controls on artesian fow.

## 2. Study Area

The study area, located in the southwest of Niger, corresponds to the geographic and administrative area of the departments of Dogondoutchi, Tibiri, Dioundiou and Gaya, in the Dosso Region. It covers an area of approximately 15,020 km$^2$ and extends between 11°07′ and 14°06′ North Latitudes and between 03°02′ and 04°06′ East Longitudes (**Figure 2**). Because of more favorable living conditions related to the availability of resources and socio-economic activities in Nigeria and other regions of Niger, the study area has a relatively higher human density compared to other regions. Its population rose from 1,012,056 inhabitants in 2012 to 1,578,359 inhabitants in 2024, of whom 50.64% are women[3]. Livestock, which is the second activity after agriculture, is expanding significantly; the herd increased from 1,674,942 head (664,026 LU) in 2012 to 2,826,693 head (1,213,126 LU) in 2024[15].

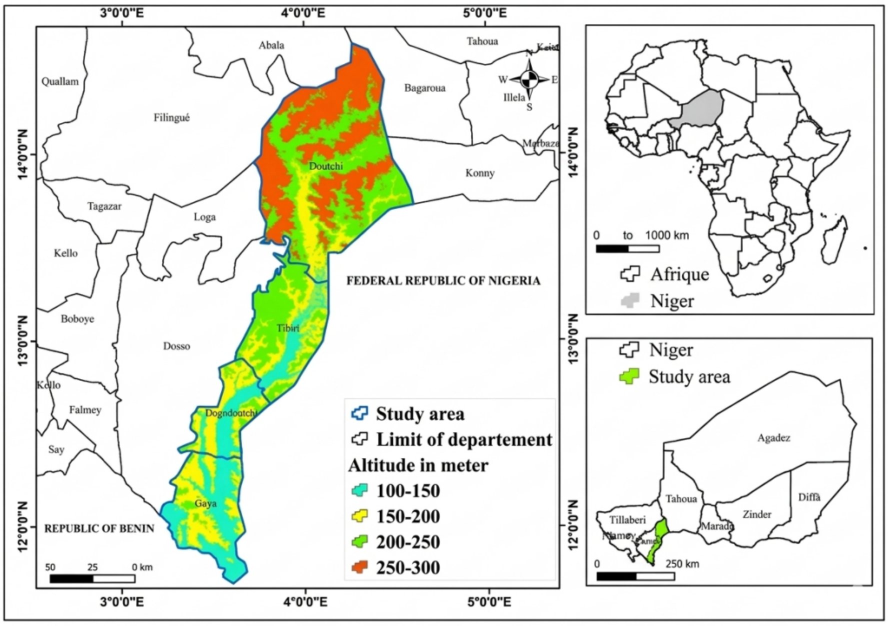


**Figure 2.** Location map of the study area.

The study area has two distinct climatic regimes separated by latitude 12°30′ N: a Sahelian climate in the north and a North-Sudanian climate in the south, with a north–south rainfall gradient of about +138 mm/100 km[1,16,17]. The region experiences a rainy season from June to September, marked by the monsoon, and a dry season from October to May, dominated by the harmattan.

The geological formations found in the study area, from bottom to top[1,4,18], are:

- The Precambrian crystalline basement, encountered at a depth of 300 to 400 m upstream, and composed of crystalline schists and gneisses;
- The deposits of the Continental Intercalaire (CI), which, according to Kilian (1931), refer to the poorly dated formations that separate the latest deposits of the Primary (Carboniferous) from those of the first marine transgression of the Secondary (Upper Cenomanian). They consist of fine to coarse sandstones with silicified wood and vertebrate remains: dinosaurs, crocodilians and Ceratodus[1,4]. Although these formations do not outcrop in the study area, several authors report that the sediments encountered in the Dogondoutchi Km 300 borehole, which did not reach the basement at 754 m, could belong to the Continental Intercalaire, on which, in this sector, the Continental Hamadian formations rest[1,4,18];
- The deposits of the Continental Hamadian (CH), of Senonian age, alternating fine sands and sandy clays. The thickness of the CH series varies from 200 m upstream in the Dogondoutchi sector to less than 10 metres south of the study area, particularly along the Ankoura–Bana–Kawara N'Débé line, then passing between Béla

and Adiga Kaboyé, where they are overlain by alluvium;

- The series of the Terminal Continental, namely the siderolithic series of Adar Doutchi ($Ct^1$), the clay-sand series with lignites ($Ct^2$) and the clayey sandstones of the Middle Niger ($Ct^3$);
- Recent Quaternary formations represented by old and recent sand dunes, and alluvium of various ages in the valleys of the Dallol Maouri and the Niger River (between 0 and 50 m).

The groundwater resources of the Dallol Maouri valley are distributed among six main types of aquifers [1,19,20] as follows:

- Basement aquifers, consisting of fractured and weathered horizons of crystalline and metamorphic formations, tapped at about 60 m in the commune of Tanda;
- The Continental Hamadian, confined and artesian, with pressures > 2 bars and flows greater than 150 $m^3/h$;
- The Terminal Continental: composed of three (3) hydrogeological units including the lower Terminal Continental ($Ct^1$), confined and artesian, with flows of about 50 $m^3/h$; the middle Terminal Continental ($Ct^2$), confined to semi-confined in the Dogondoutchi sector, non-artesian, in hydraulic continuity with the unconfined water table of $Ct^3$, which can be locally charged by clay lenses [21];
- Quaternary aquifers, alluvial water tables of the valleys of the Dallol Maouri and the Niger River, shallow and heavily used for drinking water supply, livestock watering and irrigation, with a relatively low mobilization cost. These aquifers represent a major hydrogeological potential, the unconfined water tables being the most exploited by local populations.

# 3. Materials and Methods

## 3.1. Materials

The materials used for this work include data and tools. The data include: project and program reports related to the implementation of artesian drilling in the study area; technical and lithological logs, as well as the technical characteristics of the artesian wells of the Dallol Maouri; the flow rates and pressures measured in situ, as well as the geographic coordinates of the structures recorded in the field. The tools include: a GARMIN brand Global Positioning System (GPS) for surveying geographic coordinates and locating the drillings; flow and pressure measuring equipment, including graduated buckets, a stopwatch and a manometer; a digital camera to document the sites and structures, and small camping equipment for fieldwork in isolated areas.

## 3.2. Methods

A multicriteria approach integrating hydrogeological and spatial data was used in this study to inventory and characterize artesian boreholes, and to assess the water potential of the artesian aquifers. These approaches have been used by other similar studies [15,22,23]. It comprises the following four (4) steps:

- The document review, which aims to: identify the projects and programs that drilled artesian wells in the study area; process and analyze existing activity reports; synthesize the collected information in the form of tables; present the provisional situation of the artesian boreholes of the Dallol Maouri (number, technical and lithological logs, technical characteristics); and prepare the preliminary inventory report of the artesian wells;
- The fieldwork, which made it possible to: verify, clarify and complete the preliminary inventory report; systematically list the artesian boreholes in the study area; locate the structures (department, commune, village, geographic coordinates); assess the condition of the boreholes (functionality, equipment); measure the flows and pressures of the structures; and list the uses and management methods of the boreholes. The sampling strategy was based on a comprehensive field inventory of artesian boreholes within the study area. Only boreholes exhibiting controlled artesian flow conditions were selected for flow rate measurements, in order to ensure reliable and reproducible quantitative data. Boreholes characterized by diffuse, scattered, or non-channelized flows were excluded from the quantitative analysis, as such hydraulic conditions do not allow accurate flow rate determination. This selection approach was adopted to guarantee the consistency and robustness of the discharge dataset. Artesian flow rates were measured using two complementary methods depending on borehole configuration and available equipment: (i) a volumetric method based on the time required to fill calibrated con-

tainers of known volume, and (ii) a volumetric flow meter for equipped boreholes. When possible, both methods were systematically applied to the same borehole, and measurements were repeated using containers of different volumes. The reported flow rate corresponds to the mean of repeated measurements. This protocol reduced measurement uncertainty, which was estimated to be less than 5%;

- The interviews with users, organized in order to: verify the accuracy of the data collected in the field; collect additional information on the management and operation of the artesian wells; and identify local practices as well as any problems related to the use of water resources.
- the Geographic Information System (ArcGIS 10.3) was used to produce the spatial distribution maps of the artesian boreholes and their condition using the classify option in symbology;
- the statistical analysis was designed within an explicit conceptual framework linking borehole age and depth to the observed decline in artesian flow rates through hydrodynamic and structural processes. Pearson correlation analysis was first applied to explore linear bivariate relationships and to assess potential collinearity among variables. The choice of a statistical significance threshold of $p < 0.05$ follows standard practice in hydrogeological and environmental studies. To investigate the relationships between flow rate and borehole age, flow rate and borehole depth, borehole depth and borehole age, and identify the explanatory factors, simple linear regression under the classical OLS (Ordinary Least Squares) assumptions was subsequently applied, and model validity was assessed using standard diagnostic tests implemented with R packages. Regression analysis remains a common and interpretable tool in hydrogeological research for identifying significant linear relationships between environmental predictors and hydrological responses, even when more advanced machine learning techniques are also employed for comparison or enhancement [24,25].

For each relationship, a simple linear model was fitted:

$$Y = \beta_0 + \beta_1 + \varepsilon$$

Where:

- $Y$ is the dependent variable (discharge decline or depth),
- $X$ is the explanatory variable (age or depth),
- $\beta_0$ is the intercept,
- $\beta_1$ is the slope coefficient,
- $\varepsilon$ is the error term, assumed to be normally distributed.

The coefficients were estimated using the OLS method, which minimizes the sum of squared residuals:

$$\min_{\beta_0,\, \beta_1} \sum_{i=1}^{n} (Y_i - \beta_0 - \beta_1 X_i)^2$$

The coefficient of determination ($R^2$) was used to quantify the proportion of variance explained by the model, and the statistical significance of the regression coefficients was assessed using Student's $t$-tests, with:

$$t = \frac{\widehat{\beta_1}}{\mathrm{SE}\widehat{\beta_1}}$$

where $\mathrm{SE}\widehat{\beta_1}$ is the standard error of the estimated slope.

To verify the classical assumptions of linear regression, three main diagnostic tests were applied as follows.

## Residual Normality Test (Shapiro–Wilk Test)

Null hypothesis ($H_0$): the residuals follow a normal distribution.

Test statistic:

$$\boldsymbol{W = \frac{\left(\sum_{i=1}^{n} a_i Y_{(i)}\right)^2}{\sum_{i=1}^{n} \left(Y_i - \overline{Y}\right)^2}}$$

Where $Y_{(i)}$ are the ordered residuals and $a_i$ are coefficients based on the mean and variance of the residuals.

Interpretation: $p < 0.05$ indicates non-normally distributed residuals.

## Heteroscedasticity Test (Breusch–Pagan Test)

Null hypothesis ($H_0$): constant variance of the residuals (homoscedasticity, $\sigma^2$ constant).

Test statistic: $\boldsymbol{LM = \eta .\ R^2_{aux}}$

where $\boldsymbol{R^2_{aux}}$ is the coefficient of determination of an auxiliary regression of the squared residuals on the explanatory variables.

Interpretation: $p < 0.05$ indicates significant heteroscedasticity.

## Residual Autocorrelation Test (Durbin–Watson Test)

Null hypothesis ($H_0$): absence of autocorrelation among successive residuals.

Test statistic: $DW = \frac{\sum_{t-2}^{n}(e_t - e_{t-1})^2}{\sum_{t-1}^{n}(e_t)^2}$

where $e_t$ and $e_{t-1}$ are the residuals.

Interpretation: DW ≈ 2 indicates no autocorrelation; DW < 2 indicates positive autocorrelation; DW > 2 indicates negative autocorrelation.

# 4. Results

The inventory of artesian boreholes carried out in the Dallol Maouri valley made it possible to determine their number, their geographical distribution, their operational status as well as their main uses.

## 4.1. Situation of the Artesian Boreholes of Dallol Maouri

The records related to the inventory of artesian boreholes are compiled in **Table 1**. A total of 41 artesian boreholes drilled between 1956 and 2019 by the State and its partners were recorded. The depth of the boreholes ranges from 42 m at Béllawa to 444 m at Guéchémé.

**Table 1.** Inventory of artesian boreholes of the Dallol Maouri.

| N°IRH | Commune | Village | Longitude | Latitude | Year of Completion | Aquifèr | Depth (m) | Status |
|---|---|---|---|---|---|---|---|---|
| 321015 | Dogondoutchi | Dogondoutchi | 4.0332 | 13.6399 | 1956 | Ct1 | 340 | Inactif |
| 321142 | Kiéché | Kiéché | 4.012 | 13.4823 | 1986 | Ct1 | 281 | Actif |
| 321082 | Matankari | Bagagi | 4.0441 | 13.8573 | 1969 | Ct1 | 294.7 | Actif |
| 321143 | Dankassari | Dankassari | 4.38015 | 13.72015 | 1972 | Ct1 | 208 | Actif |
| 300719 | Douméga | Gida | 4.0273 | 13.0433 | 2017 | CI/H | 375 | Actif |
| 323041 | Tibiri | Tibiri | 3.9986 | 13.1064 | 1967 | CI/H | 368 | Actif |
| 322077 | Guéchémé | Lokoko | 3.8918 | 12.8598 | 2015 | CI/H | 354 | Actif |
| 322039 | Guéchémé | Guéchémé | 3.8706 | 12.909 | 1967 | CI/H | 444 | Actif |
| 345009 | Yélou | Yélou | 3.5753 | 12.2599 | 1969 | CI/H | 129 | Actif |
| 345229 | Yélou | Sormo | 3.5808 | 12.3444 | 2014 | Ct1 | 58 | Actif |
| 345111 | Yélou | Mamaro | 3.437 | 12.3944 | 1998 | Ct1 | 50 | Actif |
| 345091 | Yélou | Béllawa | 3.4343 | 12.3778 | 1998 | Ct1 | 42 | Actif |
| 345198 | Yélou | Daniakou | 3.5224 | 12.2877 | 2009 | Ct1 | 88 | Actif |
| 345230 | Yélou | Tounga Sala | 3.4324 | 12.3862 | 2014 | Ct1 | 62 | Actif |
| - | Yélou | Garin Kio | 3.5212 | 12.228 | 2016 | Ct1 | 65 | Actif |
| - | Yélou | Illéla 2 | 3.5241 | 12.1188 | 2016 | Ct1 | 100 | Actif |
| 345009 | Yélou | Sabon Gari | 3.4325 | 12.3834 | 1969 | CI/H | 52.8 | Actif |
| 8900 | Dioundiou | Dioundiou 1 | 3.5493 | 12.6188 | 1969 | CI/H | 184 | Actif |
| 8901 | Dioundiou | Dioundiou 2 | 3.5492 | 12.6187 | 1969 | CI/H | 184 | Actif |
| 300108 | Dioundiou | Dioundiou 3 | 3.5494 | 12.6186 | 2012 | CI/H | 186.1 | Actif |
| 342118 | Dioundiou | Dioundiou 4 | 3.5478 | 12.6161 | 2016 | CI/H | 187.1 | Actif |
| 342116 | Dioundiou | Dioundiou 5 | 3.5487 | 12.6173 | 2015 | CI/H | 170 | Actif |
| 342097 | Dioundiou | Takalafia | 3.5257 | 12.3968 | 1989 | Ct1 | 102 | Actif |
| 342013 | Dioundiou | Koutoumbou 1 | 3.5824 | 12.4091 | 1970 | CI/H | 152 | Actif |
| 300127 | Dioundiou | Koutoumbou 2 | 3.5772 | 12.4085 | 2019 | CH+ Ct1 | 156 | Actif |
| 300128 | Dioundiou | Koutoumbou 3 | 3.5798 | 12.3977 | 2019 | CH+ Ct1 | 163 | Actif |
| 342102 | Dioundiou | Guéza Gado | 3.5276 | 12.4399 | 1998 | Ct1 | 72 | Actif |
| 342100 | Dioundiou | Amamara Toudou | 3.5882 | 12.5597 | 1998 | Ct1 | 134 | Actif |
| 342104 | Dioundiou | Doli | 3.632 | 12.412 | 1998 | Ct1 | 96 | Actif |
| 300114 | Dioundiou | Makangara | 3.5297 | 12.455 | 2015 | Ct1 | 45 | Actif |
| 300112 | Dioundiou | Koudoukoulou | 3.5712 | 12.4661 | 2015 | Ct1 | 50.5 | Actif |
| 300111 | Dioundiou | Shagari | 3.5495 | 12.5249 | 2015 | Ct1 | 63 | Actif |
| 342030 | Dioundiou | Madotchi | 3.5209 | 12.4086 | 1998 | Ct1 | 139 | Inactif |
| 8904 | Kara Kara | Kizamou | 3.7109 | 12.6995 | 1968 | CI/H | 251 | Actif |
| 344105 | Kara Kara | Yeldou | 3.7227 | 12.7538 | 2006 | CI/H | 192 | Actif |
| 344036 | Kara Kara | Agonga | 3.6654 | 12.7378 | 1998 | Ct1 | 110 | Inactif |
| 344052 | Kara Kara | Timba | 3.6592 | 12.6692 | 1998 | Ct1 | 123 | Actif |
| 344079 | Kara Kara | Massama | 3.648 | 12.7085 | 1998 | Ct1 | 141 | Actif |
| 344082 | Kara Kara | Angoual Laboua | 3.6282 | 12.7182 | 1998 | Ct1 | 147 | Actif |
| 343202 | Gaya | Kanda Koira Tégui | 3.5656 | 11.8163 | 2014 | CI/H | 72 | Actif |
| 341004 | Bengou | Bengou | 3.559 | 11.9795 | 1969 | CI/H | 346.35 | Actif |

**Figure 3** shows that these boreholes preferentially align along the main bed of the Dallol, following a north–south axis, with a more marked concentration in the southern part of the study area.

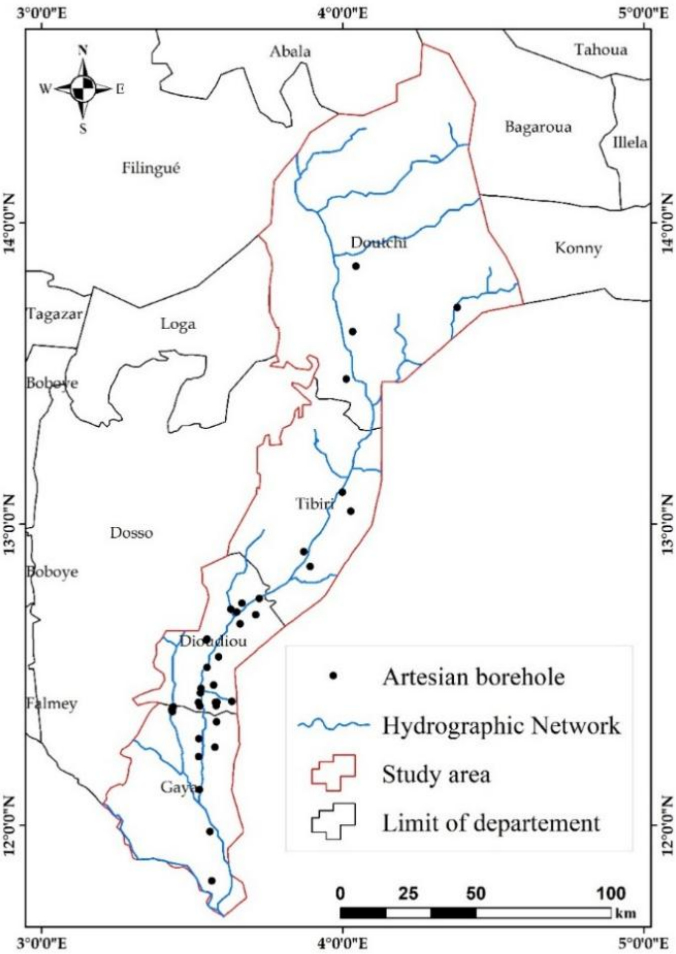


**Figure 3.** Location of the artesian boreholes of Dallol Maouri.

## 4.2. Hydrogeological Characteristics of Artesian Boreholes

The analysis of the technical and lithological logs of the works reveals that the artesian boreholes of the Dallol Maouri mainly exploit two large aquifers (**Figure 4**): the aquifer of fine to medium sands of the Lower Terminal Continental ($Ct^1$) and that of medium to coarse sandstones of the Intercalary/Hamadien Continental (CI/H).

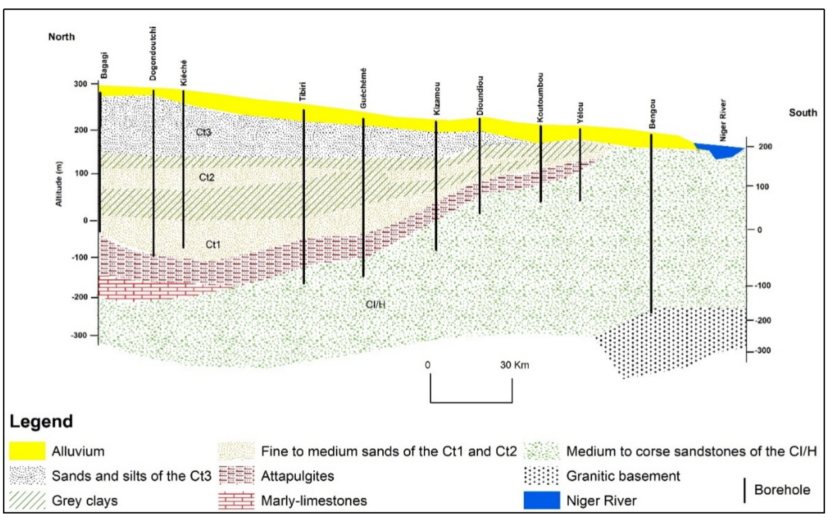


**Figure 4.** Synthetic North–South geological cross-section of the study area after modification [1].

Of the forty-one (41) boreholes identified, twenty-three (23) draw exclusively from $Ct^1$ and sixteen (16) draw from CI/H; while two (2) boreholes draw simultaneously from both aquifers. **Figure 5** shows that the works that draw from the $Ct^1$ aquifer are distributed across the entire study area, from Bagagi (Matankari Commune) in the northwest and Dankassari in the northeast, to Illéla 2 (Yélou Commune) in the south. In contrast, the boreholes that exploit the CI/H aquifer are located exclusively in the central and southern parts of the study area. The works that draw simultaneously from both aquifers correspond to the multi-use artesian boreholes of Koutoumbou, carried out in 2019 as part of the UEMOA program.

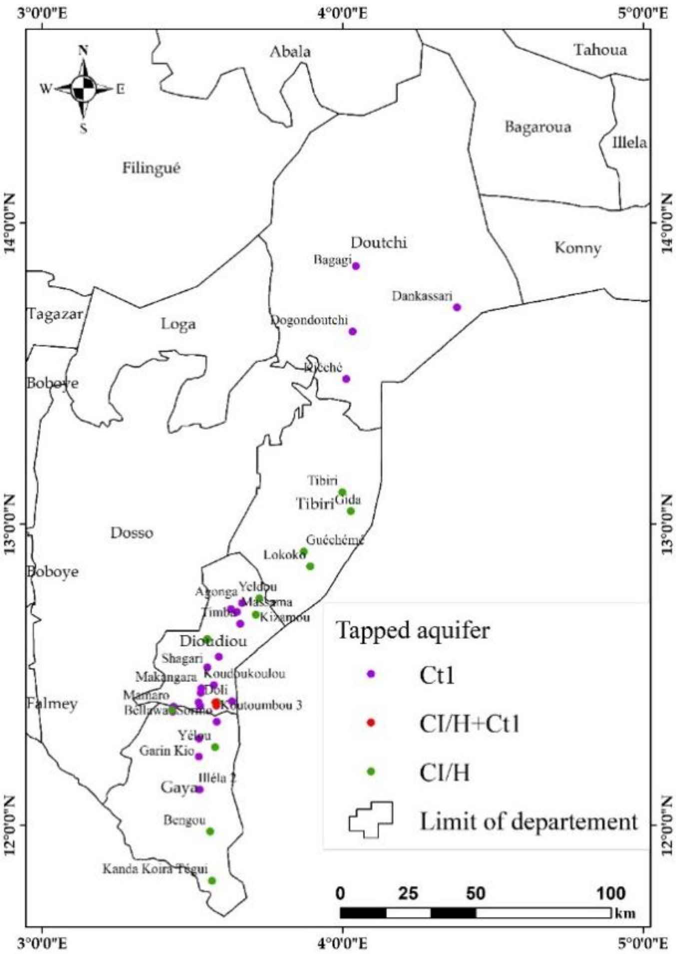


**Figure 5.** Distribution of artesian boreholes by aquifer type.

## 4.3. Operational Status of the Artesian Boreholes

In general, the artesian boreholes of Dallol Maouri are in an advanced state of degradation, with the artesian flow having ceased on some structures. **Figure 6** shows that as of November 5, 2024, thirty-eight (38) boreholes are flowing, approximately 93%, while three (3) are decommissioned, representing 7% of all structures. These include the artesian boreholes of Dogondoutchi, Agonga, and Madotchi.

Technical equipment such as casings and screens are made up of API steel tubes, stainless steel or polyvinyl chloride (PVC), of varying diameters, used to stabilize structures, ensure hydraulic isolation and the efficiency of water intakes. To this arrangement are added surface equipment, such as the wellhead and control and safety systems, which ensure the regulation and protection of the installations. However, regardless of their nature, the technical equipment of the artesian boreholes of Dallol Maouri is severely degraded. Indeed, a progressive deterioration of the works is observed, resulting from mechanical deterioration (**Figure 7a,b**) and/or chemical deterioration (**Figure 7c**) of the structures; from lack of upkeep and maintenance (**Figure 7d,e**); from the natural wear of the equipment; and from inappropriate infrastructure management. A progressive degradation of the environment is also observed, manifested by the formation of underground cavities, collapse phenomena and the gullying of the land.

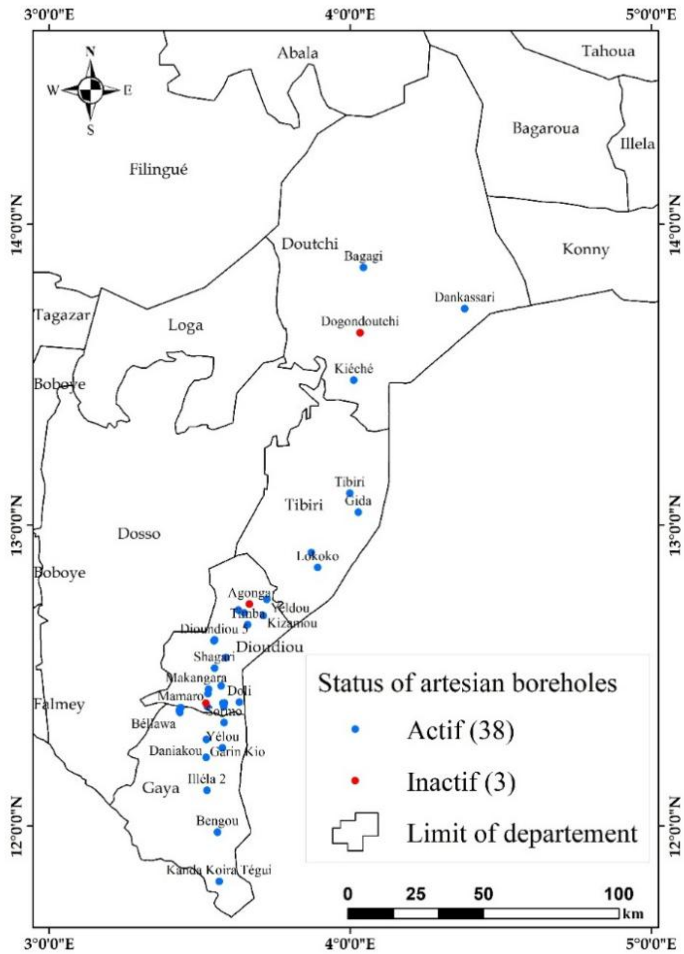


**Figure 6.** State of the artesian boreholes of Dallol Maouri on 11/30/2024.


**Figure 7.** Damaged technical equipment: (**a**) Drill head torn off by artesian pressure at Koutoumbou; (**b**) PVC casing and wellhead expelled by overpressure at Garin Kio; (**c**) Corroded drill head equipment at Yélou; (**d**) Flooded drill head at Timba; (**e**) Spontaneous and diffuse outflows on the Dioundiou 1 borehole.

## 4.4. Flow Rate Decline of Artesian Boreholes

Flow measurements were carried out on the 23 artesian boreholes whose outflows are controlled. The measured discharges, the initial discharges which represent the flows recorded on the date of commissioning of the works, and the percentage change in discharge during the observation period are presented in **Table 2**. The measured discharges range from 0.16 $m^3/h$ at Mamaro to 257 $m^3/h$ at Koutoumbou 2.

**Table 2.** Measured flow rates of the artesian boreholes of the Dallol Maouri.

| N° | Village | Longitude | Latitude | Year of Completion | Initial Flow | Flow Measured | Variation (%) |
|---|---|---|---|---|---|---|---|
| 1 | Bagagi | 4.0441 | 13.8573 | 1969 | 12 | 3.6 | −70.00 |
| 2 | Gida | 4.0273 | 13.0433 | 2017 | 49 | 54 | 10.20 |
| 3 | Lokoko | 3.8918 | 12.8599 | 2015 | 136 | 143.71 | 5.67 |
| 4 | Yélou | 3.5753 | 12.2599 | 1969 | 120 | 19.7 | −83.58 |
| 5 | Sormo | 3.5808 | 12.3444 | 2014 | 13 | 13 | 0.00 |
| 6 | Mamaro | 3.437 | 12.3944 | 1998 | 16 | 0.16 | −99.00 |
| 7 | Béllawa | 3.4343 | 12.3778 | 1998 | 6.7 | 2.25 | −66.42 |
| 8 | Tounga Sala | 3.4324 | 12.3862 | 2014 | 16 | 16 | 0.00 |
| 9 | Sabon Gari | 3.4325 | 12.3834 | 1969 | 85 | 0.72 | −99.15 |
| 10 | Dioundiou 2 | 3.5492 | 12.6187 | 1969 | 183.2 | 32.72 | −82.14 |
| 11 | Takalafia | 3.5257 | 12.3968 | 1989 | 38 | 16.36 | −56.95 |
| 12 | Koutoumbou 2 | 3.5772 | 12.4085 | 2019 | 257 | 257 | 0.00 |
| 13 | Koutoumbou 3 | 3.5798 | 12.3977 | 2019 | 100 | 100 | 0.00 |
| 14 | Guéza Gado | 3.5276 | 12.4399 | 1998 | 3.2 | 0.43 | −86.56 |
| 15 | Amamara Toudou | 3.5882 | 12.5597 | 1998 | 9 | 6 | −33.33 |
| 16 | Doli | 3.632 | 12.412 | 1998 | 13.9 | 4.5 | −67.63 |
| 17 | Makangara | 3.5297 | 12.455 | 2015 | 25 | 5.4 | −78.40 |
| 18 | Kizamou | 3.7109 | 12.6995 | 1968 | 66 | 25.5 | −61.36 |
| 19 | Yeldou | 3.7227 | 12.7538 | 2006 | 74 | 5.3 | −92.84 |
| 20 | Timba | 3.6592 | 12.6692 | 1998 | 6.6 | 1.8 | −72.73 |
| 21 | Massama | 3.648 | 12.7085 | 1998 | 14.3 | 6.27 | −56.15 |
| 22 | Angoual Laboua | 3.6282 | 12.7182 | 1998 | 15 | 3.87 | −74.20 |
| 23 | Kanda Koira Tégui | 3.5656 | 11.8163 | 2014 | 18 | 18 | 0.00 |

The **Figure 8** below reveals that the flow rates measured on the boreholes that tap Ct[1] are generally less than 40 $m^3/h$. In contrast, the boreholes that tap CI/H have overall flow rates greater than 40 $m^3/h$, sometimes even exceeding 100 $m^3/h$, except for that of Kanda Koira Tagui, which is set at 18 $m^3/h$ according to need.

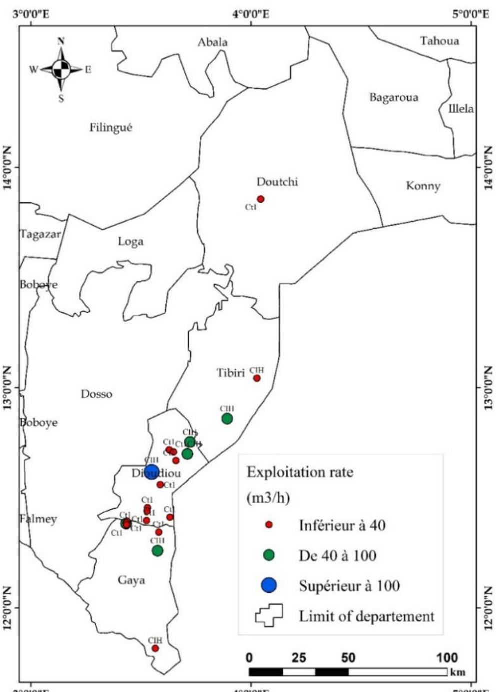


**Figure 8.** Spatial distribution of operating discharges of artesian boreholes.

The comparison of the flow rates measured at the boreholes with the flow rates recorded at the time they were commissioned (**Figure 9**) shows a significant decrease in flow for the older installations, reflecting a notable decline in productivity with length of operation. Indeed, the artesian boreholes at Dioundiou and Bagagi, drilled in 1969 as part of the Dallol Maouri development project, initially had flow rates of 183.2 $m^3/h$ and 12 $m^3/h$, respectively. Measurements taken in 2024 yielded flow rates of 32.72 $m^3/h$ and 3.6 $m^3/h$, respectively, corresponding to a reduction of about 82% at Dioundiou and 70% at Bagagi. In contrast, the new boreholes show flow rates comparable to or slightly higher than those observed at commissioning. This is notably the case for the artesian borehole at Lokoko, drilled in 2015 with an initial flow of 136 $m^3/h$ and a measured flow of 143.71 $m^3/h$ in 2024, and for Gida, drilled in 2017 with an initial flow of 49 $m^3/h$ and a measured flow of 54 $m^3/h$ in 2024.

Moreover, the Pearson correlation matrix (**Table 3**) shows a strong negative correlation (r = −0.67, $p < 0.01$) between the age of the boreholes and the decrease in flows, a moderate to weak correlation between the depth of the boreholes and the decrease in flows (r = 0.31, $p < 0.007$), and between the age and the depth of the boreholes (r = 0.05, $p < 0.41$).

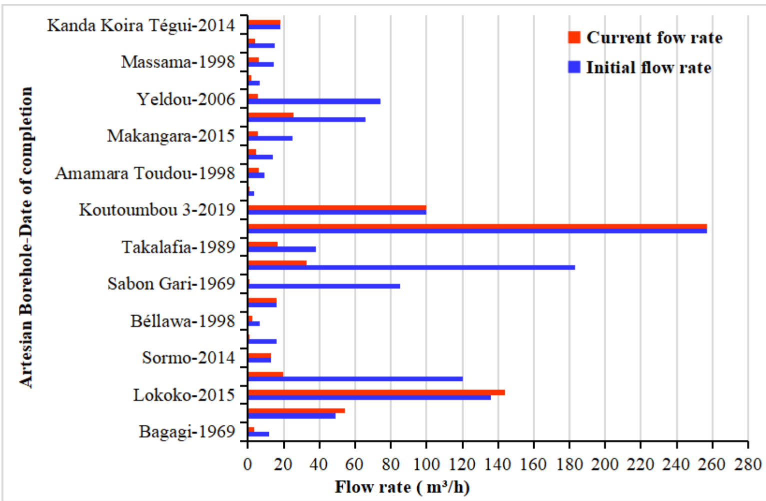


**Figure 9.** Comparison of initial and current flow rate of artesian boreholes.

**Table 3.** Pearson correlation matrix.

| Statistic | Variable | Age (year) | Decline in Artesian Flow (%) | Borehole Depth (m) |
|---|---|---|---|---|
| Correlation | Age (year) | 1 | −0.67 | 0.05 |
| | Decline in artesian flow (%) | −0.67 | 1 | 0.31 |
| | Borehole depth (m) | 0.05 | 0.31 | 1 |
| *p*-value | Age (year) | | 0.01 | 0.41 |
| | Decline in artesian flow | 0.01 | | 0.07 |
| | Borehole depth (m) | 0.41 | 0.07 | |

For the linear regression analyses, the observations for each relationship were displayed as colored points, the fitted regression as a red line, and the 95% confidence interval as a shaded gray area. The $R^2$ values, the regression equation, and the statistical significance of the coefficients were directly annotated on the plots to facilitate interpretation.

As shown in **Figure 10**, the decline in flow rate ($Y$) is explained by borehole age ($X$) according to the model: $Y = 12.91 + 1.44X$, with $R^2 = 0.443$, adjusted $R^2 = 0.416$, $p < 0.001$.

In **Figure 11**, borehole depth ($Y$) is explained by borehole age ($X$) according to the model: $Y = 136.5 + 0.26X$, with $R^2 = 0.002$, adjusted $R^2 = -0.045$, $p < 0.827$.

**Figure 12** shows that the decline in flow rate ($Y$) is explained by borehole depth ($X$) according to the model: $Y = 68.77 - 0.13X$, with $R^2 = 0.099$, adjusted $R^2 = 0.056$, $p < 0.143$. The relationship is weak and negative, indicating that each additional meter of borehole depth results in only a 0.13% decrease in flow. The model accounts for less than 10% of the variance in flow declines, suggesting that borehole depth has virtually no effect on the observed reduction in flow rate.

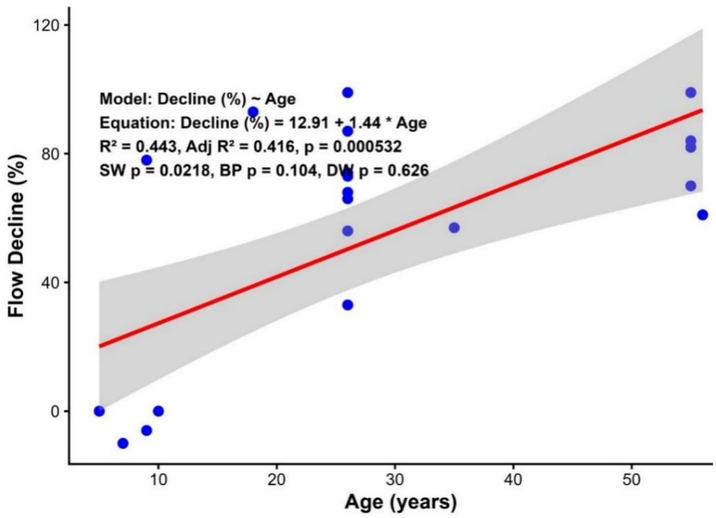


**Figure 10.** Relationship between the age of the borehole and flow decline.

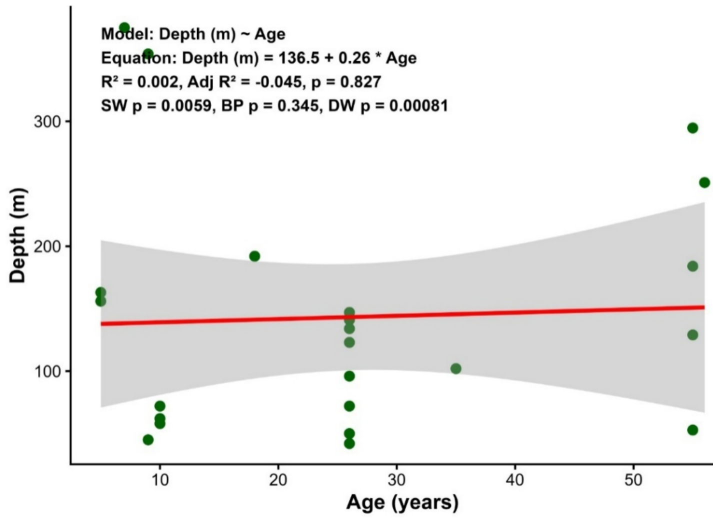


**Figure 11.** Relationship between age and borehole depth.

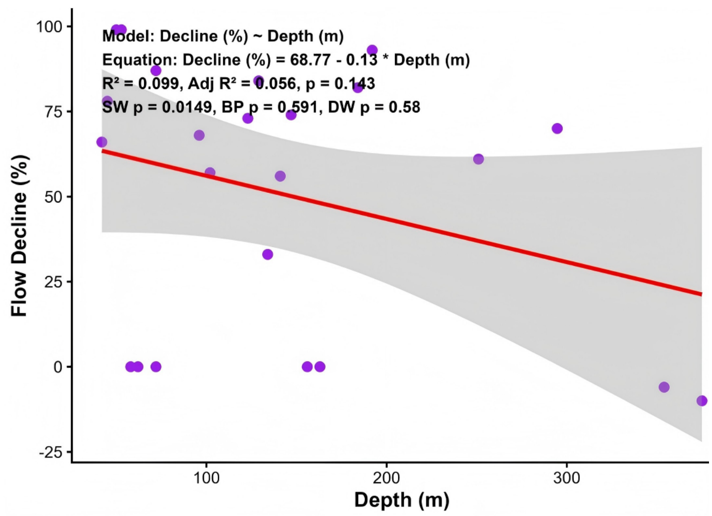


**Figure 12.** Relationship between borehole depth and decline in flow rate.

The diagnostic tests applied to the model residuals indicate overall satisfactory adherence to the classical assumptions of linear regression. The Shapiro–Wilk test ($p = 0.0149$) suggests a slight deviation from normality of the residuals. However, considering the sample size and the moderate extent of this non-normality, this deviation is deemed limited and does not compromise the overall validity of the coefficient estimates, particularly in an exploratory context.

The Breusch–Pagan test ($p = 0.591$) indicates no significant heteroscedasticity, suggesting that the residual variance can be considered constant. This reinforces the reliability of standard errors and significance tests associated with the regression coefficients.

Finally, the Durbin–Watson test ($p = 0.58$) reveals no significant autocorrelation of residuals, indicating that observations are independent and that the estimates are not affected by serial dependencies.

Overall, these results confirm the statistical robustness of the regression model and support that borehole depth has no effect on the observed reduction in flow rate.

## 4.5. Uses of Water from the Artesian Boreholes of the Dallol Maouri

Field surveys and discussions with local populations made it possible to inventory the uses surrounding the artesian wells of the Dallol Maouri. The main identified uses are: i) drinking water supply (DWS), ii) irrigation, iii) livestock watering, and iv) fish farming (**Figure 13**). Some boreholes have a multifunctional character, like the one at Yélou, used both for the drinking water supply of the populations, for irrigation, and for watering animals. Others, by contrast, are dedicated to a single use, such as the Dioundiou 2 borehole used by the NDE for supplying drinking water to the populations or those of Lokoko and Gida, used exclusively for irrigation. The 21% of structures are used for watering livestock, from the flows in the lowlands of the Dallol for transhumant herds, or from watering troughs in the villages, where sedentary herders combine agriculture and livestock on the same plots. Finally, the use for fish farming, which represents only 1% of the structures. This type of use is found only in the multi-use development of Koutoumbou, where two plastic ponds were built for this purpose. **Figure 14** shows some illustrative photos of the uses of artesian boreholes in the Dallol Maouri valley.

**Figure 13** shows that 46% of the recorded works are intended for supplying drinking water to the population. This type of use concerns urban hydraulics systems (**Figure 14a**), semi-urban hydraulics networks (**Figure 14b**), and predominantly, village hydraulics devices (**Figure 14c,d**). Uses associated with supplying drinking water also cover domestic needs such as food preparation, washing, laundry, as well as various sanitation activities within households. Artesian boreholes used for irrigation represent 32%, and concern a diversity of crops, notably cereals, market gardening, vegetables, fruit (**Figure 14e**) and fodder (**Figure 14f**). Other high value-added crops, such as moringa, sugarcane and peanut, are also grown in the study area in monoculture or polyculture arrangements. This crop diversity reflects the agronomic vocation of the Dallol Maouri valley, where artesianism constitutes an undeniable potential for the development of irrigated crops and the strengthening of the populations' resilience to climate hazards. However, the absence of control and regulation mechanisms for flows raises the issue of the use of these fossil water and soil resources, and that of sustainable agricultural development.

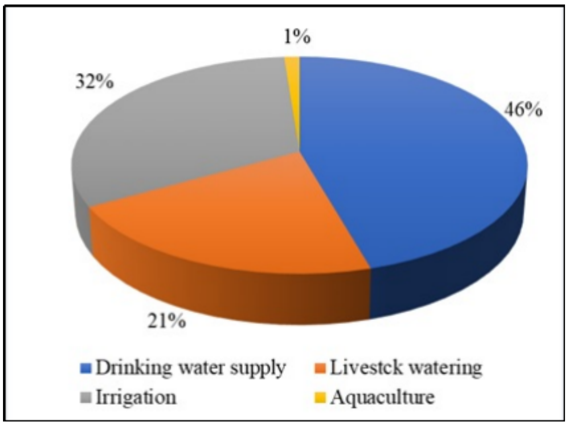


**Figure 13.** Distribution of artesian boreholes by type of use.

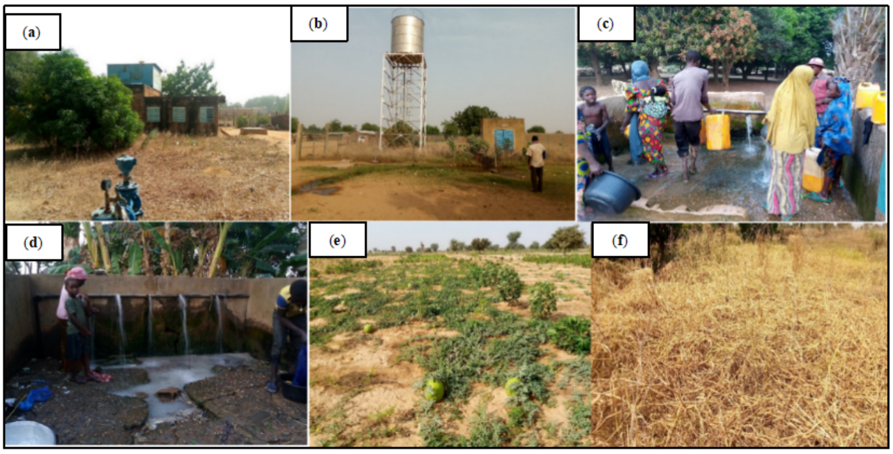


**Figure 14.** Sources of drinking water supply and crops: (**a**) Capture field of the Dioundiou AEP; (**b**) Pumping station of the Sormo mini-AEP; (**c**) Artesian borehole of the village of Takalafia; (**d**) Artesian borehole of the village of Timba; (**e**) Irrigated watermelon crops on the Gida AHA; (**f**) Irrigated forage crops on the Lokoko AHA.

# 5. Discussions

This study highlighted a considerable water potential around the artesian boreholes of the Dallol Maouri, mainly linked to the presence of the Continental Intercalaire/Hamadien (CI/H) and lower terminal Continental ($Ct^1$) aquifers, confined and flowing in the Dallol Maouri valley [1]. **Figure 4** established from the technical and lithological logs of the artesian boreholes in the study area, shows the geometry and lithology of the aquifers that condition artesianism in the valley. The CI/H aquifer, composed of medium to coarse sandstones, is pressurized by the granitic basement that constitutes the substratum and the impermeable marl-limestone series of Paleocene-Eocene age. The aquifer of the lower sands of the terminal Continental ($Ct^1$) is loaded by the overlying marl-limestone series and the lower layer of gray clays with lignites of the middle terminal Continental ($Ct^2$). The preferential alignment of the artesian boreholes along the main bed of the Dallol and its branches (**Figure 3**) clearly reflects the influence of the geomorphological and structural framework of the Iullemmeden basin on the dynamics of the aquifers. These axes, oriented generally north–south, correspond to well-established paleo-channels, inherited from the tectonic history of the basin, and constitute topographic depressions where flows and detrital deposits concentrate [1,4,16,19,26–29]. These results are consistent with the findings of Sandiford et al. [30], which highlighted the influence of the tectonic structure of the Great Artesian Basin of Armenia on groundwater flow. More recent studies [20,21] have also shown the influence of paleo-structures on groundwater circulation, thus reinforcing the hypothesis of a morpho-structural control of artesianism in the Dallol Maouri valley. The marked recurrence of artesian boreholes on the main bed of the Dallol and its secondary axes reflects the conjunction of topographic and hydrodynamic conditions that favor the loading of the aquifers, thus constituting potential artesian zones. Moreover, the number of boreholes inventoried (41) in this study is very significant, and the measurements made have shown that the CI/H aquifer, with exploitation flows that can exceed 70 L/s, offers the best prospects for the development of irrigation. According to FAO' report [31], the exploitation flows of works tapping this aquifer can exceed 50 L/s in the southern part of the study area, and it is likely that withdrawals of 1.5 to 2 $m^3$/s are compensated by recharge during years with above-average rainfall. However, although the deep aquifers have an undeniable water potential for the development of irrigation, the more accessible alluvial aquifer (0 to 10 m) is more heavily used by the population for irrigated crops in private individual perimeters and in collective perimeters developed with the support of the State and its partners. But this aquifer, limited in time and space, does not allow the development of large areas in a sustainable way. These renewable reserves were estimated at 0.73 billion $m^3$ by Sani Oumarou [32], with an average piezometric fluctuation of 1.46 m in 2015. Development of areas larger than 4,000 ha in the Dallol Maouri could risk causing overexploitation of the aquifer [33]. Furthermore, the large hydro-agricultural developments managed by ON-

AHA (Office National d'Aménagement des Hauts Plateaux de l'Ader) that use the Niger River as a water source for irrigation all face water shortages with often prolonged shutdowns of operation. River flows have been considerably reduced since 1970, with climate change, thus limiting water availability and the development of irrigation [34]. According to Guero [1], the decadal average flow of the Niger River has fallen from 2,000 $m^3/s$ to less than 1,500 $m^3/s$ due to decreased rainfall and the silting phenomenon linked to the degradation of vegetation cover. In this context, artesian aquifers that exhibit sufficient flows and pressures to allow the natural emergence of water constitute strategic resources for developing irrigation and strengthening the resilience of populations in the face of the multifaceted effects of climate change.

The malfunctions observed during the field mission and the analysis of the current state of the artesian boreholes reveal a worrying situation. Approximately 78% of the boreholes show an advanced state of degradation, compromising their productivity, and nearly 7% are completely out of service, reflecting a significant loss of water potential. A notable decrease in flow was observed on the structures, ranging from 33% in Béllawa to 99% in Sabon Gari, and even a total cessation of discharge in localities such as Dogondoutchi, Agonga, and Madotchi. The Pearson correlation matrix established to identify the explanatory factors of the decrease in the productivity of the structures highlighted a strong negative correlation ($r = -0.67$, $p < 0.01$) between the age of the boreholes and the decline in artesian flows, indicating a significant decline in hydraulic productivity with the aging of the structures. Furthermore, a first linear regression applied between the age of the boreholes and the flow decline (**Figure 10**) also indicates that the relationship between these two variables is significant, and the model accounts for approximately 44% of the variance in flow declines. The decline in flow rate ($Y$) is explained by borehole age ($X$) according to the model: $Y = 12.91 + 1.44X$, with $R^2 = 0.443$, adjusted $R^2 = 0.416$, $p < 0.001$. The slight non-normality of the residuals suggests that a robust model or a transformation could improve accuracy, but the overall trend is well captured, indicating that borehole age is a major factor driving flow reduction. The three diagnostic tests applied to the model residuals indicate generally satisfactory conformity with the classical assumptions of linear regression. The Shapiro-Wilk test ($p = 0.0218$) reveals a slight deviation from residual normality. However, given the sample size and the moderate nature of this non-normality, the deviation is considered limited and does not undermine the overall validity of coefficient estimates, particularly in an exploratory context. The Breusch–Pagan test ($p = 0.104$) does not detect significant heteroscedasticity, indicating that the residual variance can be considered constant. This condition reinforces the reliability of standard errors and associated significance tests for the regression coefficients. Finally, the Durbin–Watson test ($p = 0.626$) indicates no significant autocorrelation of residuals, suggesting that observations are independent and that estimates are not affected by serial dependence. Overall, these results confirm the statistical robustness of the regression model used and support that artesian borehole age is the principal explanatory factor for the observed flow decline. However, the scatterplot shows some dispersion of the data around the regression line, indicating the likely influence of other hydrogeological and technical factors, notably the upkeep and maintenance of infrastructure, the lithological characteristics of the aquifers, the overexploitation of the structures, as well as phenomena of crushing, clogging, and collapse of the structures. The confidence interval around the regression line underscores the uncertainty associated with the model's prediction, while confirming the general trend of a progressive deterioration of hydraulic performance with the aging of the boreholes.

The second linear regression applied between the borehole depth and borehole age (**Figure 11**) shows that the relationship between these two variables is negligible and not significant. The decline in flow rate ($Y$) is explained by borehole age ($X$) according to the model: $Y = 136.5 + 0.26\,X$, with $R^2 = 0.002$, adjusted $R^2 = -0.045$, $p < 0.827$, indicating that variations in borehole depth are independent of borehole age. Non-normal and autocorrelated residuals render the model unreliable. Alternative approaches, such as non-linear modeling or grouping by borehole type, could be considered. The diagnostic tests applied to the model residuals indicate violations of key assumptions of classical linear regression. The Shapiro–Wilk test ($p = 0.0059$) reveals that the residuals are not normally distributed. The Breusch–Pagan test ($p = 0.345$) indicates no significant heteroscedasticity, suggesting that the residual variance can still be considered constant. However, the Durbin–Watson test ($p$

= 0.00081) reveals strong autocorrelation, indicating that the residuals are highly dependent and that the observations are not independent. Overall, these diagnostics suggest that the model is unreliable, and inferences based on this regression should be interpreted with caution.

The third linear regression applied between the decline in flow rate and borehole depth (**Figure 12**) highlights a weak and negative relationship between the two variables. The decline in flow rate ($Y$) is explained by borehole depth ($X$) according to the model: $Y = 68.77 - 0.13\,X$, with $R^2 = 0.099$, adjusted $R^2 = 0.056$, $p < 0.143$, indicating that each additional meter of borehole depth results in only a 0.13% decrease in flow. The model accounts for less than 10% of the variance in flow declines, suggesting that borehole depth has virtually no effect on the observed reduction in flow rate. The diagnostic tests applied to the model residuals indicate overall satisfactory adherence to the classical assumptions of linear regression. The Shapiro–Wilk test ($p = 0.0149$) suggests a slight deviation from normality of the residuals. However, considering the sample size and the moderate extent of this non-normality, this deviation is deemed limited and does not compromise the overall validity of the coefficient estimates, particularly in an exploratory context. The Breusch–Pagan test ($p = 0.591$) indicates no significant heteroscedasticity, suggesting that the residual variance can be considered constant. This reinforces the reliability of standard errors and significance tests associated with the regression coefficients. Finally, the Durbin-Watson test ($p = 0.58$) reveals no significant autocorrelation of residuals, indicating that observations are independent and that the estimates are not affected by serial dependencies. Overall, these results confirm the statistical robustness of the regression model and support that borehole depth has no effect on the observed reduction in flow rate.

In addition, the marked dispersion of the data around the regression line indicates the likely influence of other hydrogeological and anthropogenic factors on the evolution of flows, such as drainage phenomena between aquifers, the hydrodynamic properties of the formations, hydraulic connectivity, and the operating conditions of the structures.

Although no direct pressure measurement was made as part of this study, the decrease in flows observed on the majority of the boreholes of the Dallol Maouri can be interpreted as a drop in artesian pressure, as well as a possible decrease in the piezometric level of the aquifers. According to Dodo et al. [23], the drop in the piezometric level observed in the Iullemmeden basin is the consequence of an overexploitation of the aquifers. On the other hand, Guero [1] justifies the decrease in the initial performance of the structures by a progressive deterioration of their technical condition. Although it is difficult to rule out the hypothesis of resource depletion, the drilling of the artesian wells at Dioundiou (2014), Lokoko (2015) and Koutoumbou (2019), showing flows and pressures comparable to those observed in the 1970s, and the current condition of the structures, strengthen the hypothesis of a progressive deterioration of the structures. These results confirm the substantial water potential of the artesian aquifers of the Dallol Maouri; the productivity variations recorded on some structures are more related to technical factors than to a real decline of the groundwater resource. Hence the need to optimize these structures by implementing a comprehensive rehabilitation and preventive maintenance strategy for existing boreholes. Furthermore, the establishment of a monitoring system for aquifer exploitation appears essential for a rational use of these fossil water resources. On the technical level, the deterioration of the structures results both from both mechanical and chemical factors, from poor management of infrastructures, and from equipment wear, thus limiting their initial performance. Specific cases illustrate these problems: the Timba borehole, regularly flooded by runoff waters due to inadequate siting, or Koutoumbou 1, whose borehole head was torn off by the artesian pressure. The materials used for the construction of the structures are not always adapted to the local context. PVC casings and screens, although economical and resistant to the corrosivity of the waters, show their limits in the face of mechanical constraints related to depth and pressure. Phenomena of casing collapse, observed notably at Garin Kio and Illéla 2, have caused ground subsidence, the formation of underground caverns and soil gullying by the flows. Conversely, stainless steel casings and screens, more robust, offer better resistance to compression, but have a high cost and are vulnerable to corrosion in aggressive geochemical environments. These corrosion phenomena affect most of the boreholes in the Dallol Maouri, leading to a decline in hydraulic performance and a reduction in the operational lifespan of the structures. Moreover, artesian boreholes occupy an important place in the socioeconomic activities of the Dallol Maouri valley. Some structures are used exclusively for drinking water supply (Dogondoutchi, Dioundiou 2), while others serve for irrigation (Lokoko, Gida). Other structures, such as the Yélou borehole, have a multifunctional use, which intensifies pressure on the resource and increases the risk of conflicts between users. However, the exploitation of these resources also carries health and environmental risks. According to Guero [1], the artesian aquifers of the Dallol Maouri often present high contents of hydrogen sulfide ($H_2S$), giving the water an unpleasant odor and taste. In addition, fluoride concentrations sometimes exceed the World Health Organization (WHO) guideline value (1.5 mg/L), exposing populations to risks of dental or skeletal fluorosis, which limits their suitability for human consumption. Although the construction of artesian wells requires significant investments, their use for agricultural purposes represents, in the long term, an economically advantageous option. Indeed, artesian wells make it possible to sustainably meet irrigation water needs while freeing users from the main constraint related to water unavailability. The latter is strongly influenced by climate variability and identified as a limiting factor for the sustainability of irrigation systems in semiarid regions by numerous authors [1,34–38]. Furthermore, the natural pressure of the aquifers ensures spontaneous gushing or requires little pumping, which significantly reduces operating costs and solves the problem of pump replacement faced by most hydro-agricultural developments in the Dallol Maouri. According to the regional services of ONAHA Dosso, five (5) of the six (6) pumping stations located in the Dallol Maouri valley (Tara, Kiessa, Gatawani Kaïna, Gaya Upstream and Gaya Fruitier) are currently out of service due to lack of pump replacement. However, the agricultural use of these waters is not without risks. Their fossil nature and high mineralization can lead to gradual soil degradation and compromise crop development. That is why several authors recommend the implementation of preventive measures aimed at limiting salinization and sodization processes and preserving agricultural productivity [1,10,31,39,40]. A rigorous assessment of the relevance of irrigation from artesian aquifers, therefore, appears essential [39], as does the establishment of regular monitoring of the physico-chemical parameters of soils and waters [31].

# 6. Limits of the Study

The main limitation of this study lies in the limited number of artesian boreholes for which exploitable discharge measurements could be obtained, as well as in the uncertainties inherent to the measurement procedures. Indeed, among the 41 artesian boreholes inventoried within the study area, only 23 boreholes exhibiting controlled artesian flow were suitable for reliable quantitative discharge measurements. Three boreholes were non-operational at the time of the field investigations, while the remaining 15 were characterized by diffuse, scattered, or non-channelized flows, which prevented accurate and reproducible discharge measurements.

In addition, uncertainties associated with the measured flow rates mainly stem from the limitations of the field equipment used (stopwatch, volumetric flow meter, drums, and calibrated containers), as well as from reading and handling errors during field operations. These methodological constraints did not allow a fully exhaustive and representative quantitative assessment of all artesian boreholes in the Dallol Maouri area and should therefore be taken into account when interpreting the results.

A second limitation of this study is related to the absence of long-term continuous monitoring data for artesian flow rates and piezometric conditions. The analyses presented here are based on discrete field measurements acquired during a limited observation period, which restricts the ability to capture seasonal, interannual, or longer-term variations in artesian discharge. Consequently, transient influences such as short-term climatic variability, episodic recharge events, or temporal changes in hydraulic head could not be explicitly assessed.

The lack of continuous time-series data also limits the capacity to distinguish between long-term structural declines in artesian pressure and short-term fluctuations linked to natural or anthropogenic factors. As a result, the observed decreases in discharge should be interpreted as indicative of prevailing trends rather than definitive long-term evolution. Future studies would benefit from the implementation of continuous monitoring networks, including automated flow meters and piezometric sensors, to better constrain the temporal dynamics of artesian systems and strengthen the robustness of trend analyses.

## 7. Conclusion

The study revealed significant water potential in the Dallol Maouri valley, supported by the aquifers of the Continental Intercalaire/Hamadien (CI/H) and the lower Continental terminal 1 ($Ct^1$). The high flow rates, particularly in boreholes tapping the CI/H, confirm the possibility of sustainably developing irrigation activities and strengthening local agricultural production. However, the severe deterioration of the boreholes (nearly 78% in poor condition and 7% out of service) limits this potential. The technical and hydrogeological malfunctions observed underscore the urgency of rehabilitation, maintenance, and rational management interventions for the facilities. Finally, the use of artesian wells for agricultural purposes must be accompanied by precautionary measures to prevent soil degradation and optimize yields, thereby ensuring sustainable exploitation of these strategic resources. To ensure sustainable exploitation of artesian wells and controlled development of irrigation in the Dallol Maouri valley, the following actions are recommended:

- Rehabilitate and control the flows of artesian wells to increase productivity and ensure rational use of fossil water resources;
- Evaluate the qualitative potential of artesian aquifers for different uses;
- Assess the suitability of the waters for irrigation and their impacts on the physicochemical properties of soils and on crops, in order to avoid degradation of agricultural lands;
- Equip the hydro-agricultural developments managed by ONAHA with artesian wells to ensure their water supply in a sustainable manner;
- Promote rational management of these fossil water resources, based on the implementation of integrated mobilization strategies, complementary to renewable resources or as strategic reserves mobilizable during periods of water deficit.

## Author Contributions

Conceptualization, L.H.A. and A.K.H.S.; methodology, L.H.A., A.K.H.S., I.S.T. and S.I.; writing—original draft preparation, L.H.A.; writing—review and editing, L.H.A., A.K.H.S., I.S.T. and S.I. All authors have read and agreed to the published version of the manuscript.

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## Institutional Review Board Statement

Not applicable.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

The data was collected in the field and from state technical services in documents or UBS keys. There is no possible link to access the data used.

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## Conflicts of Interest

The authors of this article declare that they have no conflicts of interest regarding the data collected and used, or the manuscript prepared.

## AI Use Statement

The authors confirm that AI tools were used during the manuscript preparation process solely for language editing and improving clarity, coherence, and readability of the text. The authors take full responsibility for the accuracy, originality, and integrity of the final manuscript.

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