

# Isotope Tracking of Surface Water Groundwater Interaction in the Beninese Part of the Iullemeden Aquifer System

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## Abstract

The Kandi basin is located in northeast Benin (West Africa). This study is focused on the estimation of water fluxes exchanged between the river Niger (and its tributaries) and the transboundary Iullemeden Aquifer System. In that framework, an innovative approach based on the application of the Bayesian Mixing Model (MixSIAR) analysis on water isotopes (oxygen-18, deuterium and tritium) was performed. Moreover, to assess the relevance of the model outputs, Pearson's correlation and Principal Component Analysis (PCA) have been done. A complex relationship between surface water and groundwater has been found. Sixty percent (60%) of groundwater samples are made of more than 70% river water and rainwater; while 31.25% of surface water samples are made of about 84% groundwater. To safeguard sustainable water resources for the well-being of the local communities, surface water and groundwater must be managed as a unique component in the Kandi basin.

## Keywords

Benin, West Africa, Kandi basin, Iullemeden Aquifer System, Surface Water Groundwater Interaction

## 1. Introduction

Due to the importance of surface water groundwater interactions for Integrated

Water Resource Management, numerous studies have been done in the world at basin scales (Kaidu river basin, lake Chad basin, lake bosumtwi area, Saloum basin, Beninese coastal basin), on global groundwater discharge in world's oceans [1]-[5]. Moreover, at national levels, in Denmark for example, mapping of groundwater-surface water interactions has been done [6]. The diversity of these studies (based on the methods used, geological and hydroclimatic characteristics) and their global coverage, highlighted the necessity to quantify water fluxes exchange between river networks and their riparian aquifer system. This will ensure sustainable water resource management.

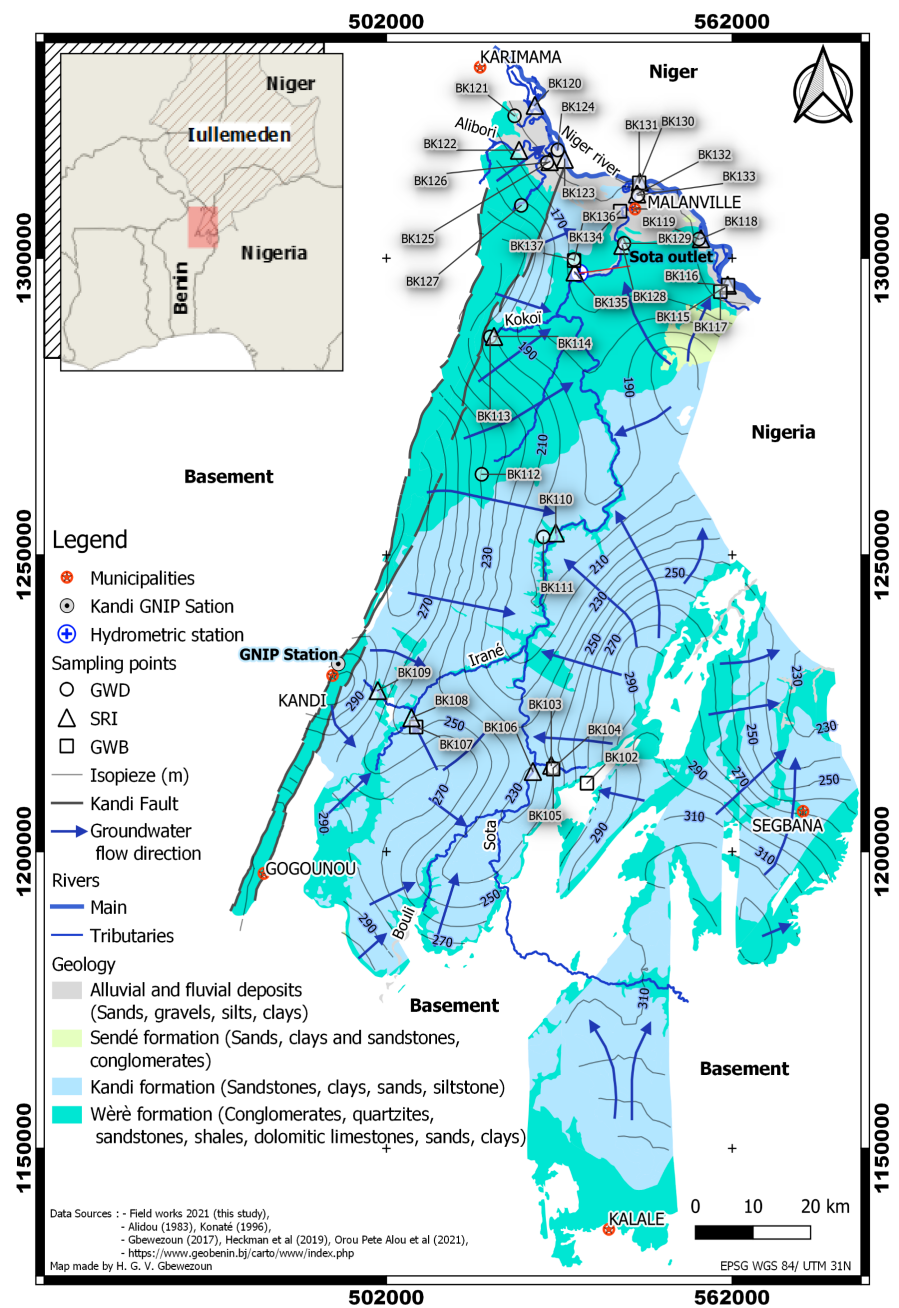
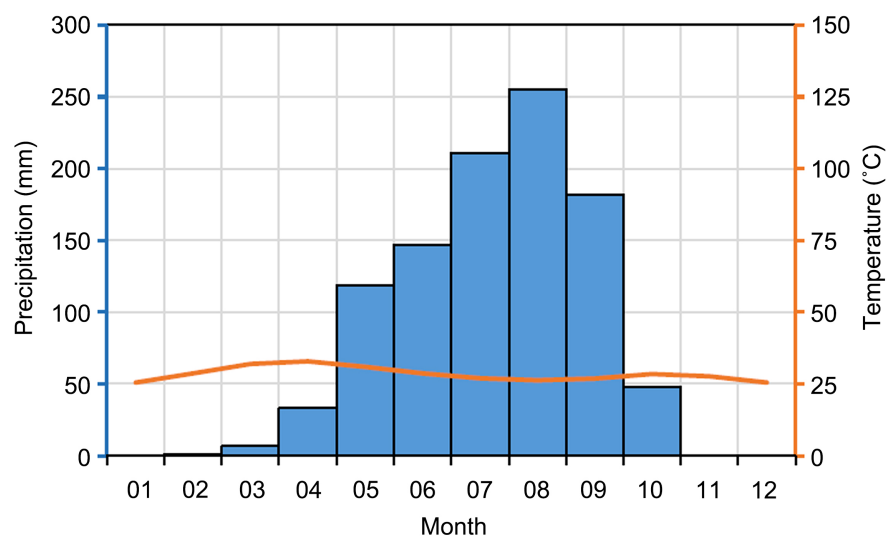


Figure 1. Study area main features and the locations sampling sites.

With a spatial coverage of about 9000 km<sup>2</sup>, the Kandi basin (**Figure 1**) is located in northeast Benin, where Benin shares borders with Niger and Nigeria. The Kandi basin (as shown in the map) is located in north-eastern Benin (West Africa). It is the Beninese part of the transboundary Iullemeden Aquifer System (IAS) and it is also located in the regional Niger River basin. The Kandi basin geology is mainly characterized by Wèrè formation (covering the basement) covered by Kandi and Sendé formations. In Niger River valley, those formations are covered by alluvial and fluvial deposits. Global groundwater flow is from south to north [7]-[10]. The climate is Sahelian. The maximum average monthly rainfall is observed in August in Kandi, Malanville and Segbana [11]. The average annual rainfall (1985-2015) at the Kandi synoptic station is 1002.4 mm and the mean annual maximum temperature (1985-2015) is 34.70°C (**Figure 2**), with the potential evapotranspiration (1985-2015) equal to 1703.3 mm at the same station [9].

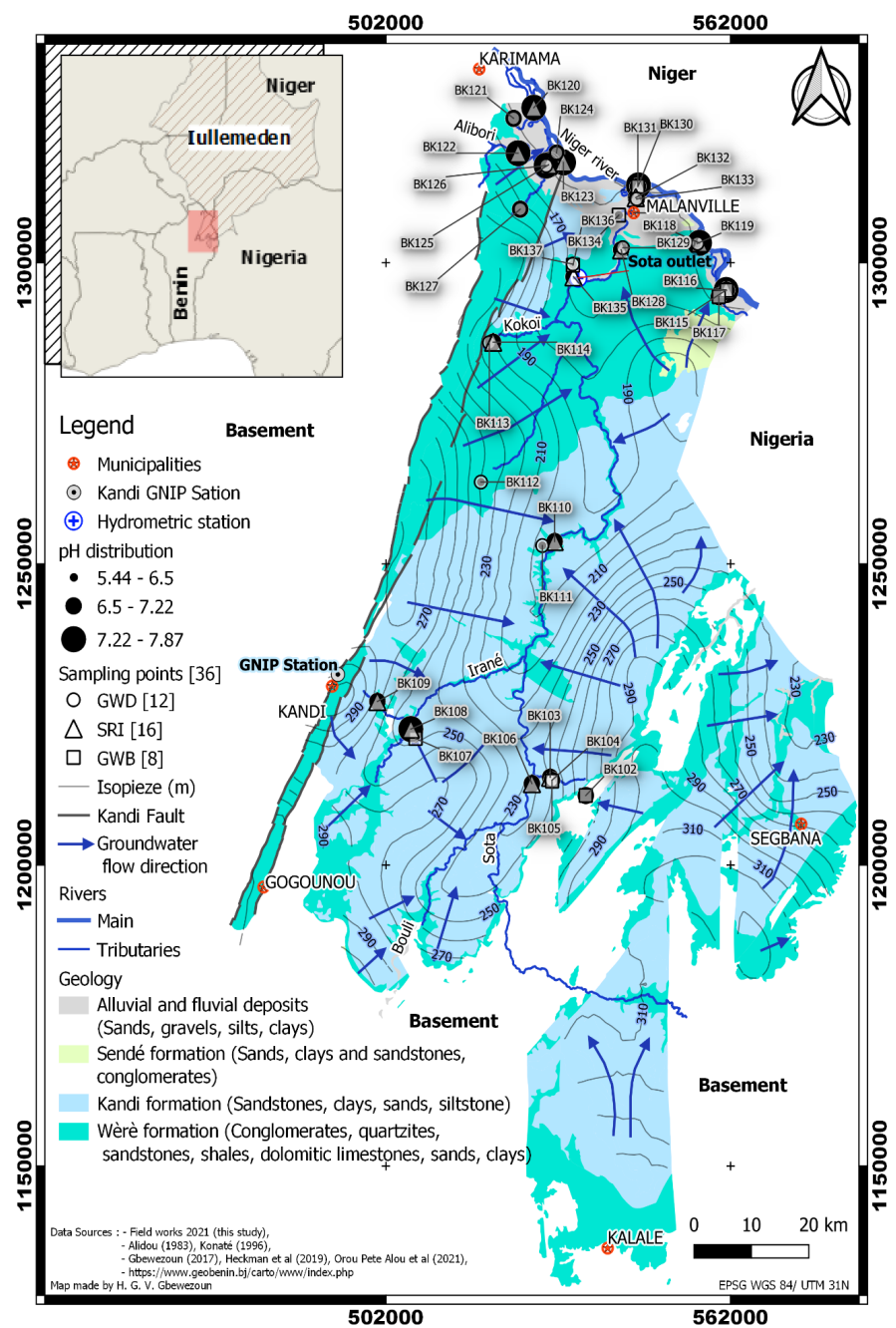


**Figure 2.** Average monthly rainfall and temperature from 1985 to 2015 [9].

In the Kandi basin, the fluxes exchanges between the Iullemeden Aquifer System and the Niger River basin have not yet been quantified. Based on the collected data (deuterium, oxygen-18 and tritium contents of rainwater from the Global Network of Isotopes in Precipitation GNIP database <https://www.iaea.org/services/networks/gnip>) combined with those generated in the current study, the overarching goal is to quantify using water isotopes (deuterium, oxygen-18 and tritium), the water fluxes exchanged between the river Niger (and its tributaries) and the transboundary Iullemeden Aquifer System (locally called Kandi basin in Benin). Altogether, the findings will provide insights into groundwater resources and river basin management for an Integrated Water Resource Management (IWRM), for the well-being of dwelling inhabitants, towards reaching SDG 6 in Benin and similar environments in Sub-Saharan Africa.

## 2. Materials and Methods

### 2.1. Sampling and Analysis



**Figure 3.** pH spatial variation.

The sampling campaign was conducted in May 2021. A total of 36 samples were collected for Oxygen-18, Deuterium and Tritium analysis. Sixteen samples were collected from the River Niger and its main tributaries Alibori and Sota. Twenty samples were collected from groundwater. The samples were analyzed at the Laboratory of Radio-Analysis and Environment, University of Sfax, Tunisia.

Two replicate samples were analyzed for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  at the Laboratoire d'Hydrologie Appliquée, Université d'Abomey-Calavi, Benin. The stable isotopes of water ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ ) were measured using laser spectroscopy. The instrumental precision is approximately 1.5‰ for  $\delta^2\text{H}$  and 0.3‰ for  $\delta^{18}\text{O}$ . Rain samples were collected on a monthly basis (May to September 2021) for tritium  $^3\text{H}$  analysis. These rain samples were analyzed at Környezetanalitikai Laboratórium, Hungary.

The spatial distribution of the measured pH in the study area is presented in **Figure 3**. pH values are mainly high in the aquifer discharge zones.

## 2.2. Bayesian Mixing Model (MixSIAR) and Principal Component Analysis (PCA)

In the framework of this study, the software R 4.2.1, Rstudio 2022.12.0 + 353 and JAGS 4.3.1 were used to carry out data processing [12]-[14].

The package MixSIAR [15] was used for Bayesian Mixing Modelling. The innovation of this study is that the model was applied to deuterium excess DEX [16] and tritium ( $^3\text{H}$ ) content to determine the relative contributions of each water source.

$$\text{DEX} = \delta^2\text{H} - 8 \times \delta^{18}\text{O} \quad (1)$$

The package FactoMineR [17] was used for Principal Component Analysis (PCA) on a set of data composed of parameters with significant correlation (p-value < 0.05) assessed with the package metan [18]: *In-situ* field measurements (pH and Depth), water isotopes ( $^{18}\text{O}$ ,  $^2\text{H}$ ,  $^3\text{H}$ ), model output (mean surface water and groundwater percentage quantified for each of the sampling sites).

## 3. Results and Discussion

### 3.1. Isotope Signatures of Rain Water, Groundwater and Surface Water

**Figure 4** highlights signatures exhibited by stable isotopes of water in the study area. In rainwater, deuterium  $\delta^2\text{H}$  varies from  $-53.6\text{‰}$  to  $23.8\text{‰}$  with a mean value of  $-16.77\text{‰}$ . Oxygen-18  $\delta^{18}\text{O}$  varies from  $-8.03\text{‰}$  to  $1.93\text{‰}$  with the mean value of  $-3.59\text{‰}$ . Tritium  $^3\text{H}$  varies from 1.8 T.U. to 5.2 T.U. with a mean value of 3.04 T.U.

In surface water, deuterium  $\delta^2\text{H}$  varies from  $-16.6\text{‰}$  to  $9.3\text{‰}$  with a mean value of  $-2.41\text{‰}$ . Oxygen-18  $\delta^{18}\text{O}$  varies from  $-2.86\text{‰}$  to  $4.12\text{‰}$  with the mean value of  $0.04\text{‰}$ . Tritium  $^3\text{H}$  varies from 0.8 T.U. to 3.83 T.U. with a mean value of 2.39 T.U.

In groundwater, deuterium  $\delta^2\text{H}$  varies from  $-41.2\text{‰}$  to  $-20.6\text{‰}$  with a mean value of  $-24.97\text{‰}$ . Oxygen-18  $\delta^{18}\text{O}$  varies from  $-6.24\text{‰}$  to  $-3.04\text{‰}$  with the mean value of  $-4.14\text{‰}$ . Tritium  $^3\text{H}$  varies from 0.07 T.U. to 3.2 T.U. with a mean value of 1.77 T.U.

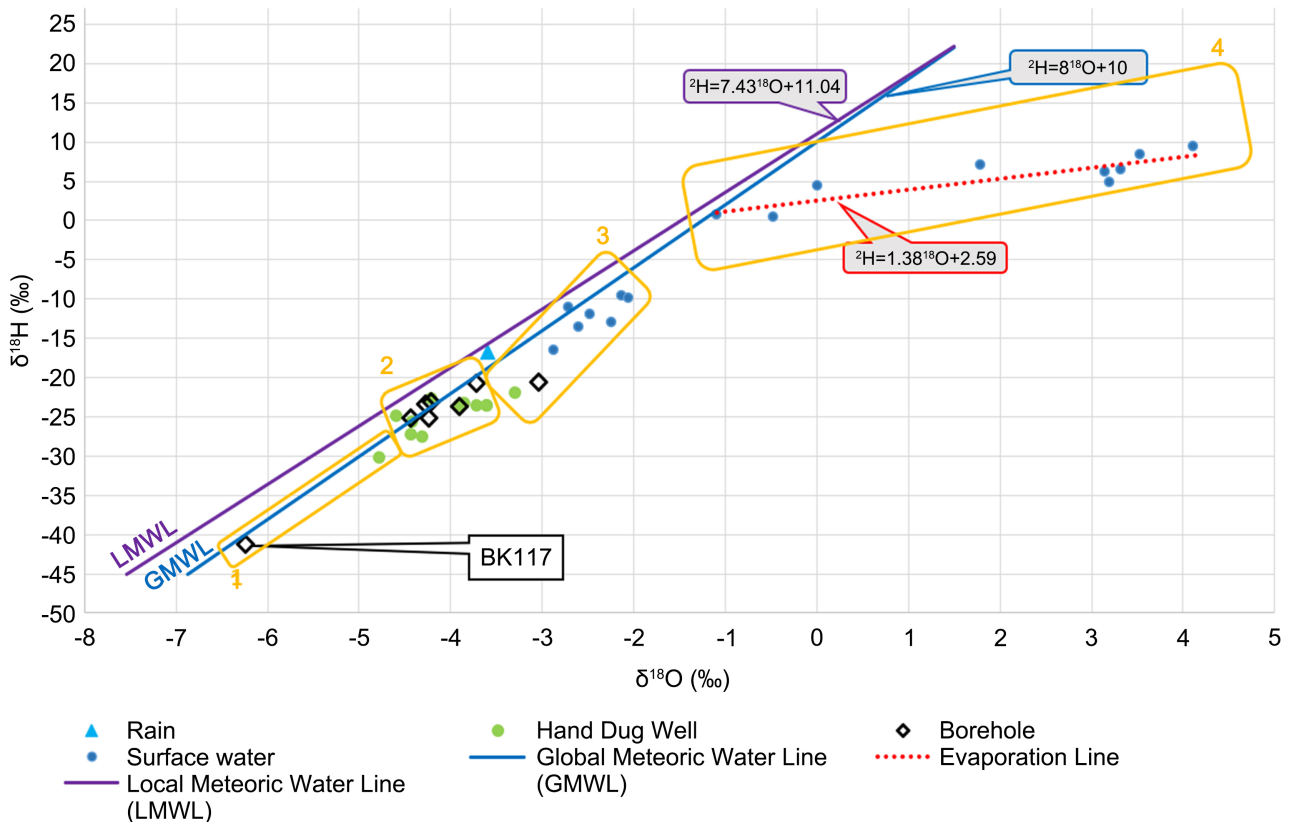
Four main groups of water have been identified (**Figure 4**):

- group 1 for relatively old groundwater (BK117, which is artesian);
- group 2 for mixing deep and relatively shallow groundwater;
- group 3 for mixing of relatively recent shallow groundwater and surface water;
- group 4 is surface water undergoing high evaporation.

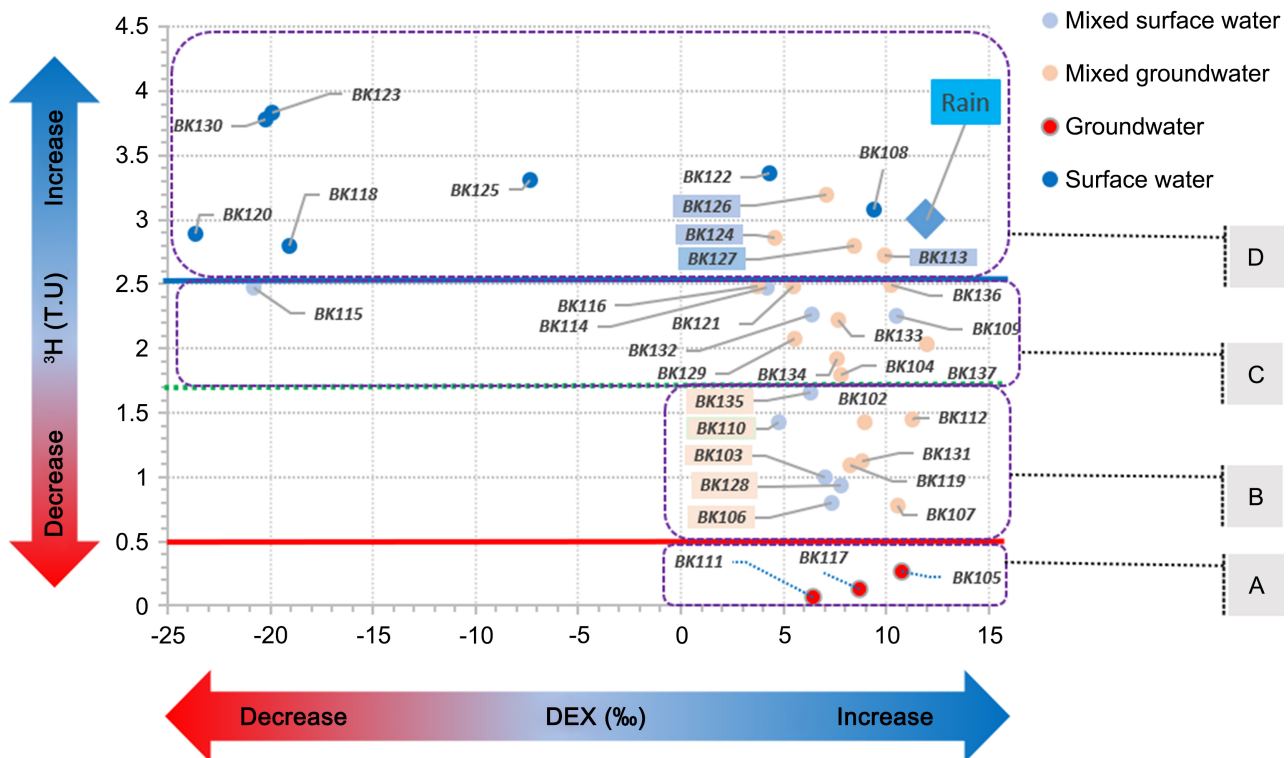
In order to have a better understanding of the identified groups of waters in the study area tritium (<sup>3</sup>H) was plotted against deuterium excess which revealed four different classes of water (Figure 5). These classes are:

- 3H < 0.5 and DEX > 3; class A containing old groundwater;
- 0.5 < 3H < 1.7 and DEX > 3; class B containing less old groundwater and surface water interacting with them;
- 1.7 < 3H < 2.5 and DEX > -25; class C containing recent groundwater with surface water interacting with them;
- 3H > 2.5 and DEX > -25; class D contains surface water and more recently young groundwater interacting with them.

The comparative analysis of Figure 4 and Figure 5 shows that in the area of study, δ<sup>2</sup>H and δ<sup>18</sup>O are no longer enough to differentiate the water type, but their combination through the deuterium excess DEX together with their <sup>3</sup>H content provides a clearer picture of the relationship within the aquifer system layers and between the aquifer system and the rivers.



**Figure 4.** Water component relationships displayed by the bivariate plot of δ<sup>2</sup>H versus δ<sup>18</sup>O in the Kandi basin, considering groundwater (boreholes and hand dug wells), river water (mainly Niger River and its tributaries Sota and Alibori) and rainwater.



**Figure 5.** Water component relationships displayed by bivariate plot of DEX versus  $^3\text{H}$  in Kandi basin, considering groundwater (boreholes and hand dug wells), river water (mainly Niger river and its tributaries Sota and Alibori) and rain water.

### 3.2. Surface Water-Groundwater Interaction

The Bayesian Mixing modelling carried out confirmed the classes previously identified in **Figure 5**. Moreover, based on the water type within each class, all of them except A have been divided in two subclasses. The average proportions of surface water and groundwater in the identified classes are presented in **Table 1** and **Figure 6**. Class A is composed of 95.47% of groundwater. For class B, groundwater (BG) is composed of 21.10% of surface water and rainwater, while surface water (BS; Sota River) is composed of 84.00% of groundwater. In class C, groundwater (CG) is composed of 73.77% of surface water/rain, while surface water (CS) is composed of 20.55% of groundwater. In the case of class D, groundwater (DG) is composed of 93.30% of surface water/rain, while surface water (DS; mainly Niger and Alibori rivers) is composed of 96.66% of surface water. Moreover, it is important to highlight that Class A's surface water composition could be considered negligible as well as subclass DS's groundwater composition, because groundwater/surface water apportionment had been done based on them.

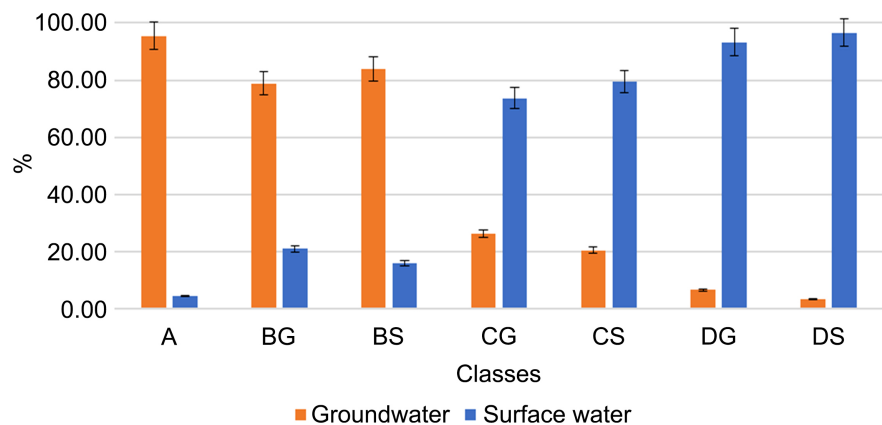
In **Figure 7(a)**, Pearson's correlation coefficient was employed for in-situ parameters, isotope contents, groundwater and surface water proportions. pH,  $^2\text{H}$ ,  $^{18}\text{O}$  and  $^3\text{H}$  have a positive correlation with each other. Water depth has a negative correlation with pH,  $^2\text{H}$  and  $^{18}\text{O}$ .  $^3\text{H}$  and %SW have a positive correlation but a negative correlation with %GW. Moreover, the Principal Component

Analysis shows that the set of parameters selected can be used in the Kandi basin, to study surface water groundwater interactions. These parameters (mainly pH, <sup>2</sup>H, <sup>18</sup>O, <sup>3</sup>H and water depth) explained about 84.86% of the processes involved in water fluxes exchange between surface water and groundwater in the study area (Figure 7(b)).

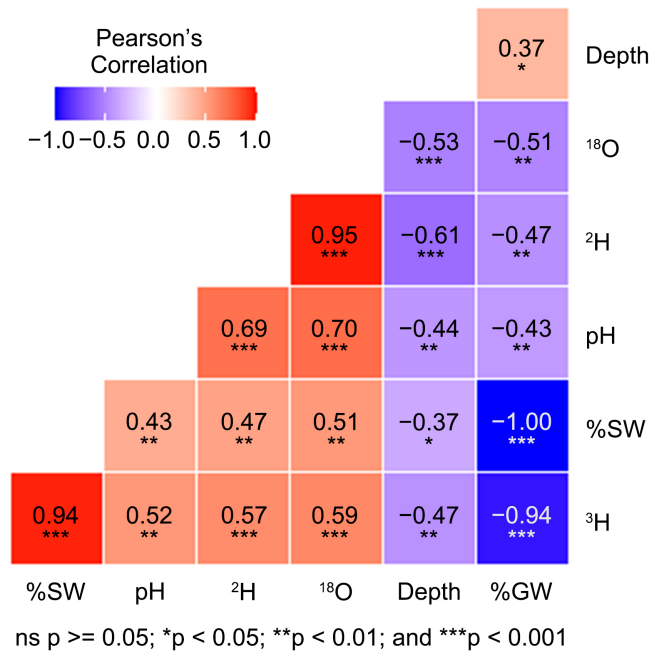
**Table 1.** The mean proportions of surface water and groundwater quantified through bayesian modeling.

Class/Subclass	Water type	Samples	Mean %GW	Mean %SW	Number of sample
A/	GW	BK105, BK111, BK117	95.47	4.54	3
B/BG	GW	BK102, BK107, BK112, BK119, BK131	78.90	21.10	5
B/BS	SW	BK103, BK106, BK110, BK128, BK135	84.00	16.00	5
C/CG	GW	BK104, BK116, BK121, BK129, BK133, BK134, BK136, BK137	26.24	73.77	8
C/CS	SW	BK109, BK114, BK115, BK132	20.55	79.45	4
D/DG	GW*	BK113, BK124, BK126, BK127	6.70	93.30	4
D/DS	SW*	BK108, BK118, BK120, BK122, BK123, BK125, BK130	3.35	96.66	7

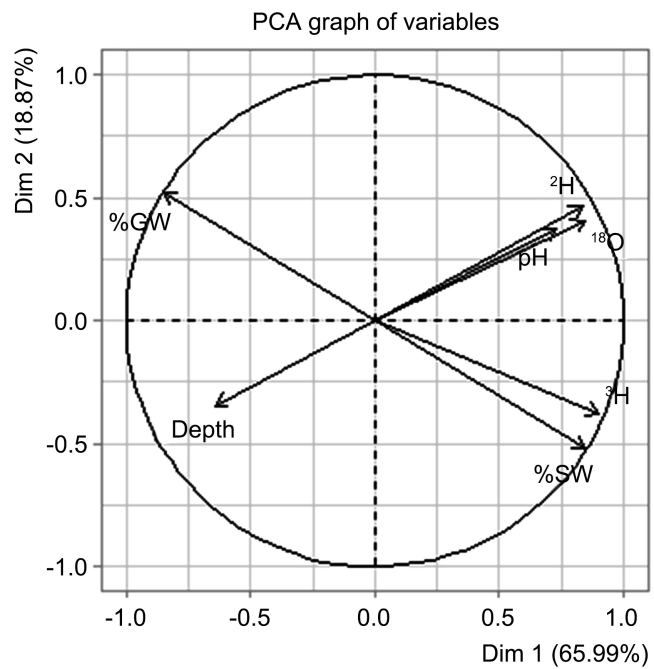
\*GW = Groundwater & SW = Surface water.



**Figure 6.** Mean percentage of groundwater and surface water quantified per class.



(a)



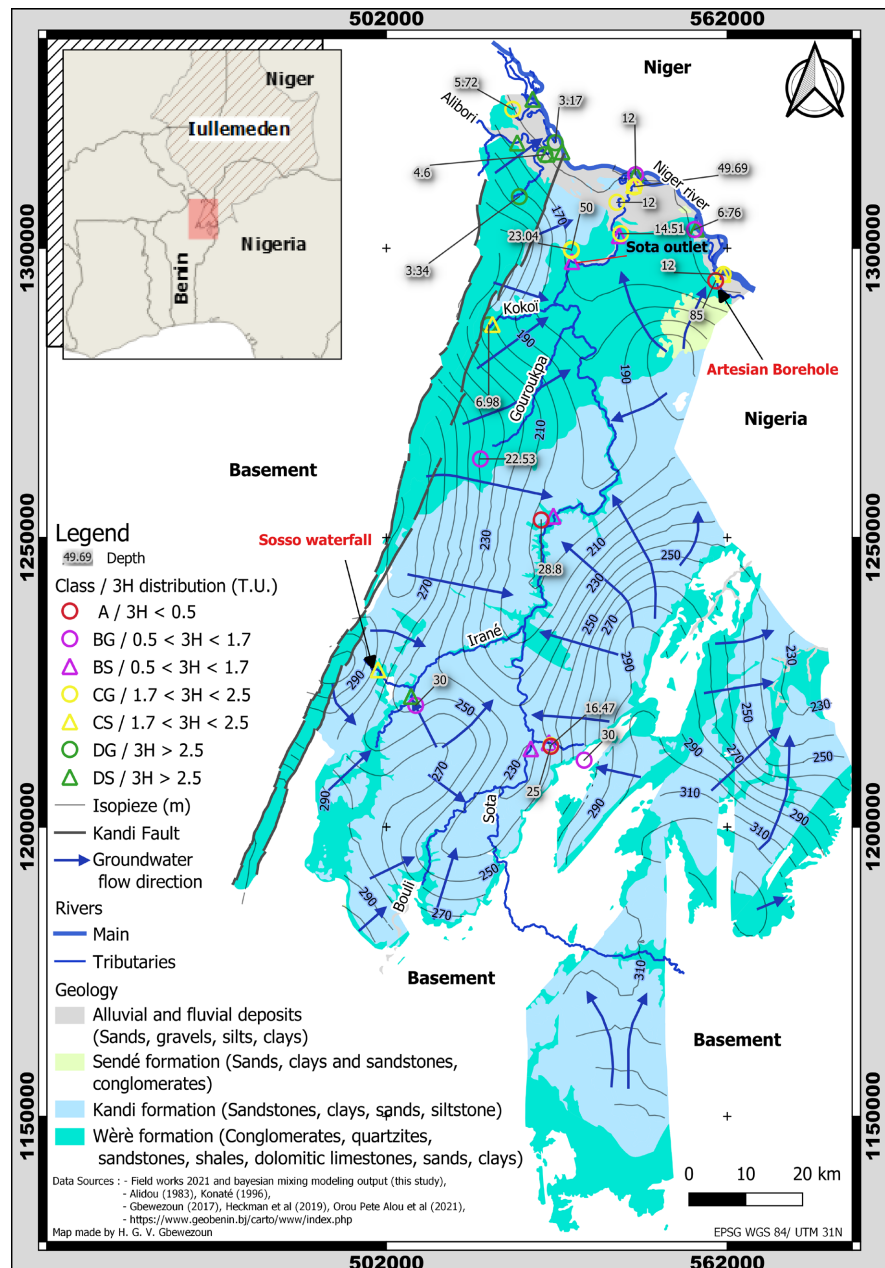
(b)

**Figure 7.** (a) Pearson’s correlation; (b) Variables’ PCA graph.

**Figure 8.** Shows a synthetic spatial overview of the surface water groundwater interactions in Kandi basin.

Surface water samples with the highest proportion of groundwater are from the Sota River (class BS; BK103, BK106, BK110, BK128, BK135). They are located in groundwater discharge areas. Moreover, groundwater samples (class DG; BK113, BK124, BK126, BK127) with the highest proportion of surface water

are located in the discharge areas (northwest, around Alibori River). They are generally very shallow in that part of the basin (sampling depth less than 5 m). But it is important to highlight 3 groundwater samples (class A; BK105, BK111, BK117): even though they are located in discharge areas, their proportion of surface water is very negligible. Furthermore, they have the lowest tritium content ( $^3\text{H} < 0.5 \text{ T.U.}$ ) and have among them the only artesian borehole identified in the basin with about 85 m depth. Also, it is important to highlight that tritium content doesn't have a general spatial trend, this could be translating the complexity of the mechanisms involved in water flux exchange in the Kandi basin.



**Figure 8.** Locations of the sampling sites including the spatial repartition of the classes identified in the Kandi basin (north-eastern Benin, West Africa).

### 3.3. Discussion

Previous studies in the Kandi basin indicated low mineralization of groundwater with less mineralized water in the recharge areas. Groundwater is mainly characterized by mixed water types. Moreover, recent groundwater recharge from modern precipitation, mixing between aquifers and recharge from surface water have influenced geochemical processes in the basin. Locations of probable groundwater discharge in the Sota river have been identified based on groundwater flow directions [9] [19]-[23].

In this study, four main processes involved in groundwater-surface water interaction have emerged. They are:

- mixing of deep and shallow groundwater resources;
- groundwater discharge into Sota River;
- replenishment of shallow groundwater by Alibori and Niger rivers;
- loss of deep groundwater in the Niger River valley.

The spatial locations of the occurrence of these processes suggest vertical hydraulic connections between deep and shallow aquifers, as well as complex hydraulic connections with aquifer systems and rivers. The detailed mapping of hydrodynamic properties of the studied aquifer system will enlighten more on the spatial extension of the identified processes, in order to quantify the groundwater reserves.

Having established the hydraulic connectivity between groundwater and surface water, it is imperative that detail assessment of the level of contamination of surface water and groundwater be carried out. It is also important to undertake in-depth assessment of groundwater vulnerability to pollution. This will enhance groundwater management in the study area.

The identified artesian borehole (in Madecali, extreme northeast) with high residence time must be monitored for abstraction to prevent groundwater mining. It is important to highlight that during the field campaign, the local communities have shown the location of another artesian borehole (located at Bodjecali, about 6 km westwards Madecali) that dried up. Therefore, in-depth studies are required to map the extent of this local artesian aquifer, in order to prevent it from drying up.

Overall, the findings improve the understanding of the processes governing surface water groundwater interactions in the Kandi basin.

### 4. Conclusion

This paper presented an innovative approach combining water isotopes (tritium, deuterium and oxygen-18) to quantify surface water groundwater interactions in the Kandi basin. The study finds that there is complex hydraulic connection between the aquifer system and the rivers (mainly Niger, Alibori and Sota). Therefore, surface water and groundwater resources must be managed as a sole and whole water bodies system, in order to secure sustainable water resources in the Kandi basin (north-east Benin), Beninese part of the Iullemeden Aquifer System.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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