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Isotopic composition of groundwater of a semi-arid carbonate terrain, Sokoto basin, Nigeria

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ABSTRACT

A study of the origin and recharge of groundwater in the semi-arid carbonate terrain, Sokoto Basin, northwestern Nigeria was performed with the aid of analyses of the environmental isotopes ^{18}O, ^{2}H, and ^{3}H at the Isotope Hydrology Laboratory, Cairo, Egypt. This carbonate aquifer belongs to the Sokoto Group of sedimentary rocks and is composed of internally karstified Paleocene limestone. Results of the environmental isotopic composition of groundwater from this aquifer have proved infiltration of surface water of meteoric origin which is recharged under the present climatic conditions. The values of δD and $\delta^{18}O$ are characteristics of modern waters from precipitation. The tritium enrichment in this groundwater shows that it is formed mainly after the thermonuclear explosions (the post-bomb) period. Deuterium and oxygen-18 results also indicate that the groundwater was recharged under cool conditions arising from intense evaporation arising from intense evaporation of the infiltrated water.

INTRODUCTION

The carbonate terrain study area is located in the Cretaceous Sokoto sedimentary basin, northwestern Nigeria. It forms part of the outcrop area of the Sokoto Group of sedimentary rocks (Fig. 1). The investigated area extends between Latitudes $13^0$53'40'' and $13^0$00'00''N and Longitudes $5^0$00'05" and $5^0$42'04''E covering about 3200km^2 of landmass. It forms a narrow outcrop which occupies a monotonous plain almost in the middle of the basin and trends slightly northeastwards across the Nigeria-Niger Republic frontier. The plain is punctuated by outliers of the "Continental Terminal" Group and attains a maximum elevation of about 396 metre above mean sea level close to the Nigeria-Niger Republic border.

This semi-arid study area is drained by part of the Sokoto and Rima Rivers and their tributaries and a number of perennial lakes are reportedly fed by groundwater discharge. The valleys of these rivers are frequently flooded after heavy storms during the May to October rainy season. The average annual rainfall amounts to 760mm in Sokoto with August being the wettest month. The mean annual air temperature is 26^0C with a range of 13^0C to 38^0C (Kowal and Knabe, 1972). The coolest months are December and January when the daily minimum temperature may decline to 15^0C. The hottest month is April with an average daily maximum temperature of 41^0C.

The Upper Paleocene, marine Sokoto Group of Sedimentary rocks (Fig. 2) comprises the following three rock formations (Kogbe, 1979), namely: Dange Formation, Kalambaina Formation and Gamba Formation. The Dange Formation is 22 to 45 metre thick bluish-grey shale with thin limestone and fibrous gypsum. Vertebrate fossils and phosphate nodules are present in the shale. The Kalambaina Formation, which is internally karstified, rests on the rocks of Dange Formation. It consists of white marine limestone, calcareous shale, marl, shale and gypsum. The formation reaches a thickness of about 25 metre and is also fossiliferous. The youngest member of the Sokoto Group, the Gamba Formation, is 20 to 30 metre thick. It is composed of grey shale with slumping structures. It is often completely removed by the Eocene erosion, very laterised at the outcrops with about three metre thick laterite grading downwards into three to five metre of oolitic ironstone.

The principal water-bearing bed in the Paleocene rocks is the semi-consolidated limestone bed in the Kalambaina Formation. This aquifer in its outcrop area has a porosity caused by joints and solution cavities formed by weathering of the limestone by circulating water. Where the aquifer is overlain by rocks of the Gwandu Formation, fractures are poorly developed and hence the permeability of the limestone is low (Oteze, 1975 and JICA, 1990).

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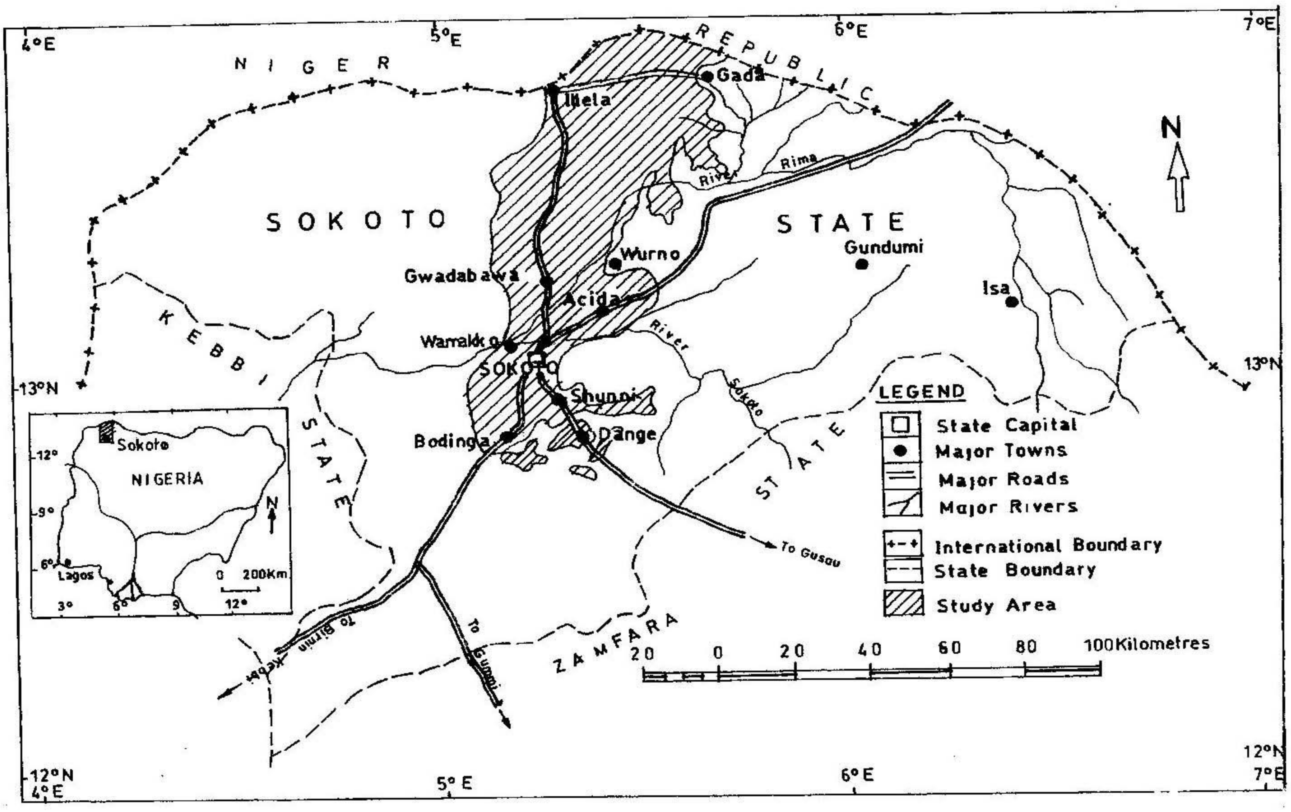

Fig. 1. Location map of the study area.

MATERIALS AND METHOD

Groundwater samples were collected from nine water points (Fig 2). To ensure complete mixing and homogeneity, the samples were collected from hand-dug wells that were in continuous abstraction for domestic and livestock needs. Furthermore, each sample container was filled to overflow, stoppered tightly and sealed with tape to avoid contamination with the atmosphere. This was to avoid evaporation that would have changed the isotopic composition of the samples, thus leading to erroneous interpretation. Oxygen-18 (^{18}O) and deuterium (^{2}H or D) were measured using a Finnigan delta S isotope ratio mass spectrometer after an initial equilibration processes with carbon dioxide and hydrogen gases respectively (Epstein and Mayeda, 1953; Roether, 1970; Drost, et al, 1974; Horita, 1988; Avak and Brand, 1995; Clark and Fritz, 1997; Finnigan Corporation, 1997). These stable isotope ratios in the groundwater samples are presented as defined below.

$$\delta = \frac{R_{sample} - R_{VSMOW}}{R_{VSMOW}} \text{ x } 10^{3}, \text{ where } R = D/H \text{ or } {}^{18}O/{}^{16}O \qquad (1)$$

The concentration of tritium (^{3}H or T) in natural waters is generally low. Therefore, electrolytic enrichment of tritium in each sample was carried out in a special electrolysis device. Thereafter, the decay rate counting in each sample, using a low-level counting Packard liquid scintillation spectrometer (Östlund and Werner, 1962) was done. This measurement is made in tritium units (T.U), defined as one tritium atom per 10^{18} hydrogen atoms.

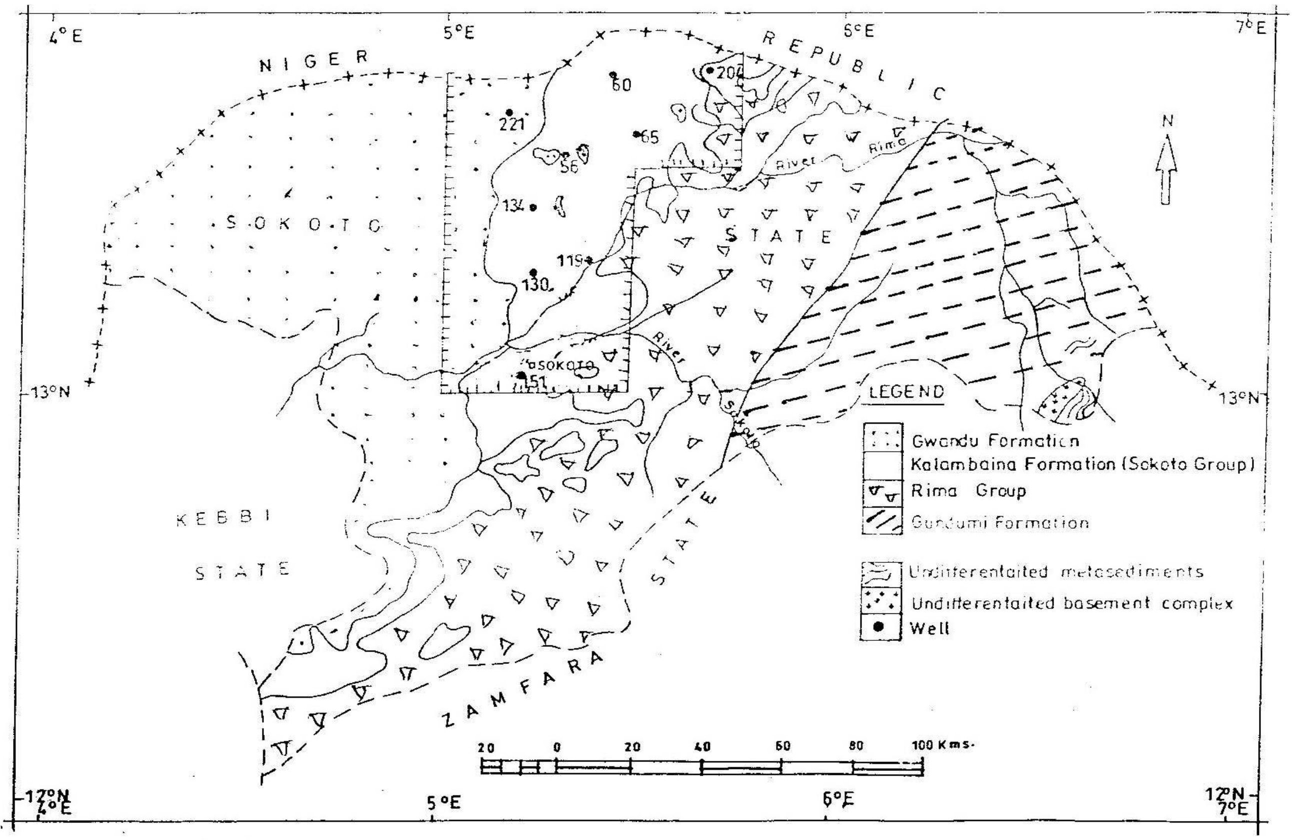

Fig.2. Geological map of Sokoto State showing location of study wells (map modified from GSN 1994)

Table 1. Isotopic Composition of Groundwater Samples from the Survey Area (for locations of sampled wells, please see Fig. 2)

Location and (well number)	Aquifer	δ^{18}O‰ VSMOW	δ^{2}H‰ VSMOW	$\delta\,^{3}$H (TU)	d-excess ‰
Sangaladam (56)	Kalambaina	-4.83	-31/05	-	7.61
Hassamawa (60)	Kalambaina	-4.07	-2.92	20.8±0.6	29.64
Chimola (119)	Kalambaina	-3.95	-30.14	31.5±0.6	1.46
Balkore (130)	Kalambaina	-7.12	-45.86	15.88±0.5	11.1
Kalambaina (151)	Kalambaina	-4.04	-32.32	12.13±0.42	0
Gida Mana (134)	Kalambaina	-4.63	-30.14	16.8±0.52	6.9
Marumaro (204)	Kalambaina	-4.80	-30.4	13.8±0.4	8.0
Kiri (209)	Wurno	-3.22	-26.38	14.97±0.45	0.62
Tumbulukum (221)	Gwandu	-2.58	-28.07	0.6	-7.43
Rainfall at IAEA Station, Kano	Meteoric water	-8.0	-23.5	nd	+40.50

Note: d-excess is calculated as follows: **$d = \delta\,^{2}H - 8\,\delta^{18}O$**

RESULTS AND DISCUSSION

Table 1 shows the result of measured isotopic compositions (^{18}O, ^{2}H, and ^{3}H) of the groundwater samples in the study area. The interpretations of variations in the isotopic composition of groundwater are of particular importance in the study of mechanism, rate and periods of groundwater recharge (Swailem, et al, 1983). The varying stable environmental isotopic composition of natural waters is due to the fractionation processes occurring in the hydrological cycle, while that of the environmental radioisotopes such as tritium is due to cosmic radiation and detonation of thermonuclear devices (Drost, et al, 1974). The deuterium and oxygen-18 content of the precipitation is a function of the temperature at the time of formation and this temperature was computed following Dansgaard method (Dansgaard, 1964) through the equations:

$\delta^{18}O = 0.695\, t_a - 13.6‰$ VSMOW and

$\delta\, ^{2}H = 5.6t_a - 100‰$ VSMOW;

where t_a = mean value of annual air temperature.

From the equations, the mean value of annual air temperature at the time of infiltration of this water is considered to be $+12.9^0$C. This low temperature of infiltrated water is approximately the same as that of the present day coolest months (December and January) in the study area. The present day air temperature in the study area has a range of 13^0C to 38^0C with a mean of 26^0C (Kowal and Knabe, 1972). The interpretation of these temperature figures on the basis of recharge from water of meteoric origin is difficult for one reason: the Sokoto Basin does not experience rains in December and January. Isotopically depleted waters are associated with cold regions and enriched waters are found in warm regions. Therefore, this carbonate aquifer must have been recharged by water that had undergone intensive evaporation (resulting in cooling) just before infiltration took place. The colder infiltrated water may also have resulted from rainout effect, because according to Clark and Fritz (1997), colder, isotopically depleted precipitation may evolve from rainout phenomenon (Fig. 3) Adelana et al, (1999) reported a temperature range of $+12.5^0$C to $+15.7^0$C (cooler climate) during infiltration for the Sokoto Basin.

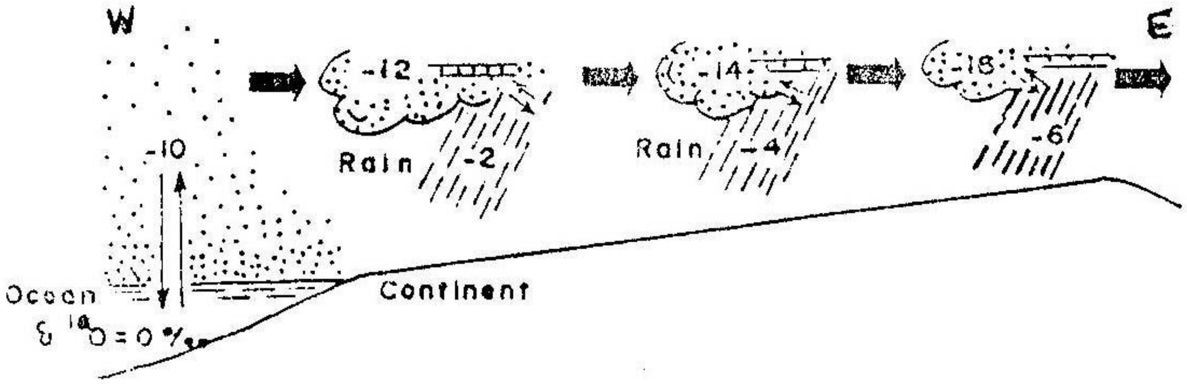

Fig.3. Diagram depicting the origin of variations in the oxygen-18 of meteoric waters as moisture rains out of air masses moving across the continents (after Olive, 1995)

The stable environmental isotope data of the ground water samples show depletion in both oxygen-18 (^{18}O) and deuterium. The oxygen-18 and deuterium contents of this limestone groundwater ranged in concentrations from -3.95‰ to -7.12‰ (average: -4.78‰) and -2.92‰ to -45.86‰ (average: -30.0‰) respectively. The mean values of precipitation at the IAEA weather station, Kano are -8.0‰ and -23.5‰ for ^{18}O and ^{2}H respectively. These delta-values of precipitation are similar to the values for the limestone groundwater which points at source of recharge as being recent water of meteoric origin.

The global distribution of deuterium and oxyghen-18 in precipitation and the factors which govern them have been adequately discussed by many authors and summarized in the International Atomic Energy Agency (IAEA) series of publications. The global precipitations are, according to Craig (1961), linearly correlated by the relationship:

$\delta D‰ = 8\, \delta^{18}O‰ + 10$

The d-parameter, i.e. deuterium excess, is usually assumed to be due to kinetic isotope fractionalization and decreases with decreasing moisture deficit of the air (Sonntag, et al, 1978). The conventional δD and $\delta^{18}O$ plot (Fig. 4) of the groundwater samples with slightly lower slope of meteoric water line of value 8 has the equation

$\delta D‰ = 7.5\, \delta^{18}O‰ + 6.9$

The decrease also in intercept of the groundwater of the carbonate (Kalambaina Formation) aquifer indicates possible evaporation processes before infiltration.

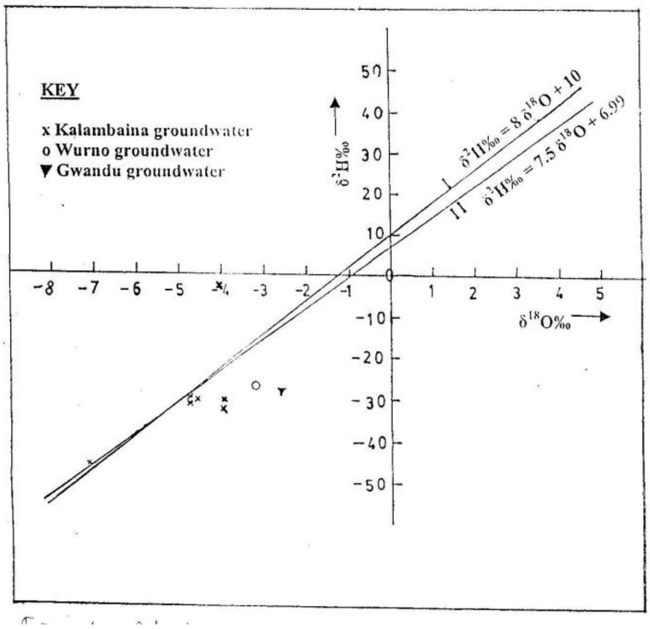

Fig.4. Graph of relationships between deuterium and oxygen-18 for the carbonate groundwater in the study area(line 1: GMWL; line II: Carbonate groundwater regression line)

The largest concentrations of tritium (^{3}H or T) in the atmosphere and consequently in precipitation occurred in the fifties and sixties as a result of atmospheric thermonuclear tests (Drost, et al, 1974; Clark and Fritz, 1997). Before these tests, the tritium content in precipitation ranged between five and 10TU on continents. Natural tritium is produced in the upper atmosphere through the action on nitrogen atoms of neurons generated by cosmic rays. The radioisotope of hydrogen, ^{3}H or tritium, has a half-life of 12.32 years (Lucas and Unterweger, 2000) and thus a lifetime commensurate with many hydrological processes (Gat, Mook and Meijer, 2000). Therefore, the hydrological evaluation of tritium measurements in natural water not more than a few decades old is now based principally on the determination of bomb-induced tritium in order to distinguish more recent from older waters (Drost *et al*, 1974). Very low tritium concentrations, around the level of detectability show that the water stems principally from the pre-thermonuclear bomb period (i.e. before the mid-fifties). Relatively high concentrations, grater than 10 TU, indicate that the water originates partly or wholly from post-thermonuclear bomb precipitation.

Tritium measurements in groundwater are a useful tool to show very modern recharges result from atmospheric condensation. The presence of tritium in groundwater (more than 10 T.U.) indicates that a considerable amount of recharge has taken place within the last fifty years (the age of thermonuclear tests). The absence of tritium means older recharge. The shallow carbonate aquifer, the Kalambaina Formation, indicates somewhat high tritium value with an average of about 18 T.U. and a range of 12.13±0.42 T.U. and 31.5±0.6 T.U. These relatively high concentrations of tritium indicate that the groundwater has originated from post-bomb precipitation. This implies that the residence time of water in this aquifer is very short, indicating rapid circulation and recent recharge by infiltration of water of meteoric origin.

In contrast, the Gwandu groundwater as sampled at Tumbulukum, immediately to the west of this carbonate terrain, yielded a very low tritium concentration of 0.6 TU (Table 1). JICA (1990) reported for the Gwandu groundwater also tritium concentration of 2.5 T.U. The sampled dug well at Tumbulukum was sunk to a depth of more than 52 metres, probably deep enough to tap the confined aquifer of the Gwandu Formation, which is separated from the upper unconfined aquifer by clayey beds. This groundwater is considered to be old, infiltrated as rain before the thermonuclear explosion era and without noteworthy recharge under the present climatic conditions.

CONCLUSION

Concentrations of environmental isotopes, oxygen-18, deuterium and tritium, have been used to study the groundwater system of the terrain in the Sokoto Basin. These environmental isotopes are very useful because they form parts of the water molecule and so are used as accurate tracers of water movement. In this study, the stable environmental isotopes have shown that the carbonate aquifer (Kalambaina limestone) receives modern recharge from the present day meteoric origin. Isotope thermometry has also shown that the recharge water must have undergone an intense evaporation (double labelling) before infiltration. Further more, all the groundwater samples contain tritium, an indication of active recharge into the groundwater system. The aquifer is open to recharge under the present climatic conditions.

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