

REVIEW

Review of Groundwater Potentials and Groundwater Hydrochemistry of Semi-arid Hadejia-Yobe Basin, North-eastern Nigeria

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ABSTRACT

Understanding the hydrochemical and hydrogeological physiognomies of subsurface water in a semi-arid region is important for the effective management of water resources. This paper presents a thorough review of the hydrogeology and hydrochemistry of the Hadejia-Yobe basin. The hydrochemical and hydrogeological configurations as reviewed indicated that the Chad Formation is the prolific aquifer in the basin. Boreholes piercing the Gundumi formation have a depth ranging from 20-85 meters. The hydrochemical composition of groundwater revealed water of excellent quality, as all the studied parameters were found to have concentrations within WHO and Nigeria's standard for drinking water quality. However, further studies are required for further evaluation of water quality index, heavy metal pollution index, and irrigation water quality. Also, geochemical, and stable isotope analysis is required for understanding the provenance of salinity and hydrogeochemical controls on groundwater in the basin.

1. Introduction

The hydrochemical assessment of subsurface for local, industrial, and agricultural uses required a valuation of the hydrochemical and hydrogeologic configurations of the subsurface aquifers^[1]. In a typical semi-arid region like north-eastern Nigeria, groundwater is the most important source of water supply for households, irrigation agriculture, and industrial demands^[2]. The quality and availability of subsurface water have been impacted by increased anthropological activities associated with urbanization, indus-

trialization, increased irrigated agriculture, and population growth^[3-6]. Groundwater protection and conservation procedures have been largely ignored in mainstream practices^[2]. Agriculture is the primary and major source of subsurface water pollution in arid and semi-arid areas^[7,8]. Results indicated that pesticides, irrigation water quality, and nitrogen fertilizers as major sources of pollutants in aquifers^[9].

In arid and semi-arid regions like the Hadejia-Yobe basin, salinization of groundwater is the major cause of the decline of water quality impacting the sustainable use of water resources. It limits the use of water for industrial,

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domestic, and agricultural uses^[10]. The problem intensifies in arid regions where the anthropological activities accelerate the deterioration of groundwater quality by a range of issues which include: (a) subsurface movement of effluents from irrigation fields; (b) upward flow of groundwater that has infiltrated the aquifer during irrigation; (c) seepage of highly effluent-rich surface flows concentrated in urban and/or municipal effluents during inundation event(s); (d) overexploitation of aquifer or recycling of wastewater; and irrigation return flows from irrigated fields^[10].

In drylands, the salinization, and anthropological activities are often followed by some natural processes such as the dissolution of soluble salts and rock-water interactions in the unsaturated zone which gradually salinizes groundwater. All these aforementioned factors necessitate continued analysis and monitoring of groundwater resources in arid environments for improved water resources management^[10]. Consequently, several studies were conducted to evaluate the physical and chemical composition of groundwater in different parts of the world^[9,11-23], results indicated that groundwater is influenced by both anthropological and lithological factors.

Groundwater analysis in some parts of the Hadejia-Yobe basin showed major variations are correlated to natural and anthropogenic processes^[24]. Evaluation of groundwater chemistry using multivariate statistics by Garba, Ekanem^[25], inferred that the status of water quality in Hadejia is fit for human consumption. Similarly, analysis of groundwater chemistry, dynamics, and storage in parts of Jigawa by Hamidu, Falalu^[26] revealed water of low hardness and dissolved salts that are within the WHO and Nigerian standard for drinking water quality. Evaluation of fluoride distribution, geogenic origin, and concentration in groundwater in some parts of Yobe showed that the area had fluoride concentrations slightly above WHO reference guidelines^[27]. Appraisal of toxicity and trace elements concentrations in Yobe revealed anthropological inputs^[28]. While there is a significant reporting on the hydrochemistry of aquifers in the Hadejia-Yobe basin, there is a need for reviewing the extent of hydrogeological and hydrochemical analysis in the basin. This is attempted in this study.

2. The Hadejia-Yobe Basin

2.1 Location and Climate

The Hadejia Yobe Basin (also known as Yobe-Jamaare floodplain), is a trilateral basin, with its summit in north-eastern Nigeria as depicted by Figure 1^[29-33]. The basin coincides roughly with the western Chad basin (unconfined aquifer) groundwater area. It is underlain by both the sedimentary formation and basement complex rocks.

The basin is drained in the southwest and northeast by the tributaries of the River Komadugu Yobe, comprising mainly Rivers Kano, Gaya, Hadejia, Katagum, Jamaare, and Gama. These rivers link up at a different point to form the drainage system of the Komadugu Yobe, flowing towards the north-eastern summit of the triangular basin^[29-34]. Together with the eastern Chad basin of Nigeria, it covers the southwestern part of the Lake Chad.

The major town in the basin includes Kano, Hadejia, Azare, Potiskum, and Katsina while Bauchi is just outside the southern boundary. It is bounded to the north by the Niger Republic. It is situated along with the latitude 10° N and has a very hot and dry climate (Figure 1). The annual rainfall is comparatively low, and annual evaporation is also very high, reaching up to 1500mm. The scenery is wide-ranging, extending from the rocky hills and inselbergs of the basement complex rocks of the southwest, to less protuberant, low lying dull rolling dunes of sedimentary formations to the northeast, along Azare, Geidam, and Gumel. A line of massive granitic mountains, which perhaps indicate the contact between the two formations marks the basement-sedimentary frontier.

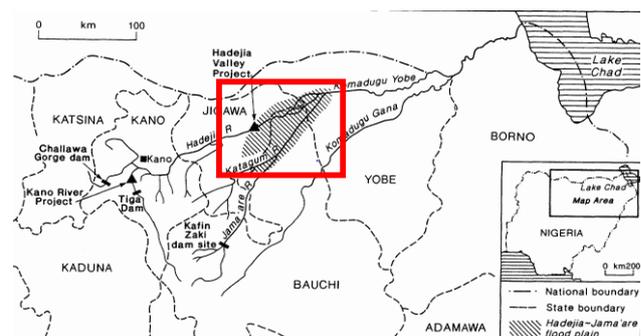


Figure 1. Hadejia-Jamaare Floodplain^[33]

2.2 Relief and Drainage

In terms of drainage, the Hadejia-Yobe-River System controls the entire basin. The tributaries of this river system rise from near western parts of the North-Central Plateau (Kano, Katsina, and Jos plateau), with comparatively higher precipitation than the rest of the province. The Delimi River, with its headwaters on the Jos Plateau and the River Igi flowing from the Mingi Hills, the River Kano from Liruwe Hills, and the Hadejia River from western Kano, all donate to Hadejia-Yobe-River System^[31,33,34]. The Hadejia-Yobe or Komadugu-Yobe, as it is sometimes described, collects water from entire tributaries before flowing to the Lake Chad. Most of the tributaries of the Hadejia-Yobe River System are mechanically measured. The river flow from the area of high precipitation in the southwestern axis to lesser precipitation in the direction of

the lake Chad. The intensity of rainfall displays a progressive fall from the southwest to the northeast. The average annual estimate of rainy days varies from around eighty days in the southwest to less than the forty days near Lake Chad. The temperatures are generally high and vary from 20°C to 28°C from southwest to northeast. The river Hadejia-Yobe is one of the most exploited and monitored river system in Nigeria ^[30-32,35,36].

Many gauging stations are set along its sequence, from its source area, in the southwest, to Gashua, near Lake Chad, where the river empties its headwaters. The river system is affluent, in the upland basement complex areas. The river also influent in the Lower Hadejia-Gashua sedimentary dispersal or wetland area, where the river valley is exposed to seasonal run-offs and flooding. Consequently, losing a substantial volume of its flow to the riparian alluvial groundwater aquifers. Owing to the high evaporation rates exceeding 90%, only about 10% or less of this flow is accessible by the river as it squalls through its course of the lake. This flow is induced to recharge into the underlying aquifers of this part of the Chad basin ^[37-40]. Later, with the increase in evapotranspiration, downstream, and the losses into the underlying groundwater aquifers, as the river feasts out and winds its sequence towards the Lake Chad, the flow drops considerably.

The river flow, between 1964 to 1965, along the Hadejia - Yobe dropped from 5.6x10m in the upland area, to 0.63x10m in Yau, after flowing through the wetland areas, 51.5 km to the lake. The situation is believed to have worsened. There is also a rise in the groundwater input to the river flow downstream, 35% at Challawa, and over 50% towards Wudil. Generally, the river system contributes very little to the water of the current Lake Chad, which added to the drying of the lake. Most of its water is lost, seemingly in the wetland swamps and pools between Hadejia and Geidam. The Hadejia-Yobe River System with its large alluvial expanses is seasonal and only starts flowing around June to July, after the onset of the rainy season.

2.3 Geological setting

The geology of the Yobe-Hadejia basin is comprised of the basement complex and sedimentary formations ^[38,41,42]. The Chad Formation is the newest in the Hadejia-Yobe Basin. A detailed stratigraphical description of the Chad Formation is not common literature compared to the other older formations in the basin. The sedimentology of the formation, which segregates the deposits into three members based on color and claystone/sandstone sections were described in detail by ^[43]. The sedimentation of the Chad Formation has been an incessant process that began in the Late Miocene to the present, whereby river and aeolian

sand and clay elements are still being added.

Some of the detailed stratigraphies of the Chad Formation indicated that the lithostratigraphy of Chad Formation encountered in Korowanga borehole, Dogara borehole and outcrop section at Abakire, represent numerous heterolithic sandstone and claystone in varying proportions. These sands range from silty, medium, and coarse-grained in size. In the Tuma well, for instance, the Chad Formation is characterized by light grey colossal claystone, minor sand particles, and some occasional pebbly horizons, and indicating some ferruginization in the deposits ^[43]. Eight lithofacies components were defined based on their physiognomies such as structure, facies type, grain size, boniness, sorting, color, and compaction ^[43]. The account of the faces components (summarized in three parts) is shown in Figure 2.

2.3.1 The Lithofacies Part 1-3

Part 1 comprises greyish sandy claystone. These facies component range from 50 to 70 meters and also is encountered between 305 m and 345 meters below the surface. It is highly rich in organic matter with insignificant sand particles ranging between silt and minor pebbles. The lithofacies is also accompanied by lignite. The lower interlude has filthy claystone displaying roughening-upward sequences and sorting from clayey granite through to sandy claystone, and weakly-sorted sandstone at the uppermost ^[43]. Part 2 is comprised of micaceous claystone which occurred only in the interval of 70-90 meters. The carbonaceous clay is mainly related to mica flecks particularly muscovite with negligible silt particles. The existence of muscovite proposes a felsic parent rock source and lengthy-distance transference. Its high content in organic matter signposts a lacustrine depositional scenery ^[43].

Part 3 is comprising mainly of lithified claystone. The lithofacies occurred at the interval of 90 to 195 meters, also exist as reedy-bedded interpolated deposits at the intermediate interlude of the entire unit. The claystone is sturdily lithified and marginally ferruginized. It is comprised of slight mica flecks with no sign of biological opulence. Near the lower part of this interlude, the claystone contrasts from bright to murky grey, signifying cumulative organic abundance and accumulation in a reducing condition ^[43].

2.3.2 The Kerrikerri Formation

This geologic formation is characterized by horizontal-laying to moderately plummeting basal conglomerate, grit, sandstone, siltstone, and clay which unconformably rests above the Maastrichtian Fika Shale and Gombe Sandstone ^[44,45]. Five stratigraphic units (including the type section at Kadi) and lithology were reviewed. The

formation attained a depth of about 200 meters at Duku [44,45]. The substantial mineral suite is comprised of rutile, zircon, kyanite, staurolite, limonite, tremolite, sillimanite, pyroxene, hornblende, and tourmaline, which are suggestive of origin from the adjoining basement complex and previous alluvial rocks [44,45].

Epoch	Formation	Depth (m)	Lithology	Lithofacies units	Marker fossils	Palaeoenvironment
Upper Miocene	Chad Formation	50	Grayish sandy claystone		[<i>Laevigatosporites</i> sp., <i>Achrostichum</i> sp.]	Continental to lacustrine
		70	Micaceous claystone		[<i>Achrostichum</i> sp.]	
		90	Lithified claystone		[<i>Nymphaea lotus</i> , <i>Monocolpites</i> sp., <i>Retistephanocolpites gracilis</i>]	Lacustrine to marine
		100			[<i>Anthracurus</i> sp., <i>Laevigatosporites</i> sp., <i>Monopores annulatus</i> , <i>Palaetricolpites crassus</i> , <i>Verrucatosporites</i> sp., <i>Nymphaea lotus</i> , <i>Monocolpites</i> sp.]	
		150			[<i>Retistephanocolpites gracilis</i> , <i>Uspacia</i> spp., <i>Achrostichum</i> sp., <i>Monopores annulatus</i> , <i>Monocolpites</i> sp.]	Continental
		195	Light gray shale		[<i>Echtricolpites spinosus</i> , <i>Nymphaea lotus</i> , <i>Zonocolpites reponae</i> , <i>Laevigatosporites</i> sp., <i>Monocolpites annulatus</i> , <i>Monosulcites</i> sp., <i>Monocolpites</i> sp.]	
		200	Lithified claystone		[<i>Monocolpites</i> sp., <i>Monocolpites</i> sp., <i>Monocolpites</i> sp., <i>Achrostichum</i> sp.]	Lacustrine
		210	Micaceous sandstone			Continental
		220	Lithified claystone			
		230	Poorly-sorted sandstone			Lacustrine
250	Clayey sandstone					
260	Claystone		[<i>Monopores annulatus</i> , <i>Echtricolpites estatae</i> , <i>Achrostichum</i> sp., <i>Monocolpites</i> sp.]	Fluvial		
280	Poorly-sorted sandstone		[<i>Elaisis guineensis</i> , <i>Verrucatosporites usmensis</i> , <i>Monopores annulatus</i> , <i>Monocolpites</i> sp., <i>Nymphaea lotus</i> , <i>Zonocolpites reponae</i> , <i>Palaetricolpites crassus</i> , <i>Palaetricolpites crassus</i> , <i>Monocolpites</i> sp., <i>Monocolpites</i> sp.]			
300	Grayish sandy claystone			Lacustrine		
350	Clayey sandstone		[<i>Monosulcites</i> sp., <i>Achrostichum</i> sp., <i>Nymphaea lotus</i> , <i>Langia</i> spore, <i>Monocolpites</i> sp., <i>Monocolpites</i> sp.]			
365	Claystone		[<i>Monosulcites</i> sp., <i>Leiotriteles</i> sp., <i>Grimadalea magnacrevata</i> , <i>Pachydermites dieckoni</i> , <i>Retimonocolpites</i> sp., <i>Monopores annulatus</i>]	Lacustrine		
Eocene	Kerri-Kerri Fm.	365				
		365				

Figure 2. Lithofacies type and depositional/precipitated palaeoenvironment of the Chad Formation [43]

The occasional basal deposits, well-sedimented siltstones and the occurrence of contraction fissures, clay-reinforced pebbles, local channel sandstones, and tinny vistas of coal and carbonaceous clay propose a distinctive deltaic, peripheral and deltaic lacustrine depositional environment. The occurrence of the pollens *Monocolpites marginatus* and *Spinizonocolpites baculatus* confirmed a Paleocene age for the formation. The explanation of the superficial and subsurface information is constant with an irregular graben edifice of the Kerrikerri basin. The western boundary of the basin was fault-controlled and active during the deposition of sediments through the Early Tertiary [44]. Borehole data showed that the intermittent nature of the Paleocene age Kerri-Kerri Formation as an aquifer in Darazo [45].

The series, parasequences, and their borders are believed to have been formed in reaction to cycles of virtual fall and increase of sea level. Within strings, several systems bands can be notable and developed all through an explicit component of a full cycle of virtual sea-level transformation [46]. The source of this layered congregations was the consequence of the interface between the ratios of variation of basin settling, residue contribution, and eustasy [46]. The stratigraphic sequences recognized are truncated stand system bands, transgressive system bands,

high stand systems bands, and a sequence boundary. The base of the Gombe Sandstone was not encountered in the Fika area perhaps owing to lack of outcrops. The unconformity between these two formations (Gombe Sandstone and Kerri-Kerri Formation), shows a most important top-most series edge [46].

Based on previous investigations, the Gombe Formation was dated as Late Maastrichtian in age, whereas the Kerri-Kerri Formation age data is not available, nonetheless, Palaeocene pollens were traced [46]. The formation of progression frontiers can be credited to tectonics. However, there is some indication for Santonian-Campanian folding simultaneously with the existence of a sharp unconformity [46]. The major stratigraphic sequence of the Kerrikerri Formation is presented in Figure 3. It is dominated by thick limestone and sandstone which are Paleocene in age. The stratigraphic sequence occurred under erratic conditions with each sediment correspond to one full cycle of transgression and regression [47]. The Kerri-Kerri Formation superimposed a slight area in the southeast, toward Azare. The formation, containing a succession of grits sandstones and clays, lies against the crystalline rock in this area. It is usually not easy to differentiate the formation from the younger superimposing Chad Formation, as both seem to be in contact and present the same lithological physiognomies. The formation is up to 200 meters thick in its core area of existence in the upper Benue and thins out to the northwest near Azare in the Hadejia-Yobe basin.

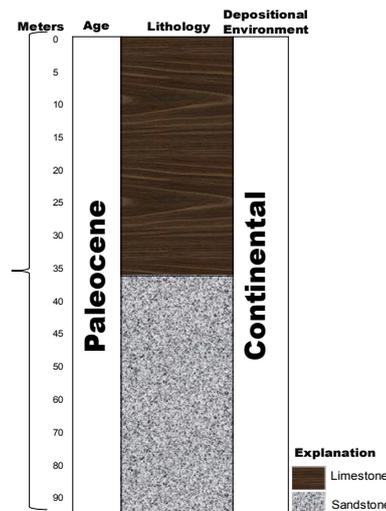


Figure 3. Stratigraphic section of Kerrikerri Formation [47]

2.3.3 The Gundumi Formation

The Gundumi Formation is characterized by the river and lacustrine deposits, which include moderately grainier materials (Figure 4). The formation is also characterized by intermittent lenses of quartz and feldspar pebble grav-

el, which are interbedded with the richer clay and clayey sand [48]. However, the formation contained a great deal of melled clay. The sandy beds decline, and clay beds upsurge with depth down to the contact with the pre-Cretaceous basement rocks. Near the base of the Gundumi Formation, a conglomerate of smoothed quartz stones up 0.0381 meters in diameter occurred in an outlier [48]. The sand and gravel beds are comprised of sharp to sub-angular quartz particles, but several beds are abundant in feldspathic and micaceous substance and rock fragments. Colors in the Gundumi varied widely. Brown, red, pink, yellow, white, and even purple are regular, and in some clay layers, some of these colors may exist in spotted forms. The sedimentary formations lie above the Precambrian basement complex formation. The formation ranged in age from Palaeozoic to Quaternary. It is assumed to be a tectonic cross point between the northeast and southwest trending the “Tibesti-Cameroun Trough” and a north-west-trending Air-Chad Trough”. It has been estimated that over 3600 m sediments have been deposited [49].

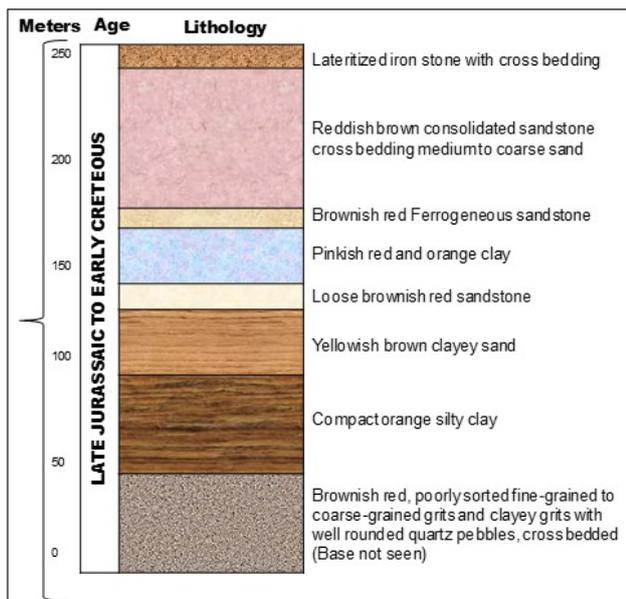


Figure 4. Stratigraphic section of Gundumi Formation

The outcrops of the basement complex formation in the east, southeast, southwest, and the north of the basin are noticeable. The configuration below the sediments across the lake was similar to the graben and horst zone [49]. The hydrogeology and hydrochemistry of the basement complex section of Chad formation are characteristic of Nigeria’s basement complex terrain. There are some published data on Nigeria’s basement complex [50-60]. Results indicated that the groundwater evolution hangs on reactivity and pH. The hydrochemistry of aquifers is a direct signal of the catchment geology [58].

3. The Sedimentary Aquifers

Hydrogeologically, the Chad Formation is a profound aquifer in the Hadejia-Yobe basin [26,61,62]. The aquifer comprises of a series of clays, sandy clays, and silt, in which bands and lenses of silt and grit appear at several spots. The coarse sand and gravel are well developed. In this area, the Chad Formation superimposes the Kerrikerrri Formation which lies on a more stable basement rock [37]. The Chad Formation does not exceed 165 meters in thickness and thins out erratically, nonetheless gently towards the southern and western borders where it seems to overstep the basement complex terrain [37,63]. At Gumel (Jigawa State), the sediment is reported to attain a thickness of 132 meters, 115 meters at Nguru (Yobe State), 132 meters at Marguba, and 76 meters at Kunshe. In this province, groundwater is found an underwater table or sub artesian conditions depending on the existing hydrogeological condition (Figure 5).

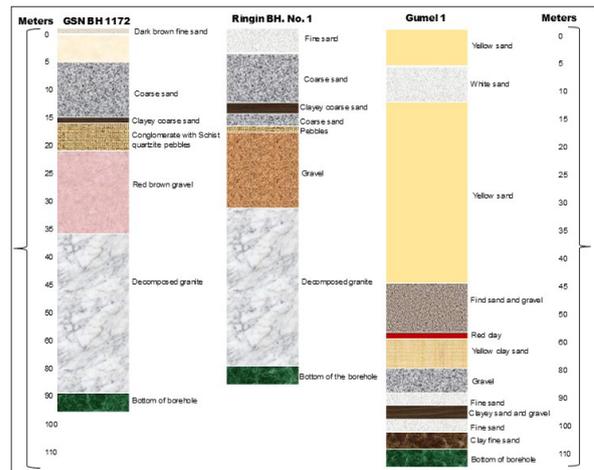


Figure 5. Lithologic section of boreholes penetrating Chad Formation.

Borehole yields ranged from 3.3 to 5 lits/sec on average. However, transmissivity ranged from 6.87m²/day and 429.4m²/day, with a mean value of 65.7m²/day [37]. The parting of the Chad Formation into the Upper, Middle, and Lower aquifers cannot be defined in this part of the basin. Alternatively, it shows recurrences of clays, sand, and silts, the sandy layers intersecting the aquiferous layers. The upper 20-30 meters of the grainy sands of the Hadejia-Yobe basin, store a lot of water as bank storage, directly recharged from the river flows [37]. A lithological unit along the river outline, based on available borehole records, displays a top 0-10 meters silty fine-grained sands, underlain by a thick sequence of coarse sand and gravel, with two main interbedded clay/shale deposits. Some of the borehole drilled in this area gave the following lithological sections and output [37,64].

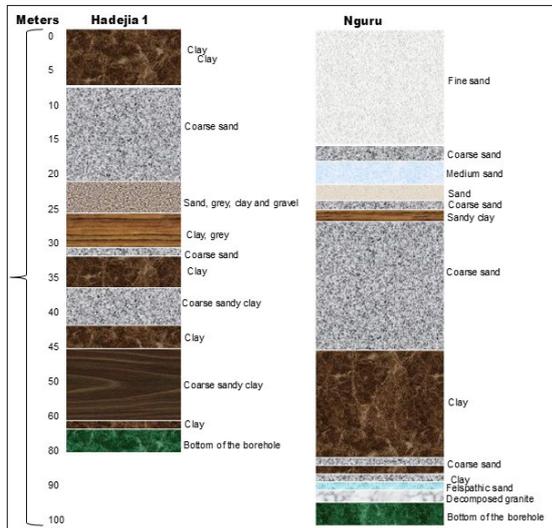


Figure 6. Lithologic section of boreholes penetrating Chad Formation

The borehole GSN BH 1172 was drilled at Ringin Railway Station. No information on yields was available. The second borehole in Figure 5 was also constructed at Ringin. This well had yielded 5 lits/sec. The depth of the aquifer here ranged between 2.1-3.3 meters. The third borehole in Figure 5 was drilled at Ringin. The total depth of this well reached up to 106 meters below the surface [37]. No data on estimated yield. In a similar borehole in Hadejia (Figure 6), the borehole attained a total depth of 75.7 meters. There is no information on borehole yields for this well. But in another borehole in Nguru (Figure 6), an estimated yield of 3.8 lits/sec was obtained. The aquifer depths at this location ranged between 21.2 to 36.4 meters. The total depth of this borehole is 95.4 meters [37]. Generally, the lithology of these boreholes which penetrates the Chad Formation is characterized by predominant layers of clay [41,65-67].

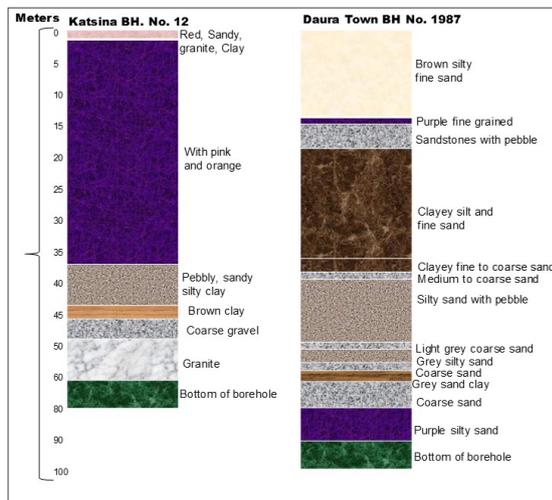


Figure 7. Lithologic section of boreholes penetrating the Gundumi Formation

The sediments described illustrated in Figure 7 are characteristic of the Gundumi Formation which lies directly on the basement complex [37,48,61]. Groundwater in the region is found underwater table conditions. The Coarse sand illustrated in Figure 7 formed good aquifers, but in the outskirts where the sediment appears too thin to hold reasonable quantities of water, mainly, around the basement inliers. Previous studies revealed that 24 boreholes drilled in this area have an average depth of 45 meters, with a depth ranging from 20 to 85 meters. A maximum yield of 6.25 lits/sec and an average yield of 3.2 lits/sec, with only two boreholes, abandoned. This range of yield is reasonable and good enough for small rural water supply schemes [37]. The Hydrogeology of Gundumi Formation is also described in detail under the Sokoto Basin by Anderson and Ogilbee [48]. This geologic formation also underlies parts of Katsina and Daura areas to the north-western angle of the basin and gave the lithology in Figure 7.

3.1 The Basement Complex Terrain

The basement complex rocks underlay most of the south-western section of the basin [49,61,68,69]. The groundwater condition is as discussed in Nigeria’s Basement Complex areas [58,70,71]. Published data of the water resources and engineering construction agency, Kano, found that several successful boreholes have been drilled in the basement area of the basin. From the available lithological data [37], a typical borehole section is illustrated in Figure 8. The borehole at Kano Trade Centre reached a depth between 20.3 to 32.4 meters, which has yielded 106.0 lits/min and a specific yield of 8.7 lits/min/m [37]. The second borehole has no data on yield and specific yield.

However, a similar borehole at Gaya (Figure 8), has a total depth of Total Depth 42.7 meters, Yielded 2.2 lits/Sec and a Specific Yield of 9.2lits/min/m. The majority of the boreholes seemed to be in valley lowland areas with the substantial deepness of alluvium and deep weathering of the underlying basement complex rocks. At Danbatta about 45 km north of Kano approximately all drilled boreholes, passed roughly through 40 to 50 meters lateritic, clay, coarse quartz sands and gravel, and bottoming in decomposed granite, as illustrated in Figure 4 [37]. The coarse sands or gravel formed the major aquifers, and borehole yields were abstemiously good. The Dambatta BH. No. 3 gave a discharge of 0.75 lits/sec. while Danbatta 1 and 2 and Dambatta Hospital 1 produced very high yields of 1.8, 6.3, and 9.1 liters/sec [37].

At Dawankin Kudu, some 25km south of Kano-Gaya road, about 60km southeast of Kano, a similar yield of 4.5 liters/sec and 2.7 liters /sec were obtained from 30-50m of the same kind of sediments lying on the basement complex.

These are quite a high yield and could have been derived from alluvial beds, or deeply fractured zones of the hard rock environment. Elsewhere, the yield is poorer, giving a range of 0.6 to 1.3 liters/sec [37]. Out of seven boreholes, only one, Kano BH No. 5, gave up to 2.5 bits/sec. This set of results relates more to the groundwater situation in Basement Complex rocks regions of Nigeria [50-60]. The borderline between the basement complex terrain and the sedimentary area is not certain to separate the sedimentary layer from the deeply weathered basement rock with which it has hydrologic interaction. The depth of weathering appears to thicken near the basement/sedimentary frontier, forming about 20 meters around Wudil, to over 40 meters in the Dabi-Dutse geological frontier [37]. The thickening towards the sedimentary boundary implied a hydrologic joining with and recharge to the Chad aquifers.

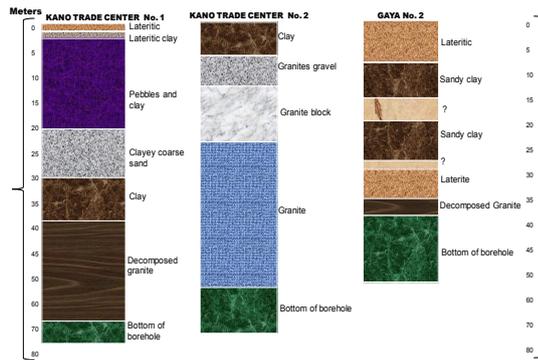


Figure 8. Lithologic section of boreholes in the Basement Complex Terrain

An assessment of water resources potentials by Sobowale, Adewumi [34], revealed that about 2619 million m³ of surface water are accessible yearly upstream of Wudil, 658 million m³ is obtainable between Wudil and Hadejia, while 905 million m³ is accessible between Gashua and Hadejia. Examination of direct groundwater recharge discovered that 86 mm, 94 mm, and 8 mm of water are restored to groundwater yearly in the three hydrological units. The least groundwater renewal occurs in the Hadejia-Nguru Wetlands. As at the time of this review, no water stress was detected in the sub-catchment, the prospective water balance of the area indicates that about 75% of the accessible water between Wudil and Hadejia zone would be used up by 2010. Estimates show that the water use rate will reach 100% by 2018. Thus, water scarcity and conflicts would be faced in this sub-catchment if critical steps are not undertaken to tackle the circumstances. Analysis of provisioning ecological services offered by the Hadejia-Nguru Wetlands had indicated water shortage and competition for water resources and conflicts [72]. Thus, designing a new management approach that defines a resource use timetable particularly for herders and farm-

ers is required to lessen the conflicts [72].

3.2 Groundwater Hydrochemistry

3.2.1 Groundwater Classification Based on Physical Parameters

Figure 9 presents a summary of synthesized data on physical parameters from the Hadejia-Yobe basin. The pH concentrations varied from 4.7 to 9 with a mean value of 6.8. Groundwater having a pH level varying between 6.5-8.5 is considered suitable for drinking [73,74]. A synthesis of EC levels from 95 locations showed EC ranged from 45 to 1891 μS/cm With a mean value of 430.45 μS/cm. Similarly, the temperature ranged from 8 to 34.1°C with a mean value of 27.55 °C. Also, TDS ranged from 9.72 to 1060 mg/l with a mean value of 216.39 mg/l. Total hardness is highly variable and ranged from 25.41 to 703 mg/l with a mean value of 162.08 mg/l. Studies on DO, BOD, and COD are very few in Hadejia-Yobe Basin. Waziri and Ougbuaja, (2010)'s, interrelationships between physicochemical water pollution indicators showed that DO ranged from 5.87 to 7.38 mg/l with a mean value of 6.74 mg/l. The BOD varied between 2.43 to 3.34 mg/l with a mean value of 2.72 mg/l. The COD ranged from 146.83 to 189.89 mg/l with a mean value of 165.70 mg/l.

In a similar study by Waziri and Audu [75], showed average DO concentration varied from 4.50, 4.32, 4.68, 4.72, 5.02, and 5.22 mg/l during the dry season. Also, BOD varied from 3.20, 3.09, 3.16, 3.19 3.82, and 3.22 mg/l during the dry season. Mean COD concentration varied between 170.0, 163.22, 163.83, 158.17, 157.90, and 176.17 mg/l throughout the dry season. In contrast, mean DO concentration during wet season varied from 8.08, 9.47, 8.48, 7.35, 6.78, and 8.92 mg/l. The BOD varied between 2.52, 2.11, 2.20, 2.27, 2.09 and 2.23 mg/l. The COD also varied between 178.83, 192.17, 191.83. 219.50, 214.13 and 156.33 mg/l. The significance of these parameters in drinking water has been explained in detail in the literature [76-79].

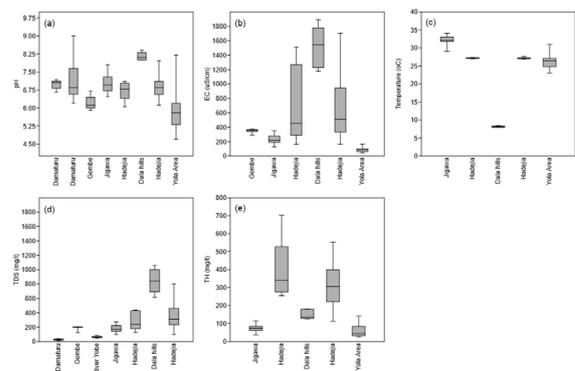


Figure 9. Physical parameters (a) pH, (b) EC, temperature, TDS, and hardness

Figure 10 presents the groundwater classification-based hardness, TDS, EC, and pH. Based on hardness, 39.19% fell in soft class, 29.73% fell in hard class, 13.51% fell in is hard/moderately class, and 17.57% fell in the very hard class. Based on TDS, 91.59% is essential for drinking. Further classification based on EC, revealed that 13.68% fell in good class and 86.32% fell in permissible class. Based on these physical parameters, groundwater in Ha-dejia-Yobe Basin is suitable for drinking.

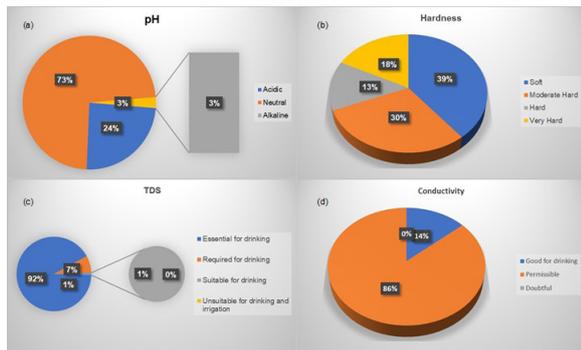


Figure 10. Groundwater classification (a) pH, (b) Total hardness, (c) TDS and (d) Conductivity

3.2.2 Chemical Characteristics

The evaluation of the hydrochemical composition of groundwater is central to understanding the range in which these elements fall [80-89]. When their concentration is exceeding the recommended reference values, these basics may render groundwater injurious for human health. Chemical parameters including Ca, Mg, Cu, Cd, B, Al, K, PO₄, SO₄, As, and Cl, are mostly derived from rock mineral. Even so, elements like NH₄ and SO₄ are increasingly derived from anthropogenic bases. Assessment of the derivation and absorption level of these chemical constituents is required for effective groundwater monitoring. Studies on Al, NH₄, and As are common.

Quality assessment of hand-dug well in Song town (neighboring Adamawa State), revealed that NH₄ varied from 1.22 to 2.35 mg/l with a mean value of 1.90 mg/l [90]. This measurement cannot be used as a representative value for NH₄ in the basin, owing to the difficulty involved in the delineation of boundaries of the Hadejia-Yobe basin. There was no reporting of NH₄ from Hadjia, Jigawa, and Damaturu zones, which constituted the core areas of this basin. However, the titrimetric determination of arsenic from Hadejia Emirate Council, Jigawa State, Nigeria, by [91], revealed that ranged from 0.006 mg/l to 0.014 mg/l with a mean value of 0.011 mg/l; while that of irrigation canals ranged from 0.006 mg/l to 0.010 mg/l with a mean value of 0.009 mg/l. These results also show that all the analyzed water samples from irrigation canals have As

level below WHO as well as Nigerian reference values. Based on these revelations, more studies on Al, As and NH₄ are recommended.

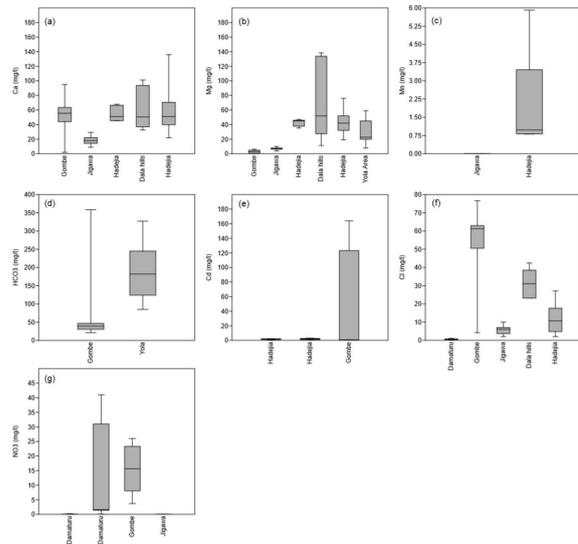
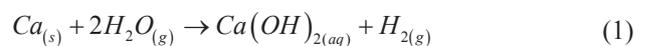


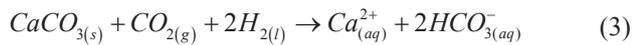
Figure 11. Hydrochemical parameters of water quality.

Barium concentration from the neighboring Gombe showed that Ba ranged between 0 to 0.54 mg/l with a mean value of 0.22 mg/l [92]. Based on this revelation, Ba remained poorly known in the basin; mean Ba concentration is within SON reference guideline value (0.7 mg/l). A major reason for limiting Ba in groundwater is its connection with hypertension [93]. However, there was a considerable number of reports on HCO₃ (Figure 11). HCO₃ concentrations ranged from 6.0 to 126.0 mg/l with a mean value of 23.79 mg/l [94]. Other studies reporting HCO₃ from the Hadejia-Yobe basin indicated that HCO₃ ranged from 21.2 to 359 mg/l with a mean value of 53.05 mg/l [95]. HCO₃ ranged from 85 to 327 mg/l with a mean value of 194.05 mg/l [96]. Based on Nigeria's standard, no reference value was set for HCO₃ in drinking water.

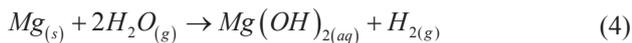
A synthesis of Ca concentration from 95 sites revealed that it varied from 1.9 to 136 mg/l with a mean value of 41.29 mg/l. Calcium concentration in drinking water tends to be beneficial to human health. However, aquifers that have high Ca levels, are associated with hardness. The significance of Ca in hydrochemical analysis relates to hardness. Calcium is found naturally in various environmental settings and occurs widely in groundwater aquifers [97-99]. It is an integral component of coral and is found in high concentrations (400mg/l) in brine. In lime regions, Ca attain 100 mg/l. Elementary calcium at normal temperature can react with water, based reaction process indicated by Eq. 1:



Dissolved calcium hydroxide forms soda and hydrogen gas. It typically occurs when CO_2 is freed, resulting in the development of carbonic acid, affecting Ca compounds. The carbon weathering reaction and the total reaction are defined in equations 2 and 3, respectively.



Consequently, calcium hydrogen carbonate is produced. Groundwater aquifers can be affected by changes in temperature since Mg is a relatively low reducing element. Thus, rising oxygen can increase the reduction process. Additionally, Mg can react with water vapor to produce hydrogen gas or magnesium hydroxide as defined in Eq. 4.



Magnesium concentrations from 95 sites showed it ranged from 0.1 to 138.22 mg/l with a mean value of 23.71 mg/l. Based on this revelation, the mean Mg concentration in this basin is above Nigeria's reference value (0.2 mg/l). High Mg concentration in drinking water has not been associated with any adverse health risk; high levels can affect the consumer acceptability [93]. Hamidu, Falalu [26]'s analysis of storage, chemistry, and dynamics of groundwater discovered no Mn concentration in groundwater. This result is doubtful because Mn is an inherently appearing and copious element that is indispensable in natural systems. The chemical behavior of Mn is controlled by pH, reduction, and oxidation reactions. As a naturally occurring element, Mn is also omnipresent in the environment, and so is found in soils, sediments, surface water, and groundwater. This result throws doubt on the entire measurements reported by their study. Therefore, new investigations are required for further evaluation.

Manganese (Mn) varied from 0.33 to 19.79 mg/l with a mean value of 2.49. [100] Mn appears spontaneously in surface water and subsurface water, particularly in O_2 reduced or anaerobic environments. Mn concentration in aquifers is controlled by several factors such as the chemistry precipitation, lithology of the aquifer, geochemical nature, groundwater movement paths, and dwelling time. Most of these factors can be extremely unpredictable over comparatively small temporal and spatial scales. Mn can be leaked from superimposing soils and mineral deposits in underlying rocks and from the crystals of the aquifer itself. Baseline varieties of Mn concentrations in ground-

water differ both in the interior aquifers and between distinct aquifers over numerous orders of enormity, dominated mainly by prevalent Eh (reducing conditions) and pH, which react to seasonal water table variations within the aquifer. The environmental threats related to Mn in groundwater are comparatively rare and may occur most significantly only when Mn-rich aquifers considerably sustain streams.

Sodium concentrations in some parts of the basin (Yola area) ranged from 0.029 to 1.73 mg/l with a mean value of 0.74 mg/l [96]. The potassium (K) concentrations ranged from 4 to 12.1 mg/l with a mean value of 7.43 mg/l. The Na and K concentrations remain poorly known. Therefore, more measurements of Na and K are required for further evaluation. Appraisal of some heavy metal concentrations in the water revealed that Cd concentration was highly variable [92]. Mean Cd concentration was 0.29 mg/l in borehole water, 0.01 mg/l in hand-dug well, and 0.45 mg/l in mine drain. Nigeria's standard defined 0.003 mg/l as the maximum permissible limits for Cd in drinking water. A major reason for limiting Cd in drinking water is because of its toxicity to the kidney [93]. Studies on Cd from core areas within the basin (Hadejia, Jigawa, Yobe), were not accessed.

Fluoride concentration was 1.42 mg/l in the deep groundwater, 1.02 mg/l in shallow groundwater, and 0.21 mg/l in mine drain [92]. Assessment of the chemical and biological quality of deep groundwater revealed a range varying from 0 to 0.4 mg/l with a mean value of 0.18 mg/l [101]. Figure 11 further presents a synthesis of lead in the Hadejia-Yobe basin. Cadmium concentration ranged from <0.001 to 164 mg/l with a mean value of 11.98 mg/l. The NSDWQ [93] set 0.01 as the maximum permissible limits of Pb in drinking water. A major reason for limiting Pb in drinking water is its link with cancer and interfering with Vitamin D metabolic rate. It also disturbs mental growth in babies and is toxic to the central and peripheral nervous systems. A synthesis of Cl from 85 sites showed that Cl concentration ranged from 0.17 to 76.6 mg/l with a mean value of 20.11 mg/l. Mean Cl is below the NSDWQ guideline value (250 mg/l). Figure 11 presents a summary of NO_3 concentration. Nitrate ranged from 0 to 41 mg/l with a mean value of 6.55 mg/l. Mean NO_3 is within the NSDWQ [93] reference guideline (50 mg/l). It is limited in drinking water because it causes cyanosis, and asphyxia (blue-baby syndrome) in infants under 3 months.

3.3 Summary and Research Knowledge gaps

The literature is unanimous about the significance of understanding the hydrogeology and hydrochemistry of aquifers in a semi-arid Hadejia-Yobe basin. Based on the

analyzed literature reports, the following remarks can be made:

(1) The Chad Formation is the prolific aquifer in the Hadejia-Yobe Basin, and it is characterized by high sandy and clay formations.

(2) The aquifer provides considerable amounts of groundwater. It had a considerable number of successful boreholes even in the basement area of the basin.

(3) The Gundumi Formation which lies directly on the basement complex also provides groundwater under water table conditions. Most of the boreholes drilled in the formation have a depth ranging from 20-85 meters.

(4) Based on physical and chemical composition, the basin holds water of excellent quality; all the studied parameters were found to have concentrations within WHO and Nigerian standard for drinking water reference guidelines.

Although the physical and chemical composition of groundwater is good, this basin is yet to be fully explored hydrochemically. As a result, more studies are required for further evaluation. Reports on water quality index, heavy metal pollution index are lacking. Similarly, irrigation water quality assessment using water indices such as sodium adsorption ratio, sodium percent, residual sodium carbonate, Kelly's index, magnesium hazard, permeability index, and potential salinity are lacking as well. Besides, geochemical analysis employing geochemical modeling and stable isotope techniques are required for understanding the provenance of salinity in aquifers.

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