Ground-Water Hydrology of the Chad Basin in Bornu and Dikwa Emirates, Northeastern Nigeria, with Special Emphasis on the Flow Life of the Artesian System

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1757-I

Prepared in cooperation with the
Geological Survey of Nigeria
under the auspices of the
United States Agency for
International Development

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By R. E. MILLER, R. H. JOHNSTON, J. A. I. OLOWU, *and* J. U. UZOMA

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GROUND-WATER HYDROLOGY OF THE CHAD BASIN IN BORNU AND DIKWA EMIRATES, NORTHEASTERN NIGERIA WITH SPECIAL EMPHASIS ON THE FLOW LIFE OF THE ARTESIAN SYSTEM

By R. E. Miller, R. H. Johnston, J. A. I. Olowu, and J. U. Uzoma

ABSTRACT

Bornu and Dikwa Emirates lie in the Nigerian sector of the Chad Basin, a vast region of interior drainage encompassing about 600,000 square miles of north-central Africa. The report area includes about 25,000 square miles of the basin that lie in Nigeria. Most of the area is a featureless plain that slopes gently northeast and east from the uplands of central Nigeria towards Lake Chad. On its eastern side the lake has one surface outlet which overflows only during exceptionally high stages of the lake. This outlet spills into the channel of Bahr al Ghazal, which in turn drains into the Bodélé depression. Because the lake is shallow, the shoreline fluctuates markedly with high and low stages corresponding to the wet and dry seasons. The semiarid climate of Bornu and Dikwa Emirates is characterized by a long dry season and a short wet season that correspond to seasonal winds. Annual rainfall ranges from 15 inches in the northern part of the area to 32 inches in the southern.

The Chad Basin in Dikwa and Bornu Emirates is underlain by interbedded sand and clay, collectively termed the Chad Formation. These alluvial and lacustrine sediments were deposited in or near Lake Chad when it occupied a much greater area during Pliocene and Pleistocene time. The Chad Formation has a very slight primary dip in the direction of Lake Chad and conforms to the gentle slope of land surface. The known thickness of the formation ranges from a few feet where it overlies bedrock on the periphery of the basin to at least 1,800 feet at Maiduguri; however, its total thickness probably exceeds 2,000 feet in the central part of the basin.

Three water-bearing units termed upper, middle, and lower zones occur within the Chad Formation. The upper zone yields water to numerous dug wells throughout the rural areas and also is the major source of the Maiduguri municipal water supply. The middle zone yields water from flowing artesian boreholes that have heads ranging from a few feet to 70 feet above land surface throughout a 13,000 square-mile area of the basin in Nigeria. The lower zone also yields water from flowing boreholes; however, its areal extent has not been proved beyond the environs of Maiduguri.

The present investigation is concerned primarily with the middle zone, which is the source of water for some 190 flowing boreholes used as cattle-watering points in the Nigerian sector of the Chad Basin. The thickness of beds of water-bearing sand in the middle zone ranges from less than 1 foot to 200 feet, and the artesian head ranges from land surface at Maiduguri to 70 feet above land surface at Lake Chad. The depth to the top of the middle zone in the area of flowing boreholes ranges from 500 to 1,250 feet below land surface. The water-bearing properties of the middle zone differ greatly from place to place. Also, the yields of individual flowing boreholes generally range from 50 to 20,000 imperial gallons per hour (gph). On the basis of water availability, the middle zone can be divided as follows: Areas of high-, moderate-, and low-yield artesian aquifer; areas of low- and moderate-yield subartesian aquifer; and an area where the yields from boreholes are insignificant or the aquifer is missing. Recommended maximum rates of long-term withdrawal from individual boreholes for the three artesian areas range from 100 to 5,000 gph with boreholes spaced 5 to 10 miles apart. By limiting flows to the recommended maximum rates, the boreholes should continue to flow for at least 30 years. The present average use per borehole (265 gph in 1965) is considerably less than the recommended maximum rates.

Recharge to the upper zone occurs in significant but as yet unmeasured quantities, mostly in the vicinity of the major streams. Apparently, however, no significant amount of recharge reaches the middle zone from the upper zone. Although the middle zone is, in effect, being "mined" by existing flowing wells, the present (1965) rate of withdrawal is so low that no significant areal decline in artesian head has yet been observed.

The chemical quality of water from the three water-bearing zones is generally acceptable both for livestock and village use. For certain industrial uses, however, water from the middle zone would require treatment.

INTRODUCTION

SCOPE AND PURPOSE OF PRESENT INVESTIGATION

For hundreds, if not thousands, of years the principal sources of water in the Chad Basin have been wells, commonly 2 to 3 feet in diameter, hand dug by the villagers and lined with twigs and sticks. Some of the wells reach depths of more than 200 feet. In 1933, however, the Government of Northern Nigeria (Northern Region Government) initiated a program of improved well construction in the southern part of the Chad Basin, where Government crews constructed dug wells 3 to 4 feet in diameter and lined them with concrete rings down to beds of water-bearing sand. During the long dry season, when most of the surface ponds and rivers dry up, such wells have been the chief sources of water for the rural population and cattle in the area. Even so, water for livestock had to be laboriously drawn by hand in leather buckets and transferred into troughs made from hollowed-out logs.

To improve living conditions and the local economy, an artesian borehole-drilling program was started in northeastern Nigeria in 1955; by the end of 1962, 166 boreholes[1] had been completed successfully. During this period, the United States Agency for International Development (US AID) contributed funds for the well-drilling program on a matching grant basis. The primary purpose of the artesian boreholes was to provide watering points for cattle herds, on which the seminomadic economy of the area is dependent.

As drilling progressed, the Government of Northern Nigeria became concerned about the eventuality of decline in artesian pressure and loss of flow from the boreholes, if overdevelopment were to occur. Consequently, a request was made to US AID for assistance in undertaking a hydrologic evaluation of this problem in the artesian area of the Chad Basin in Nigeria. In June 1961 the area was visited by H. E. Thomas and L. C. Dutcher of the Geological Survey, U.S. Department of Interior, who submitted a report to US AID identifying the water problems of the region and outlining the scope of the present investigation. In January 1963, a 2-man team from the U.S. Geological Survey was assigned to the US AID Mission in Nigeria to make groundwater investigations in the Chad Basin. The purpose of the project was to evaluate the ground-water potential of the Chad Basin in Nigeria and particularly the flow life of the existing artesian boreholes. An integral part of the project was the training of Nigerian geologists in ground-water hydrology and its application to field problems.

PREVIOUS INVESTIGATIONS

The first published account dealing in some detail with the hydrology of the Nigerian part of the Chad Basin was by Raeburn and Jones (1934), who were first to recognize the Chad Formation and to suggest that artesian water might be found in its basal beds. The first flowing artesian borehole in the basin was drilled in 1946 by the Geological Survey of Nigeria. Regional exploration for flowing artesian boreholes began in 1955, and by the end of 1962 government and contract drillers had drilled 231 boreholes in the artesian aquifers. Of these, 166 were completed as successful flowing boreholes. Barber and Jones (1960) recognized three water-bearing zones in the Chad Formation of the Maiduguri area, which they termed the upper, middle, and lower zones. A large part of the middle zone and the explored sector of the lower zone yield water from boreholes by artesian flow; however, wells in the upper zone must be pumped. A description of the occurrence of the ground water based on the results of production drill-

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[1] The term "borehole" as used in Nigeria is virtually synonomous with "drilled well."

ing is given by Barber (1965). His report includes a detailed account of the geographic, geologic, and hydrologic features of the area and forms the basis for the present investigation.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for the excellent cooperation received from all personnel, including department heads, technicians, and field personnel of the Government of Nigeria. Because of the limitations of space, however, it is not possible to single out by name the many individuals who contributed to the project. Special acknowledgment is due to the personnel of Balakhany (Chad), Ltd., who furnished many well records and data that otherwise would not have been available.

The investigation was carried out with the cooperation and assistance of the Geological Survey of Nigeria (GSN), Ministry of Mines and Power and its timely completion was due in large measure to assistance from W. Barber of the GSN and D. A. Phoenix of the U.S. Geological Survey. Field work, including test drilling, began in February 1963, and the compilation of the data on which this report is based was completed in May 1965. The Nigerian geologists assisting in the project were Jonathan A. I. Olowu and Joseph U. Uzoma, both of the Geological Survey of Nigeria. Frank E. Clarke, U.S. Geological Survey, visited the project area between February 25 and March 2, 1965, to gather data for study of the corrosive properties of the artesian water. A summary of the preliminary results of Mr. Clarke's work is included in this report.

LOCATION AND EXTENT OF AREA

The Chad Basin (fig. 1), the largest basin of interior drainage in Africa, occupies an area of about 600,000 square miles in the southern Sahara and in the Sudan region. The basin is named for its most conspicuous feature, Lake Chad; however, the lowest point is the Bodélé depression, 200 miles northeast of Lake Chad and about 270 feet lower than the lake level. Lake Chad is connected with the Bodélé depression by an ephemeral stream, Bahr al Ghazal, which carries overflow only during exceptionally high stages of the lake. Only about one-tenth of the basin (60,000 sq mi) lies in Nigeria, and of this the area of flowing boreholes covers 13,000 square miles. The area described in the present report comprises about 25,000 square miles of the basin southwest of Lake Chad in the Bornu and Dikwa Emirates of Nigeria.

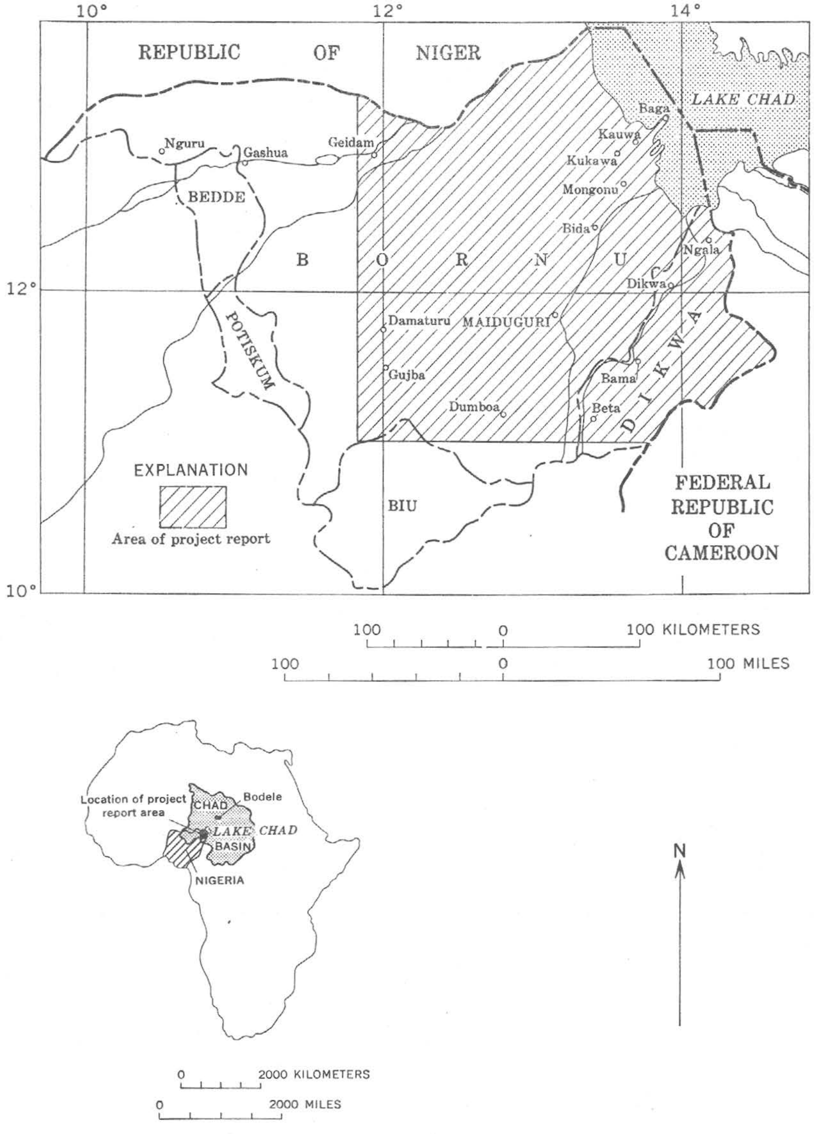

FIGURE 1.—Location of Chad Basin and Bornu and Dikwa Emirates.

ADMINISTRATIVE DIVISIONS

Bornu and Dikwa Emirates (also termed Divisions) are two of the five emirates that form Bornu Province (fig. 1), which in turn is part of the Northern Region of Nigeria. The Bornu Provincial Government, at Maiduguri, acts directly under the Northern Region Government in the supervision of such activities as schools, roads, water supplies, health, and agriculture.

On the local level, administration is carried on by the Bornu and Dikwa Native Authorities. These are headed by the Shehus of Bornu and Dikwa Emirates, the traditional political and religious leaders of the area. The chief administrator of the Native Authority government is the Waziri, who directly supervises the various district governments. (District boundaries are shown in pl. 1.) The District Head, in turn, supervises Lawans (heads of large villages or groups of smaller villages) and Bullemas (village headmen).

The Ministry of Works (Northern Region Government), through the provincial offices at Maiduguri, is responsible for construction of urban and rural water-supply installations. Maintenance of existing boreholes and concrete wells in the rural areas is generally carried on by the Native Authorities.

GEOGRAPHY

TOPOGRAPHY AND DRAINAGE

Bornu and Dikwa Emirates are for the most part, a featureless plain, which slopes gently east and northeast towards Lake Chad. The vegetation of the area is typical African savanna with thorny trees (mostly of the genus *Acacia*) separated by open grassland in the north and by tangled scrub and high grass in the south. Much of the land in the south has been cleared for agriculture. The only features which break the monotony of the plain are stabilized sand dunes in the north and a sand ridge near Maiduguri. Dune sand occurs in the northeast and hummocky sand in the north-central part of the area. In the interdunal swales are clay flats, locally know as "firiki."

Lake Chad lies in a shallow depression and its shoreline changes markedly in response to seasonal fluctuations in lake level. During December and January the lake reaches its highest annual level owing to the wet-season inflow of the Chari River, which forms the boundary between the Cameroon and Chad Republics to the east. Thereafter, evaporation exceeds river inflow and the lake level gradually declines until July, when it resumes its rise. Because of a series of wet years, the lake level was higher in 1965 than it had been, according to the memory of the present inhabitants. The area of Lake Chad has fluctuated from about 3,700 to 6,200 square miles during historic time. The hydrology of the lake is described in detail by Bouchardeau and Lefevre (1957).

An arcuate sand ridge about 60 miles west and southwest of the lake and subparallel to the lake shore extends from a point west of Maigumeri, past Maiduguri and Bama, to as far as Dar-al-Jimeil—a distance of about 100 miles. The ridge, known locally as the Bama Ridge, is probably an ancient Pleistocene shoreline of the lake (Grove, 1958).

None of the rivers in the report area is perennial, and most of them flow into marshy areas on the plain and disappear by evapotranspiration before reaching Lake Chad. However, the Komadugu Yobe in the north and the Yedseram and El Beid (Ebeji) Rivers to the south are relatively large streams that discharge into Lake Chad during the wet season. Nevertheless, about 95 percent of the total surface flow into the lake comes from the Chari-Lagone Rivers systems, which lies east of the report area in the Cameroon and Chad Republics.

In the northern part of the report area, the Komadugu Yobe passes through the sand dunes in a narrow flood plain which is marked by larger alluvial tracts on the inner bends of the river. Flooding of these tracts by overflow from the river and drainage from the sand dunes creates permanent marshlands. Nearer the lake the flood plain fans out in several distributaries with scattered marshy and ponded areas, most of which lie in cutoff river meanders. The Komadugu Yobe begins to flow in June or July, and reaches peak discharge in January and February. Following the rainy season discharge decreases rapidly, and by March only disconnected pools remain in the main stream channel.

The Yedseram River, which flows through Bama, has a relatively small catchment area. The flow, which is markedly seasonal, usually begins in July in the Bama area but ceases by December. North of Dikwa the river breaks up into a series of braided channels which flow across the extensive firiki plains and finally empty into Lake Chad.

El Beid River, also known locally as the Ebeji, forms part of the border between Nigeria and the Cameroon Republic. This stream flows most of the year, beginning in June or July and ending the following May. Peak discharge occurs in November and December. The Ebeji is by far the largest of the Nigerian rivers flowing into Lake Chad, but part of its relatively large catchment basin extends into the Cameroon Republic. The lower reach of the river has moved progressively to the west, resulting in a wide stretch of abandoned channels all following westerly courses. These channels break up in the north and enter the lake on a delta.

The Ngadda River, which flows through Maiduguri, has a relatively small catchment basin and, like other rivers of the report area, is seasonal in character. The river flows from August to February and usually reaches peak discharge in September. The Ngadda cuts through the Bama Ridge at Maiduguri in a well-developed water gap. Where it leaves the gap, it flows through a system of braided channels and deltaic deposits. Farther north, the river gradually loses its identity as it fingers out on a marshy plain. Upstream from Maiduguri, the Ngadda passes through Lakes Yare and Alo, both of which are perennial. At high water, the surface area of Lake Yare is about 10 square miles and that of Lake Alo about 2½ square miles. The Ngadda enters Lake Yare and leaves by twin channels, one of which flows into Lake Alo. The outlet from Lake Alo joins the bypass channel 12 miles south of Maiduguri.

CLIMATE

The semiarid climate of Bornu and Dikwa Emirates is typical of the Sudan region of north-central Africa. The climate is characterized by a long dry season (October to May) and a short rainy season (June to September), which are related to seasonal winds. During the winter months the cool, dry, dust-laden "harmattan" blows from the Sahara in the north, bringing low humidity, cool nights and warm days. In the summer months, moisture-laden winds blow from the Gulf of Guinea in the south, bringing higher humidity, rains, and more uniform diurnal temperature.

Rainfall occurs mainly in the 3 summer months of July, August, and September. The monthly distribution of rainfall at Geidam on the north edge of the report area, at Maiduguri and at Gwoza near the south edge are shown in figure 2. From these data it is evident that there is a gradual decline in rainfall from south to north. Typically, large variations in annual rainfall may occur from year to year at any one station. For example, at Maiduguri, where the average annual rainfall is 26 inches, only 17 inches fell during 1964.

Yearly extremes in temperature range from 50°F during winter nights to 110°F during the day in April and May. During the cool harmattan season, which extends from late November to early March, night temperatures are generally in the fifties or sixties and rise to the low nineties during the day. The highest temperatures occur between mid-March and early June, when daytime temperatures generally exceed 100°F and night temperatures are in the seventies. During the rainy season from June to early October, day temperatures are generally in the eighties and nineties, occasionally dropping into the seventies during and after heavy rains.

Evaporation rates are very high, particularly during the dry, hot season from March to June. The total annual evaporation is about 80 inches from free water surfaces.

CULTURAL AND ECONOMIC FEATURES

The people of the area belong predominantly to the Kanuri, Shuwa, and Fulani tribal groups. Of these, the Kanuri are the most numerous and are also the traditional ruling group. They are descended from the ancient empire of Bornu, which flourished in the region for centuries. Numerous tribal divisions occur within the three groups, and each has its individual customs and language differences. In general, the Kanuri live in villages and practice agriculture in more or less fixed locations. However, the Kwoyam, an important subgroup, are nomadic cattle keepers. The Shuwa and Fulani people traditionally have been nomads, who move their cattle with availability of water and grazing land. With the advent of year-round water supplies provided by

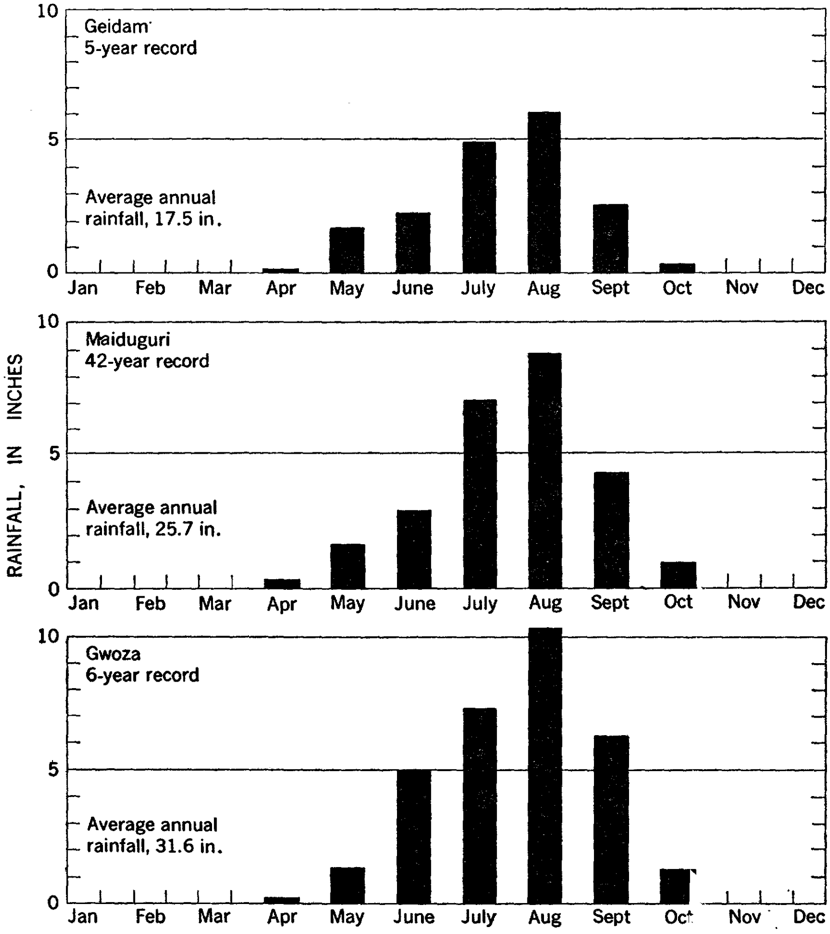

FIGURE 2.—Average rainfall at Geidam, Maiduguri, and Gwoza.

artesian wells, however, nomadism is decreasing. A number of southern Nigerians, particularly Ibos, are engaged in commercial activity in Maiduguri and larger villages.

The greatest concentration of people live in the southern part of the report area near Maiduguri, which is the largest town in Bornu Province, having a population of more than 100,000. The population density gradually decreases northward to less than 25 persons per square mile near Lake Chad and the Komadugu Yobe.

The important cash products are hides and skins, groundnuts, and to a lesser extent, cotton. The staple foods of the rural population are millet and masakwa (a sorghum), which are grown nearly everywhere. Although there are about 1 million head of cattle in the report area, the traditional custom of acquiring cattle for prestige and selling only when necessary limits their impact on the local economy. An abattoir has been built, however, and the number of cattle being slaughtered for meat and hides is increasing. Industrial development is relatively small at present (1965). A large mill for processing groundnuts into oil recently began operation in Maiduguri. In addition, small plants which process cattle hides and goat, sheep, and reptile skins for export are at several places in the area.

Maiduguri is linked to the rest of Nigeria by scheduled air service, several all-weather trunk roads, and a recently completed rail line. Although the major villages are connected by graded roads, much of the area is accessible only by "bush" tracks. During the rainy season, a large part of eastern Bornu Province, underlain by clay cotton soil (firiki), becomes impassable to motor traffic.

GROUND-WATER GEOLOGY

The Chad Basin has apparently been a structural depression since early Tertiary time and, therefore, has been a locus of subsidence and sedimentation rather than erosion. The youngest of the sediments, known as the Chad Formation, contains the principal identified aquifers of the basin. This formation was deposited in or near a large ancestral Lake Chad during late Tertiary and Quaternary time on an uneven surface; it is underlain by the Tertiary Kerri-Kerri Formation, Cretaceous sedimentary rocks, and the basement crystalline complex. At Maiduguri, a deep borehole has shown the Chad Formation to be at least 1,800 feet thick. Near Lake Chad, however, the thickness of the formation probably exceeds 2,000 feet, but the total thickness is not known. To the southeast and northwest, the formation thins to less than 200 feet where it rests on granite, granite gneiss, and mica schist of the basement complex. Southwest of Maiduguri, the Chad Formation rests on cemented sandstone and clay that are believed to be part of the Kerri-Kerri Formation which crops out along the edge of the basin farther to the west; in parts of this area, however, and at Maiduguri, the Kerri-Kerri Formation is missing and the Chad Formation directly overlies shaly sediments of Cretaceous age.

The Chad Formation dips gently east and northeast toward Lake Chad in conformity with the slope of the land surface. Except for a belt of alluvial deposits around the edge of the basin, the formation is of lacustrine origin and consists of thick beds of clay intercalated with irregular beds of sand, silt, and sandy clay.

As a result of artesian pressure noted in hand-dug wells near the western margin of the basin, Raeburn and Jones (1934, p. 45–51) predicted that artesian flows might be found in boreholes penetrating deeper water-bearing beds toward Lake Chad. In 1943, a borehole 5 miles west of Maiduguri was drilled to a depth of 735 feet. It struck artesian water which rose to 30 feet below the land surface. The first flowing borehole was drilled at Maiduguri in 1946. By 1959, 42 boreholes had been drilled into aquifers of the Chad Formation to depths of as much as 1,841 feet. Based on data from these wells, Barber and Jones (1960, p. 14–16) divided the Chad Formation (pl. 2) into three water-bearing zones, which they designated upper, middle, and lower.

The upper zone consists of a widespread series of interbedded sand, clay, silt, and sandy clay which extend from the surface to an average depth of 200 feet but locally to 600 feet. The middle zone is composed of interbedded sand and clay, which underlie at least 20,000 square miles of northeastern Nigeria. A clay layer, 200 to 1,000 feet thick, confines the water in this zone and separates it from the overlying upper zone. The lower zone, presently (1965) known only in the Maiduguri area where it occurs at depths of 1,390 to 1,676 feet, consists of about 250 feet of interbedded clay, sandy clay, and sand.

The water in the upper zone occurs under both confined and unconfined conditions. Where it is confined, the artesian pressure is not sufficient to produce flowing boreholes. The water in both the middle and the lower zones is confined. The majority of the boreholes, however, tap the middle zone, where artesian heads are as high as 70 feet above land surface.

AQUIFER SYSTEMS (CHAD FORMATION)

UPPER ZONE

LITHOLOGIC CHARACTER AND AREAL EXTENT

The upper zone is composed of interbedded sand, clay, silt, and sandy clay which generally extends to an average depth of 200 feet but locally to as much as 600 feet below land surface (pl. 3). As shown in the generalized geologic section (pl. 2), there is much lensing and interfingering of the beds. The upper zone as defined by Barber (1965) was restricted to the Maiduguri area. However, as shown in the geologic section of plate 3, sandy beds in the upper part of the Chad Formation have proved to be as extensive as those in the middle zone, and the term "upper zone" has been extended to include these beds throughout the report area.

The upper zone deposits are relatively thicker to the north of Magumeri where the Bama Ridge, which is the topographic feature marking the shoreline of an ancestral Lake Chad, can no longer be defined at the surface. The distribution of the deposits (pl. 3) suggests that they were laid down in part in a delta of the Komadugu Yobe when it flowed south of its present course into a greatly expanded ancestral Lake Chad.

South of Maiduguri, it is difficult to define the upper zone from the middle zone on the basis of borehole logs. Exploration drilling northwest of Gwoza indicates that in this area oxidized alluvial deposits, consisting primarily of medium to very coarse arkosic sand, extend from the surface down to granite bedrock. The thickness of the deposits is as follows:

Location	*Borehole number*	*Thickness (feet)*
Yamtage	3181	47
Tokombere	3182	75
Beta	3186	118
Garanya	3183	175

At Mulgwe and Mutube, farther west along the Ngadda and Yedseram Rivers, oxidized alluvial deposits still predominate, but many thin clay beds are present that at least partly confine the water in the underlying sand. In this area the base of the Chad Formation is not easily defined, as it grades with no apparent break into the underlying oxidized sand, clay, and sandstone that may be part of the Kerri-Kerri Formation. The deepest exploratory hole in this area was drilled at Mutube to a depth of 341 feet (table 1). The water-bearing beds are the coarse sand and gravel layers above 111 feet. It is not known if the water-bearing sand in this area is upper zone or is equivalent to the middle or lower-zone sand that occurs further to the north. The underlying sand, which is not waterbearing, is either clayey or cemented and the clay is bright yellow, red, or white. It does not seem to be typical of the Chad Formation and may be a part of the Kerri-Kerri Formation.

WATER-BEARING PROPERTIES

Ground water occurs under both unconfined and confined conditions in the upper zone; where it is confined, the pressure rise is insufficient to produce artesian flow. As shown in plate 4, the depth to

TABLE 1.—*Driller's log of borehole at Mutube*

Mutube 1 (GSN 3184). Bama District, Dikwa Emirate, Bornu Province. Exploration borehole drilled in 1964 by Balakhany (Chad), Ltd.]

	Thickness (feet)	*Depth (feet)*
Chad Formation:		
Clay, brown, yellow, and gray, mottled	21	21
Sand, coarse; some fine to coarse gravel; water bearing	10	31
Clay, gray; interbedded thin sand beds at base	5	36
Clay and silt, yellow to gray	7	43
Sand, medium to coarse, brown; water bearing	26	69
Clay, silty, yellowish white	2	71
Sand, coarse; some gravel with interbedded clay layers; water bearing	40	111
Kerri-Kerri(?) Formation:		
Clay, sandy, mottled, yellow and brown	11	122
Sand, medium to coarse; thin interbedded clay	10	132
Clay, sandy, mottled, yellow-brown, white and reddish	1	133
Sand, medium to coarse; mottled interbedded clay	40	173
Clay, red, yellow, brown, and white; thin interbedded sand	52	225
Sand, medium, clayey	48	273
Clay, sandy, yellow-brown; thin interbedded clayey sand	12	285
Sandstone, yellow to white, very hard	11	296
Sand, coarse, clayey and partly cemented, white	11	307
Sandstone, gray	3	310
Clay, sandy, yellow and white	4	314
Clay, sandy, white	27	341

water in the upper zone ranges from land surface at Lake Chad to about 250 feet near Maiduguri. In general, ground-water levels are nearest the land surface along the streams or former stream channels and deepest in the interstream tracts. The water table is also near the land surface around the granite hills of the Gwoza area on the edge of the basin.

The hydraulic characteristics of the upper zone are best known in the vicinity of Maiduguri, where several aquifer tests were made during the present investigation. The upper zone was also tested at Mulgwe (pl. 1), but the boreholes tested may tap equivalents of both the upper and middle zones.

The Maiduguri tests were made as part of an investigation to improve the municipal water supply (Miller and others, 1965). The test results, summarized in table 2, indicate that transmissibility[2] ranges

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[2] Definitions of all aquifer constants are given in the section of this report dealing with "Hydraulic characteristics."

TABLE 2.—*Summary of aquifer tests*

Location	Boreholes: flowing (f), pumped (p), observation (o)	Screened interval (feet below land surface)	Date of test	Duration of test (hours)	Average flow rate (imp gal per hr)	Drawdown at end of test (ft)	Transmissibility (gal per day per ft)	Storage coefficient	Remarks
Pump tests in upper zone									
Mulgwe	GSN 3180 (p)	195–216	Dec. 22, 1964	4	4,500	13.0	87,000	0.0002	Aquifer may contain equivalents of upper and middle zones. Pumping rate too low to evaluate the aquifer properly.
	3167 (o)	200–215	-----------	----	------	.8	------	--------	
Maiduguri (Government Residential Area)	3179 (p)	214–234	Nov. 3–5, 1964	48	9,900	30.1	6,000	.0009	Test of GSN/US AID production hole for Maiduguri water supply. Long-term yield; 25,000 gph.
	3172 (o)	214–234	-----------	----	------	17.4	------	--------	
Maiduguir (Gwange)	3162 (p)	180–190	Dec. 16–18, 1964	48	4,500	131.5	440	.0008	Production hole for Maiduguri water supply. Low long-term yield; 2,000 gph.
	3162 (o)	180–190	-----------	----	------	80.0	------	--------	
Maiduguri	3042 (p)	206–216	Nov. 19–21, 1963	48	7,500	139.0	900	.0006	Production test hole by Stanley International Ltd. Long-term yield; 400 gph.
	3042A (o)	206–216	-----------	----	------	82.0	------	--------	

Flow tests in middle zone										
Dalori	GSN 2274	(f)	733–773	Oct. 7–10, 1964	48	498	10±	525	0.000014	Results applicable to area *c* in pl. 2.
	3032	(o)	740–760	------------	----	------	7.4	------	--------	
Ngala	3029	(f)	934–954	Oct. 26–28, 1964	48	7,130	36.6	11,300	.00012	Results applicable to area *b* in pl. 2.
	3028	(o)	------------	------------	----	------	8.5	------	--------	
Sabsawa	3025	(f)	1,086–1,106	Nov. 16–20, 1964	56	9,000	24.4	72,500	.00018	Results applicable to area *a* in pl. 2.
	3024	(o)	1,086–1,106	------------	----	------	1.6	------	--------	
	3026	(o)	1,086–1,106	------------	----	------	1.2	------	--------	

from 440 to 6,000 gpd per ft (imperial gallons[3] per day per foot). Permeabilities[2] range from 260 gpd per sq ft at the test site in the Government Residential Area, where the upper zone contains 23 feet of coarse sand, to 44 gpd per sq ft at the Gwange site, where the zone contains 10 feet of silty sand. The coefficient of storage[2] for the three Maiduguri tests ranges from 0.0006 to 0.0009, indicating confined conditions. Because of the wide range in permeability and transmissibility, the long-term yields of individual boreholes range from about 2,000 to 25,000 gph (gallons per hour). In general, the most permeable beds of sand (and thus the most promising sites for boreholes) are found in two locations: (1) just west of Maiduguri (at the site of the present water works) and (2) at the site of the Government Residential Area pump test.

At Mulgwe, where the depth to water is 34 feet, beds of fine to very coarse sand with thin clay beds extend from the land surface to a depth of 250 feet. The lower part of the section may be equivalent, in part, to the middle zone. The pumping test at Mulgwe showed that the aquifer had a high transmissibility (87,000 gpd per ft) and a low storage coefficient (0.0002). The test was only moderately successful because with the available pump it was not possible to maintain a pumping rate high enough to test the aquifer properly. It can be conservatively estimated, however, that 10 mgd (million gallons per day) could be obtained from properly spaced boreholes in the Mulgwe area.

PRESENT UTILIZATION

The most concentrated water withdrawal from the upper zone, at present (1965), is in the Maiduguri area, where six upper-zone boreholes, including the one drilled as part of this investigation, produce about 500,000 gpd for the municipal water supply. These boreholes, 6 to 8 inches in diameter, are equipped with submersible pumps. A borehole in the upper zone at Konduga, drilled in 1958, originally produced 750 gph. This borehole served as a source of water supply during the construction of the road from Maiduguri to Bama, but has not been used since. Two production boreholes in the upper zone were drilled by the Ministry of Works, Northern Region, at Geidam for a proposed municipal water supply. These boreholes are reported to have test yields of about 4,000 gph each, but are not presently in use. The only other boreholes tapping the upper zone are 2½-inch diameter observation boreholes and 8-inch diameter boreholes, equipped with recorders, at Dalori, Belle, and Gombole.

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[3] Imperial gallons are used throughout this report.

The withdrawal of water by hand from earth- and concrete-lined dug wells in the upper zone is now (1965) relatively small. The greatest density of wells of this type is in the south half of the report area. In the northern part of the report area—especially in Kanembu, Nganzei, Gubio, Mongonu, and Mobber Districts—only a few concrete-lined wells have been constructed. The earth-lined wells, which at one time served the report area, have largely been abandoned because of the more convenient sources of water now furnished by artesian boreholes. Probably less than 1,000 concrete- and earth-lined wells are now in use in Bornu and Dikwa Emirates. The rate of withdrawal from this type of well ranges from about 10 to 50 gph. Consequently, it is estimated that no more than about 1 mgd of water is taken from open wells tapping the upper zone. Thus, the present total withdrawal from the upper zone in the report area is approximately 1.5 mgd.

FUTURE DEVELOPMENT

The future potential of the upper zone as a source of ground water has not been (1965) fully evaluated. Results obtained in the Maiduguri area suggest that well yields will be quite variable from point to point throughout the Chad Basin. The greatest development of the upper zone probably will be in those areas where water-bearing beds in the middle zone are absent or nonproductive, such as in Geidam and Gulumba Districts.

By 1975 Maiduguri will require an estimated additional 3 mgd of water for municipal and industrial uses. Exploratory drilling and pumping tests in the Maiduguri area indicate that at least 4 mgd can be produced from water-bearing beds in the upper zone (P. E. Miller, R. H. Johnston, and J. U. Uzoma, 1967, unpub. data).

To develop the upper zone, considerable test drilling will be required to locate the best sites for productive boreholes. Also, because of the wide range in the yields of individual boreholes in the upper zone, careful attention will have to be given to borehole spacing, and to screen and pump settings, if the full potential of this zone is to be realized.

MIDDLE ZONE

The middle zone contains the most extensive and important water-bearing beds presently (1965) known in the Chad Basin of Nigeria. With respect to lithologic character and extent, water-bearing properties, and long-term yields from boreholes, the middle zone can be conveniently divided for descriptive purposes into six different areas. This areal breakdown, shown in plate 5, forms the basis for the following discussion.

LITHOLOGIC CHARACTER AND AREAL EXTENT

The middle zone includes interbedded sand and clay which occurs throughout at least 20,000 square miles in northeastern Nigeria. A geologic section (plate 2), constructed from drillers' logs, depicts the lithologic character of the middle zone from the edge of the Chad Basin to Lake Chad. As shown in the section, the zone has a highly variable lithology, containing fine to coarse water-bearing sand, cemented and clayey sand, sandy clay, and clay. In general, the permeable sand beds thicken toward the center of the basin (in the direction of Lake Chad), whereas clayey or cemented sand beds predominate toward the edge of the basin.

The water-bearing beds are predominantly fine to coarse-grained poorly sorted sand and locally contain fine gravel lenses. These beds are commonly light gray or light brown and consist almost entirely of angular to subangular quartz grains. Granitic fragments (feldspar and mica) are common in the sand beds to the south and southeast of Maiduguri. Successful boreholes are nearly everywhere screened in the sand beds that lack clay binder or cementation. These beds of so-called "free" sand occur throughout the known extent of the middle zone, except in area *d* as shown in plate 5.

Beds in the middle zone that yield little or no water to wells include clayey sand, silicified sand, sandy clay, and clay. Silicified sand beds occur chiefly in the area of unsuccessful boreholes (area *d*, pl. 5). In these beds, silica cement accounts for about 25 percent of the rock fabric (Barber, 1965). Clayey sand is also widespread. In the low-yield area *c* of plate 5, clayey sand, intercalated with the "free" sand lenses a few inches to a few feet thick, makes up most of the section. The clay beds in the middle zone of this area are oxidized yellow to reddish brown, contrasting with the reduced clay beds above and below the zone that are bluish to greenish gray. In addition, the clay beds in the middle zone commonly contain angular quartz grains, giving them a gritty texture.

The top of the middle zone, throughout much of its known extent, is marked by an oxidized horizon of yellowish or reddish-brown clay to red clayey sand. The color change from the overlying bluish-gray clay is commonly sharp and is easily recognized by drillers. Locally, the top of the zone is marked by the first sandy layer below the thick confining blue-gray clay.

The depth to the top of the middle zone in the area of flowing wells ranges from about 500 to 1,250 feet below land surface. As shown in plate 6, the deepest known point is in the vicinity of Lake Chad. In the area of nonflowing boreholes, the top of the middle zone lies nearer the land surface; and at depths of 200 feet or less, the middle zone cannot be positively identified. In the peripheral areas of the basin the middle zone sediments are intercalated with alluvial debris from the surrounding highlands; however, near Geidam the middle zone becomes clayey and disappears completely at depth.

The total thickness of the middle zone ranges from a few feet to as much as 400 feet; however, the individual beds of water-bearing sand in the zone range in thickness from less than 1 foot in the low-yield area (area c_1, pl. 5) to 200 feet in the high-yield area (area *a*, pl. 5). Probably, however, greater thicknesses of sand are present because very few boreholes fully penetrate the middle zone in the high-yield area. In fact, most boreholes are completed in the first section of water-bearing sand and are capable of producing a few thousand gallons per hour.

WATER-BEARING PROPERTIES

Ground water occurs only under confined conditions in the middle zone and, throughout 13,000 square miles in the Chad Basin of Nigeria, the pressure is sufficient to cause artesian flow at the land surface. By common local usage, the term "artesian" is restricted in Nigeria to confined conditions where the pressure rise in a borehole is sufficient to cause free flow at the land surface. The term "subartesian" is used to describe the condition where the pressure rise in a borehole is above the top of the water-bearing bed but not above land surface.

Plate 7 shows that the artesian head ranges from land surface at Maiduguri to 70 feet above land surface at Lake Chad. The zero pressure contour (limit of flowing boreholes) lies along a northwest-southeast trending line which passes through Maiduguri. In the subartesian area, to the west and south of this line, the water level in boreholes (representing the pressure rise above the water-bearing bed) becomes progressively farther below land surface.

In the following sections, the areal availability, the hydraulic characteristics of the middle zone, and their relation to the yield and method of borehole construction are discussed in some detail.

AREAL AVAILABILITY

The availability of water from the middle zone differs greatly from place to place in the report area. On the basis of its water-yielding capability, the middle zone can be divided into six aquifer areas, shown in plate 5. The areal divisions and map designations are as follows:

High-yield artesian aquifer (*a*),
moderate-yield artesian aquifer (b_1),
moderate-yield subartesian aquifer (b_2),
low-yield artesian aquifer (c_1),

low-yield subartesian aquifer (c_2), and
aquifer missing or yields from boreholes inadequate (d).

Within each aquifer area, the hydraulic character and thickness of water-bearing sand beds are similar. As a result, transmissibilities observed in aquifer tests can be applied through each areal division to forecast long-term trends in yields of boreholes. The division of area b into b_1 and b_2 and c into c_1 and c_2 is based on whether or not artesian flow is available.

The high-yield artesian aquifer (a) occurs in a narrow band paralleling the shoreline of Lake Chad and extends as a lobe into the center of the area of flowing boreholes (pl. 5). The beds of water-bearing sand (fine to coarse) range from 70 to at least 200 feet in thickness. Many boreholes in this area, however, do not fully penetrate the middle zone, and it is more probable that the average thickness is closer to 200 feet as at Sabsawa (table 3), where the middle zone contains about 200 feet of water-bearing sand. Artesian heads range from 35 to 65 feet above land surface; and as of 1965, there has been no regional decline in head. Artesian pressure recorders installed at Kauwa and Sabsawa

TABLE 3.—*Driller's log of borehole in Chad Formation at Sabsawa*

[Sabsawa 4 (GSN 3026). Nganzei District, Bornu Emirate, Bornu Province. Observation borehole drilled in 1963 by Balakhany (Chad), Ltd.]

	Thickness (feet)	Depth (feet)
Upper Zone:		
Sand, fine, yellow	22	22
Sand, fine to medium, yellowish	41	63
Sand, fine to medium, yellowish, thin clay layers	41	104
Clay, sandy, white	164	268
Clay, white	41	309
Clay, white to gray	247	556
Clay, gray to bluish-gray	267	823
Clay, shaly, bluish	171	994
Clay, shaly, bluish; some thin silt and fine sand layers	43	1,037
Middle Zone:		
Sand, fine to coarse, silty	21	1,058
Sand, fine, silty and firm	24	1,082
Sand, coarse	1	1,083
Sand, fine to coarse, silty	13	1,096
Sand, medium to coarse	3	1,099
Sand, fine to coarse, silty fine sand and clay layers	52	1,151
Sand, fine to coarse, a few very thin clay layers	13	1,164
Sand, fine to medium silty	32	1,196
Sand, coarse	1	1,197
Sand, fine to coarse, silty	78	1,275
Sand, fine to coarse	6	1,281
Clay, gray, hard	11	1,292

(locs. shown in pl. 1) indicated no significant head decline during 1963–65.

The moderate-yield aquifer (*b*) occupies about half the area of proven artesian flow and also includes a small part of the subartesian area (pl. 5). The beds of water-bearing sand here range from 20 to 70 feet in thickness and are fine to coarse grained. They contain, however, a higher percentage of silt and fine sand than the water-bearing beds of area *a* and, as a result are less permeable. Where artesian conditions occur (b_1), the positive head ranges from land surface to 70 feet above land surface. In subartesian area b_2, water levels range from land surface to 75 feet below land surface. Regionally, no significant decline in artesian head had been observed up to 1965; however, a local cone of depression developed near Ngala during a period when a number of boreholes were allowed to flow uncontrolled (see p. I 33).

The low-yield aquifer (c_1) occurs in a narrow band in the artesian area parallel to the limit of flowing boreholes and through most of the subartesian area (pl. 5). The middle zone in this division contains less than 20 feet of fine to coarse water-bearing sand. Commonly, permeable beds occur only as layers less than a foot thick through a section of clayey sand. In the area of flowing boreholes (c_1), artesian heads range from land surface to 20 feet above land surface. Where subartesian conditions occur (c_2), water levels are as great as 200 feet below land surface. Whether a regional decline in artesian head has occurred in area c_1 has not been definitely established; however, local cones of depression have developed around flowing boreholes.

In the area *d*, where the middle zone is missing or yields are insignificant, the zone, if present, contains only clayey or cemented sand. Although a few flowing boreholes exist in area *d*, yields are very low. Other aquifers, particularly the upper zone, provide much better sources of water in area *d* than the middle zone.

HYDRAULIC CHARACTERISTICS

The hydraulic properties of a water-bearing formation or aquifer depend on its ability to transmit and to store water, and these properties are described quantitatively by the cofficients of permeability, transmissibility, and storage. Collectively, these terms are called aquifer constants. The coefficient of permeability (*P*) is defined as the rate of flow of water in gallons per day through a cross-sectional area of the aquifer of one square foot under a unit hydraulic gradient (1 ft vertical drop for each 1 ft of horizontal distance) at a temperature of 60°F. The coefficient of transmissibility (*T*) is the rate of flow in gpd, at prevailing water temperature, through a one-foot wide vertical strip of aquifer extending the full saturated height of the aquifer under a unit hydraulic gradient. The term "transmissibility" was introduced by Theis (1935) to describe the water-transmitting capacity of an aquifer as a whole. The coefficient of transmissibility is equal to the coefficient of permeability multiplied by the saturated thickness of an aquifer. The coefficient of storage (*S*) is defined as the volume of water an aquifer releases from or takes into storage per unit surface area (such as per square foot) of the aquifer per unit change in head normal to that surface (Ferris and others, 1962, p. 74).

Values of *T* and *S* given in this section are based on data obtained from flow tests of boreholes in the middle zone. In such tests a borehole is permitted to flow at a constant rate, while measurements of drawdown are made in observation holes tapping the same aquifer. After the closing of the valve at the well head and the cessation of flow, measurements of the recovering artesian head are made in both production and observation boreholes. The measurements of artesian pressure are made with mercury manometers, and constant flow rates are maintained using water meters. The values of *T* and *S* quoted were calculated by the Theis nonequilbrium method of analysis. (For a description of the Theis method and other methods of analysis, see Ferris and others, 1962.)

Aquifer tests were conducted on boreholes tapping the middle zone at four localities—Dalori, Kauwa, Ngala, and Sabsawa (pl. 1). The purpose of the tests was to obtain aquifer constants for the middle zone at widely spaced sites in areas of high, moderate, and low permeability. The test results, with the exception of Kauwa, are summarized in table 2. The Kauwa test was unsuccessful because the flowing and observation boreholes were not screened in the same horizon within the middle zone. The test was terminated after it became apparent that the observation hole was not responding effectively to the withdrawal of water from the aquifer.

DALORI TEST

The site of the Dalori test is in the low-yield area (c_1, pl. 5), and the test results are probably representative of this area. The middle zone at Dalori contains poorly sorted silty and clayey sand, and most of the water is obtained from a 6-foot section of fine to coarse silty sand. Three middle zone boreholes have been drilled at Dalori: a 6-inch village-supply borehole (GSN 2274), a 2½-inch observation borehole (GSN 3019), and a 4½-inch observation borehole (GSN 3032). Of these boreholes, only two appear to tap water-bearing beds that are hydraulically connected. Observation borehole GSN 3032 responds immediately to withdrawals from the flowing village borehole (GSN 2274), whereas observation hole GSN 3019 shows a very sluggish response. Thus only drawdown and recovery data from GSN 3032 were used to calculate aquifer constants.

The method of conducting the test was to permit the village borehole (GSN 2274) to flow at a constant rate of 500 gph for 24 hours and then to allow it to recover for 24 hours. Artesian pressure measurements were made throughout the drawdown and recovery phases at both observation boreholes.

A low transmissibility (525 gpd per ft) and a very low storage coefficient (0.000014) were obtained at Dalori, and the permeability is approximately 90 gpd per sq ft. These constants indicate that very large pressure declines over an extensive area would result from substantial long-term withdrawals, and conversely, that withdrawals must be modest in order to maintain artesian flow because of the low available head (19 ft). The long-term decline of head at Dalori under various rates of withdrawal is discussed in the section on the "Flow life of the artesian system."

Another feature of the Dalori test was the higher *T* (800 gpd per ft) obtained from data collected during the first stage of the test, as compared with the lower *T* (525 gpd per ft) obtained from data collected during the latter part of the test. This decline in transmissibility is caused by a hydraulic barrier nearby. The nature of the barrier is not precisely known, but it is probably caused either by thinning of the aquifer or by an increase in the clay content of the water-bearing sand beds.

NGALA TEST

The Ngala test site is in the moderate-yield area (B_1) of the middle zone (pl. 5), and the test results probably represent average conditions for this area. At Ngala, the middle zone is 124 feet thick and contains 47 feet of fine to coarse sand. Elsewhere in the moderate-yield area, the middle zone contains 20 to 70 feet of fine to coarse sand. The flowing borehole (GSN 3029) and the observation borehole (GSN 3028) at Ngala are 200 feet apart, and there is a close correlation between the drillers' logs of the two boreholes.

The Ngala test was conducted in the same manner as the Dalori test with a 24-hour drawdown phase and a 24-hour recovery phase. A constant flow of 7,100 gph was maintained from the flowing production borehole for 24 hours. Artesian-head measurements were made at the observation borehole during the drawdown phase and at both observation and production boreholes during the recovery phase.

A moderately high transmissibility (11,300 gpd per ft) and a low storage coefficient (0.00012) were obtained. Based on a saturated thickness of 47 feet of sand, the permeability is 240 gpd per ft.

A log-log plot of artesian-head recovery for the observation borehole is shown in figure 3. A very close match exists between the recovery curve and the standard Theis curve, which suggests that the test conditions fulfill the assumptions of the Theis formula. Two of these conditions are a homogeneous aquifer and a coefficient of transmissibility that is constant at all times and at all places within the cone of influence of the discharging well. The transmissibility obtained at the test site is probably representative of the middle zone in area *b* (pl. 5), as the thickness (47 ft) of water-bearing sand at Ngala is average for area *b*.

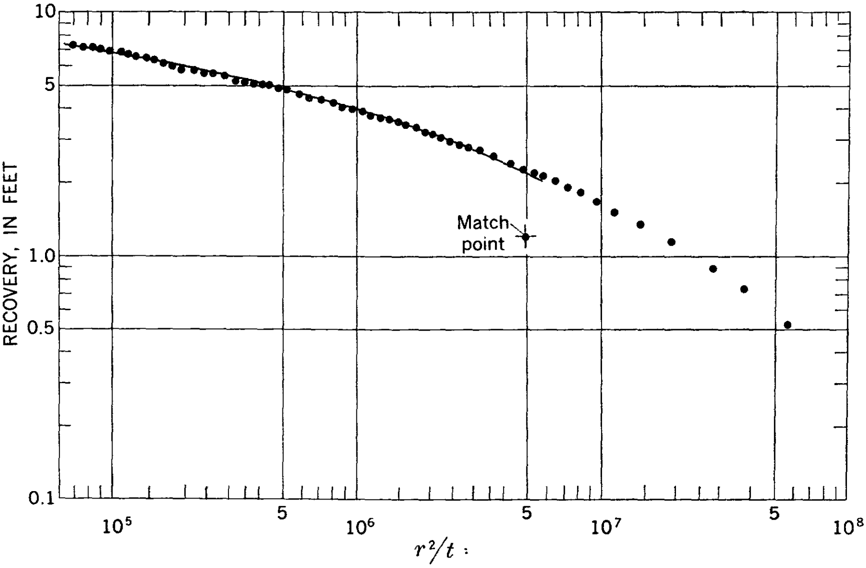


Figure 3.—Theis curve plot of recovery versus r^2/t in observation borehole, Ngala middle-zone aquifer test, October 26–28, 1964. Symbols: r^2, distance, in feet, squared from the discharging borehole to the point of observation; t, time in days since discharge started.

The moderately high T for this area indicates that artesian-pressure declines will be small for the present rate of withdrawal.

SABSAWA TEST

The Sabsawa test site is in the high-yield area (*a*) shown in plate 5, and the test results are generally applicable to area *a*. At Sabsawa, the middle zone is 288 feet thick and contains 191 feet of fine to coarse sand (table 3). The sand members are generally poorly sorted and silty, but many beds of clean sand and fine gravel occur in the section.

A production borehole (GSN 3025) and two observation boreholes (GSN 3024 and 3026), 200 and 500 feet, respectively, from the production borehole, were constructed at the site. All three boreholes are screened in the same interval of coarse sand. The test consisted of a 44-hour drawdown phase and a 12-hour recovery phase. A constant flow of 8,900 gph was maintained during the drawdown phase. Artesian-head measurements were made at both observation boreholes during the drawdown phase and recovery phase, and in the production borehole during the recovery phase.

A high transmissibility (72,500 gpd per ft) and a low storage coefficient (0.00018) were obtained. The permeability, based on 191 feet of saturated sand, is 380 gpd per sq ft. The high transmissibility indicates that the areal decline in artesian head will be slight under the present (1965) rather low rates of withdrawal.

A much higher flow rate would have been preferable to test properly the high-yield aquifer at Sabsawa. The drawdowns at the 200- and 500-foot observation boreholes were only 1.2 and 1.6 feet, respectively, at the end of the 44-hour drawdown phase. Furthermore, the rates of change of drawdown were so low that after 12 hours they were masked by barometric and other minor fluctuations. Equilibrium conditions had almost been reached by the end of the drawdown phase. Application of the Thiem equilibrium formula to the Sabsawa test data gave a *T* of 79,000 gpd per ft, which is not substantially different from the *T* calculated by the Theis nonequilibrium formula.

The principal problem in making flow tests in the high-yield aquifer at Sabsawa and elsewhere is that flow rates are limited by the rather small diameter of the boreholes. (Because of the depth, approx 1,000 ft, it is prohibitively expensive to construct large-diameter boreholes.) As a result, much of the head loss measured at the production hole is due to friction loss, caused by water moving up the 1,000-foot length of casing, rather than pressure declines within the aquifer. At Sabsawa, the measured drawdown at the production borehole was 24.4 feet after 44 hours; however, the drawdown computed from the flow test in the aquifer at the production borehole was only 4.4 feet. The difference of 20 feet can be attributed primarily to friction loss in the casing and secondarily to some head loss at the well screen.

In summary, there is a wide range of permeabilities and transmissibilities in the middle-zone aquifer. Permeabilities of the water-bearing sands in the zone range from 90 to 380 gpd per sq ft in the area tested; transmissibilities range from 525 to 72,500 gpd per ft. Storage coefficients are low (0.000014 to 0.00018), as is typical of artesian aquifers.

YIELD, CONSTRUCTION, AND MAINTENANCE OF BOREHOLES

The potential yield of a flowing borehole depends upon the transmissibility of the aquifer and the available artesian head at the site. The yield obtained is also greatly influenced by construction features of the borehole, particularly the casing diameter, length, and slot size of the well screen, and the method of development.

Middle-zone boreholes are cased with mild-steel casings (API line pipe) ranging from 1½ to 6 inches in diameter. The newer 1½- to 2½-inch holes are fitted with well screens of stainless steel or Everdur bronze, whereas in the older 4- to 6-inch diameter boreholes perforated casing or button-type screen was used. Figure 4 shows the construction features of a typical borehole of 2½-inch diameter (the most common size used). Float-operated valves on the cattle troughs and automatic shutoff faucets at boreholes used for village water supply are now generally installed at most water points and help greatly in reducing waste of water.

Most of the middle-zone boreholes are of very small diameter (2½ in.) in relation to their depth (500 to 1,200 ft). The result of this method of construction is that head loss due to the friction of water moving upward inside the casing is considerable. In any flowing borehole the total head loss is the sum of: (1) the loss within the aquifer required to maintain a given flow, (2) the loss at the screen entry, and (3) the loss due to friction in water moving up the casing from the screen to land surface. The head loss due to the third factor is very high in comparison with the first two factors in the 2½-inch diameter middle-zone boreholes; that is, the limiting factor of the yield of the boreholes may be the casing diameter rather than the transmissibility of the aquifer.

The use of 2½-inch casing restricts the flow to about 4,000 gph from middle-zone boreholes of 1,000- to 1,200-foot depth. It is impossible for water to move up a 2½-inch pipe 1,000 feet in length at more than 4,000 gph under the available head (up to 70 ft) and water viscosity (taken at 105°F). A number of boreholes tapping the most permeable aquifer flow at or near this limit of 4,000 gph.

A comparison of the average initial yields of 2½-inch diameter boreholes gives an indication of the aquifer's ability to yield water on an areal basis, but the limitation of borehole yields to 4,000 gph should be recognized. The average initial yield from 22 boreholes tapping the high-yield aquifer (area *a*, pl. 5) is 3,300 gph; from 77 boreholes tapping the moderate-yield aquifer (area b_2 is 2,200 gph; and from 24 boreholes tapping the low-yield aquifer (area c_1) is 600 gph. These average yields are far less than could be obtained from larger-diameter boreholes. For examples, at Mongonu (in the high-yield aquifer area), a 4½-inch diameter borehole produced an initial flow of 20,000 gph.

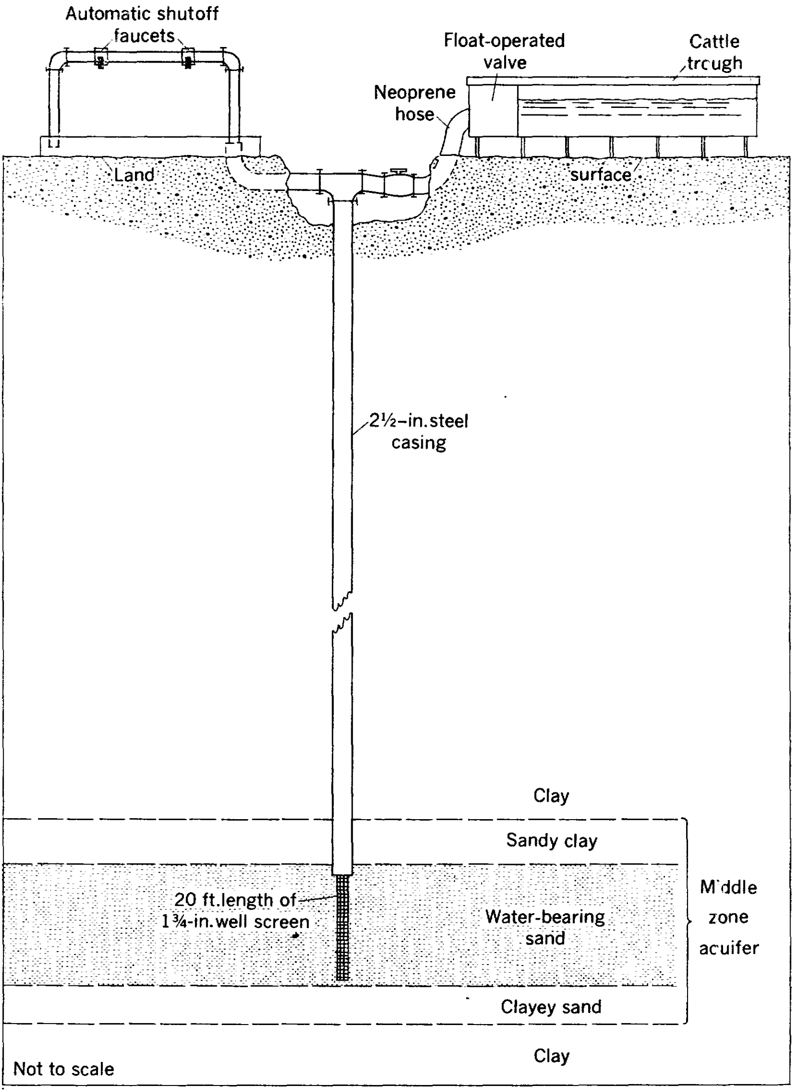


FIGURE 4.—Typical artesian borehole installation in middle zone.

It must be pointed out, however, that there are important economic advantages in constructing boreholes with small-diameter casings in the Chad Basin: (1) the cost for construction of individual boreholes is much less than that of larger diameter boreholes, and (2) waste is reduced and artesian pressure is conserved, if the boreholes are allowed to flow uncontrolled.

Corrosion of steel casings and resulting deterioration of boreholes is a serious problem in the Chad Basin but is most common in the northeastern and southeastern areas of the Nigerian sector of the basin, where ground-water conductivity is also high. Commonly, in these areas, the heads and yields of many of the flowing boreholes fell off drastically only 1 to 2 years after construction, and a few boreholes ceased flowing altogether. To combat the problem, 1⅝-inch diameter plastic liners were inserted in the 2½-inch diameter boreholes. The liners extended from the well head to the top of the well screen. At the well head, bronze fittings were used and neoprene hose replaced the original mild-steel pipe connecting the troughs and water taps. The plastic liners retarded corrosion by trapping the water between the liner and the casing, where the trapped water approached chemical equilibrium. The plastic liner, however, also reduced the inside diameter of the borehole. Consequently, the lined boreholes regained only 50 to 70 percent of their initial flow. This is not a serious problem, as the initial yields of the boreholes were generally two to three times the required minimum yield. Stainless-steel well screens are now being used in most of the boreholes in place of Everdur bronze screens, because the stainless steel has proved to be less costly and more resistant to the corrosive properties of the middle-zone water.

Experiments are now under way in the Chad Basin, using Fiberglas pipe instead of API line pipe for casing. Use of Fiberglas, although more costly, will eliminate the need for plastic liners, and its resistance to corrosion should greatly lengthen the life expectancy of the boreholes.

PRESENT UTILIZATION

An estimated 1,200,000 gpd was being withdrawn from the middle zone as of April 1965. Table 4 summarizes water use by districts. The average use per borehole was only 6,350 gpd (or 265 gph). Fortunately, this rate of use is well below the rate which would cause excessive decline in artesian head (see following section).

The primary use of water from the artesian boreholes tapping the middle zone is for cattle watering, but the water is also used for domestic purposes in villages and for three small municipal supplies. The large villages of Kukawa, Magumeri, and Mongonu have piped systems which altogether utilize about 37,000 gpd.

The greatest use of water from the middle zone is concentrated in the districts of Gubio, Kanembu, Marte, Mobber, and Mongonu in northern Bornu Province, where there are heavy cattle concentrations. The lightest use is in the area near the limit of flowing boreholes, where use is limited by low yield. In the area of boreholes of greater flow (more than 1,000 gph), the present withdrawal is considerably less than the maximum potential yield. To evaluate use throughout the basin, particularly in the area of high-yield boreholes, six watermeters were installed at typical boreholes. The average use (on a 24-hr basis) at the metered boreholes was as follows: Dalori, 100 gph; Gajibo, 246 gph; Gubio, 350 gph; Mbutta, 250 gph; Ngala, 900 gph; and Sabsawa, 500 gph. In additon, cattle counts at various boreholes were available for establishing a relation between metered and nonmetered wells. In areas of low flow, use is restricted to the current maximum yield of the well. With data of this type, estimates of use were made. The resulting estimate of 1.2 million gpd is a reasonably accurate estimate of the use in 1965.

TABLE 4.—*Current (1965) use of water from middle-zone aquifer*

District	Number of active middle-zone boreholes April 1, 1965	Estimated average water use [1] (gpd)	District	Number of active middle-zone boreholes April 1, 1965	Estimated average water use [1] (gpd)
Auno	6	10, 700	Mafa	11	49, 000
Bama	1	2, 400	Magumeri	11	59, 700
Damaturu	0	0	Maiduguri	10	50, 300
Dikwa	14	76, 300	Marte	13	117, 000
Galumba	8	16, 500	Mobber	19	152, 000
Geidam	0	0	Mongonu	11	95, 600
Gubio	20	109, 000	Ngala	12	85, 400
Kaga	3	7, 600	Nganzei	12	112, 500
Kala	7	36, 000	Rann	11	57, 600
Kanembu	16	156, 000			
Konduga	5	12, 000	Total	190	1, 205, 600
Kumshe	0	0			

[1] Avg 6,350 gpd per borehole.

During the years 1959–63 the total use was somewhat greater than 1.2 mgd. A decline in use during 1963 resulted from the installation of control valves at boreholes which had previously been allowed to flow free.

A total of 255 boreholes (pl. 1) have been completed in the middle zone; and of these, 190 were active producers as of April 1, 1965. The inactive boreholes include those from which the casing has been removed because of low initial yield, unused subartesian boreholes in which pumps have not been installed, and a few boreholes which have ceased to flow because of corroded casings. In addition, 19 boreholes were drilled into the middle zone as part of the present Chad Basin investigation. These boreholes were drilled for geologic information, for installation of pressure and water-level recorders, and for use as production boreholes in aquifer tests.

FLOW LIFE OF THE ARTESIAN SYSTEM

At present (1965) the most important water question in the Chad Basin is: "How long will the artesian boreholes continue to flow?" The local economy is largely dependent on cattle, for which the boreholes are an important source of water, particularly during the dry season. If the boreholes should cease to flow, installation of pumping equipment would be required, and this measure is not considered economically feasible at the present stage of the region's development. Also, maintenance of pumps in the rural areas would pose many problems which could not be adequately resolved with the present resources of the indigenous population.

The middle zone should continue to provide water from flowing boreholes for at least 30 years, if the conservation measures described in this section are taken into account and generally followed. This forecast is based on the results of the aquifer tests conducted at Dalori, Ngala, and Sabsawa. By using the aquifer constants (coefficients of transmissibility and storage) obtained at these test sites, it is possible to estimate the drawdown at any future time at any middle-zone borehole or at any distance from the borehole. Knowing the initial head, it is possible to estimate approximately how long a borehole will flow at any given rate or what the effect will be on the borehole from nearby flowing boreholes. If a certain flow rate is desired, the spacing between boreholes necessary to maintain this flow can be calculated. Conversely, if boreholes are spaced at any specified interval, it is possible to compute the flow rate which can be maintained for any period of time.

Figure 5 shows the drawdown at distances of 1 to 100,000 feet from the Sabsawa, Ngala, and Dalori production boreholes after 30 years of continuous flow. The slope of the lines is related to the cones of depression (pressure relief) for the flow rates shown. At Dalori the slope is much steeper than at Ngala or Sabsawa because of the much lower transmissibility there. The steep hydraulic gradient supplies only 100 gph at Dalori, whereas relatively gentle gradients supply much greater flows of 2,500 and 5,000 gph at Sabsawa. The declines in head for Sabsawa, Ngala, and Dalori in figure 5 have been applied to the aquifer areas of high, moderate, and low yield (areas a, b_1, and c_1 in pl. 1) to compute the 30-year decline in artesian head. The assumption is made that the values of transmissibility and storage coefficient obtained at the Dalori, Ngala, and Sabsawa test sites are average values for areas a, b_1, and c_1. Existing knowledge of the lithology and geometry of the aquifer suggests this assumption to be generally valid, but there are some exceptions which are discussed later.

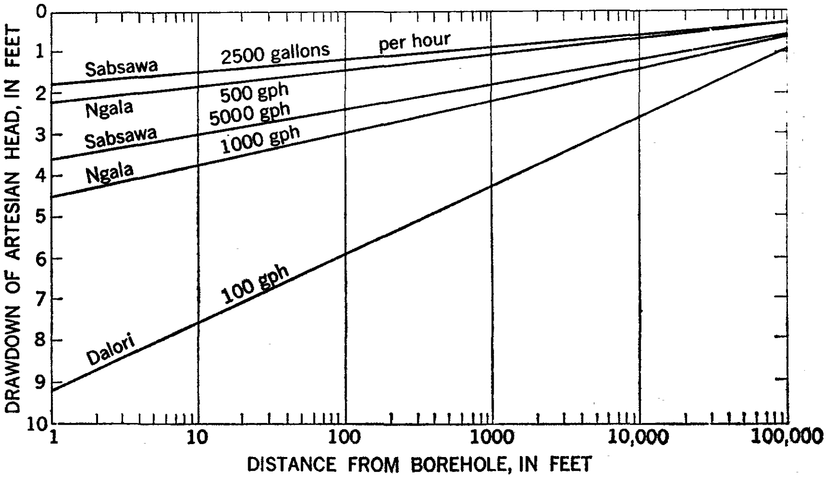


FIGURE 5.—Drawdown of artesian head in middle zone at various continuous flow rates after 30 years at Dalori, Ngala and Sabsawa.

The computed decline in artesian head after 30 years of continuous flow at 2,500 and 5,000 gph in the area of the high-yield aquifer (*a*, pl. 5) is indicated in the following tabular summary:

	2,500 gph	*5,000 gph*
5-mile spacing between boreholes:		
Decline in artesian head at borehole................(ft)..	1.8	3.6
Areal decline in artesian head caused by interference among all boreholes within 20-mile radius (based on fig. 5).....(ft)..	15.6	31.2
Total artesian head decline....................(ft)..	17.4	34.8
10-mile spacing between boreholes:		
Decline in artesian head at borehole................(ft)..	1.8	3.6
Areal decline in artesian head caused by interference among all boreholes within 20-mile radius (based on fig. 5).....(ft)..	4.2	8.4
Total artesian head decline....................(ft)..	6.0	12.0

The original artesian head at boreholes in the high-yield area ranged from 33 to 65 feet. By use of the minimum figure of 33 feet, it can be computed that the artesian head will have declined to slightly below land surface after 30 years in boreholes permitted to flow at 5,000 gph and with 5-mile spacings. The 5,000 gph flow can be readily maintained with 10-mile spacing and flows of even 10,000 gph probably can be sustained with the 10-mile spacing. Because the transmissibility at Sabsawa may be higher than average for the high-yield aquifer, the head-decline figures given above may be optimistic. At Sabsawa the aquifer contains about 200 feet of water-bearing sand, which is the thickest section known in the high-yield area. Even so, very few boreholes in the area of the high-yield aquifer fully penetrate the middle zone, hence the zone may contain more than 200 feet of water-bearing sand at other localities.

There has been no significant decline in artesian head in the high-yield area during 1963–64 as shown by pressure recorders installed at Sabsawa and Kauwa (loc. shown in pl. 1). During this period the average withdrawal per borehole was less than 500 gph.

In summary, if flows are restricted to 2,500 gph with 5-mile spacing between boreholes or to 5,000 gph with 10-mile spacing, the flow life of the boreholes in area *a* of plate 5 can be stated conservatively to be more than 30 years.

In the area of the moderate-yield aquifer (b_1, pl. 5), the decline in artesian head after 30 years of continouus flow at 500 gph and 1,000 gph would be as follows:

	500 gph	*1,000 gph*
5-mile spacing between boreholes:		
Decline in artesian head at borehole (ft)	2.2	4.5
Areal decline in head caused by interference among all boreholes within 20-mile radius (based on fig. 5) (ft)	16.0	32.0
Total artesian head decline (ft)	18.2	36.5
10-mile spacing between boreholes:		
Decline in artesian head at borehole (ft)	2.2	4.5
Areal decline in head caused by interference among all boreholes within 20-mile radius (based on fig. 5) (ft)	5.3	10.6
Total artesian head decline (ft)	7.5	15.1

Originally the artesian heads within area b_1 (pl. 5) ranged from near land surface to 70 feet above land surface. From the above table, it is apparent that flows of 500 gph can be maintained readily with boreholes spaced 5 miles apart, but continuous flows of 1,000 gph with this spacing would result in cessation of flow at boreholes where the original head is less than 36 feet. Flows of 1,000 gph, however, can be maintained with boreholes spaced 10 miles apart, and flows of 2,000 gph can be maintained in areas where the head exceeds 31 feet.

The aquifer constants obtained at Ngala are probably representative of average values for the area of the moderate-yield aquifer. At this site the middle zone contains 47 feet of water-bearing sand, which is about average because similar beds of sand range from 20 to 70 feet thick elsewhere in the moderate-yield aquifer area. Thus, predicted declines in head at Ngala can be considered typical of the moderate-yield aquifer which underlies about half of the area capable of artesian flow in the middle zone.

The effects of exceeding the flow rates indicated above are illustrated by the decline in artesian head which occurred in Ngala District during 1959–63. During this period several high-yield boreholes were allowed to flow at rates exceeding 5,000 gph; and as a result, the artesian head declined from 42 to 33 feet, as measured from land surface at the Ngala observation borehole. In late 1963 the flows were brought under control by installation of float-operated valves on the cattle troughs. This measure reduced the withdrawal to about one-tenth the former flow, and within 4 months the artesian head had recovered from 33 to 41 feet. Fortunately, the waste occurred only in a relatively small area, and water moving toward the pressure-depleted area from adjoining parts of the aquifer soon reestablished the pressure head. If this uncontrolled waste had been widespread throughout the basin, there would have been little or no recovery in head; and if continued, the boreholes ultimately would have ceased to flow.

Forecasting the long-term head decline in the area of the low-yield aquifer (c_1, pl. 5) poses certain problems. The 30-year decline in head shown in figure 5, on which computations of the long-term decline in head are based, were computed from the Theis nonequilibrium equation. As discussed in the section on aquifer tests, the Theis equation assumes that the aquifer is homogeneous and that the coefficient of transmissibility is constant at all places within the cone of influence of a discharging well. These assumptions are only partly fulfilled in the low-yield area of plate 5, where there is great interfingering of sand and clay and hence much lateral variation in transmissibility; thus the values for artesian-head decline after 30 years of continuous flow, which are given below, can only be considered as approximate.

	100 gph	*200 gph*
Decline in artesian head at borehole (ft)	9.2	18.4
Areal decline in artesian head caused by interference among 4 boreholes within 5-mile radius (based on fig. 5) (ft)	7.6	15.2
Total artesian head decline (ft)	16.8	33.6

The initial artesian heads at boreholes within area c_1 (pl. 5) ranges from a few feet to 45 feet above land surface, but artesian heads of 15 to 25 feet are most common. Thus, most boreholes can be expected to maintain a flow of 100 gph for at least 30 years with a 5-mile spacing. Boreholes with initial heads of less than 10 feet cannot be expected to maintain this low flow, even assuming no interference from other boreholes. For boreholes with initial artesian heads of 40 feet or more, continuous flows of 200 gph could be maintained for 30 years.

Flows from boreholes within the low-yield aquifer initially may exceed 1,000 gph but will decline rapidly if permitted to continue at this rate. For example, the observation borehole at Dalori (GSN 3032) initially flowed at 1,400 gph, but after 2 hours the flow had declined to 840 gph and after 8 hours the flow was only 450 gph.

In summary, the middle-zone artesian boreholes in the Chad Basin of Nigeria will continue to flow for at least 30 years if rates of use are controlled. If boreholes are spaced 5 miles apart, flows of 500 gph (adequate for cattle-watering points) can be maintained for 30 years throughout the moderate and high-yield aquifer areas, shown in plate 5, which constitute about 75 percent of the present artesian-flow area. In addition, flows of at least 5,000 gph (useful for town supplies or small irrigation schemes) can be maintained for 30 years from boreholes spaced 10 miles apart in the area of the high-yield aquifer. With a spacing of 5 miles between boreholes, flows of 100 to 200 gph (adequate for small village supplies but not for cattle-watering points) could be maintained for 30 years in most of the area underlain by the low-yield aquifer.

LOWER ZONE

LITHOLOGIC CHARACTER AND AREAL EXTENT

The lower zone is now (1965) known only in the Maiduguri area, where it is about 285 feet thick and consists of fine to coarse sand, clayey sand, sandy clay, and clay. A few thin beds of sandstone also occur in the zone. The chief water-bearing beds consist of loose medium-to coarse-sand layers, generally about 5 to 15 feet thick. The alternation of sand and clay in the zone and general lack of grading suggest that the sediments were deposited on the delta of a large river subject to marked seasonal variations in flow.

A deep borehole at Muna, 12 miles northeast of Maiduguri, was drilled to 1,815 feet and only a few thin beds of sandstone were found below the middle zone. At Kunari, in Mobber District, a borehole (GSN 1995) was drilled to basement rock at a depth of 1,795 feet. At this site, sandy beds between 1,709 and 1,771 feet may represent the lower zone, but these beds of sand are not very permeable. Elsewhere in the report area, the presence or absence of the lower zone has not been proved by exploratory drilling.

WATER-BEARING PROPERTIES

The water-bearing properties of the lower zone as yet (1965) have not been well defined. No transmissibility or storage coefficients have been determined, but specific capacities of successful 4- to 6-inch diameter wells tapping this zone and perforated in 30 feet of aquifer range from 200 to 250 gph per foot of drawdown. This range of specific capacities is similar to that of large-diameter wells in the middle zone of the moderate-yield area (b_1), shown in plate 5. This similarity would suggest that the water-bearing properties of the lower zone in the Maiduguri area are similar to those of the middle zone in the area of moderate-yield wells. A transmissibility of 11,000 gpd per ft was indicated.

Initial pressure measurements on the lower zone boreholes indicate that the piezometric surface in the Maiduguri area is relatively flat (Barber, 1965). Positive pressure heads that have been measured range from 14.5 to 19 feet above land surface.

PRESENT UTILIZATION

There were only four boreholes in 1965 that were producing from the lower zone. The total average production was about 50[illegible],000 gpd and all was used as part of the Maiduguri water supply. Two boreholes were being pumped by airlift at a combined rate of 14,000 gph, and the remaining two flow into an underground concrete reservoir at the combined rate of 7,400 gph. Water is pumped from this reservoir directly into the city pipelines as needed.

FUTURE DEVELOPMENT

Development costs will greatly control the future exploration and use of the lower zone as a source of water. Under current (1965) conditions it is far cheaper to tap the middle zone for cattle-watering points and the upper zone for the municipal supply at Maiduguri. In the future, however, when more water is required than the upper zone can supply, the lower zone can be developed as a supplemental supply. Present indications are that the aquifer in the lower zone may have a rather limited areal extent. Consequently, the rate of pressure decline would probably be rapid, and pumping would be necessary even in the early stages of development of the lower zone. The depth of the lower zone would permit large pumping drawdowns; but if submersible pumps are used, they should be designed to operate in water temperatures of 120°F.

There is no indication that the lower zone is hydraulically connected with the middle zone, so pressure declines in one should have relatively little effect on the other. Before the lower zone is intensively developed as a source of water, however, aquifer tests need to be made using existing boreholes to determine the optimum spacing and yields for additional boreholes tapping this zone.

REGIONAL HYDROLOGY

GROUND-WATER MOVEMENT

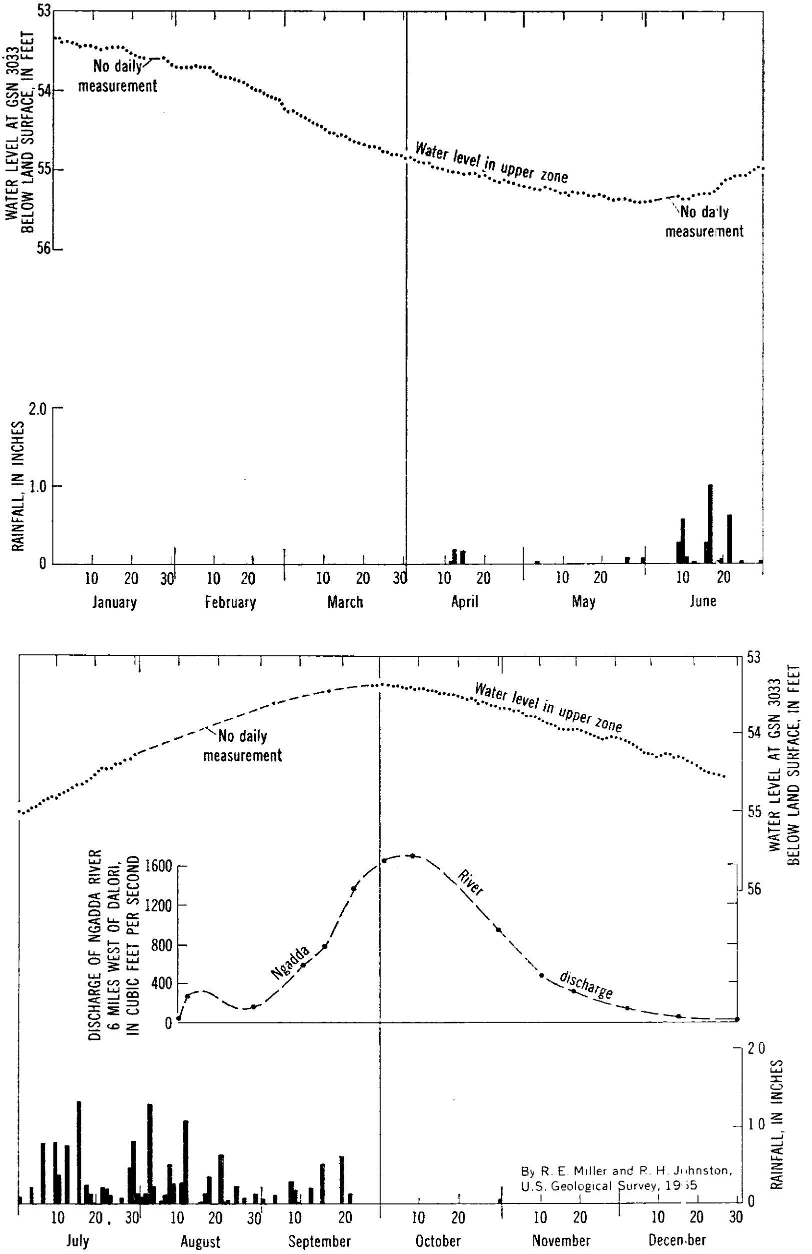
Using elevations interpolated from an earlier altimeter survey of the Chad Basin in Nigeria, a generalized contour map was constructed for the piezometric surface of the middle zone (pl. 8). In the area of flowing boreholes the piezometric surface has a very gentle gradient toward Lake Chad and in most localties, appears to be nearly flat or to have a gradient of less than 1 foot per mile. Northwest and southeast of Maiduguri, marked troughs occur that possibly indicate areas of pressure relief in the middle zone due to upward leakage of water into the upperzone. However, water moving upward in these pressure areas would have to move through 100 to 250 feet of hard shaly clay that separates the upper and middle zones. The troughs are more likely related to change in the rate of water movement, as they correlate with areas of low permeability in the middle zone. The piezometric contours (pl. 8) indicate that in the Nigerian part of the Chad Basin water is moving toward the area of flowing boreholes principally in the corridor south of Maiduguri, between the two troughs.

Middle-zone boreholes along the edge of Lake Chad have artesian heads of 65 to 70 feet above the lake level, indicating an upward component in ground-water movement from the middle zone in the lake area. Any significant vertical movement in this lake area, however, would be greatly impeded by 800 to 1,000 feet of impervious clay that overlies the middle zone.

The depth to water in the upper zone is shown in plate 4. Altitude control on the well collars of upper-zone wells in the report area was not sufficiently detailed to construct a map showing the altitude of the water surface. Nevertheless, depths to water show that ground-water highs occur along the edge of Lake Chad and along all major rivers in the report area. A marked ground-water low extends from the Gubio area to just a few miles northwest of Maiduguri, a fact suggesting that water in the upper zone comes from Lake Chad and nearby rivers and moves toward the interstream areas away from the lake. The ground-water high that extends between Bama and Magumeri along the Bama Ridge suggests that water is infiltrating from the Ngadda and Yedseram Rivers into the sand that forms the ridge.

RECHARGE

Recharge to the upper zone occurs in a significant but as yet unmeasured quantity. Presently (1965) available data indicate that such recharge occurs chiefly in the vicinity of the major streams. The water level in the recorder well tapping the upper zone at Dalori, 9 miles east of Maiduguri, is related to rainfall and the flow of the Ngadda River (fig. 6). This illustration shows that a rise in the ground-water level at Dalori in June was apparently initiated by infiltration from runoff due to local rains and later supplemented by infiltration from surface flow of the Ngadda River. Although surface flow in the river



By R. E. Miller and R. H. Johnston, U.S. Geological Survey, 1965

FIGURE 6.—Water level in upper-zone well at Dalori related to Ngadda River discharge and daily rainfall at Maiduguri during 1964.

does not begin in the Dalori area until August, subsurface flow probably begins earlier. As expected, the yearly high water level in the upper zone at Dalori correlates with peak discharge of the Ngadda River. Similar relations occur in upper-zone wells near other large rivers of the report area. On the other hand, water levels in upper-zone wells in the interriver areas such as at Gajigana and Gajram in Nganzai District show no perceptible seasonal fluctuations that might be attributed to recharge.

Recharge to the middle zone in the Chad Basin of Nigeria is probably very small. In the area between Lake Chad and the inner limit of recharge (pl. 8), the artesian pressures in the middle zone are great enough to prevent downward movement of water from the upper zone into the middle zone. Moreover, little downward movement of water from the land surface is likely to occur in the rocky fringe of the basin, as this fringe consists primarily of cemented sandstone and granite. Therefore, the only area of potential recharge to the middle zone, as shown in plate 8, lies between the edge of the rocky area fringing the basin (outer limit of recharge) and the line marking the intersection of the planes of the water table and piezometric surface (inner limit of recharge). Our earlier discussion of ground-water movement in the basin indicated that water from Lake Chad could not move into the middle zone; therefore, recharge from the surface would have to come from rivers in the Chad Basin, as high evapotranspiration rates and low precipitation would preclude significant direct recharge by rainfall. Large declines in the artesian head in boreholes in the Chad Basin would steepen the pressure gradients and shift the limit of artesian pressure toward the lake. Also, they would increase the area of potential recharge and the rate of recharge. Nevertheless, a decline in artesian head to land surface near the lake, which would cause all the boreholes in the Nigerian sector of the basin to cease flowing, would still not be great enough to affect significantly the middle-zone recharge area, which is 80 to 120 miles away from the lake.

Pressure recorders installed on middle-zone boreholes at Kauwa and Sabsawa in northern Bornu Emirate registered no significant changes in artesian pressure during 1963–64; but as discussed earlier, pressure recorders in Dikwa Emirate indicate pressure increases during these years. These increases were not due to regional recharge but to decreased withdrawals of the artesian water as float-controlled valves and cattle troughs were installed on many previously uncontrolled flowing boreholes. Now that the rate of water withdrawal has nearly stabilized, future pressure measurements should reflect long-term pressure declines in the middle zone.

Komadugu Yobe area.—Recharge to the middle zone in the Komadugu Yobe area probably does not occur for the following reasons: (1) The middle zone is not present in the area of potential recharge west of Geidam. The exploration borehole, GSN 3164, drilled at Geidam showed that sand beds in the middle zone are cemented with silica and overlain by several hundred feet of silty to shaly clay. Borehole GSN 3165 at Belle, 16 miles to the west of GSN 3164, showed the middle zone to be absent. (2) The gradient of the piezometric surface in the area of potential recharge (pl. 8) between Geidam and Ngamdu, 80 miles to the south of GSN 3164, would not permit movement of water into the middle zone in the Nigerian sector of the basin. Instead, the water would be diverted to the northwest into the Niger Republic and away from the area of flowing wells.

Ngadda River area.—Favorable conditions for recharge to subsurface beds of sand occur along the Ngadda River and its tributaries between the rocky fringe of hills near the edge of Chad Basin and the village of Mulgwe. At Mulgwe, where the depth to water is 34 feet, coarse sand with thin clay beds extends from the land surface to a depth of 250 feet. The high transmissibility (87,000 gpd per ft) of the sand beds at Mulgwe and the nearness of the river suggest that there is considerable recharge to these beds. Furthermore, static water levels in a 40-foot well and in Mulgwe observation borehole GSN 3067 (screened from 195 to 215 ft) show seasonal fluctuations of about 10 feet. Probably very little of the water entering the sand beds in this area, however, reaches the middle zone. Between Mulgwe and the area of flowing boreholes to the north, the middle zone is only a few feet thick and consists of beds of clayey sand that are frequently cemented. Middle-zone static levels in the observation boreholes GSN 3035 and 3036 at Abba Marwa and Gambole, respectively, indicated seasonal fluctuations of less than 0.5 foot during 1963–64. However, a few measurements in shallow wells indicated seasonal fluctuations in the water table of at least 3 feet, suggesting that most of the recharge water moving north from the Mulgwe area to the Abbe Marwa area is rejected by the Middle zone and is taken by sand beds in the upper zone. Therefore, any recharge to the middle zone in the Chad Basin from the Ngadda River area is probably very small.

Yedseram River area.—The Yedseram River contributes recharge to the thick surficial sand beds which underlie the river between the granitic hills west of Gwoza and the village of Mutube about 20 miles to the north. Movement of this water northward toward the area of flowing boreholes, however, would be greatly hindered by an area of very low permeability in the middle zone north and east of Bama (area *d*, pl. 5). The geologic section in plate 2, shows that the middle zone there contains only clayey or cemented sand. The gradient of the piezometric surface south of Bama indicates that water moving through the middle zone at this point would be diverted to the southeast and away from the area of flowing boreholes. Consequently, in this part of the Chad Basin, the Yedseram River probably contributes little recharge to the middle zone.

El Beid (Ebeji) River and Chari River area.—It is not known if there is recharge to the middle zone from the El Beid (Ebeji) River and the Chari River systems, for areas where recharge could occur lie beyond the border of Nigeria in the Cameroon and Chad Republics. The gradient of the piezometric surface indicates that movement of water through the middle zone into Nigeria from Cameroon could occur only in a 60-mile belt extending southeast from Lake Chad. However, if there is recharge to the middle zone in this belt, movement of the water would be exceedingly slow, as the gradient of the piezometric surface is nearly flat.

QUALITY OF WATER

GENERAL FEATURES AND RELATION TO USE

The chemical quality of the artesian water in the Nigerian sector of the Chad Basin is generally good. It has been discussed in some detail by Barber (1965), who based his study on water samples from 52 different middle-zone boreholes and one lower-zone borehole that have been analyzed in the laboratory of the Geological Survey of Nigeria at Kaduna. Samples from three additional middle-zone boreholes were analyzed in the U.S. Geological Survey laboratory, Washington, D.C., to determine the corrosion characteristics of the water. In addition, 94 specific-conductance measurements of borehole water were made in the field as part of the present investigation. The boreholes sampled are shown in plate 9, and nine representative chemical analyses of middle-zone water are listed in table 5.

The total salinity of the waters analyzed ranges from 288 to 1,065 ppm (parts per million) and the specific conductance, from 285 to 1,450 micromhos at 25°C. The principal cations are sodium, potassium, calcium, and magnesium; sodium is everywhere dominant. Bicarbonate, sulfate, and chloride are the important anions. The carbonate ion does not occur, as free carbon dioxide is everywhere present in the original state in quantities ranging from 16 to 135 ppm. Owing to pressure reduction, carbon dioxide bubbles form as the flowing water rises to the surface in the boreholes.

TABLE 5.—*Chemical analyses of water from typical middle-zone boreholes, Chad Basin, Nigeria*

[Results in parts per million except as indicated]

Constituents	Mbutta, Mafa Dist. GSN 1648 [1]	Laraba, Gubio Dist. GSN 1992 [1]	Garunda, Kanembu Dist. GSN 2083 [1]	Nyau, Kanembu Dist. GSN 2091 [1]	Sabsawa, Nganzei Dist. GSN 1984 [1]	Shuari, Mafa Dist. GSN 1643 [2]	Kauwa, Kanembu Dist. GSN 3020 [2]	Ngala, Ngala Dist. GSN 1996 [2]	Dalori, Konduga Dist. GSN 2274 [2]
Silica (SiO_2)	48	67	69	63	52	109	65	66	66
Aluminum (Al)	Trace	Trace	Trace	Trace	.03	Trace	.1	.1	.1
Copper (Cu)	----	----	----	----	----	----	.02	0	.04
Iron (Fe)	.18	1.5	1.3	1.3	.6	.1	4.5	[3] .25	[3] 7.0
Manganese (Mn)	1.0	8.5	4.2	2.5	1.0	2.4	1.4	.55	1.2
Calcium (Ca)	19	64	51	45	7	25	50	8	14
Magnesium (Mg)	4.0	37	23	20	3.7	19	22	4.1	6.8
Sodium (Na)	85	192	180	188	70	141	243	176	76
Potassium (K)	16	23	18	19	13	18	18	9	14
Bicarbonate (HCO_3)	183	170	237	243	160	268	295	354	----
Sulfate (SO_4)	61	449	320	319	43	180	368	83	29
Chloride (Cl)	32	112	88	88	23	41	71	34	10
Fluoride (F)	.3	.6	.6	.6	.10	.2	----	----	----
Nitrate (NO_3)	.6	0	13.3	13.3	.4	6.6	0	.8	.1
Dissolved solids, residue on evaporation	536	1,065	890	885	288	678	955	543	[3] 334
Hardness as $CaCO_3$	72	320	230	205	35	148	216	37	63
Free CO_2	----	125	95	85	40	115	[3] 95	[3] 76	[3] 95
Specific conductance micromhos at 25° C	400	1,300	1,085	800	340	800	1,300	775	425
pH	6.6	6.2	6.4	6.4	6.4	6.3	[3] 6.5	[3] 6.7	[3] 7.3
Sodium adsorption ratio (SAR)	4.7	4.7	5.3	5.9	5.3	5.2	[3] 7.3	[3] 12.8	[3] 4.1
Oxidation-reduction potential (Eh)	----	----	----	----	----	----	[3] −79	[3] −39.5	[3] −163

[1] Analyzed by Geol. Survey of Nigeria Lab., Kaduna, Nigeria.

[2] Analyzed by U.S. Geol. Survey lab., Washington, D.C.

[3] Field determinations by Frank E. Clarke, U.S. Geol. Survey.

Dissolved iron is generally present in analyzed water samples in concentrations of less than 1 ppm; but in the native formational water, the iron content may be as much as several parts per million. Manganese also commonly occurs in concentrations of less than 1 ppm but may be as much as 8.5 ppm. After withdrawal from boreholes and on standing exposed to air, the waters become discolored as the oxides and hydroxides of iron and manganese are precipitated. If these waters were to be used for industrial purposes, the manganese and iron would have to be removed by oxidation and filtration. The high manganese content of the water suggests that concentrations of manganese may occur in some of the lateritic beds of the Chad Formation.

The fluoride concentration of the middle-zone water ranges from a trace to 0.9 ppm. This concentration is safe for drinking, as water must contain more than 0.9 ppm to cause mottled enamel in children's teeth, and more than 3 ppm is necessary to cause endemic cumulative fluorosis and skeletal defects (California State Water Pollution Control Board, 1952, p. 257).

As shown in plate 9, a belt, about 20 miles wide, of lower-salinity water extends through the middle zone from Magumeri to Mongonu. This belt is approximately coextensive with the principal area of high-yield wells (pl. 2). Waters from middle-zone wells north of this belt are predominantly of the sodium sulfate bicarbonate type, whereas waters to the south are primarily sodium bicarbonate sulfate. A blending of the waters occurs within the belt of lower salinity.

All the borehole waters are safe for cattle use, as livestock can tolerate salinities of several thousand parts per million. In respect to irrigation use, more detailed chemical studies of the water are needed, especially before application to poorly drained soils. Determination of boron content is particularly important; for if boron is present in excess of 1 ppm, the water may not be suitable for irrigation.

The quality of the water in the upper and lower zones is known only from water samples from boreholes in the Maiduguri area. The waters from these two zones at Maiduguri differ from middle-zone waters in several respects. They have lower salinities, 218 to 340 ppm, and low iron and manganese content. The dominant cations in the upper-zone water are sodium and calcium, but in the lower zones, sodium is the only dominant cation. The dominant anion in both zones is bicarbonate. Water for the Maiduguri municipal water supply is obtained in about equal quantities from boreholes tapping the upper and lower zones.

The hardness of the middle-zone water, which ranges from 35 to 350 ppm, is the major hazard in using it for urban supply. The hardness is well within tolerance limits for human consumption, but where it is more than 80 ppm, it may cause scale formation in pressure boilers.

Water used in high-pressure boilers and turbines, more than 400 pounds per square inch, must have nearly zero hardness. Commercial laundries, textile mills, and bleaching, dyeing, soap, and tanning industries also require soft water for efficient operation.

Measurement of specific conductances of waters in upper-zone concrete-lined and dug wells in the Chad Basin was started as part of the present investigation, but had not been completed in May 1965. Test results to date (1965) indicate that waters in upper-zone wells in or near the "firiki" areas and clay flats bordering Lake Chad have moderately high salinities as indicated by specific conductances ranging from about 1,000 to 5,000 micromhos at 25°C. In such areas of relatively impermeable surface materials, surface water accumulates in ephemeral ponds during the rainy season and later evaporates, leaving a residual salt concentration in the soil. Infiltrating seepage through such salt concentrations builds up the salinity in underlying upper-zone ground water. Where the soil is sandy and permeable, waters from upper-zone concrete-lined or dug wells have low salinities, generally with specific conductances ranging from 100 to 500 micromhos.

As the possibility of utilizing beneficially the water from Lake Chad is frequently considered, the chemical characteristics of the lake water become increasingly important. These characteristics have been discussed in some detail by Bouchard and Lefevre (1957). The lake water is predominantly of sodium bicarbonate type, and about 95 percent of the water flowing into the lake comes from the Chari River. Where the river enters the lake toward its south end, the total salt concentration is about 40 ppm; but owing to evaporation, the concentration gradually increases until at the north end it reaches about 400 ppm. This salt balance is maintained because, along its north and northeast borders, the lake shore is composed of sand dunes through which lake water infiltrates during high lake stages and evaporates in interdunal swales, leaving efflorescent deposits of salt on the surface. The predominant salt, sodium bicarbonate, known as "natron," is collected by local workers and transported across the lake for sale in other localities.

WATER TEMPERATURE

Water-temperature measurements have been made at wells and boreholes of various depths over a large part of the project area. On the deep flowing boreholes, true maximum temperatures could not be measured at borehole head unless the borehole had been flowing for 12 to 24 hours. Maximum temperatures measured for boreholes of different depths are shown in figure 7. A temperature measurement for only one lower-zone borehole is available, but it is considered to be representative of borehole water from this zone. The temperature

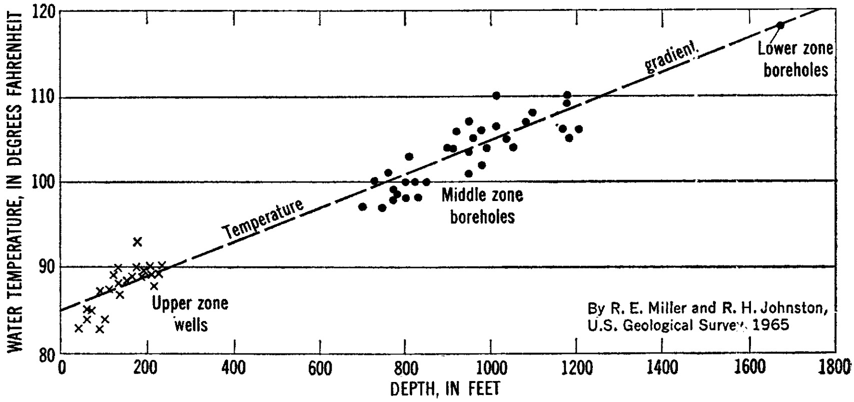


FIGURE 7.—Vertical temperature gradient.

gradient of water in the Chad Formation, based on borehole-head measurements, is about 2°F per 100 feet of depth (fig. 7). Dug wells and concrete wells less than 100 feet deep have temperatures several degrees cooler than the projected temperature gradient. This could be caused by infiltration of surface water, as the majority of shallow wells are located along rivers or near the lake. The diameter of these wells ranges from 2 to 4 feet, so the water in the wells also may be cooler than the normal gradient owing to wind-produced convection air currents in the well and the resultant cooling effect of evaporation.

CORROSION CHARACTERISTICS[4]

Water analyses and electrical resistance-type corrosion probe tests were made at three widely separated boreholes to obtain information on the nature and probable magnitude of corrosion effects. The boreholes tested were at Kauwa (GSN 3020), Ngala (GSN 1996), and Dalori (GSN 2274). The samples of water from these boreholes, whose analyses are shown in table 5, represent a considerable range in solute concentration. Two of them are predominantly sodium bicarbonate types and the third is a sodium sulfate-bicarbonate type. All samples have relatively low pH and oxidation-reduction (Eh) potentials and relatively high concentrations of silica and free carbon dioxide. Significant concentrations of ferrous iron occur at Dalori and Kauwa boreholes.

Electrical resistance-type corrosion probes were installed at the three boreholes from which the water samples were taken. The probes contained U-shaped 40-mil (about 1-mm) diameter wire loops (elements) inserted through the borehole casings by means of suitable bushing-

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[4] Based on a report by Clarke (1965), U.S. Geol. Survey.

shield assemblies (probe bodies). A part of each loop, representing one leg of a resistance bridge circuit, is covered with waterproof coating so that it senses and compensates for water-temperature variation, but is not affected by corrosion. A battery-powered meter is used to compare the electrical resistance of the exposed wire loop with the resistances of the reference legs in the bridge circuits. Resistance readings are converted to metal penetration, in inches per year, by means of the equation:

$$IPY=\frac{\Delta D}{\Delta T}\times 0.000365\times 10$$

where

ΔD=change in corrosometer dial readings between data points (electrical resistance),
ΔT=exposure time, in days, between data points,
10=a multiplier characteristic of the 40-mil probe wire,
0.000365=a factor for converting diameter change of the wire to inches penetration per year, and
IPY=inches penetration per year.

The corrosion probe data plotted in figure 8 show the effects of the tested water on mild-steel, Everdur-bronze, and stainless-steel specimens. The maximum corrosion rate of approximately 0.1 observed for mild steel in the Ngala and Dalori boreholes is far greater than the 0.02 usually considered the upper limit for acceptable long-term performance of mild steel parts. The fact that many small-diameter boreholes in the Nigerian sector of the Chad Basin have collapsed because of corrosion failure in their steel casings supports these data.

As shown by the horizontal rate curves observed at the Ngala and Dalori boreholes, no corrosive effects on the stainless-steel probes were evident. The performance of Everdur bronze at the Kauwa borehole lies between those of mild steel and stainless steel, and represents moderately severe atack, which normally does not occur on Everdur bronze in anaerobic (oxygen free) water unless the sulfide ion is present. Field test equipment was not available for checking this component. Despite differences, the three waters sampled all belong to a general class of anaerobic groundwaters, typified by relatively low Eh potentials and pH values and relatively high free carbon dioxide concentrations. The combined effect of low Eh and low pH results in a high capacity for dissolving ferric oxide protective films and therefore makes such waters extremely destructive to iron and steel borehole components. This effect is intensified by the abundant supply of acidic carbon dioxide, particularly where this component exists in part as gas bubbles surrounded by envelopes of highly destructive carbon dioxide saturated water.

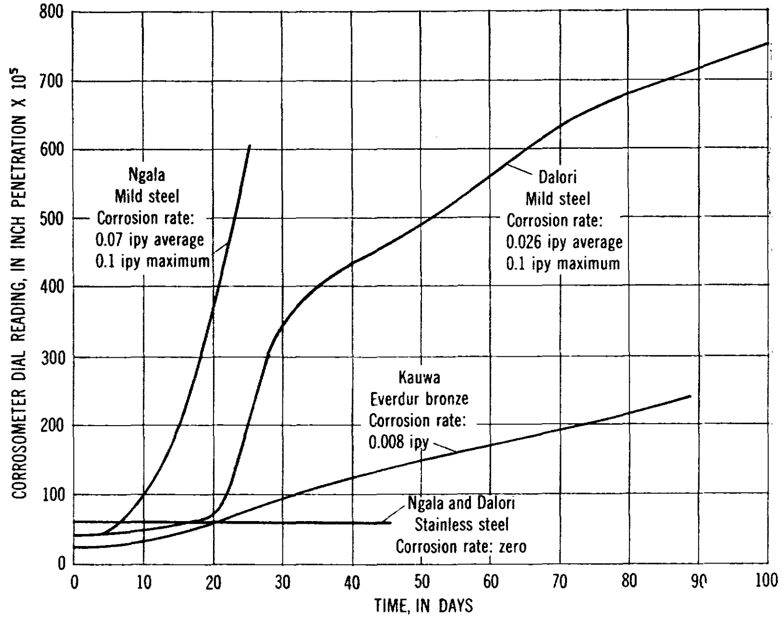

FIGURE 8.—Corrosion-rate curves for selected middle-zone boreholes (1965); ipy, inches penetration per year.

The limited testing described here suggests that waters from the middle zone of the Chad Basin are generally destructive to mild steel, and that other construction materials should be used where long well life is important. Stainless steel, Everdur bronze, and high-strength plastics are suitable alternatives. For well screens in this environment, stainless steel is preferable to Everdur bronze, as it is more resistant to the corrosive properties of middle-zone water.

CONCLUSIONS

No significant amount of recharge reaches the middle zone in the Chad Basin of Nigeria, but withdrawals from this zone are presently (1965) quite small; that is, less than 1.25 mgd. For at least 30 years, however, flowing artesian water from boreholes tapping the middle zone will be available for village and cattle use in Dikwa and Bornu Emirates, provided the following conditions are fulfilled:

1. With boreholes spaced 5 miles apart, flows of 500 gph can be maintained throughout the moderate and high-yield areas of the middle zone shown in plate 5.
2. With boreholes spaced 10 miles apart, flows of at least 5,000 gph (useful for town supplies or small irrigation schemes) can be maintained in the high-yield areas of the middle zone.

3. In the low-yield areas of the middle zone, flows of 100 to 200 gph can be maintained with a spacing of 5 miles between boreholes.

Recharge to the upper zone occurs in a significant but as yet unmeasured quantity, and occurs principally in the vicinities of the major streams as indicated by the correlation of stream discharge with water-table fluctuations. About two-thirds of the water withdrawn from the upper zone in the project area comes from native hand-dug wells, from which the present (1965) estimated rate of withdrawal is about 1 mgd. Six upper-zone boreholes, including the one drilled as a part of this investigation, are presently pumped at about 500,000 gpd for the Maiduguri municipal water supply. During the next 10 years the withdrawal rate from the upper zone for the municipal water supply will probably be increased by an additional 3 mgd to meet the projected demands, and close attention will have to be given to construction and spacing of boreholes, if this rate of withdrawal is to be maintained satisfactorily.

The chemical quality of the ground water in the Nigerian sector of the Chad Basin is generally good both for livestock and village use. For industrial or urban use, however, water from the middle-zone boreholes will need treatment for removal of high iron and manganese concentrations. Also, for certain industrial uses the hardness, which ranges up to 350 ppm, will have to be reduced. Waters from the upper and lower zones, in general, do not require treatment. In respect to potential irrigation use, the chemical analyses of table 5 indicate that most of the waters present a low sodium hazard but a medium to high salinity hazard.

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