Aquifers in the Sokoto Basin, Northwestern Nigeria, With a Description of the General Hydrogeology of the Region

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1757-L

Prepared in cooperation with the Geological Survey of Nigeria under the auspices of the U.S. Agency for International Development

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By HENRY R. ANDERSON *and* WILLIAM OGILBEE

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CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

AQUIFERS IN THE SOKOTO BASIN, NORTHWESTERN NIGERIA, WITH A DESCRIPTION OF THE GENERAL HYDROGEOLOGY OF THE REGION

By HENRY R. ANDERSON and WILLIAM OGILBEE

ABSTRACT

The Sokoto Basin of northwestern Nigeria lies in the sub-Saharan Sudan belt of west Africa in a zone of savannah-type vegetation. Rainfall, averaging about 30 inches annually in much of the basin, occurs chiefly in a wet season which lasts from May to October. A prolonged dry season extending from October to April is dominated by dusty harmattan winds from the northeast. April and May are the hottest months, when temperatures occasionally reach 105°F.

Flow in streams of the Sokoto Basin is mostly overland runoff. Only in a few reaches, fed by ground-water discharge from the sedimentary rocks, are streams perennial. In the River Zamfara basin, ground-water discharge contributes almost 1 inch of the average 3.33 inches of total annual runoff. In the vicinity of Sokoto, the River Rima flows throughout the year sustained by spring discharge from perched ground water in limestone of the Kalambaina Formation. On the crystalline terrane where most of the streams rise, total annual runoff may exceed 5 inches, very little of which is ground-water discharge.

The sedimentary rocks of the basin range in age from Cretaceous to Tertiary and are composed mostly of interbedded sand, clay, and some limestone; the beds dip gently toward the northwest. Alluvium of Quaternary age underlies the lowlands of the River Sokoto (now Sokoto) and its principal tributaries. These rocks contain three important artesian aquifers, in addition to regional unconfined ground-water bodies in all the principal outcrop areas, and a perched water body in the outcrop of the Kalambaina Formation. Artesian aquifers occur at depth in the Gundumi Formation, the Rima Group,

and the Gwandu Formation and are separated from one another by clay beds in the lower part of the Rima Group and the Dange Formation. In outcrop, clay in the Dange Formation also supports the perched water of the Kalambaina Formation.

The Gundumi Formation, resting on the basement complex, is composed of varicolored clay, sand, and gravel and attains a thickness of 800 to 1,000 feet in its downdip extensions. Most of the formation is thin bedded and clayey and therefore does not yield large quantities of water to boreholes; the average yield is 2,700 gph (gallons per hour). (All gallons are imperial gallons.) Nevertheless, the upper part of the formation is sandy and more permeable and forms a regional artesian aquifer from which yields of as much as 6,600 gph are obtained from single boreholes. Clay in the lower part of the Rima Group confines the Gundumi aquifer downdip, so that at Rabah and Sokoto, for example, in the River Sokoto fadama (valley floor), artesian flow is found in boreholes screened in the Gundumi.

Aquifer tests indicate low transmissivities, ranging from 300 to 5,000 gpd per ft (gallons per day per foot) in the lower part of the Gundumi Formation; but in the upper sandy zone the transmissivities are much higher, reaching 66,000 gpd per ft. In the western part of the Sokoto Basin, more productive aquifers with higher heads usually lie above the Gundumi aquifer so that it is not attractive for development, except in the River Sokoto fadama where artesian flow is possible.

The Illo Group, which is in part contemporaneous with the Gundumi Formation, includes interbedded varicolored clay and grit in the southern part of the Sokoto Basin. The upper part of the Illo is known to be water-bearing; however, except for the test borehole at Mungadi, little is known of its subsurface extent and water-yielding potential.

Overlying the Gundumi Formation in the central and northern part of the Sokoto Basin are interbedded fine gray sand and dark gray clay of the Wurno and Taloka Formations, separated in the extreme north by clay shale of the Dukamaje Formation. Collectively known as the Rima Group, these sediments attain a thickness of more than 1,000 feet near the Niger border. At depth and downdip the clayey beds practically disappear; the sandy beds become thicker and coarser grained. The Rima Group contains an extensive artesian aquifer which is economically important in the Sokoto and Birnin Kebbi areas. The aquifer generally provides moderate quantities of water to boreholes (average yield of 5,400 gph among 30 boreholes), but the depth to the water may be as much as 173 feet below land surface. In the Sokoto area the sand of the Rima aquifer is fine to medium; nevertheless, boreholes readily yield as much as 7,000 gph. Moreover, with drawdowns in boreholes of 10 to 65 feet, several aquifer tests have indicated transmissivities averaging about 45,000 gpd per ft. In western Sokoto Province (now part of North-Western State), the Rima aquifer is confined by clay in the Dange Formation so that in the River Sokoto fadama the aquifer yields artesian flow to boreholes. At Birnin Kebbi, for example, where fine to coarse sand of the aquifer extends from a depth of 360 to more than 1,000 feet, single boreholes flow as much as 7,000 gph and yield by airlift as much as 18,000 gph.

Above the 60-foot-thick calcareous marine clay of the Dange Formation is a shallow perched ground-water body in limestone of the Kalambaina Formation. This aquifer sustains numerous dug wells, springs, and ponds that extend in a belt for 140 miles all the way from Jega northward beyond the Niger frontier. However, after the rains and as a result of seasonal depletion of ground-water storage, many wells not fully pentrating the limestone or situated near the edge of the outcrop may go dry. Some springs, such as the spring at Angwan Tudu (Tundun Kudu), yield as much as 6 to 10 cubic feet per second, sufficient to provide minor agricultural projects with water for irrigation even during the dry season. In addition, overflow from the perched water body in the Kalambaina provides some recharge to the intake area of the Gwandu artesian aquifer that blankets the limestone. In its downdip extensions the Kalambaina is largely impervious and provides little or no water to boreholes.

Covering the western third or 8,000 square miles of the Sokoto Basin are interbedded massive clay and fine to coarse sand of the Gwandu Formation, which attains a maximum thickness of 1,000 feet near the Niger border. In the basal part of the Gwandu is an extensive and productive artesian aquifer contained in a sandy zone a few tens to a few hundred feet thick. This aquifer can produce artesian flow in five subareas totaling about 1,000 square miles in the River Sokoto fadama, in low-lying tracts near Kurdula and Bacaka, in an elongate lowland extending from Masallaci (now Masalachi) through Balle and Karfin Sarki to the Niger border, and in a narrow lowland extending some 20 miles southwest of Yeldu (now Yaldu). Most promising are the Balle and Karfin Sarki areas, where the aquifer is thickest, transmissivities are high (108,000 gpd per ft), and pressure heads and flows attain +72 feet and 12,000 gph, respectively. In general the water-yielding capacity of the aquifer diminishes westward as the sand of the aquifer becomes finer and interbedded with clay. A body of unconfined ground water marked by a regional water table extends throughout the area of Gwandu outcrop. This water table lies near the surface in ponds near Gande and Tangaza but is more than 300 feet below the surface near the Niger border.

In the River Sokoto fadama, considerable potential exists for development of unconfined ground water from permeable Quaternary alluvium. Extraction of this water would require low-lift pumping from shallow wells or boreholes (less than 75 feet deep). The shallow ground water in the alluvium is quickly and readily replenished by the River Sokoto, while in flood during the rainy season.

With the exception of high iron content, the chemical quality of ground water in the Sokoto Basin is suitable for most uses. It is noted, however, that the dissolved-solids content increases with depth. Also, the shallow ground water in the vicinity of villages commonly has high nitrate concentrations attributed to pollution.

Except for the River Sokoto fadama, where there is potential for use of ground water for irrigation, the soil in areas of artesian flow is very sandy and generally unfavorable for agricultural development. Thus under existing economic conditions, the artesian water can best be utilized for livestock watering, for the domestic requirements of villages, and for municipal and industrial purposes.

INTRODUCTION

PURPOSE AND SCOPE OF PROJECT

The present report describes the results of a two-phase ground-water-exploration project begun in March 1963 and completed in May 1967. The purpose of the project was to define the hydro-

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geologic framework of the Sokoto Basin in northwestern Nigeria with respect to the areal distribution of artesian aquifers, the hydraulic characteristics of the aquifers, the potential yields from flowing boreholes,[1] the areas of artesian flow, and the chemical quality of the ground water. The first phase of the project dealing with Tertiary aquifers, was carried out under the direction of the Geological Survey of Nigeria, Federal Ministry of Mines and Power. In the second phase, related to the Cretaceous aquifers, the Geological Survey of Nigeria participated with the northern Nigeria Ministry of Works and the Sokoto Native Authority initially in drilling for village water supplies and later in an extension of the exploratory phase of the project. The U.S. Agency for International Development (AID) provided the technical services of the authors of the U.S. Geological Survey and financial support for exploratory test drilling. Balakhany (Overseas), Ltd., was the drilling contractor throughout the life of the project.

The first phase of the project, begun in March 1963 and completed in March 1965, was directed toward ground-water exploration of the Gwandu Formation, which crops out in the western part of Sokoto Province.[2] Initially the goal was to define areas where flowing water might be obtained from the artesian aquifer in the basal Gwandu to satisfy the water needs of livestock and villages, principally in the arid region west of the River Sokoto. During this study the source of the water, the direction of groundwater flow, and the areal extent and the physical, chemical, and hydraulic characteristics of the Gwandu artesian aquifer were evaluated from the results of 23 exploratory boreholes put down at nine sites. These boreholes, ranging from 180 to 1,972 feet deep, have proved that the artesian aquifer in the basal Gwandu lies under about 5,700 square miles of western Sokoto Province (Ogilbee and Anderson, 1965) and yields water of good chemical quality. Free flow, with pressure heads ranging from a fraction of a foot to 83 feet above land surface, was found at five sites and subartesian conditions in the remainder. Also, artesian flows sufficient for livestock and village water supplies can be obtained from boreholes tapping the basal Gwandu aquifer in five subareas totaling about 1,000 square miles.

Following completion of exploratory drilling in the Gwandu Formation in March 1965, some 30 boreholes were put down in Cretaceous formations in the eastern half of Sokoto Province, beginning the second phase of the project. These boreholes also

[1] The term "borehole" is used synomymously with the term "drilled well."
[2] Now part of North-Western State.

were drilled by Balakhany (Overseas), Ltd., while under contract to the Ministry of Works and the Sokoto Native Authority to provide water for villages and road construction. Although the boreholes were drilled primarily for local water needs, they also provided valuable data for regional evaluations of the physical, chemical, and hydraulic characteristics of aquifers in the Gundumi Formation and the Rima Group.

In July 1966 test drilling was resumed through agreement between the Geological Survey of Nigeria and AID to explore the downdip extensions of the Cretaceous aquifers underlying the western part of Sokoto province. Altogether five boreholes were drilled to depths ranging from 900 to 1,600 feet. The results did show, in fact, that flowing water could be obtained from Cretaceous aquifers but only in the very low lying tracts, such as in the River Sokoto fadama (valley floor).

LOCATION AND EXTENT OF AREA

The principal area of study, the Sokoto Basin in northwestern Nigeria, covers about 25,000 square miles and lies between latitudes 10° and 14° N. and longitudes 3° and 7° E. The area is bounded on the north and west by Niger and on the southwest by Dahomey (fig. 1) and includes parts of Sokoto, Argungu, and Gwandu Emirates (now Divisions) in Sokoto Province. Although it is extensive, the Sokoto Basin of Nigeria occupies only about one-tenth of a much larger elongate sedimentary and structural basin centered in Niger, where it is known as Bassin des Iullemeden (Greigert, 1961).

PREVIOUS INVESTIGATIONS

Geologic work in the Sokoto region dates back to the late 1800's but most of the published material from this work relates to general geologic observations or descriptions of fossil localities. The first important stratigraphic study in the Sokoto region was that by Jones (1948). More recently (1965), D. H. Parker of the Geological Survey of Nigeria has updated past work and mapped the geology of a large segment of Sokoto Province. The water resources of the Sokoto region were first described by Raeburn and Tattam (1930) and more recently by du Preez and Barber (1965).

Test drilling in Niger between 1948 and 1956 first revealed the presence of artesian water in the Gwandu Formation. Of 18 test boreholes put down in Niger, however, only two flowed, one at Dogondoutchi and the other at Kiéssé, both near the Nigerian frontier. The pressure heads were 19 and 30 feet above land

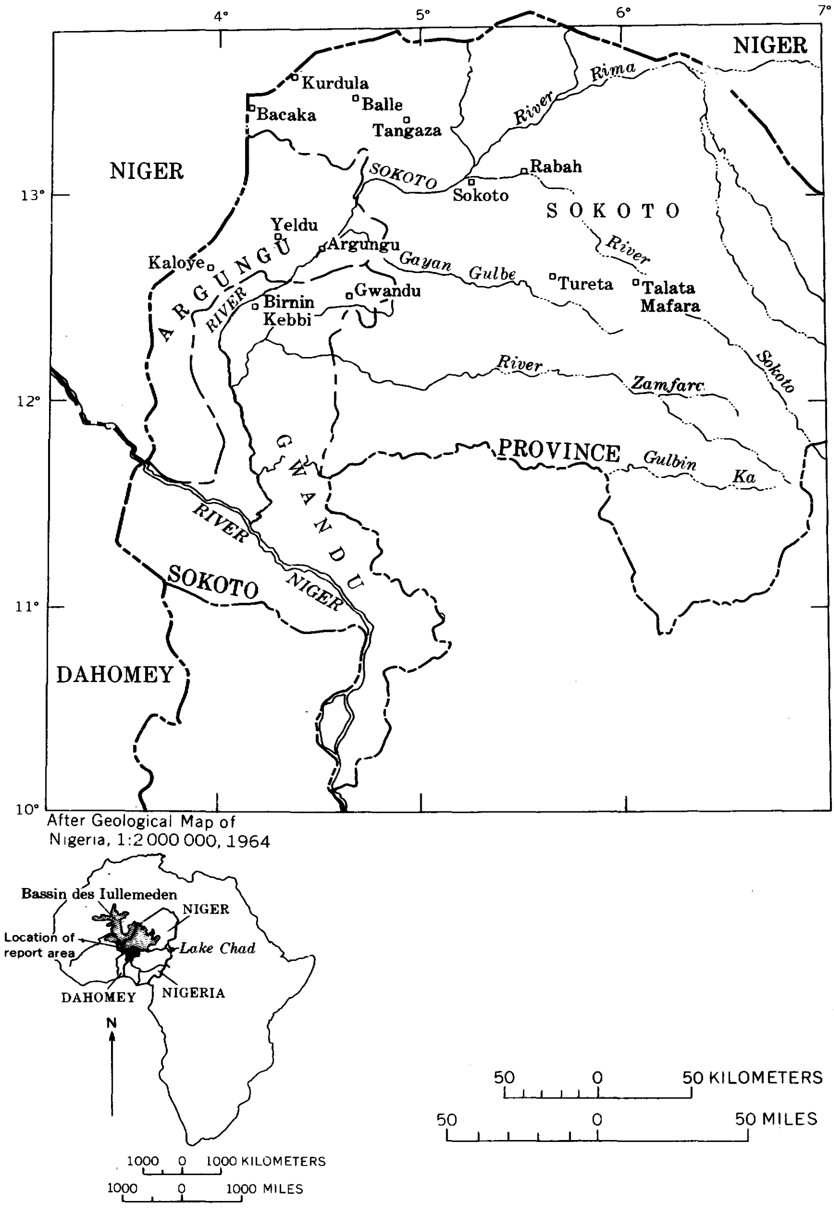


FIGURE 1.—Location of report area.

surface, and the free flow was 1,900 and 2,800 gph [3] respectively. Both boreholes tapped on aquifer in the lower part of the Gwandu Formation. From this evidence geologists of the Geological Survey of Nigeria postulated that artesian water should also occur in the Gwandu Formation in Nigeria. A few years later, in 1961, the Ministry of Work drilled exploratory borehole GSN 2481 at Birnin Kebbi to a depth of 392 feet and found artesian water between 160 and 170 feet in the Gwandu Formation that ultimately broke through to the surface, forcing the drillers to abandon the hole. Subsequently, several other boreholes found flowing water, not only in the Gwandu at depths ranging from about 148 to 216 feet but also in the upper part of the Rima Group from depths of about 340 to 410 feet.

In 1962 a U.N. team under the sponsorship of the Food and Agriculture Organization (FAO) began a hydrologic study of the Sokoto-Rima drainage basin. The annual reports (Food and Agriculture Organization, 1963, 1964, 1965) on this project, which include water-level observations in wells and also streamflow and precipitation data, have been very useful to the objectives of the present ground-war investigation.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to J. D. Carter, Director, and C. N. Okezie, Deputy Director, Geological Survey of Nigeria, for initiating and giving their fullest cooperation to the project. The Federal Surveys Department, under Collin Emmet, Senior Surveyor, provided valuable unpublished data on elevations and contour maps of the Sokoto region. M. R. West and M. I. Slatter, with Balakhany (Overseas), Ltd., the drilling contractor, were especially cooperative in supplying borehole information and assisting with aquifer tests and water sampling. M. Etuk and M. E. Offodile, geologists with the Geological Survey of Nigeria, provided direct assistance during the field stages of the project from January 1965 to June 1966. F. J. Mock, Senior Hydrologist, FAO, provided surface-water data and hydrologic information pertaining to the Sokoto-Rima drainage basin. The authors also wish to express their appreciation to officials of the Regional Irrigation Division and the Ministry of Works, as well as to local government and provincial authorities for their cooperation and assistance. The project was under the general supervision of D. A. Phoenix, chief of party, U.S. Geological Survey, stationed in Kaduna. The section entitled "Chemical

[8] In this report all gallons referred to are imperial gallons.

Quality of Water" is based on material provided by R. T. Kiser, chemist, U.S. Geological Survey, who was on assignment as a technical adviser to the Geological Survey of Nigeria.

GEOGRAPHIC, CLIMATIC, AND CULTURAL FEATURES

The Sokoto Basin in northwestern Nigeria is underlain by a sequence of semiconsolidated sedimentary rocks which in their surface expression form undulating plains broken by clay hills. Characteristically, the hills are capped by resistant crusts of laterite or ironstone. Generally, the hills are less than 150 feet high, but locally the relief between the stream valley floors (fadamas) and the hilltops reaches 300 feet. One conspicuous feature is the Dange scarp, a resistant cuesta ridge of limestone having local relief up to 150 feet that trends northeast through the central part of the basin. Generally, elevations in the Sokoto Basin range from less than 600 to more than 1,200 feet above sea level. Lowest elevations occur in the south near the River Niger, and the highest points are found on the ironstone-capped hills and the Dange scarp in the north. South and east of the Sokoto Basin, crystalline rocks form a dissected upland surmounted by isolated steepsided hills (inselbergs).

Vegetation in the Sokoto Basin is that typical of the Sudan savannah and is characterized by sparse scrub, generally less than 20 feet high, and interrupted by large isolated trees. The trees are generally fine-leafed and thorny and of the genus *Acacia*. Some broad-leafed varieties such as palms are more common in the wetter southern part of the region. Short feathery grasses form an almost continuous ground cover in the wet season.

The Sokoto Basin has a two-season climate, dry and wet. During the wet season, May to October, rains are induced by the northward movement of the moist Equatorial Maritime airmass from the Gulf of Guinea whose prevailing winds are from the southwest. The average annual rainfall during this season for 35 years of record is about 30 inches at Sokoto (table 1). It is somewhat greater in the south, up to 50 inches, but diminishes northward to about 20 inches toward the Sahara. During the largely rainless months from October through April, the dry dust-laden harmattan winds of the Tropical Continental mass blow in from the northeast. The coolest months in the Sokoto region are December and January when the average daily minimum temperature may decline to 60°F. The hottest month is April when 105°F is

TABLE 1.—*Monthly rainfall, in inches, at Sokoto airport, 1950–64, and Birnin Kebbi, 1952–64*

[No records kept for Sokoto airport in 1952. Tr., trace]

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total annual
Sokoto airport													
1950	0.08	0	0	0	1.12	0.40	5.89	17.44	7.60	1.08	0	0	33.61
1951	0	0	.35	0	1.82	2.42	6.34	7.67	3.42	1.24	0	0	23.26
1953	0	0	0	0	6.06	4.31	6.68	5.48	5.50	.08	0	0	28.11
1954	0	Tr.	Tr.	1.52	1.52	1.33	8.12	20.06	3.17	.86	Tr.	0	36.58
1955	Tr.	0	Tr.	1.49	.97	4.44	7.05	4.35	9.99	.62	0	0	28.91
1956	Tr.	0	.11	Tr.	.14	1.22	12.05	9.73	3.14	1.46	0	Tr.	27.85
1957	0	0	Tr.	.43	4.88	2.24	9.71	9.47	7.01	.93	0	0	34.67
1958	.12	0	0	.47	.49	6.80	7.87	11.71	4.72	.32	0	Tr.	32.50
1959	0	0	Tr.	.50	.68	1.30	4.49	12.54	2.58	0	0	0	22.09
1960	Tr.	0	0	0	2.46	6.40	10.65	10.56	5.27	.10	0	0	35.44
1961	0	0	0	.09	.89	6.77	6.37	7.86	3.24	0	0	0	25.22
1962	0	0	0	.29	1.27	6.38	7.28	7.42	4.47	.33	.02	0	27.46
1963	0	0	0	.16	1.67	4.04	7.45	9.75	4.64	2.49	0	0	30.20
1964	0	0	.15	0	1.86	6.61	8.89	5.83	5.37	0	0	0	28.71
Average	.014	0	.044	.35	1.85	3.90	7.77	9.99	5.01	.68	.001	0	29.61
Birnin Kebbi													
1952	0	0	0	0.45	2.59	3.66	8.15	11.37	8.81	1.44	0	0	36.47
1953	0	0	.20	0	9.89	4.65	8.11	5.88	5.07	.35	0	0	34.15
1954	0	0	0	1.16	6.12	3.76	8.69	11.87	4.99	.45	0	0	37.04
1955	0	0	0	.91	.31	6.24	9.71	8.29	9.72	1.28	0	0	36.46
1956	0	0	0	0	.48	3.95	10.56	7.14	6.47	.95	0	0	29.55
1957	0	0	0	.34	2.31	2.08	9.52	8.73	9.17	.92	0	0	33.07
1958	0	0	0	.47	1.80	4.73	6.06	10.62	3.86	.95	0	0	28.49
1959	0	0	0	3.42	0	0	9.29	14.72	7.14	0	0	0	34.57
1960	0	0	0	0	.46	3.00	9.99	11.19	3.59	.10	0	0	28.33
1961	0	0	0	0	0	1.89	3.20	8.48	3.52	0	0	0	17.09
1962	0	0	0	0	.09	4.37	7.88	9.09	7.39	2.11	0	0	30.93
1963	0	0	0	.55	.34	3.32	6.31	3.94	6.32	1.12	0	0	27.40
1964	0	0	0	0	1.66	5.62	10.67	11.28	7.76	0	0	0	36.99
Average	0	0	.015	.56	2.00	3.67	8.32	9.82	6.45	.74	0	0	31.58

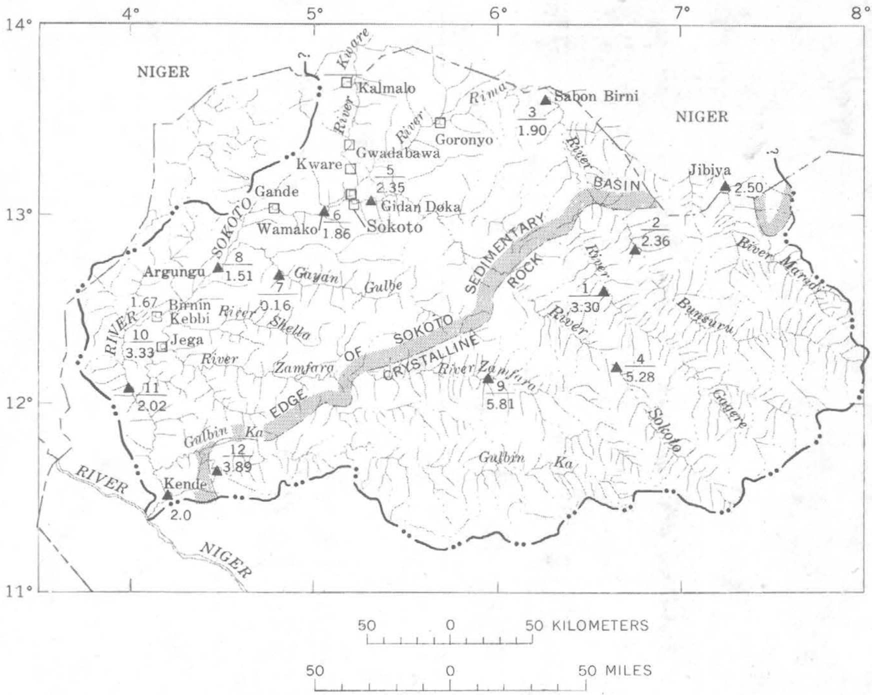
the maximum and 76°F the minimum average daily temperature. Throughout the year at Sokoto the average daily maximum is 96°F and the average daily minimum is 70°F.

Sokoto Province is second largest in area and also in population in Nigeria. Hausa tribal groups predominate with nomadic Fulanis intermixed throughout the more than 2 million inhabitants of the province. Hausa is the principal language spoken. The economy of the province depends chiefly on agriculture; rice, cotton, tobacco, and groundnuts (peanuts) are the most important crops. Fish from the streams of the region provide an important local source of food protein. Also, more than 100,000 cattle are exported annually to other regions of Nigeria. The processing of hides and skins, textile manufacture, and a new cement plant are among the growing industries.

HYDROLOGY

The River Sokoto–River Rima system is the principal drainage network of the Sokoto region. The headwaters of the Rivers Sokoto and Rima and their tributaries rise in pre-Cretaceous crystalline-rock terrane east of the Sokoto Basin and flow west and south across a terrane underlain by sedimentary rocks of the Gundumi Formation, the Rima and Sokoto Groups, and the Gwandu Formation. The Rivers Gagere, Bunsuru, Rima, Kware (now Shela), Shella, Zamfara, and Gulbin Ka and Gayan Gulbe are the principal tributaries to the Sokoto above its confluence with the River Niger (fig. 2). West of the fadama of the River Sokoto, on the outcrop of the Gwandu Formation, surface drainage is largely ephemeral and poorly integrated. Rainfall in this area percolates directly into the sandy soil or flows in short streams to small closed basins (tabkis) where it infiltrates or evaporates.

Stream discharge has been measured on a daily basis at a number of points on the Sokoto-Rima system. The northern Nigeria Ministry of Agriculture began measurements in 1949 at Birnin Kebbi on the River Sokoto. More recently (1962) a U.N. FAO Special Fund team, based at Sokoto, enlarged the stream-gaging program in the Sokoto-Rima drainage basin to 26 gaging stations established for periodic measurement. Among these, rating curves based on stream-discharge measurements were developed for 12 stations (fig. 2) so that the river-stage readings could be converted to discharge, in cubic feet per second. Table 2, which sum-



EXPLANATION

▲ 1 / 3.30

Stage-discharge station

Upper number is referred to in table 2; lower number is average annual runoff, 1962–65, in inches

Basin boundary

□ Stage station

Figure 2.—Rivers Sokoto and Rima drainage basin.

marizes the streamflow behavior at these stations, is based largely on data obtained by the U.N. FAO Special Fund team during 1962–65.

TABLE 2.—*Summary of discharges in the Sokoto-Rima drainage basin, 1962–65*

[Remarks: A, measures runoff from terrane of impervious crystalline rocks—stream discharge at station is flashy; B, measures flow from intermittent reach of stream; C, measures flow from gaining reach of stream; D, measures flow from losing reach of stream]

Station No. (fig. 2)	Stream	Gaging station	Catchment area above gaging station (square miles)	Discharge (cubic feet per second)			Average annual runoff (inches)	Percent of rainfall that runs off (runoff coefficient)	Volume of runoff Apr. 1, 1964–Mar. 31, 1965 (cubic feet $\times 10^8$)	Remarks
				Maximum	Minimum	Average				
1	River Gagere	Kaura Namoda	2,387	12,391	0–1	[1] 1,003	3.30	9.4	173	A, B, C
2	River Bunsuru	Zurmi	2,640	10,360	0–1	[1] 1,114	2.36	8.0	173	A, B, C
3	River Rima	Sabon Birni	7,669	10,821	0–1	[1] 2,328	1.90	6.2	363	B, C
4	River Sokoto	Gusau	1,026	8,650	0–1	[1] 590	5.28	11.6	100	A, B, C
5	do	Gidan Doka	4,862	7,820	0–1	688	2.35	6.8	217	C
6	do	Wamako	13,657	14,220	7	1,728	1.86	----------	550	D
7	Gayan Gulbe	Sainyinan Daji	1,522	61	0–1	10.1	.16	----------	1.18	C
8	River Sokoto	Argungu	16,818	14,098	12	1,709	1.51	----------	539	D
9	River Zamfara	Anka	1,596	10,121	0–1	[1] 803	5.81	15.0	146	A, B, C
10	do	Kalgo	6,451	9,935	152	1,300	3.33	8.5	410	C
11	River Sokoto	Bunza	19,038	17,200	53	----------	2.02	----------	----------	C
12	Gulbin Ka	Fokku	5,862	8,635	Tr.	----------	3.89	6.0	----------	A, B, C

[1] Average of discharges when stream is flowing.

The highest runoff from rainfall is found in the reaches of streams draining across the uplands of pre-Cretaceous crystalline rock, where precipitation is greatest and infiltration least. Thus, the headwater reaches of the River Sokoto and its tributaries, where they flow across crystalline terrane, are typically "flashy"; that is, they rise to peak discharge soon after rainstorms and then recede just as rapidly. The characteristic high runoff is shown in table 2 for the Rivers Gagere, Bunsuru, Sokoto, Zamfara, and Gulbin Ka, the stations being at Kaura Namoda, Zurmi, Gusau, Anka, and Fokku, respectively. At these stations, runoff coefficients range from 6 to 15 percent and average 9 percent of the rain that falls on the basin upstream of the station. During the dry season, moreover, the streams practically cease to flow at these stations, as the crystalline rock terrane, which they drain, does not yield sufficient effluent ground-water discharge to sustain base flow.

Westward as they enter the sedimentary terrain of the Sokoto Basin, several of the streams of the Sokoto-Rima system become perennial. While the overland runoff is low compared with that of the crystalline terrane, the base flow in streams increases. In the Rivers Sokoto and Rima, for example, base flow as observed at Sabon Birni and Gidan Doka all but ceases during the dry season, yet downstream at Wamako (fig. 3) the River Sokoto carries a small perennial base flow sustained during the dry season by spring discharge from limestone of the Kalambaina Formation (Sokoto Group). Also, north of Sokoto the limestone contains perched ground water that sustains, in addition to the springs, a number of small perennial lakes and ponds near Kware, Gwadabawa, and Kalmalo. Between Wamako and Argungu during the dry season, there is an increase in the base flow of the River Sokoto which is largely effluent ground-water discharge from the Quaternary alluvium of the River Sokoto fadama and from the Gwandu Formation. Nevertheless, the total annual runoff from the basin upstream of Argungu is less than that upstream of Wamako (table 2). This water loss is attributed to evapotranspiration as the fadama widens downstream from Gande and to recharge to ground-water storage in the alluvium.

Farther south is the River Zamfara which transects all the important aquifers in the basin, including those in the Gundumi Formation, the Rima Group, and the Gwandu Formation. Ground-water overflow from these aquifers sustains a substantial perennial base flow as observed at the Kalgo station (fig. 3). In June 1964, for example, an increase in base flow of approximately 80 cfs

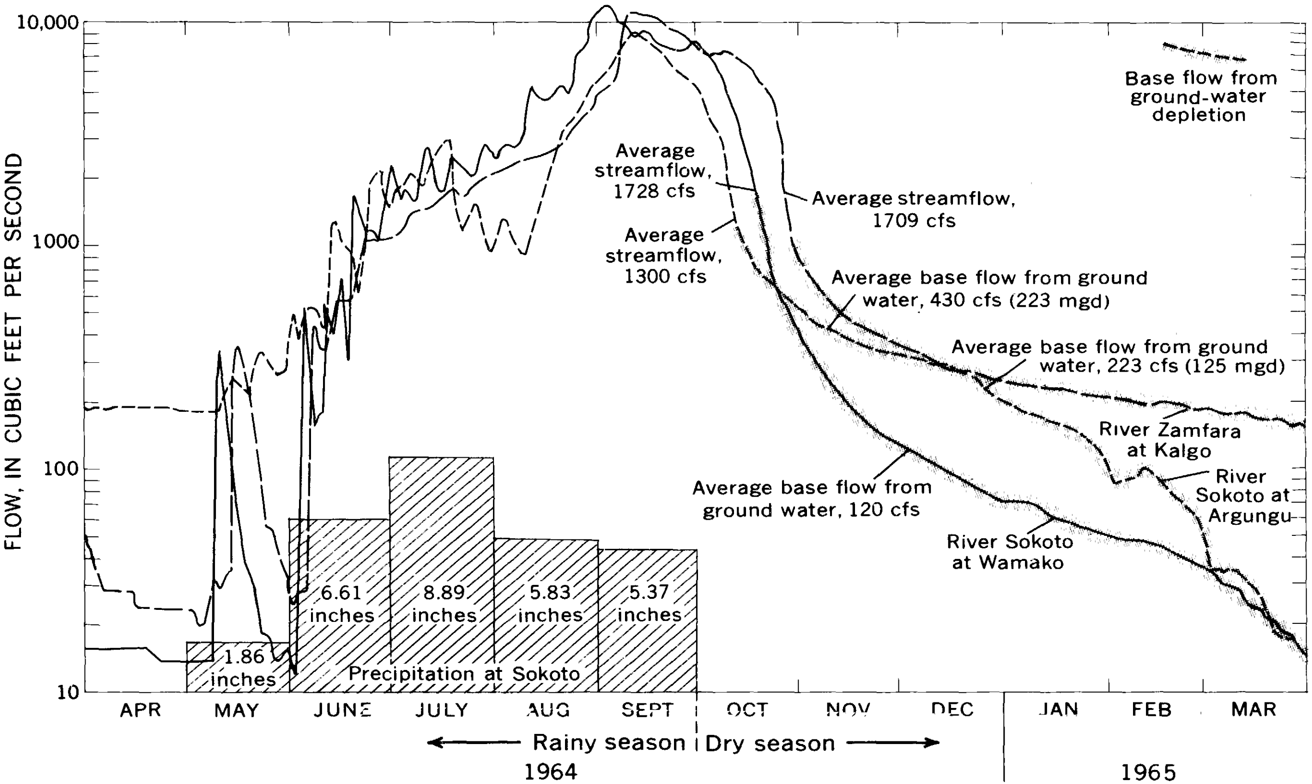


Figure 3.—Hydrographs of perennial reaches of the Rivers Sokoto and Zamfara showing flow due to ground-water depletion, 1964–65.

(cubic feet per second) was measured in the River Zamfara between Jega and Kalgo, largely representing ground-water inflow from the Kalambaina and Gwandu Formations.

Comparative flow-duration curves to illustrate the flow characteristics on the different geologic terranes are shown in figure 4. These are based on records extending from June 1962 to April 1965 for the Rivers Rima, Sokoto, and Zamfara. The gaging station at Sabon Birni, on the sedimentary terrane, and that at Anka, on the crystalline rock terrane, measure intermittent flow or runoff resulting almost entirely from rainfall. Surface runoff occurs about half of the time. It is slightly greater in the south as represented by Anka, where the rainfall is greater, and is spread over a longer wet season than in the north near Sabon Birni.

The gaging stations at Wamako and Kalgo measure perennial reaches of the Rivers Sokoto and Zamfara, respectively, or those fed, after the rainy season, solely from ground-water inflow. The lower slopes of the curves for these stations, shown in figure 4, represent ground-water or base flow. The base flow of the River Zamfara is sustained largely from relatively large ground-water storage in extensive sand aquifers, but base flow of the River Sokoto, which recedes more rapidly, is fed chiefly from temporary storage in the perched-water body of the Kalambaina Formation.

In the River Zamfara drainage basin the total annual runoff during water year 1965 was 2.75 inches at Kalgo. Almost two-thirds of the runoff, or 1.83 inches, largely representing overland runoff, was derived from crystalline terrane and 0.92 inch, largely representing ground-water inflow, from sedimentary terrane in the lower part of the basin. The average annual precipitation at Jega is about 36 inches. If this precipitation is assumed to prevail throughout the River Zamfara drainage basin, the total annual runoff would be equivalent to about 8 percent of the rainfall, of which overland runoff amounts to almost 6 percent and effluent ground-water discharge is about 2 to 3 percent. Provided there is no change in ground-water storage, the minimum recharge to ground water in the River Zamfara drainage basin would be at least on the order of the base flow of the River Zamfara, or about 0.92 inch for the 1965 water year.

The total annual runoff, in millions of acre-feet, from streams of the Sokoto-Rima system during water years 1963 to 1965, measured by the U.N. FAO, is shown in the estimates on page L16.

Stream	1963	1964	1965	Average
Gulbin Ka	1.0	0.58	0.92	0.83
River Zamfara	1.2	.92	.92	1.01
River Sokoto	.8	.45	.50	.58
Rivers Gagere and Bunsuru	1.0	.50	.74	.74
Others	.4	.15	.02	.19
Total	4.4	2.60	3.10	3.33
Total inches equivalent	2.6	1.6	1.9	2.0

In the semiarid Sokoto region, some 90 percent of the total rainfall is apparently lost by evapotranspiration. Evaporation measured by the U.N. FAO from open-surface class A pans at Gusau and Sokoto in 1964 indicated potential annual rates of 59 and 67 inches, respectively, or about double the annual rainfall. In Sokoto the evaporation rate gradually increases with the progress of the dry season, reaching a peak in May before the rains start, and then diminishes through the more humid wet season until September.

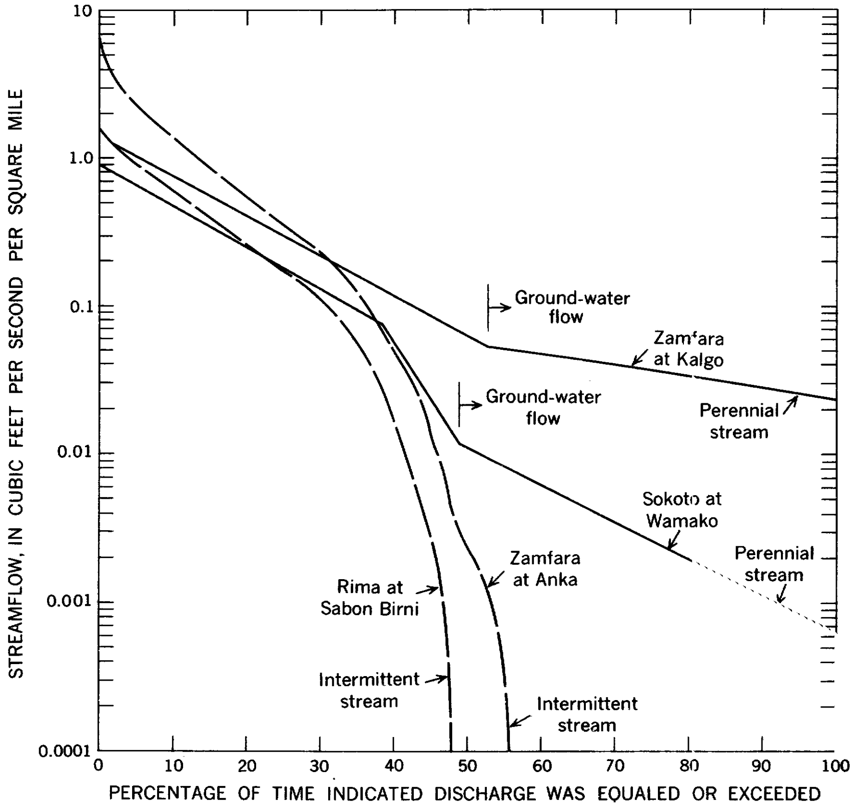


FIGURE 4.—Comparative flow-duration curves for the Rivers Rima, Sokoto, and Zamfara, 1962–65.

HYDROGEOLOGY

GENERAL FEATURES

The Sokoto Basin, which constitutes the Nigerian sector of the Iullemeden sedimentary basin centered in Niger, is underlain by a sequence of interbedded semiconsolidated gravel, sand, clay, and some limestone (pl. 1). This sequence attains a gross thickness of some 3,500 feet and ranges from Cretaceous to Quaternary in age (pl. 2). Oldest rocks of the sedimentary sequence are terrestrial deposits of the Gundumi Formation and Illo Group of Cretaceous age. These include varicolored gravel, sand, and clay resting on crystalline basement rocks of pre-Cretaceous age. Above the Gundumi and Illo lies the Cretaceous Rima Group, a sequence of fine gray sand and clay deposits. The Rima is made up of the Wurno and Taloka Formations, which are separated in the northern part of the Sokoto Basin by calcareous clay shale of the Dukamaje Formation, and also a basal clay member. Sediments of the Rima Group are transitional from the terrestrial deposits of the Cretaceous Gundumi Formation and Illo Group to the overlying marine calcareous deposits of the Tertiary Sokoto Group.

The Sokoto Group of Paleocene age includes at the base the Dange Formation, a greenish-gray clay, which is overlain by the Kalambaina Formation, generally a gray clayey limestone having concentrations of nodular crystalline limestone. The sediments of the Sokoto Group now form a prominent northeast-trending ridge, the Dange scarp, which rises about 150 feet above the sandy plains of the Rima Group to the east. Following the recession of Paleocene seas, the depositional environment changed once again to terrestrial conditions, and beds of sand and massive clay were laid down constituting the Gwandu Formation of Eocene age. The exposed clay beds of the Gwandu now form a series of low tabletop hills capped with a veneer of ironstone. Their flat accordant summits are the remnants of what was once an extensive peneplain in the Sokoto region, since uplifted and dissected. In addition, outliers of the Gwandu and the Sokoto Group also give evidence that the areal distribution of the Tertiary sediments was once more extensive.

Generally, the Cretaceous and Tertiary formations in the Sokoto Basin strike in a northeasterly direction and dip about 20 feet per mile to the northwest. These formations also generally thicken downdip, but southward along the outcrop all become thinner and the Rima and Sokoto Groups pinch out completely. Underlying the fadama of the River Sokoto and its larger tributaries are thin unconsolidated deposits of alluvial sand, silt, and gravel of Quaternary age.

Ground water in the Sokoto Basin is found, both confined as artesian water or unconfined just beneath the water table, in most of the permeable members of the Cretaceous-Tertiary sedimentary sequence. Confined water occurs downdip and at depth in semiconsolidated sand or gravel of at least three important aquifers (pl. 3), in the Gundumi Formation, the Rima Group, and the Gwandu Formation. Results of hydraulic tests and other hydrologic data for boreholes tapping these aquifers are given in table 3. Water-table conditions occur in the outcrop areas of all three aquifers. A local but important perched ground-water body is present in limestone of the outcrop area of the Kalambaina Formation. Unconfined ground water also occurs in the Quaternary alluvial fill of the fadamas of the River Sokoto and its larger tributaries.

PHYSICAL CHARACTER OF ROCKS AND OCCURRENCE OF GROUND WATER

CRYSTALLINE ROCKS (PRE-CRETACEOUS)

Underlying the sedimentary rocks of the Sokoto Basin and rising to the land surface in the uplands to the south and east of the basin are crystalline rocks of pre-Cretaceous age. These include intrusive granite of igneous origin and deformed metamorphic rocks, chiefly gneiss, schist, phyllite, and quartzite. Ground water in the upland areas of crystalline rocks is generally available in small quantities from fractures or other tabular partings and from the weathered rock (regolith) just beneath the land surface. The fractures are usually most open above a depth of 300 feet but, even so, yields to boreholes are relatively low and cause high drawdowns.

du Preez (1965, p. 29), who compiled data on 70 boreholes in the pre-Cretaceous basement rocks of northern Nigeria, computed an average borehole yield of 880 gph from an average depth of 123 feet. He concluded, however, that few boreholes in the unweathered rock, usually granite or gneiss, produced more than meager supplies of water; in 23 boreholes no water was found. Boreholes tapping weathered granite and gneiss, where saturated, generally were found to produce the highest yields (individual maximum 3,100 gph), the average for 37 boreholes tapping weathered rock being 1,400 gph per borehole. Moreover, drawdowns during pumping from some boreholes were found to be as great as 205 feet. The average depth of boreholes ending in weathered rock was calculated to be 126 feet, and the average depth to water was 19 feet. Most of the boreholes included in du Preez's compilation have been finished with slotted casing or screens. In some boreholes, however, only the upper part was cased and the borehole was left open in solid rock. Boreholes penetrating both weathered and solid rock draw most of their water from the weathered zone.

In 1965–66 boreholes were first put down in crystalline rocks of Sokoto Province to supply water for construction along the Gusau-Sokoto road. At mile 23 from Gusau three test boreholes were drilled from 94 to 135 feet into granite, and the water table was found at about 30 feet. Thin weathered veins, with quartz fragments and sand and clay fillings, were found to contain most of the extractable water. In the deepest borehole (135 feet), the yield was greatest but, after 8 hours of pumping with a maximum drawdown of 60 feet, the yield declined from 420 to 60 gph. Along the same road at mile 30 from Gusau, a borehole was put down in the weathered rock to a depth of 214 feet. The water table at 172 feet was considered too deep and the supply too meager to merit development. At mile 54¼, where the water table is 40 feet below land surface, a 97-foot borehole cased to 90 feet produced 2,500 gph from the weathered rock by airlift pumping.

The few boreholes extant in Sokoto Province indicate that the swales in weathered rock lying between fresh rock outcrops are generally the most favorable sites for drilling. Existing dug wells also give clues for favorable drilling sites, as they may indicate the depth and character of the weathered zone as well as the depth to water.

GUNDUMI FORMATION (LOWER CRETACEOUS)

PHYSICAL CHARACTER

The Gundumi Formation includes stream and lacustrine deposits, which contain comparatively coarser materials than any of the younger overlying formations of the Sokoto Basin. In the north near Isa and Sabon Birni, discontinuous lenses of quartz and feldspar pebble gravel are interbedded with the more abundant clay and clayey sand. Farther south, along the Gusau-Sokoto road, sandy beds prevail over gravel; however, the formation still contains a great deal of intermixed clay. The sandy beds decrease and clay beds increase with depth and to the east toward the contact with the pre-Cretaceous basement rocks but, near the base of the Gundumi, a conglomerate of rounded quartz pebbles up to 1½ inches in diameter occurs in outcrop. The sand and gravel beds are composed chiefly of angular to subangular quartz grains, but many beds are rich in feldspathic and micaceous material as well as rock

TABLE 3.—*Summary of aquifer tests*

Location: Name of town, village, or mile post in or near which corresponding borehole is located.

Borehole: Serial numbers are assigned by Geological Survey of Nigeria (GSN) to all boreholes in northern Nigeria.

Average yield: Average withdrawal during test by pumping (P) or by artesian flow (F).

Drawdown: At end of test drawdown in water level or pressure head in observation borehole (OB) or in producing borehole (PB).

Distance: Distance between observation borehole and producing borehole.

Transmissivity: Computed from flow or pumping test.

Permeability: Estimated from computed transmissivity divided by aquifer thickness at producing or observation borehole.

Storage: Coefficient of storage, a dimensionless constant.

Aquifer: Top and bottom of aquifer. (+) indicates aquifer extends to some depth below bottom of borehole.

Screen: Setting of top and bottom of screen.

Lithology of screened zone: Mcs, medium to coarse sand; G, fine gravel; Fcs, fine to coarse sand; Cs, coarse sand; Fs, fine sand; Fms, fine to medium sand.

Remarks: A, aquifer is apparently lenticular; R, recovery test on single pumping or flowing borehole; B, possible recharge boundary intercepted, very little drawdown after first 20 minutes.

Location	Borehole	Date of test	Duration of test (hours)	Average yield (gallons per hour)	Drawdown (feet)	Distance (feet)	Transmissivity (gallons per day per foot)	Permeability (gallons per day per square foot)	Storage	Aquifer (feet below land surface)	Screen (feet below land surface)	Lithology of screened zone	Remarks
Gwandu Formation													
Dange	GSN 3512	Oct. 21–22, 1965	9	1,570 P	6.3 OB	50	22,800	457	----------	580–630	608–623	Mcs	
Sabon Birni	3513	Dec. 1965	21	4,030 P	43 OB	33	2,600	130	3.7×10^{-4}	390–410	390–504	G	
Isa	3514	Jan. 8–10, 1966	24	1,800 P	69.6 OB	41	300	30	4×10^{-3}	405–415	397–413	G	A
Gusau-Sokoto road, mile 99 +4,000 feet	3521	July 14–15, 1965	20	6,420 P	2.4 OB	29	65,600	850	4×10^{-3}	250–318+	270–285	Fcs	
Bakura-Gumgi pasture	3701	Apr. 8–9, 1966	9	5,600 P	20 OB	50	4,900	245	1.9×10^{-4}	250–270	257–272	Fcs	
Girawsi	3704	Aug. 1966	3	2,400 F	.22 OB	--------	58,000	1,500	----------	884–922	905–920	Cs, G	R

Rima Group														
Sokoto	GSN 2859	Mar. 7-10, 1966	25	6,000 P	1.38	OB	457	44,000	--------	2.5×10^{-4}	--------	167-182	Fs	
Do	3504	May 21, 1965	22	3,000 P	.34	OB	2,800	41,200	--------	1.2×10^{-4}	330-391+	360-375	Fs	
Do	3505	July 10, 1965	6	2,800 P	.37	OB	1,064	52,000	325	--------	200-360	340-360	Fms	R
Wurno	3506	Apr. 26-27, 1965	24	4,050 P	55	PB	--------	2,800	147	--------	485-504	485-500	Fcs	R
Dogwandaji	3507	June 4-6, 1965	24	6,000 P	2.2	OB	22	264,000 (?)	--------	--------	220-265+	250-265	Fcs, G	B
Bodinga	3508	July 11-12, 1965	24	5,140 P	3.1	OB	33	65,000	266	1.8×10^{-6}	100-345	310-325	Fms	
Shuni (now Shunni)	3511	Aug. 20, 1965	12	5,290 P	8.75	OB	37	23,200	171	1×10^{-4}	250-350	281-296	Fms	
Gundumi Formation														
Birnin Kebbi	GSN 2482	Sept. 1963	72	4,200 F	1.8	OB	1,200	23,400	350	6×10^{-5}	170-243	170-190	Fms	
Rafin Kubu	2499	Oct. 27-29, 1964	24	2,880 F	.55	PB	--------	52,600	560	--------	360-454	436-451	Fcs	R
Bacaka	2674	Jan. 26-28, 1965	21	1,200 F	21	PB	--------	700	46	--------	979-994	979-994	Fms	R
Balle	3054	Feb. 9-12, 1965	--------	6,900 F	.7	PB	--------	170,000	840	--------	402-604	514-519	Fcs	R
Do	3055	-----do-----	15	6,600 F	7	PB	--------	9,100	340	--------	352-379	367-372	Fs	R
Kurdula	3056	Nov. 17-20, 1964	45	3,000 F	7.56	OB	75	9,600	213	1.1×10^{-4}	805-850	820-835	Fms	
Tangaza	3059	Feb. 1965	42	7,500 P	1.82	OB	200	83,020	585	2.7×10^{-5}	150-292	172-197	Fms	
Yeldu	3063	May 30-June 3, 1964	48	4,200 P	4.5	OB	100	14,600	246	1.2×10^{-4}	475-536	508-523	Fcs	
Karfin Sarki	3069	Jan. 5-7, 1965	21	12,000 F	2.15	OB	75	108,600	1,450	8.2×10^{-6}	582-657	591-606	Mcs	
Safla	3501	Apr. 1965	46	7,500 P	1.35	OB	54	128,000	2,320	2.8×10^{-5}	100-155	135-145	Mcs	B

fragments. Colors in the Gundumi, as in the Illo Group and Gwandu Formation, are varied. Brown, red, pink, yellow, white, and even purple are common, and in some clay beds a number of these colors may be present in mottled patterns.

Parker (oral commun., 1965) pointed out, "There is no field evidence of the precise [stratigraphic] relationship of the Gundumi Formation to the younger Taloka Formation [Rima Group]." In boreholes the sand from either formation may be white or light gray; however, the Gundumi is usually indicated when the sand is coarse to very coarse and the strata are thin bedded. Downdip in the Sokoto Basin, the Gundumi attains thicknesses of 800 to 1,000 feet near the Niger border. The regional dip is about 24 feet per mile to the northwest on the top of the formation.

GROUND-WATER OCCURRENCE

Water in the Gundumi Formation occurs under water-table conditions in the outcrop area, but downdip it is confined in an artesian aquifer beneath clay beds of the lower part of the Rima Group. Besides numerous dug wells, 11 boreholes listed in table 4 tap the unconfined water in the Gundumi outcrop area. Along the Gusau-Sokoto road nine of these boreholes are screened in beds of fine to coarse sand ranging from 15 to 100 feet in thickness, the thickest beds being in the upper part of the Gundumi. Tests in a number of the boreholes indicate lower yields and higher drawdowns as basement rock is approached, principally because the water-bearing beds become thinner and contain more clay near the basement-rock contact. For example borehole GSN 3521, near mile 100 on the Gusau-Sokoto road, yields 6,600 gph, whereas borehole GSN 3526, at mile 73, yields only 1,300 gph near the basement-rock contact (table 4). Furthermore, an aquifer test in borehole GSN 3521 indicated a transmissivity of 65,600 gpd per ft (table 3) in the upper Gundumi compared with the low value of 4,900 gpd per ft in borehole GSN 3701, which taps the lower part of the formation at Bakura. In other tests at Sabon Birni and Isa, boreholes GSN 3513 and 3514, respectively, were screened in gravel beds which are very common in the Gundumi in the northern part of the Sokoto Basin; nevertheless, transmissivities were low, 2,600 and 300 gpd per ft (table 3), respectively. The beds of gravel, while highly permeable, are evidently local and lenticular and hence have low water-yielding capacity.

As shown in the table on page L23, water levels in dug wells tapping unconfined water in the outcrop area of the Gundumi Formation are generally 45 to 125 feet below land surface. Moreover, they reach their high stage shortly after the end of the rainy season and thereafter decline as water is released from storage. Assuming a specific yield of 0.2 and an average fluctuation of 2.5 feet in a year, an estimated 0.5 foot of water would be lost or gained from storage each year in the unconfined water body in the Gundumi outcrop area.

Locality	Year	Depth to water (feet)				Range (feet)
		Month	Maximum	Month	Minimum	
Bakura Junction	1964	May	124.8	Aug.	121.0	3.8
	1965	Mar.	124.6	Sept.	120.9	3.7
Numba and Tureta	1964	July	82.6	Mar.	81.3	1.3
	1965	July	83.2	Sept.	80.4	2.8
Talata Mafara	1964	Feb.	47.9	Nov.	45.2	1.7
	1965	Jan.	46.7	Nov.	45.0	1.7
Average						2.5

Downdip the Gundumi Formation passes beneath the Rima Group, and the aquifer in the upper part of the Gundumi becomes confined by the basal clay in the lower Rima. At Rabah, the Gundumi aquifer yields artesian flows of 60 to 500 gph from individual boreholes with pressure heads of 1 to 12 feet above land surface. The water-producing sand is in the 600- to 700-foot depth range. The heads in the Gundumi artesian aquifer are as much as 18 feet higher than the water table in the Rima Group in this vicinity. (Compare boreholes GSN 2491 and 2492, table 4, with boreholes GSN 2488 and 2489, table 5.)

At Dange on the limestone scarp, borehole GSN 3512 is screened between 608 and 623 feet in coarse gray sand of the Gundumi, but here, as might be expected, the aquifer is subartesian. The subartesian water level is 280 feet below land surface and even 100 feet below the water table in the overlying Rima Group. An aquifer test (table 3) indicated a transmissivity of 22,800 gpd per ft for the Gundumi artesian aquifer at this borehole.

In another test at Sokoto, borehole GSN 2497 yielded 1,200 gph from a screen set in water-bearing gravelly sand between 876 and 898 feet. In this borehole the water level in the Gundumi artesian aquifer stands 152 feet below land surface. This level is about 20 feet higher than that in the Rima aquifer (see table 5, borehole GSN 3503) but still more than 100 feet below the perched water table in the overlying limestone of the Kalambaina Formation in this area. At lower elevations in the Sokoto region, boreholes tapping the Gundumi aquifer can yield flowing water. In the River Sokoto fadama, for example, exploratory borehole GSN 3704 at Girawsi flowed 2,500 gph with a pressure head of +21.5 feet from a zone 905 to 920 feet below land surface.

TABLE 4.—*Records of boreholes screened in Gundumi Formation, Sokoto Basin*

Location: Name of village, mile post, or point in Sokoto Basin near which corresponding borehole is located.
Borehole: Serial numbers are assigned by Geological Survey of Nigeria (GSN) to all boreholes in northern Nigeria.
Approximate elevation: Measured by aneroid barometer from nearby Federal Survey bench-marks.
Casing: American Petroleum Institute (API) line pipe (mild steel casing) used to case most boreholes.
Screen: Most screens are of stainless steel. Setting indicates top and bottom of borehole screen.
Static pressure head: Pressure head at time borehole was completed, in feet above (+) or below (—) land surface.
Yield: At time borehole was drilled. F, natural flow; A, airlift pump; P, turbine pump.
Remarks: C, chemical analysis in table 7; M, borehole drilled by Ministry of Works for public water supply; A, abandoned test hole, casing pulled and hole plugged; B, borehole drilled by Balakhany (Overseas) Ltd.; T, flow or pumping test carried out at borehole; L, geologic log in table 8; O, observation borehole drilled by Balakhany (Overseas) Ltd. for the Geological Survey of Nigeria.

Location	Borehole	Approximate elevation (feet above sea level)	Date completed	Casing		Total depth (feet below land surface)	Screen			Static pressure head	Yield (gallons per hour)	Drawdown (feet)	Remarks
				Diameter (inches)	Setting (feet below land surface)		Diameter (inches)	Setting (feet below land surface)	Slot openings (thousandths of an inch)				
Rabah	GSN 2490	860	5– 7–63	8 2½	0–32 32–653	960	1¼	653–673	--------	+10	500 F 1,750 A	100	C, M
Do	2491	860	5–14–63	8 2½	0–29 29–656	703	--------	656–676	--------	+12	450 F 2,700 A	100	M
Do	2492	860	5– 63	8 2½	0–35 35–618	713	1¼	618–638	--------	+1	60 F 3,800 A	110	M
Sokoto GRA	2497	995	4– 63	4	0–876	950	1¾	876–898	12	–152	600– 1,200 A	--------	A, M
Sokoto commercial area	----------	935	----------	8 4	0–302 302–780	835	--------	780–801	12	–97	600– 1,200 A	204	A, M
Sokoto fadama	----------	825	2–28–64	2½	0–615	711	1¾	615–630 201–213	--------	+18	2,500 F	--------	A, B
Bakura	3509	950	7–28–65	2½	0–202	257	1¾	221–226	20	–41	2,600 A	--------	
Dange	3512	1,112	10–18–65	6⅝ 4 2½	0–384 384–594 594–608	630	3½	608–623	10	–280	1,770 A	24	B, C, T
Sabon Birni	3513	1,003	11–25–65	6⅝ 4 2½	0–145 145–377 377–390	420	3½	390–405	20	–21	4,000 P	112	B, C, T

Isa	3514	1,060	1- 3-66	6⅝ 4 2½	0-163 163-390 390-397	420	3½	397-413	20	−24	1,600 P	121	B, C, T
Gusau-Sokoto road, mile 109+4,400 ft	3519	965	1-10-65	6 4	0-241 241-252	273	3½	252-267	10	−118	4,800 P	58	B
Gusau-Sokoto road, mile 105+800 ft	3520	1,047	5-16-65	6 4 2½	0-270 270-280 280-296	312	3½	296-312	10	−199	2,600 P	22	B, C
Gusau-Sokoto road, mile 99+4,000 ft	3521	933	7-12-65	6⅝ 4 2½	0-229 229-246 246-270	318	3½	270-285	10	−81	5,600 A 6,600 P	19	B, T
Gusau-Sokoto road, mile 95+200 ft	3522	935	8-24-65	6⅝ 4 2½	0-239 239-281 281-285	317	3½	285-300	20	−74	1,500 A	147	B, C
Gusau-Sokoto road, mile 89+2,500 ft	3523	986	10-4-65	6⅝ 4 2½	0-280 280-603 306-321	357	3½	321-336	10	−109	4,200 A 5,600 P	35	B, L
Gusau-Sokoto road, mile 83	3524	1,058	11-19-65	6⅝ 4 2½	0-262 262-276 276-290	315	3½	290-303	10	−163	2,500 A	69	B, C
Gusau-Sokoto road, mile 78	3525	1,113	5- 1-66	6 4 2½ 2½	0-311 311-373 376-385 400-470	494	3½	385-400 470-485	20 25	−182	800 A	--------	B
Gusau-Sokoto road, mile 73	3526	1,064	6-24-66	6 4 2½	0-280 280-345 345-353	440	3½	353-363	20	−135	800 A 1,300 P	100	B, C
Gusau-Sokoto road, mile 68	3527	1,011	7-14-66	6 4 2½ 2½ 2½	0-229 229-296 296-370 380-383 388-390	421	3½	370-380 383-388 390-393	--------	−67	small	--------	B
Bakura-Gumgi pasture	3701	+950	4- 7-66	6⅝ 4 2½	0-163 163-244 244-257	300	3½	257-272	25	−58	5,600 P	84	B, T
Gusau-Sokoto road, mile 93+3,400 ft	3703	918	5-24-66	6 4 2½	0-229 229-292 292-295	313	3½	295-310	10	−63	1,000	130	B, C
Girawsi	3704	805	8-25-66	2½	0-905	1,600	1¾	905-920	20	+21.5	2,500 F 3,300 P	--------	C, O, L, T
Kaloye	3708	673	3-20-67	2½	0-1,305	1,560	1¾	1,305-1,325	20	+19	2,000 A 360 F	--------	A, C, L, O
Sainyinan Daji	3709	----------	4-21-67	2½	0-760	900	1¾	760-780	20	−5	1,600 A	12	A, B, C, L

Among 24 boreholes in the Gundumi Formation, individual yields by pumping range from 600 gph in boreholes screened in the lower part of the formation to 6,000 gph in the upper part, the average yield being 2,700 gph. In western Sokoto Province more productive artesian aquifers overlie the Gundumi Formation; consequently, with its great depth and relatively low water-yielding capacity, the Gundumi aquifer is not presently (1967) attractive for ground-water development.

The Gundumi Formation is recharged, chiefly on its outcrop area, directly by infiltration from precipitation and also by effluent seepage from streams while in flood during the wet season. Once underground, water in the Gundumi generally moves westward, then southward into the Illo Group; it finally discharges into the River Niger or the lower reaches of the River Sokoto system in the southern part of the Sokoto Basin (pl. 4).

ILLO GROUP (CRETACEOUS)

PHYSICAL CHARACTER

The Illo Group includes nonmarine cross-bedded pebbly sand and clay that underlie an area of about 4,000 square miles in southwestern Sokoto Province. The lower "grits" member, as much as 400 feet thick, is a white friable medium to coarse pebbly sand with interbedded red, yellow, and blue clayey sand and clay. In outcrop this member contains a basal gravel that lies on pre-Cretaceous basement crystalline rocks. The lower member forms a sloping plain traversed by the River Niger, and exposures of this member occur beneath a middle member of pisolitic and nodular clay which in surface expression forms linear hills paralleling the River Niger (pl. 2). The middle member of nodular aluminous clay is about 30 feet thick, is chalky in appearance, and contains concretions from ¼ to 6 inches in diameter. The upper "grits" member, like the lower, is varicolored friable sandstone containing intermixed clay. It thins westward from 300 to 20 feet near the Niger Republic border. The Illo Group, although similar in lithology to the Gundumi Formation, may be also in part contemporaneous with the Rima Group.

At Mungadi 794 feet of coarse sand and fine gravel with some clay that corresponds to the upper part of the Illo Group was found by exploratory borehole GSN 3707 (table 10). This section probably merges toward Birnin Kebbi into an equally thick section (from 365 to 1,003 feet in borehole GSN 2484) of fine to coarse sand of the Rima Group, interpreted here as representing a deltaic deposit that becomes finer grained northward away from the source area. Between a depth of 882 feet and bedrock at 1,276 feet, borehole GSN 3707 passed through a thick section of clay intermixed with gravel that corresponds either to the lower part of the Illo Group or possibly to the Gundumi Formation. The middle aluminous clay member of the Illo, if present, cannot be identified in the borehole.

GROUND-WATER OCCURRENCE

Very little information is presently (1967) available on the water-bearing character of the Illo Group. In GSN 3707 at least 600 feet of the Illo is a highly permeable coarse-sand and fine-gravel aquifer, under subartesian conditions and containing good-quality water. Judging, however, from exploratory borehole GSN 3707 at Mungadi, the Illo appears to be hydraulically continuous with the artesian aquifer in the Rima Group at Birnin Kebbi. The potentiometric map (pl. 4) suggests that water moves south from the Rima aquifer into the aquifer of the Illo Group, which in turn discharges into the lower reaches of the River Sokoto and also the River Niger. West of the River Sokoto and 20 to 30 miles north of the area where the confining bed of the Dange Formation is absent, it is probable also that even the Gwandu artesian aquifer is hydraulically continuous with the Rima-Illo aquifer.

RIMA GROUP (UPPER CRETACEOUS)

PHYSICAL CHARACTER

The Rima Group consists of a marine transgressive series of fine-grained sand and friable sandstone, mudstone, and some marly limestone and shale. North of the River Sokoto in the northern part of the Sokoto Basin, the group is divided into three formations, the Taloka at the base, the Dukamaje in the middle, and the Wurno at the top (Jones, 1948; Parker and others, 1964). The Taloka Formation, where exposed in the northern part of the Sokoto Basin, attains a thickness of 400 feet and consists of white fine-grained friable sandstone containing some thin intercalated beds of carbonaceous mudstone or shale (Parker and others, 1964). The Dukamaje Formation, between the Taloka and the Wurno, crops out only north of the River Rima. Originally named the "Mososaurus Shales," it consists at Dukamaji of 70 feet of shale, thin limestone, and mudstone, and some gypsum and an assemblage of invertebrate and vertebrate fossils at the base. The uppermost formation of the Rima Group, the Wurno, consists of 75 feet of pale fine sand and some silt. According to Jones (1948, p. 21) the Dukamaje Formation has not been found south of Rabah on the River Sokoto, and hence south of this point the Wurno and the Taloka are mapped together as a unit.

In the northern part of the Sokoto Basin, samples from boreholes closely resemble those taken from surface outcrops of the

Rima Group. Thick beds of well-sorted fine white sand and dark-gray lignitic clay containing iron sulfide (pyrite) are found in boreholes near Sokoto and also at Rabah and Wurno. Individual beds may exceed several hundred feet in thickness and grade laterally from clay to fine sand within short distances. Coarse sand in thin beds occurs near the base of the Taloka Formation at Wurno, Dange, and Sokoto. For example, borehole GSN 2497 in Sokoto starts in limestone of the Kalambaina and passes through 700 feet of black clay and fine sand before penetrating coarse gravelly sand at depths of 810 to 910 feet. These sediments are believed to represent the transition from the Gundumi into the Taloka Formation. Eastward in boreholes along the Gusau-Sokoto road, the clay beds in the Rima change from black to white, yellow brown, and light gray as they approach the surface outcrop.

Downdip at Balle, in borehole GSN 3053 (table 8), the Rima Group is found below a depth of 935 feet, where it is more indurated and also coarser textured than in the facies near the outcrop. Shale of the Dukamaje Formation occurs at Balle between sandy formations of the Wurno and Taloka. The total thickness of the Rima Group at Balle is 1,007 feet.

Toward the southern part of the Sokoto Basin, the Wurno-Taloka lithology departs once again from the typical fine-grained lithology observed in outcrop. Clay beds become less abundant than sandy beds, and the sand changes from the characteristic fine texture of the north to medium and coarse texture in the south. For instance, in borehole GSN 3507 at Dogwandaji the sediments even become gravelly, and the colors change from the typical black and gray to yellow, brown, and also white. Thus, these borehole samples begin to resemble the clay and coarse sand of the Illo Group exposed farther to the south.

At Birnin Kebbi, in the Wurno-Taloka section between 365 and 1,003 feet in borehole GSN 2484, clay appears to be absent and one thick section of white fine to coarse sand is present. A similar section of sand was penetrated in borehole GSN 2485 at Argungu between depths of 435 and 900 feet.

The total thickness of the Rima Group ranges from zero at the eastern limit of its outcrop to more than 1,000 feet in its downdip extensions near the Niger frontier. The regional dip of the Rima near Sokoto is about 20 feet per mile in a direction N. 55° W. (pl. 5).

GROUND-WATER OCCURRENCE

Water in the Rima Group occurs under unconfined or water-table conditions in the outcrop area. Downdip, however, the Rima contains an artesian aquifer which is confined below by a plastic clay horizon in the basal part of the Rima Group and above by clay in the Dange Formation of the Sokoto Group (pl. 4). Most of the 30 existing boreholes screened in the Rima Formation (table 5) tap water under water-table or subartesian conditions. In Sokoto, for example, the boreholes tapping the Rima are usually screened with 10- or 20-slot screen at depths of 200 to 400 feet. The water-bearing zones here are thin beds of medium sand interspersed among the fine sand and clay. The water levels in boreholes in Sokoto generally range from 110 to 170 feet below land surface depending on the elevation of the borehole site. These levels are also 100 or more feet below the shallow perched-water zone in limestone of Kalambaina Formation.

Although beds of water-bearing sand in the Rima Group are very fine to fine in texture, they transmit water very readily. They are commonly thick, some being more than 100 feet, but grade laterally into beds of black clay. For example, except for 5 feet of sand at 60 feet, borehole GSN 3518 at Dange penetrated about 370 feet of clay in the Rima before ending in very fine sand. Yet, only several hundred yards away a 630-foot borehole (GSN 3512) passed through a number of thick sand beds in the Rima which were not found in borehole GSN 3518. Thus, near Dange the Rima Group apparently contains one thick section of discontinuous sand and clay beds that together form a single aquifer.

Borehole GSN 3512 was actually screened between 608 and 623 feet in the confined Gundumi aquifer and below the extensive basal clay of the Rima (see table 4). Even so the water level in the confined Gundumi aquifer is 141 feet lower than the water level in the overlying unconfined Rima aquifer (compare boreholes GSN 3512 and 3518). In another borehole at Wurno, about 500 feet of clay and sand too fine for a six-slot screen was penetrated before a coarse sand bed was found at the base of the Rima.

Farther downdip the coarse sand beds become more conspicuous throughout the Rima section. For example, in borehole GSN 3053, beds of coarse sand occur but the yields obtained from water-bearing zones in the Rima during test pumping were low. The two zones tested were between 980 and 1,010 feet in the Wurno and between 1,260 and 1,290 feet in the Taloka; each zone had a subartesian water level 30 feet below land surface and produced 1,500 gph by pumping. In contrast, the Gwandu aquifer at the same site with 46 feet of pressure head above land surface produced an artesian flow of 7,000 gph from a screen set between 514 and 519 feet.

Based on initial yield tests following drilling, the average yield among 30 boreholes tapping the Rima aquifer was 4,540 gph; the

TABLE 5.—*Records of boreholes screened in Rima Group, Sokoto Basin*

Location: Name of village, milepost, or point in Sokoto Basin near which corresponding borehole is located.
Borehole: Serial numbers are assigned by Geological Survey of Nigeria (GSN) to all boreholes in northern Nigeria.
Approximate elevation: Measured by aneroid barometer from nearby Federal Surveys bench marks.
Casing: American Petroleum Institute line pipe (mild steel casing) used to case most boreholes.
Screen: Screens are stainless steel or Johnson Everdur. Setting indicates top and bottom of slotted casing or borehole screen. SC, slotted casing.

Static pressure head: Pressure head at time borehole was completed, in feet above (+) or below (—) land surface.
Yield: At time borehole was drilled. A, airlift pump; P, turbine pump; F, natural flow.
Remarks: M, borehole drilled by Ministry of Works for public water supply; B, borehole drilled by Balakhany (Overseas), Ltd.; C, chemical analysis in table 7; T, flow or pumping test carried out at borehole; L, geologic log in table 8; O, observation borehole drilled by Balakhany (Overseas), Ltd., for the Geological Survey of Nigeria; A, abandoned test hole, casing pulled and hole plugged; I, screened in Illo Group.

Location	Borehole	Approximate elevation (feet above sea level)	Date completed	Casing: Diameter (inches)	Casing: Setting (feet below land surface)	Total depth (feet below land surface)	Screen: Diameter (inches)	Screen: Setting (feet below land surface)	Slot openings (thousandths of an inch)	Static pressure head	Yield (gallons per hour)	Drawdown (feet)	Remarks
Sokoto, Ministry of Works plant yard	GSN 932	965	1–30–41	10¾	0–150	870	--------	150–177	SC	−148	1,900 A	--------	M
Do	933	965	1–31–42	8⅝ 6⅝	0–182 182–453	453	--------	153–165 169–180	SC	−147	5,000 P	--------	M
Sokoto, abattoir	2458	925	8– 9–62	6 3	0–285 285–390	392	3	-------------	SC	−101	4,800 A	18	B
Birnin Kebbi	2483	675	9–30–61	4	0–340	733	3½	340–370	--------	+21	14,000 A 5,500 F	90 --------	C, M
Do	2484	679	----------	4	0–368	1,003	--------	368–414	20	+17	18,000 A 7,000 F	--------	M
Rabah	2488	860	11–17–62	6, 2½	0–100	480	1¾	373–392	--------	−8	1,700– 2,000 A	--------	M, C
Do	2489	870	3–13–63	10¾, 6, 2½	0–357	390	5⅝	375–390	25	−18	3,000 A	--------	M
Sokoto, GRA No. 2	2859	935	1964	6 4	0–167 182–193	--------	5⅝	167–182	25	−119	7,200 P	25	C, M, T
Sokoto-Jaredi road, mile 2	2906	971	1– 4–62	6	0–313	346	--------	313–327	--------	−134	4,020 A	58	B
Sokoto-Jaredi road, mile 7	2907	945	1–22–62	6	0–136	355	--------	136–150	12	−102	1,300 A	4	B

Sokoto-Jaredi road, between miles 18 and 19	2909	892	6-21-62	6	0-198	355	5	190-211	--------	−44	1,440 A	2	B
Sokoto, abattoir	2910	925	8-22-62	6 3	0-269 269-402	403	3	292-379	SC	−104	2,700 A	--------	B
Balle	3053	782	8- 9-63	6	0-645	1,972	1¾	980-1,010 1,260-1,290	15	−30	1,500 A	--------	B, L, C
Sokoto, Interregional secondary school	3503	1,003	1-31-65	6⅝ 4	0-214 214-367	392	3½	367-382	10	−166	4,500 P	--------	B
Sokoto, cement-company residential area	3504	995	5-16-65	6⅝ 4 2½	0-260 260-323 323-360	378	3½	360-375	10	−164	3,600 P	30	B, T
Sokoto, GRA No. 4	3505	995	6-29-65	8	0-338	390	3½	340-360	12	−173	2,500 A	10	M, T, C
Wurno	3506	916	4-27-65	6⅝, 4, 2½	0-485	520	3½	485-495 495-500	10 20	−65	4,050 P	56	B, T
Dogwandaji	3507	840	6- 2-65	6⅝, 4, 2½	0-250	267	3½	250-265	20	−111	5,400 P	37	B, T
Bodinga	3608	981	7-10-65	6⅝, 4, 2½	0-310	405	3½	310-325	10	−135	5,142 P	43	B, C, T
Sokoto, ECN powerplant	3510	960	6-14-65	6⅝ 4 2½	0-243 243-350 350-363	444	3½	363-378	6	−50	3,000 P	--------	B
Shuni	3511	1,065	8-18-65	6⅝, 4, 2½	0-281	365	3½	281-296	10	−151	5,290 P	28	B, C, T
Gusau-Sokoto road mile 128	3515	1,008	3-18-65	6 4¼ 2½	0-288 288-305 305-308	430	3½	308-323	10	157	4,000 P	26	B
Gusau-Sokoto road mile 124	3516	1,060	2-16-65	6 4	0-257 257-265	310	3½	265-280	10	−141	3,600 A	52	B
Gusau-Sokoto road, mile 120+600 ft	3517	944	3-18-65	6, 4, 2½	0-180 180-204	335	2½	304-319	6	−27	3,800 A	85	B, C
Gusau-Sokoto road, mile 115+3,800 ft (at Dange)	3518	1,080	1-27-65	6 4	0-332 332-366	400	3½	366-381	6	−139	4,000 A	52	B
Girawsi	3705	805	9-10-66	3 2½	0-15 15-250	268	1¾	250-260	20	−2.5	2,500 F	--------	C, O
Sokoto, ECN power station	3706	960	8-29-66	6 4 2½	0-206 206-216 216-222	257	3½	222-237	6	−37	6,600 P	66	C, B
Mangadi	3707	625	109—66	2½	0-100	1,305	1¾	100-120	20	−13	1,800 A	12	B, A, C, I, L
Kaloye	3708	673	3-20-67	2½	0-700	1,560	1¾	700-720	20	+23	1,050 F 2,520 A	--------	C, L, O
Sokoto, GRA No. 3	2498	995	1965	6	0-353	390	3½	353-377	12	−173	4,000 A	--------	M

range in yield was 1,300 gph to a maximum of 18,000 gph. The latter yield was obtained from artesian borehole GSN 2484, in the River Sokoto fadama at Birnin Kebbi, which by natural flow can produce 7,000 gph with pressure head of +17 feet.

Aquifer tests were conducted at boreholes tapping the Rima Group at seven sites (table 3) in Sokoto Province, and the computed transmissivities ranged from a low of 2,800 gpd per ft at Wurno (borehole GSN 3506) to a high of 264,000 gpd per ft (borehole GSN 3507) at Dogwandaji. At Dogwandaji only slight interference effects were observed in the aquifer test. In an observation borehole 22 feet from pumped borehole GSN 3507, the water level declined 1.95 feet after 2 minutes of pumping. During the next 23 hours of pumping at 6,000 gph from GSN 3507, the water level declined only 0.25 feet more, for a total drawdown of 2.2 feet after 24 hours of pumping. The computed transmissivity, 264,000 gpd per ft, may be somewhat high and possibly reflects a recharge source such as a river or spring intercepted during the test. In a more typical test on the Rima aquifer at Bodinga, the computed transmissivity was 65,000 gpd per ft in borehole GSN 3508. At Bodinga, in an observation borehole 33 feet from GSN 3508, the drawdown was 3.1 feet after 24 hours of pumping at 5,140 gph. At Sokoto, 15 miles north of Bodinga, the transmissivities in the Rima aquifer are slightly lower than that at Bodinga. In observation borehole GSN 3504, which is 2,800 feet away from GSN 3505, the water level declined 0.34 feet after 22 hours of pumping at 2,800 gph. The transmissivity at borehole GSN 3504 in Sokoto is 41,200 gpd per ft.

From the limited data available from boreholes, it appears that areas in which the Rima artesian aquifer will provide flowing water to boreholes occur only to the west of the outcrop of the Sokoto Group and at low elevations, such as in the fadama of the River Sokoto. In most parts of western Sokoto Province, the Gwandu artesian aquifer has higher heads and lies at shallower depths and therefore is more attractive for borehole development. Nevertheless, toward the southern part of the Sokoto Basin, as at Birnin Kebbi and Kaloye, the Gwandu aquifer thins out whereas the Rima aquifer produces higher yields to boreholes and also has higher heads than the Gwandu in this region.

Recharge to ground water in the Rima Group occurs directly from penetration of rainfall on the outcrop, infiltration from streams while in flood, and also in part by leakage from the overlying perched water body in the limestone of the Kalambaina Formation, as indicated by a mound on the potentiometric surface extending from Dange to Sokoto (pl. 4). The potentiometric contours of plate 4 also indicate that water moves southwestward through the Rima Group across the Sokoto Basin and into the Illo Group and thence discharges to the River Niger and the lower reaches of the River Sokoto system.

SOKOTO GROUP (PALEOCENE)

PHYSICAL CHARACTER

The lower unit of the Sokoto Group, the Dange Formation, is exposed at the base of the Dange scarp in a bed as much as 60 feet thick near Sokoto. The Dange thins southward in outcrop but becomes much more prominent in boreholes down dip. Lithologically, it is a marine clay shale, usually having flaky texture and yellowish to greenish-gray color. The upper part contains phosphatic nodules and gypsum, and the lower part is calcareous with occasional limestone bands. A bright pistachio green clay, less than 5 feet thick, generally marks the base of the Dange Formation.

The upper unit of the Sokoto Group is a light-gray and white clayey limestone and nodular crystalline limestone, known as the Kalambaina Formation. Its outcrop forms a sloping plain through the north-central part of the Sokoto Basin increasing in width (as much as 20 miles) and elevation (up to 1,300 ft) toward the northeast and the Niger frontier. The Kalambaina is generally blanketed by about 15 to 25 feet of laterite overlain by sand drift about 10 feet thick derived from the Gwandu Formation. At the top of the Kalambaina in some places is a contorted noncalcareous clay up to 12 feet thick that rests on 10 feet of calcareous clay. Beneath this upper clay is the characteristic limestone of the Kalambaina that is of chalky or crystalline texture and up to 60 feet thick. At the base of the Kalambaina section is another calcareous clay which is rather widespread and about 10 feet thick. Toward the edge of its outcrop, the limestone in the Kalambaina thins and the dip appears to flatten somewhat so that along the scarp the beds appear to dip in the opposite direction or to the east. In a study of the limestone formation, Jones and Bell (1960) have attributed this feature to solution and a consequent slumping of the limestone and possibly some plastic movement of the underlying clay in the Dange Formation. At Kalambaina the formation is 84 feet thick but thins out to the southwest in outcrop. The Sokoto Group dips toward the northwest at about 17 feet per mile and thickens to about 150 feet in Niger (pl. 5).

GROUND-WATER OCCURRENCE

The Dange Formation is relatively impermeable clay and serves as a confining layer or aquiclude above the Rima aquifer. In the outcrop area of the Sokoto Group, the Dange Formation also supports the perched ground-water body in the limestone of Kalambaina Formation. Downdip the limestone is virtually impermeable and forms a confining layer with the Dange beneath the confined aquifer in the basal Gwandu Formation. For example, in a borehole test at Km 300, Dogondoutchi in Niger, the limestone of the Kalambaina between 1,328 and 1,482 feet yielded only 400 gph with a drawdown of 100 feet.

In the outcrop area, limestone of the Kalambaina Formation, together with capping ironstone (laterite) and sand drift from the Gwandu, contains a perched water body (pl. 7) that supplies water to hundreds of dug wells, generally less than 60 feet deep. These yield water freely during and shortly following the rainy season, but those not fully penetrating the formation or located near the edge of the outcrop commonly fail during the dry season. Some wells, such as the one at Tambagarka, exceed 200 feet in depth and tap both the underlying regional ground-water body in the Rima Group as well as the perched water body. For example, just after the wet season the Tambagarka well had a water level 14.4 feet below the land surface (Oct. 15, 1965), which marks the position of the perched water table in the limestone. At this time of year, water is leaking from the perched zone down into the Rima aquifer. In the following dry season, as the perched water was dissipated by spring discharge or downward leakage, the water level in the well declined to 140.8 feet below land surface (Apr. 15, 1966), a level which marks the regional water table in the Rima Group.

Water-level fluctuations in shallow dug wells tapping only the perched water body also fluctuate markedly. Seven wells measured on Oct. 15, 1965, just after the rains had an average depth to water of 16.3 feet but declined an average of 11.4 feet during the following dry season. The average depth to water on Apr. 15, 1966, was 27.7 feet. The hydrograph of a dug well at Kware (fig. 5) shows the typical behavior of the perched water table in the limestone. As the rains replenish the perched water body, the water table rises and migrates updip toward the eastern edge of the limestone. Thereafter, as ground-water storage gradually dissipates, the water table declines and migrates downdip. At the same time the shallow wells at higher level begin to fail but residual storage continues to feed the lower level springs.

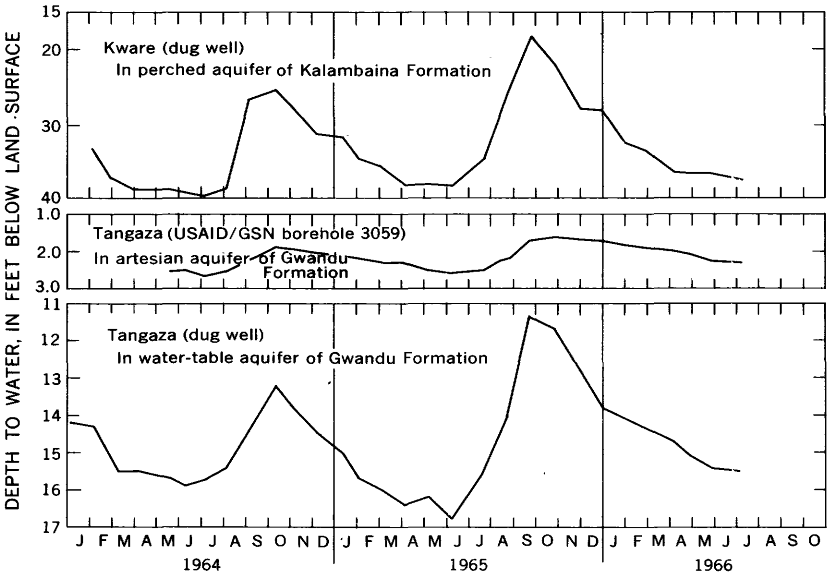


FIGURE 5.—Water-level fluctuations in dug wells tapping unconfined ground water in Kalambaina and Gwandu Formations.

Porosity in the limestone occurs chiefly in joints, bedding planes, and solution cavities formed by ground-water circulation in the outcrop area. Solution openings may be several feet in diameter and are most common in a zone from 10 to 30 feet above the base of the Kalambaina (Jones and Bell, 1960). Ground-water flow occurs chiefly in interconnected solution cavities, and some cavities tapped by well shafts have produced inflows, under pressure, of as much as 7,000 gph. In a dug well at Dabaga, an artesian rupture occurred in early 1962 that caused the well to flow for about a year before subsiding. Also springs may appear or disappear irregularly. At Angwan Tudu (Tudu Kudu), for example, the spring which began to flow in 1957 now (1967) supplies an irrigation project with 6 to 10 cfs throughout the year.

Perennial ponds (Kalmalo Lake) and spring-fed streams (River Kware) in the Kalambaina are also sustained by the perched ground-water body. In addition natural springs are common on the back slope of the Dange scarp at the contact of the limestone with the underlying clay of the Dange, and springs also issue from ironstone (laterite) overlying the limestone. The springs from ironstone are believed to seep out over the contorted clay layer lying just above the Kalambaina.

If proper measures for pollution control are used, the Kalambaina limestone aquifer is probably best suited for development of small domestic supplies from dug wells and springs and for limited irrigation from springs and spring-fed streams. Furthermore, should future water development in the Sokoto area deplete the Rima aquifer, some recharge from the Kalambaina could conceivably be induced by puncturing shafts or wells through the Dange Formation and allowing the perched water to flow downward.

GWANDU FORMATION (EOCENE)

PHYSICAL CHARACTER

The Gwandu Formation crops out over 8,500 square miles in the western third of the Sokoto Basin. The sediments of terrestrial origin are made up of interbedded semiconsolidated sand and clay. The clay beds of the Gwandu are commonly thick and massive and white, red, or gray brown to black. The sand beds are fine to very coarse, predominantly quartz containing some limonite nodules, cemented in places by limonite. Lignite is common in some beds of black peaty clay and whitish-gray sand. Characteristically, sand beds underlie the low plains, and resistant clay beds form the tabular-shaped hills capped with residual ironstone. The Gwandu Formation unconformably overlies the Kalambaina Formation in the northern and central parts of the Sokoto Basin. Southward, however, the Gwandu overlaps the Kalambaina and rests directly on the Rima and Illo Groups in the southern part of the basin. The erosional outliers of the Gwandu on these older formations indicate its once greater areal extent. From a featheredge at its eastern limit in the central part of the Sokoto Basin, the formation thickens to the northwest and downdip to about 1,000 feet near the Niger frontier (pl. 6). The regional dip of the base of the Gwandu is 17 feet per mile toward the northwest.

UNCONFINED GROUND WATER

Besides the important artesian aquifer in the basal section of the Gwandu, the formation also contains an extensive body of unconfined ground water in its upper section of sand and clay beds. The water table of the unconfined ground-water body in places lies at or near the surface to form a chain of ground-water lakes (pl. 9) extending from Gande and Tangaza north to Ruawuri. Elsewhere the water table is as deep as 300 feet in the upland areas near the Niger border (pl. 7). On the average, however, the depth to water, as measured in 12 widely scattered observation wells, is about 64 feet. The water table slopes generally toward the southwest, indicating that the shallow ground water also moves generally in that direction.

Recharge to the shallow ground water in the Gwandu is by direct infiltration from precipitation as well as by seepage from the streams while in flood during the rainy season. Also, there is some upward leakage from the deeper Gwandu artesian aquifer. During the rainy season, as the shallow ground water is replenished, the water table rises, reaching a seasonal high between the months of September and January. Through the following dry season, the water table declines until the beginning of the rains in June. The seasonal fluctuation of the water table measured in 12 observation wells tapping shallow ground water in the Gwandu during 1965–66 ranged from 0.5 to 10 feet during the year, the average being 3.3 feet.

CONFINED GROUND WATER

The most important part of the Gwandu Formation with respect to ground water is a sandy zone in the basal section that, where traced at depth, forms the most extensive and productive artesian aquifer yet identified in the Sokoto Basin. This sandy zone thickens from only 12 feet in Gwandu Emirate to several hundred feet at Balle and in Niger (pl. 8). In outcrop it forms a sandy blanket on the Kalambaina Formation that underlies a wide plain from Sokoto to Illela. Boreholes at four sites from southwest to northeast and about 15 miles west of the eastern limit of the Gwandu Formation have revealed the nature and stratigraphic position of the confined sand aquifer downdip. In the southwest, at the Danzomu (now Janzomo) borehole (GSN 3502), the aquifer is 42 feet thick and consists largely of fine to very coarse sand. It is underlain by 48 feet of gray plastic clay which rests on the Kalambaina Formation. At the Safla (now Sabla) borehole (GSN 3072) 30 miles to the northeast, the gray clay, here 62 feet thick, also forms the base of the Gwandu Formation and is overlain by about 73 feet of the aquifer. At Danzomu (now Janzomo) and Safla (now Sabla) the top of the aquifer is about 75 to 80 feet below the land surface and lies underneath a 30-foot layer of confining clay. About 45 miles northeast of Safla (now Sabla) at Tangaza, the basal clay is absent in borehole GSN 3058 and the aquifer of fine to coarse sand rests directly on the Kalambaina. At Ruawuri, 24 miles north of Tangaza near the Niger border, the aquifer is 111 feet thick in borehole GSN 3070 and is also, for the most part, the basal bed of the Gwandu. A thin lignite and peat horizon at the base of the Gwandu marks the Kalambaina contact both at Tangaza and Ruawuri.

The confined aquifer of the basal Gwandu increases in thickness toward the northwest from 40 to more than 200 feet and dips to the northwest at about 11 feet per mile. Toward the northwest, however, clay and lignite beds become increasingly abundant in the aquifer and the sandy zones become thinner and also finer textured, so that the water-yielding capacity of the aquifer diminishes downdip. The overlying confining clay also thickens to the northwest from about 30 feet to more than 250 feet on the Niger border. In surface exposures this clay forms a conspicuous ridge west of the Sokoto-Illela road.

The first-phase study (Ogilbee and Anderson, 1965) of the present project included extensive test drilling in the Gwandu Formation, about 25 boreholes at 10 sites, for geologic and hydrologic data (table 6). Artesian flows were obtained at five sites with heads ranging from a few inches up to 83 feet above land surface (borehole GSN 3056 at Kurdula) and free flows up to 12,000 gph (borehole GSN 3069 at Karfin Sarki). In addition artesian flows have been recorded at five other sites in boreholes drilled for the Ministry of Works (table 6) and in one not listed at Masallaci.

Aquifer tests (table 3) conducted at 10 sites in boreholes tapping the Gwandu artesian aquifer indicate a wide range in transmissivity. The lowest values, one less than 1,000 gpd per ft at borehole GSN 2674 in Bacaka, generally characterize the downdip areas near the Niger border, such as at Kurdula and Bacaka. Higher values occur eastward at Safla where at borehole GSN 3501 a transmissivity of 128,000 gpd per ft was measured. The artesian aquifer also has a high transmissivity (108,000 gpd per ft) in borehole GSN 3068 at Karfin Sarki; the highest natural flow, 12,000 gph, is also at GSN 3068 where the aquifer is thickest, 200 feet.

In addition to aquifer tests, cyclic water-level fluctuations can also be used to compute transmissivity. Fluctuations in the water level in a well can result from the change in stage of a nearby surface-water body. For the Sokoto Basin this method (Ferris, 1950) was applied in the Kalgo area where the River Zamfara cuts across the Gwandu aquifer. Here water-level observations have been made for both the river and for a nearby dug well in the Gwandu aquifer. The computed transmissivity, 20,000 gpd per ft, is low but reflects, like the value of 23,400 gpd per ft computed from an aquifer test at borehole GSN 2482 at Birnin Kebbi, the thinness of the aquifer in the southern part of the Sokoto Basin.

The Gwandu artesian aquifer, extending under an area of about 5,700 square miles, can provide flowing artesian water to boreholes in lowlands totaling approximately 1,000 square miles: chiefly in the River Sokoto fadama; in a lowland trending southwest from Masallaci through Ruawuri, Balle and Karfin Sarki; along the Niger frontier near Kurdula and Bacaka (pl. 9); and in a narrow lowland stretching some 20 miles southwest of Yeldu. With its large proven areal extent, shallow depth, and high heads, the Gwandu artesian aquifer at present (1967) offers the most attractive development potential among the three artesian aquifers identified in the Sokoto Basin.

The Gwandu aquifer is recharged principally by infiltration from precipitation and from runoff on the outcrop area. North of the River Sokoto fadama, precipitation runs off the clay ridge formed by the middle member of the Gwandu on the west and the Dange scarp on the east and infiltrates into the sandy outcrop of the Gwandu aquifer between these divides. Any rejected recharge from the aquifer north of Sokoto probably discharges into the River Kware. In the dry season the aquifer may also be replenished by spring discharge from the perched zone in the limestone of the Kalambaina. In the southern part of the Sokoto Basin, discharge by natural outflow occurs where the Gwandu aquifer crops out, and this discharge combined with that from the Cretaceous aquifers helps to sustain the dry-season flow of the River Zamfara and the lower reaches of the River Sokoto. Water also discharges from the confined Gwandu aquifer by leakage through the confining beds above and below it. West of the River Sokoto and 20 to 30 miles north of the River Niger, however, the lower confining bed in the Sokoto Group is absent and the Gwandu aquifer merges with the Rima-Illo aquifer.

Artificial discharge from the Gwandu artesian aquifer by withdrawal from boreholes at present (1967) is very small and occurs only at Birnin Kebbi and Balle. At least two flowing boreholes tapping the Gwandu aquifer contribute to the public water supply at Birnin Kebbi, but the estimated withdrawal is currently less than 100,000 gpd.

A flow net (pl. 10) for the Gwandu aquifer was constructed to estimate the amount of ground water moving downgradient from the recharge area to the discharge area. The flow lines A and B enclose roughly the area of the artesian aquifer in Nigeria. Using the method of Bennett and Meyer (1952), ground-water flow through the aquifer was estimated to be on the order of 21.2 mgd (million gallons per day).

TABLE 6.—*Records of boreholes screened in Gwandu Formation, Sokoto Basin*

Location: Name of village in or near which corresponding borehole is located.
Borehole: Serial numbers are assigned by Geological Survey of Nigeria (GSN) to all boreholes in northern Nigeria.
Approximate elevation: Measured by aneroid barometer from nearby Federal Surveys bench marks.
Casing: American Petroleum Institute line pipe (mild steel casing) used to case most boreholes.
Screen: Most screens are of Johnson Everdur. Setting indicates top and bottom of borehole screen.
Static pressure head: Pressure head at time borehole was completed, in feet above (+) or below (—) land surface.
Yield: At time borehole was drilled. F, natural flow; P, turbine pump; A, airlift pump.
Remarks: M, borehole drilled by Ministry of Works for public water supply; C, chemical analysis in table 7; T, flow or pumping test carried out at borehole; A, abandoned test hole, casing pulled and hole plugged; B, borehole drilled by Balakhany (Overseas), Ltd.; O, observation borehole drilled by Balakhany (Overseas), Ltd., for the Geological Survey of Nigeria; F, Foxboro pressure recorder installed; S, Stevens water-stage recorder installed.

Location	Borehole	Approximate elevation (feet above sea level)	Date completed	Casing diameter (inches)	Total depth (feet below land surface)	Screen			Static pressure head	Yield (gallons per hour)	Draw-down (feet)	Remarks
						Diameter (inches)	Setting (feet below land surface)	Slot opening (thousandths of an inch)				
Birnin Kebbi	GSN 2480	674	9-10-61	6	250	6	170-230		+13	2,200 F 9,000 P		M
Do	2481	679	7- 5-61	2	400	1¼	170-190		+10	500 F		C, M
Do	2482	679	7-21-61	4	332	4	148-198	20	+9	3,600 F 17,000 A		M, T
Argungu	2485	711	3-13-62	4¾	913	4	160-180		+25			
Do	2486		6-30-62		205		135-142		+15	8,000		M, A
Do	2487		10-27-62	6	450	4	203-228			8,000		M

Rafin Kubu	2499	787	8- 8-64	3	465	1¾	436–451	10	+39	2,000 F	0.55	B, C, T
Tapkin Kwato	2500	780	9- 2-64	3	590	1¾	560–575	10	+52	3,000 F	--------	B
Bacaka	2674	803	10- 9-64	2½	1,005	1¾	979–994	10	+40	1,200 F	21	B, C, T
Balle	3051	750	5- 3-63	2½	279	1¾	253–269	10	+51	1,200 F	--------	C, O
Do	3052	750	5-29-63	2½	398	--------	350–393	Open hole	+70	12,000 F	--------	A, O
Do	3054	782	9- 9-63	6	520	3¾	514–519	15	+46	7,000 F	.7	C, T, O
Do	3055	782	9-23-63	6	376	3¾	367–372	15	+46	5,000 F	7	C, F, T, O
Kurdula	3056	760	10-13-63	2½	858	1¾	820–835	15	+83	3,000 F	--------	C, F, O, T
Do	3057	760	10-31-63	6⅝	255	1¾	237–255	15	+40	250 A	--------	O
Tangaza	3058	845	3- 9-64	2½	302	1¾	189–199	10	+2	90 F 2,100 A	--------	A, O
Do	3059	847	3-19-64	6⅝, 4, 2½	219	1¾	172–197	10	0	6,000 P	46	C, S, T, O
Do	3060	847	3-29-64	3	177	1¾	175–185	10	0	1,900 A	--------	O
Yeldu	3061	785	5- 5-64	2½	660	1¾	520–530	10	−27	1,500 A	48	A, O
Do	3062	745	5-16-64	3	540	1¾	520–530	10	+13	1,200 F 2,000 A	--------	O
Do	3063	744	5-28-64	6, 4, 2½	540	3½	508–523	10	+15	1,200 F 4,200 A	-------- 48	C, F, T, O
Kaloye	3065	673	6-18-64	3	480	1¾	455–465	10	−10	1,900 A	--------	O
Kurdula	3066	760	9-21-64	3	853	1¾	824–834	10	+83	1,500 F	--------	O, T
Karfin Sarki	3068	727	12- 1-64	3	615	1¾	595–605	20	+69	4,800 F	--------	O, T
Do	3069	725	12-14-64	4, 2½	610	3½	591–606	20	+71	12,000 F	--------	C, F, O, T
Ruawuri	3070	836	1-11-65	2½	390	1¾	347–352 352–357	10 20	−1	900 A	--------	C, O
Safia	3072	832	2-26-65	2½	220	1¾	130–140	20	−65	500 P	--------	O
Do	3501	832	3- 7-65	6	162	3½	135–145	20	−65	7,500 P	13	C, S, T, O
Danzomu	3502	726	3-18-65	4, 2½	180	3½	112–117	20	−4.5	3,500 A	15	C, O, S

SURFICIAL DEPOSITS (QUATERNARY)

Thin but generally discontinuous surficial deposits of windblown sand, red loamy drift, lateritic ironstone, swamp and lake deposits, and stream alluvium are present in much of the Sokoto Basin. Except for alluvium, the surficial deposits are generally above the water table and unimportant as sources of water. Alluvium fills most of the larger stream valleys of the Sokoto-Rima system to an average depth of about 45 feet in bands ranging in width from a few hundred feet up to 5 miles, as for example in the River Sokoto fadama at Argungu. The alluvium generally consists of interbedded stream-laid gravel, sand, silt, and clay; the gravel and sand beds in the larger stream valleys are generally water bearing.

At Sokoto the water-bearing alluvium is tapped by shallow boreholes to supplement the public water supply, which is normally taken from the river and a few deep boreholes. In 1964 about eight shallow boreholes were drilled in the River Sokoto fadama adjacent to the river. The boreholes penetrated interbedded silt, sand, and gravel, at depths of about 20 to 40 feet, in hydraulic continuity with the river. About 10 to 15 feet of perforated 8-inch casing was set in each well in the water-bearing section and then gravel packed. The individual yields obtained were as high as 4,400 gph, but the average among the five successful boreholes was 3,260 gph, pumping by airlift. Although water in the alluvium is generally unconfined, the 25- to 35-foot zone has a water level only 7 feet below land surface; this is 3 feet higher than the water level of the 20- to 24-foot zone, which is approximately the same as that of the river. The lower zone, confined by a thin clay bed, probably receives water from upstream, resulting in the slightly higher head. One other borehole tapping water in alluvium is at Tunfafia near the headwaters of the River Sokoto. At this site an irrigation well is screened and gravel packed between 20 to 40 feet below land surface in water-bearing alluvium about 46 feet thick. By suction pump the well has yielded 12,000 gph with only 2.5 feet of drawdown below a static water level of 6.5 feet below land surface. During the rainy season, however, when the river floods, the well may produce even larger yields and with a smaller drawdown, as the aquifer becomes fully saturated.

In the crystalline terrane east of the Sokoto sedimentary basin, boreholes may yield little, if any, water from the rock; therefore the alluvium, where water bearing, is often the best source of water to boreholes. Because stream gradients are high in the crystalline-rock terrane, the alluvium is commonly coarser and contains less silt than that found in the fadamas of the sedimentary terrane. As a result the alluvium on the crystalline bedrock is usually very permeable. Nevertheless, during the dry season the alluvium in the smaller stream valleys often becomes dewatered, and the water table declines into the underlying crystalline rocks.

Assuming in the River Sokoto-River Rima fadama an average alluvium thickness of 45 feet, a fadama width of 3 miles, and an average water-table gradient of 2 feet per mile, Dr. F. J. Mock, U.N. FAO hydrologist (oral commun., 1965), computed the rate of ground-water flow to be 1,000 gph through the cross section of the fadama. Actually, this quantity of water is very low in comparison with the surface-water outflow.

UTILIZATION OF GROUND WATER

Traditionally, ground water in the Sokoto Basin has been drawn largely from dug wells either by handlines attached to leather or rubber inner-tube bags or, from some of the deeper wells, by windmill-powered pumps. In the early days of construction, dug wells were often lined with logs or ironstone blocks, but after the 1930's a concrete-lining method was devised that made it possible to dig below 200 feet. One at Dabaga was dug to a depth of more than 300 feet but still did not reach the water table.

In terms of water use, the present (1967) total draft of water from dug wells in the Sokoto Basin is estimated to be less than 5 mgd, the individual draft per well being about 1,000 gpd. In individual terms this amounts to less than 5 gpd per person. Regardless of manner of construction the dug wells are subject to seepage from nearby livestock and village wastes, and consequently the water is often contaminated.

Boreholes, which are relatively safe from contamination, were first constructed at Sokoto in the early 1940's; however, it was not until the 1960's that boreholes became common in the Sokoto Basin. By September 1966 about 75 boreholes had been put down in the basin. Less than a third of these, however, were actually in use, because most tap unconfined or subartesian water and are remote from power sources for pumping. Artesian flow has been encountered in 24 boreholes, of which 11 are used by the Geological Survey of Nigeria for observation (table 6), another eight contribute to the public water supplies of Birnin Kebbi and Rabah, and the rest for various reasons are either capped or abandoned.

In the vicinity of Sokoto, the most important city (fig. 6) in the region, five publicly and four privately owned boreholes at six sites tap the fine- to medium-sand aquifer in the Rima Group.

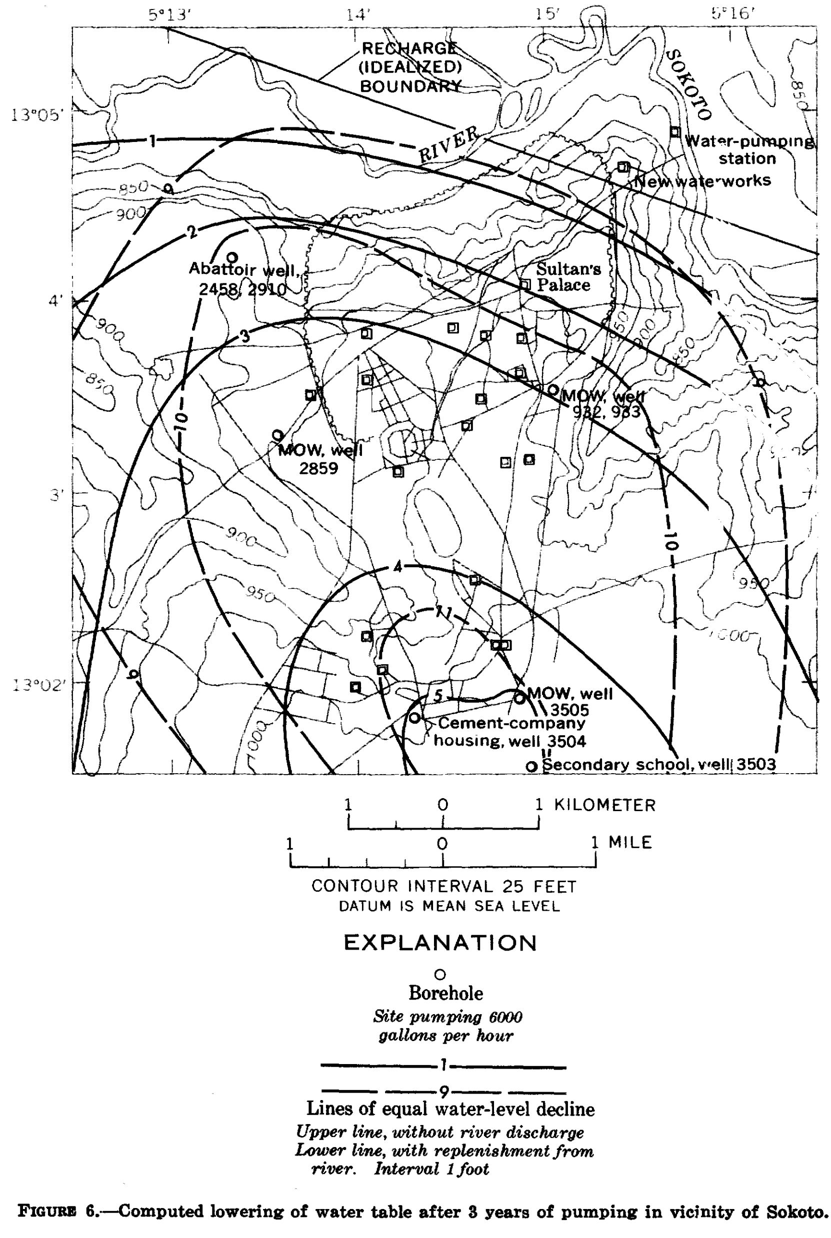


Figure 6.—Computed lowering of water table after 3 years of pumping in vicinity of Sokoto.

Each borehole regularly yields from 1,200 to 7,200 gph, but the total daily withdrawal from all these boreholes presently (1967) does not exceed 200,000 gallons. Figure 6 shows several of the probable shapes that the water table in the Rima aquifer might assume if the daily withdrawal near Sokoto were increased to 6,000 gph at each of the six sites. In 3 years the water table probably would take a position somewhere between a depressed water table without any recharge from the River Sokoto and a depressed water table with induced infiltration from the river. In either circumstance the drawdowns shown are not extreme. It is believed that recharge from the river would materially offset any drawdowns caused by pumping in the area.

The deeper Gundumi artesian aquifer in the vicinty of Sokoto has a pressure head more than 20 feet higher than the water table in the unconfined Rima aquifer. Therefore at lower elevations, in the fadama, individual test boreholes tapping the Gundumi aquifer can flow up to 2,500 gph with +23 feet of head (pl. 11). Also the test in borehole GSN 3704 at Girawsi near Sokoto indicates moderate to high transmissivities for the Gundumi aquifer. Because it is virtually untapped, the Gundumi aquifer could supplement the present draft from the Rima aquifer, when and if water levels become seriously depressed. Also, if needed, added recharge to the Rima aquifer near Sokoto could be induced by boring through clay of the Dange Formation to permit perched water in limestone of the Kalambaina Formation to move downward and replenish the Rima.

The public water supply of Sokoto, presently (1967) about 0.5 mgd, is obtained from four boreholes equipped with submersible pumps, a pumping station on the River Sokoto, and several shallow dug wells near the river at the pumping station. During the past few dry seasons it has been necessary to dam the river temporarily below the pumping station to insure a surface-water supply until the rains begin. Now under construction, however, are a new distribution system and also a treatment plant that will draw surface water by pipeline from a perennial stream, the spring-fed River Rima, several miles north of Sokoto.

Birnin Kebbi, the second most important city in the basin, obtains a water supply from five flowing boreholes tapping artesian aquifers in the Gwandu Formation and in the Rima Group. A total of 120,000 gpd is obtained from the 150–220-foot confined zone in the Gwandu and the 365–1,005-foot confined zone in the Rima. First drilled in the River Sokoto fadama in 1961–62, the boreholes had initial heads of +9 to +13 feet in the Gwandu and +17 to +21 feet in the Rima and individual flows of 500 to 3,600 gph and 5,500 to 7,000 gph, respectively. Pumping by airlift, however, in 1962 produced up to 18,000 gph from borehole GSN 2484 tapping the Rima aquifer. Because of continued free flow, the heads and yields of boreholes have declined in recent years, especially in those tapping the Gwandu aquifer. It has been suggested that to reduce these losses, the draft be taken alternately from the two aquifers. For example, while drawing water from the boreholes tapping the Rima aquifer for 3 months or so, the boreholes tapping the Gwandu aquifer could be shut down and allowed to recover.

After the boreholes at Birnin Kebbi were completed, the drillers for the Ministry of Works moved on to Rabah. In all five boreholes were drilled at Rabah in the River Sokoto fadama during 1962–63; however, artesian water was tapped in the Gundumi aquifer instead of in the Rima. Three boreholes were screened between the depths of 618 and 676 feet and had pressure heads of +1 to +12 feet and free flows of 60 to 500 gph. Two boreholes screened in the overlying Rima aquifer between depths of 372 and 390 feet were subartesian and as a result were not put into use. The three flowing boreholes, however, are now (1967) fitted with faucet attachments and supply the village's public and domestic needs.

At Argungu, the Ministry of Works attempted in the past to develop the artesian aquifer in the Gwandu; however, the boreholes flowed out of control during drilling operations and had to be capped. Considering the present importance of Argungu as an agricultural center and seat of the Argungu Emirate, the town is in need of an adequate sanitary water supply. It is suggested that with adequate precautions taken in drilling, including the use of heavy-base drilling mud, it would probably be possible to complete boreholes tapping the Gwandu aquifer and perhaps also the Rima aquifer.

BOREHOLE SPACING

In the Sokoto Basin where artesian water is for all practical purposes still (1967) an untapped resource, production boreholes can be properly spaced so that optimum yields will be obtained with minimal loss of pressure head. Careless development or withdrawal practices can contribute to the permanent reduction of artesian pressure and the resulting loss of free flow. During the present investigation, controlled aquifer tests have made it possible to compute and show graphically the drawdown and interference effects in the vicinity of some pumping or flowing boreholes. These factors of drawdown and interference between boreholes can be used to govern their optimum spacing in a given area so that artesian pressures in the Sokoto Basin can be maintained for as long as possible.

In the Karfin Sarki area, for instance, the Gwandu aquifer has a moderately high transmissivity and therefore relatively small pressure declines are observed. As shown in the graphs of figure 7, the pressure decline in a borehole flowing at a rate of 12,000 gph or 200 gpm (gallons per minute) for about 3 years (1,000 days) would be only 5 feet at a distance of 10 feet from the borehole. After flowing for about 30 years (10,000 days) at the same rate, the total head decline would be only 6 feet. If, however, the boreholes are clustered in groups of two or more, the pressure decline in one is the sum of its own pressure decline plus the interference effects from the neighboring producing boreholes. To illustrate this effect, a graph (fig. 8) was constructed on the basis of a method formulated by Lang (1961). Thus, two boreholes of the same construction at Karfin Sarki, each flowing 12,000 gph for 100 days, would experience a pressure decline of 10 feet if spaced 1,000 feet apart, and 9 feet if they were 2 miles apart. It is estimated, then, that with nominal flows of 3,000 gph from individual boreholes spaced a mile or more apart, there probably would not be a significant overall decline in the artesian pressures in the Karfin Sarki area. Furthermore, in the Balle area, where the transmissivities are comparably high, the interference effects would be similar to those in the Karfin Sarki area. However, at Tangaza, near the Gwandu aquifer's intake area, the pressure-head loss at 10 feet from a borehole discharging 3,000 gph would be about 2 feet after 30 years of continuous withdrawal (fig. 7), still only slightly more than at Karfin Sarki.

Farther downdip at Kurdula, where the transmissivity of the Gwandu artesian aquifer is less than 10,000 gpd per ft, a borehole would experience much higher drawdowns than at Karfin Sarki, Balle, or Tangaza. For example, at a discharge of 30,000 gph in the Kurdula area, the head decline would be more than 90 feet in a single discharging borehole after 30 years of withdrawal, which in effect would erase the present (1967) pressure head of 83 feet above land surface. With two boreholes each discharging 3,000 gph for a period of 100 days, the pressure would decline only 16 feet in each of the boreholes with a 1,000-foot spacing and about 12 feet with a 2-mile spacing (fig. 8). The interference from the second borehole at 2 miles is estimated to be about 4 feet. On the basis of these considerations, the optimum spacing between individual boreholes, each tapping the Gwandu aquifer in the Kurdula area and having a nominal discharge of 3,000 gph, would be no less than 5 miles. The same conditions apply in the Yeldu area where the transmissivity is also relatively low. The aquifer tests reveal that the transmissivities of the Gwandu aquifer in

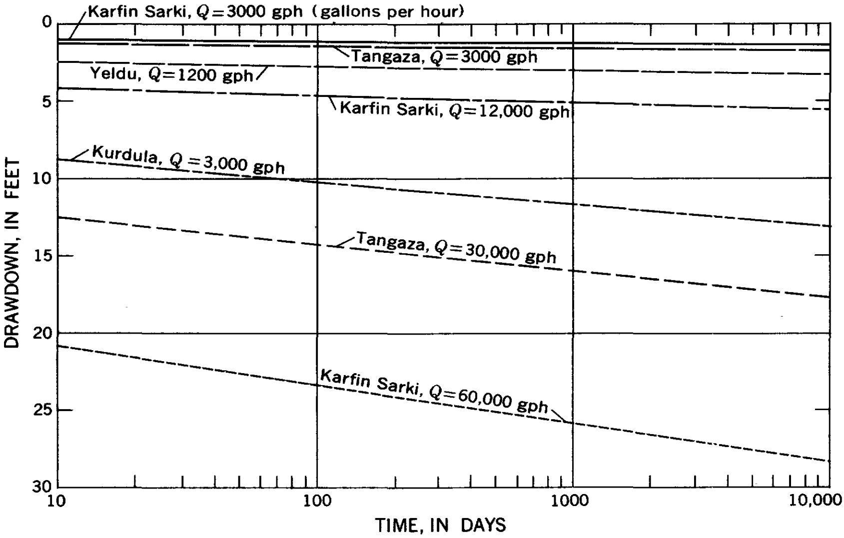


Figure 7.—Predicted decline in pressure head at distance of 10 feet from borehole tapping Gwandu aquifer at various discharge rates.

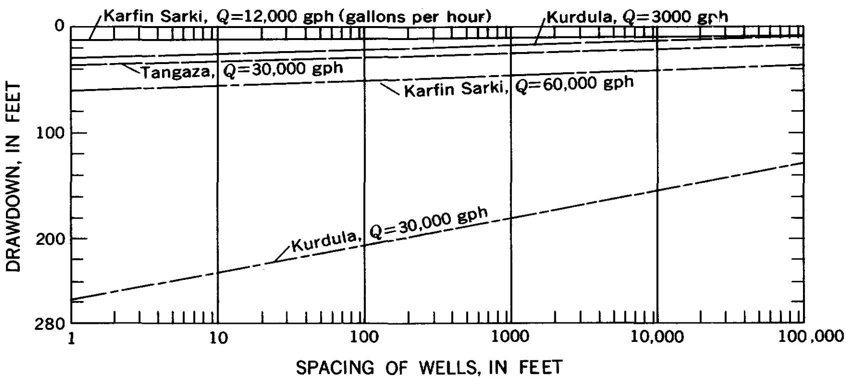


Figure 8.—Predicted interference between two boreholes tapping Gwandu aquifer spaced at varying distances after 100 days of continuous discharge.

the Karfin Sarki and Balle areas diminish to the west, toward Kurdula, and to the southwest, toward Yeldu, and as a consequence the spacing between boreholes should increase in these directions.

Available test data on the Cretaceous artesian aquifers are not as complete as those for the Gwandu artesian aquifer. Figure 9 shows drawdowns that may be expected after almost 3 years (1,000 days) of continuous withdrawal at boreholes tapping the Gundumi aquifer at Bakura and at mile 99 on the Gusau-Sokoto road, the Rima aquifer at Sokoto, and the Gwandu aquifer at Birnin Kebbi. Comparatively speaking, the Gwandu aquifer at Birnin Kebbi has significantly higher drawdowns than the Rima aquifer at Sokoto, owing in part to the higher transmissivity of the Rima. The characteristics of the Gundumi as an aquifer are suggested by data for borehole GSN 3701 at Bakura, representing the lower, least productive part of the aquifer, and for borehole GSN 3521 at mile 99 on the Gusau-Sokoto road, representing the upper, more productive part. Assuming only modest withdrawal at a rate of 6,000 gph (100 gpm) from GSN 3701, large drawdowns of more than 50 feet would occur in the borehole itself. At borehole GSN 3521, on the other hand, only about 20 feet of drawdown would occur at a discharge rate of 30,000 gph (500 gpm), five times greater.

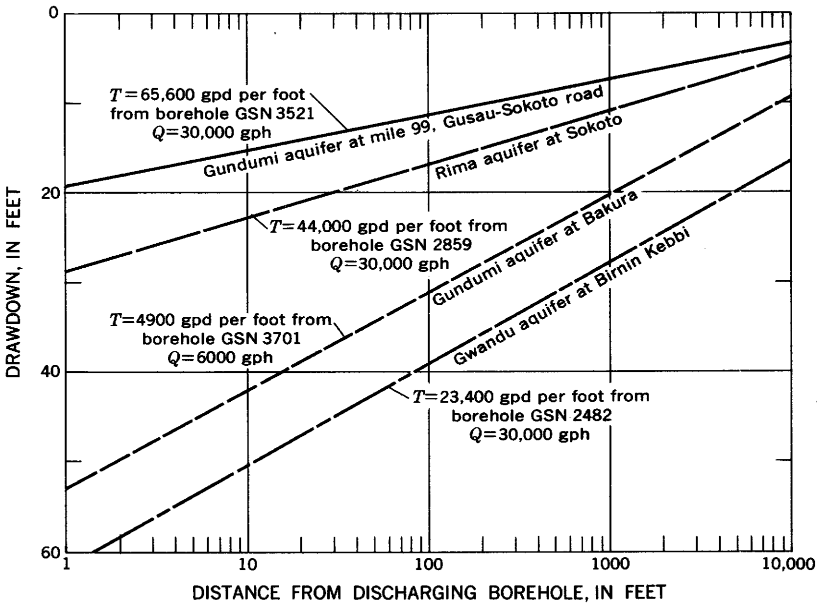


FIGURE 9.—Predicted drawdowns at discharging boreholes at Sokoto, Birnin Kebbi, Bakura, and mile 99 on Gusau-Sokoto road after 1,000 days of continuous withdrawal.

CHEMICAL QUALITY OF WATER

With few exceptions the water in the Sokoto Basin is of good quality and is suitable for most uses (table 7). In boreholes in the vicinity of Sokoto, iron concentrations, up to 14 mg/l (milligrams per liter), are excessive in both the Rima and Gundumi aquifers and also at places in the Gwandu aquifer in western Sokoto Province. The iron would first have to be removed before the water could be utilized industrially. Water having high iron or low pH (below 7.0) or both is likely to be corrosive to iron pipes and fittings. This tendency is increased by the high native water temperatures, from 27° to 38°C, that prevail in all boreholes at which temperature was measured (table 7). Waters high in sodium chloride such as those at Isa (borehole GSN 3514) and Kaloye (borehole GSN 3708) in the Gundumi Formation, are undesirable for irrigation. The deeper waters in the Rima Group become increasingly mineralized downdip (up to 1,090 mg/l total dissolved solids in borehole GSN 3053), but these are of sulfate type rather than chloride. Near the intake areas of all three principal artesian aquifers, the dominant ions are calcium and bicarbonate but, as the water moves downdip, sodium replaces calcium as the positive ion. In the shallow ground water tapped by dug wells, high nitrates commonly indicate pollution caused by contamination from livestock or from wastes of nearby villages. Shallow ground water from the limestone of the Kalambaina, besides having high nitrates, is characteristically hard with a slightly alkaline pH as compared with the deeper artesian aquifers of the basin.

The chemical quality of water from the several formations of the Sokoto Basin and also of water from lakes and streams is discussed in more detail in the following paragraphs.

CRYSTALLINE ROCKS

On the basis of two water samples collected from the crystalline rocks, such water is likely hard but moderate in dissolved-solids content. It is a calcium, sodium, or magnesium bicarbonate water and is probably suitable for most purposes.

GUNDUMI FORMATION

The sodium or calcium cations and the bicarbonate or sulfate anions predominate in the water from most boreholes in the Gundumi Formation. Sodium chloride water occurs at Isa (borehole GSN 3514) and in the deep aquifer at Kaloye (borehole GSN 3708).

East and south of Sokoto along the Gusau-Sokoto road is found the most acidic water sampled in the Sokoto Basin. The pH is 5.1 at Dange (borehole GSN 3512) and mile 105 (borehole GSN 3520), and it is 3.7 at mile 110 (borehole GSN 3519) on the Gusau-Sokoto road. These sources are low in dissolved solids, ranging from 28 to 79 mg/l. The predominant anion is sulfate, which may have resulted from the oxidation of pyrites. If so, this process would also account for the acidity of the water. The water at borehole GSN 3519 contains 32 mg/l of iron and 1.8 mg/l of manganese, the highest values for these ions yet (1967) determined for water samples from Sokoto Basin. The outcrop area of the Gundumi Formation east of Sokoto, as at Sabon Birni (borehole GSN 3513), Isa (borehole GSN 3514), and mile 73 (borehole GSN 3526) on the Gusau-Sokoto road, contains the most alkaline water sources in Sokoto Basin. In all these boreholes the water attains a pH of 8.7.

In general, water in the Gundumi tends to be soft and low in dissolved solids. It is suitable for many uses, but there are some limitations. Several boreholes yield water which is high in iron and has the attendant tendency to staining. The waters with low pH and high iron are probably corrosive. Also, boreholes yielding water high in sodium such as at Sabon Birni (GSN 3513), Isa (GSN 3514), and Kaloye (GSN 3708) are not suitable for irrigation. Only at Isa and Kaloye is boron sufficiently high to be injurious to sensitive plants. Also the high dissolved-solids content at Kaloye makes this water unsuitable for most purposes and may indicate generally poor quality of the water in the Gundumi aquifer at depths exceeding about 1,300 feet. Water temperatures from boreholes tapping the Gundumi range from 32° to 36° C.

RIMA GROUP

Most sources of water in the Rima Group have calcium and bicarbonate or sulfate as the predominant ions. These ions may be derived from limestone and gypsum. Magnesium is sometimes present in significant quantities, but sodium or potassium is rarely so. Only in the water from Kaloye (borehole GSN 3708) is sodium the predominant cation. Nitrate is generally low, except in water from dug wells.

The water from the Rima Group is mostly moderately hard to hard, but a few sources are soft. Dissolved-solids values range from 44 to 1,090 mg/l, but except for the deep Rima aquifier at Balle, they are less than 500 mg/l. Values for pH range from 6.0 to 8.1. Several water sources from boreholes tapping Rima water in the vicinity of Sokoto have high iron content (up to 14 mg/l) and sufficient manganese to contribute to the staining properties of the iron. The high iron concentrations and accompanying low pH of the water seem to be characteristic of those areas where black peaty clay and silt containing pyrite (iron sulfide) are found in the Rima Group. Such peaty clay and silt are present in the Rima of the Sokoto area, as for example in borehole

GSN 2498. Waters with high iron or low pH or both are probably corrosive. Water temperatures in boreholes tapping the Rima range from 29° to 37°C.

KALAMBAINA FORMATION

As might be expected in limestone, the water from the Kalambaina is basically a calcium bicarbonate type. Moreover, all samples taken from this aquifer are from dug wells or springs that are subject to pollution by animal and human wastes. Such pollution generally results in high concentrations of nitrate and sometimes high concentrations of potassium and chloride. Water from the well at Chimola, for example, has extremely high nitrate (1,210 mg/l in September 1965) and potassium concentrations and is also high in calcium and chloride; it is extremely hard and high in dissolved solids. The spring at Angwan Tudu is the only source sampled that, in milliequivalents per liter, has magnesium exceeding calcium.

Water in the Kalambaina Formation is hard but generally moderate in dissolved-solids content. It is alkaline, having pH values from 7.2 to 8.3. The water is very good for irrigation and is suitable for most other uses, except that pollution may make some sources unfit for drinking without treatment. Water temperatures from wells tapping the Kalambaina range from about 30° to 32°C.

GWANDU FORMATION

The chemical character of the water in the Gwandu Formation is extremely varied. The most common type of water indicated by available analyses (table 7) is a calcium-magnesium bicarbonate type. A sodium bicarbonate type is found at greater depths to screen, as at Kurdula (borehole GSN 3056) and at Bacaka (borehole GSN 2674) (fig. 10). Most of the remaining waters are calcium sulfate type, particularly near the outcrop area where sulfate is relatively abundant, or calcium-sodium nitrate type, particularly in waters from village dug wells, such as at Balle and Kurdula (table 7).

Water in the Gwandu Formation is soft or only moderately hard and is low in dissolved solids. The pH, in the range of 6.6 to 7.7, indicates that slightly acidic to slightly alkaline conditions generally prevail in Gwandu water. The water is of excellent quality for most purposes, except where excessive iron is found. Water temperatures in wells and boreholes range from 27° to 38°C.

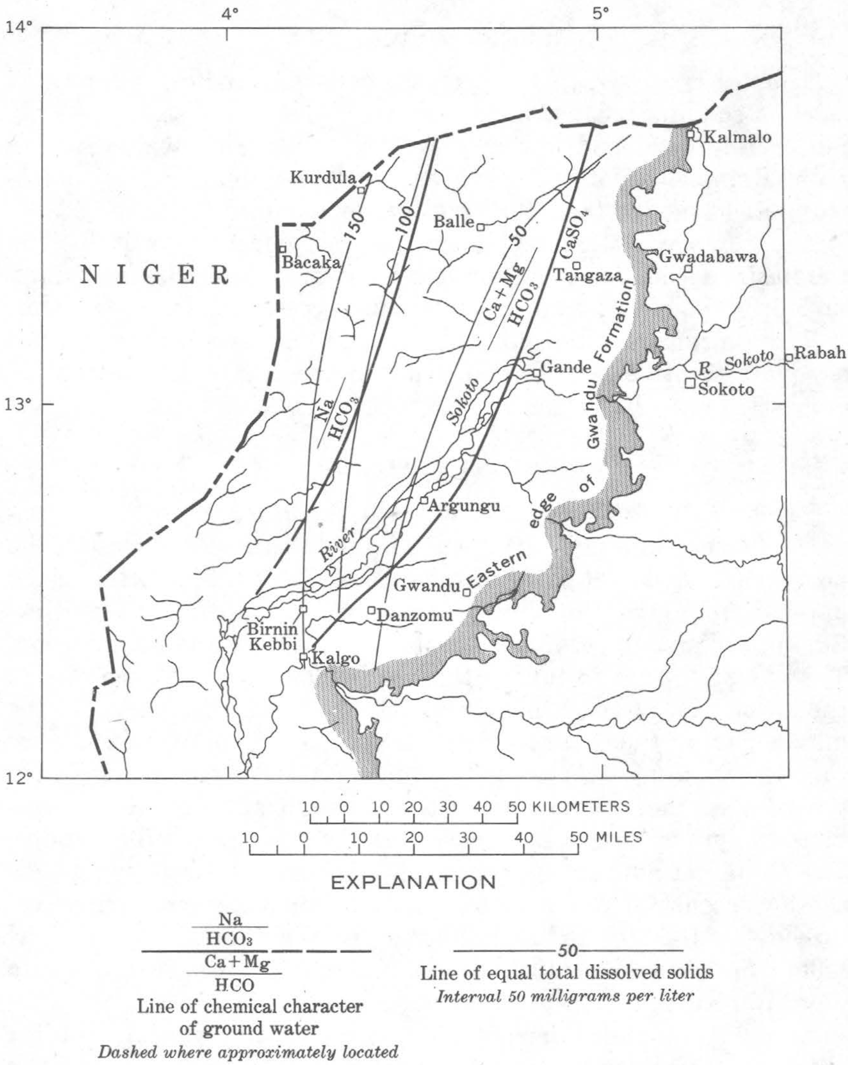


FIGURE 10.—Chemical character of ground water in Gwandu Formation.

SURFICIAL DEPOSITS

Water from the alluvial deposits in stream valleys is generally low in dissolved solids, generally less than 150 mg/l and is very soft. Adjacent to limestone tracts, however, such as near Sokoto, the dissolved-solids content and hardness may be fairly high.

SURFACE WATER

Samples from streams and rivers generally indicate waters of calcium-sodium bicarbonate character. They are soft or only moderately hard and low in dissolved solids. One water sample from Kalmalo Lake had significantly higher magnesium, potassium, and fluoride than the river water samples.

The surface waters of the region are generally suitable, on the basis of chemical analysis, for most purposes. The prevailing turbidity, however, makes filtration necessary for many uses, and the probable presence of harmful bacteria suggests that adequate treatment is needed prior to the use of the water for domestic or public water supply.

CONCLUSIONS

Exploratory drilling has confirmed the presence of three important artesian aquifers in semiconsolidated sandy zones in the northern and central parts of the Sokoto Basin: an aquifer in the upper part of the Gundumi Formation, an aquifer in the Rima Group, and an aquifer in the basal part of the Gwandu Formation. These aquifers are in turn separated by confining clayey zones in the lower part of the Rima Group, the Dange Formation, and the middle part of the Gwandu Formation. Existing borehole evidence suggests that only two artesian aquifers are present in the southern part of the Sokoto Basin: the Gwandu aquifer and a Cretaceous aquifer formed by a mergence of the Rima and Illo Groups. The Gundumi aquifer is apparently absent here or merges with the lower part of the Illo Group. Artesian water from the Cretaceous aquifer (either the Gundumi or the Rima-Illo) will flow from boreholes located along the fadama of the River Sokoto from Rabah south to about Bunza.

In the Gundumi Formation the productive artesian aquifer occurs in the upper part of the formation. The lower part of the formation near bedrock is generally clayey, so yields to boreholes are low and drawdowns high. In the aquifer itself the clay content becomes more abundant toward the south and downdip, and yields to boreholes are considerably reduced. Artesian flow can be obtained from boreholes tapping the Gundumi aquifer in the River Sokoto fadama from Rabah west to and beyond Sokoto.

The Illo Group, originally divided in the outcrop area into three members by Jones (1948), apparently contains only two members at depth. The upper "grits" member, which forms the principal artesian aquifer in the Illo Group, can be traced consistently downdip. The middle bauxitic clay member, however, may pinch out at depth. The lower "grits" member downdip becomes clayey and is not considered water bearing.

Near the outcrop the Rima Group is typically a fine sandy black clay sequence, but downdip the clay fraction virtually disappears. The fine sandy beds in turn become coarse grained and southward merge with coarse sand and fine gravel of the upper Illo Group. The Rima aquifer yields artesian flow not only in the River Sokoto fadama from Argungu to Birnin Kebbi but also in some of the deeper valleys and lowlands west of the River Sokoto. Collectively, the Rima and Illo make up the thickest known artesian aquifer (638 feet at Birnin Kebbi) in the Sokoto Basin.

The Kalambaina Formation, although not water bearing in its downdip extensions, contains an important perched ground-water body in limestone along some 150 miles of its area of outcrop. Springs issuing from the limestone contribute some recharge to the Rima aquifer as well as to the Gwandu aquifer. At the same time they sustain streamflow during the dry season in the middle reaches of the River Sokoto.

The artesian aquifer in the basal part of the Gwandu Formation, underlying the western third of the Sokoto Basin, is potentially the most productive aquifer in the basin, yet it is currently (1967) the least developed. Artesian flow can be obtained from boreholes in some 1,000 square miles of lowland underlain by the Gwandu, notably as follows: Along the River Sokoto fadama; in a 350-square-mile lowland, extending from Masallaci through Balle and from Karfin Sarki into Niger, that has highest potential yields from boreholes with smallest drawdowns (pressure declines); in smaller lowlands along the Niger border near Bacaka and Kurdula; and also in a narrow lowland extending some 20 miles southwest of Yeldu. Generally, the water-yielding potential of the Gwandu artesian aquifer decreases westward because the sediments become finer grained and more clayey. Still farther south and across the River Niger the Gwandu aquifer appears to merge with the Cretaceous aquifer of the Rima-Illo to form one thick artesian aquifer.

Of the three artesian aquifers in Sokoto Emirate (Tangaza district) and northern Argungu Emirate, the highest pressure heads are found in the Gwandu Formation. In the southern part of the basin in Gwandu Emirate, however, pressure heads in the Rima aquifer exceed those in the Gwandu aquifer, as the pressure heads in the Gwandu rises toward the land surface. In short, then, the Gwandu contains the principal artesian aquifer of the basin, followed very closely in the importance by the Rima aquifer. Because of its very thickness and coarse texture downdip, the Rima with additional exploration may eventually prove to be more productive than it is presently (1967) known to be. The Gundumi artesian aquifer, however, seems to offer the least potential for development among the three artesian aquifers presently identified in the northern and central parts of the Sokoto Basin.

Ground-water flow patterns in the artesian aquifers suggest that the most significant recharge areas are in the outcrop areas in Niger and Nigeria. Flow is toward the west and south, and the artesian water is eventually discharged naturally in the lower reaches of the River Sokoto and its lower tributaries and also in the River Niger.

Base-flow (ground-water) discharge of streams ranges from practically nil in the pre-Cretaceous crystalline-rock terrane east and south of the Sokoto Basin to a average maximum annual value 1 inch in the River Zamfara basin, which is about one-third of the total streamflow. Ground-water discharge to streams is also significant in reaches of the River Rima fed by spring flow from the perched water body in the outcrop of the Kalambaina Formation. Elsewhere in the Sokoto Basin, streams are intermittent and flow measurably for only about half the days of the year. Of the average 4.4 million acre-feet of runoff from the River Sokoto drainage basin, approximately 0.5 million acre-feet (350 mgd) is estimated to be overflow from aquifers of the ground-water reservoir.

The shallowest ground water in wells and boreholes put down in the Sokoto Basin is the "first water" found just below the water table, commonly at depths of 50 to 75 feet, in the outcrop areas of all the Cretaceous to Quaternary sedimentary formations. In places, however, wells have been dug to depths of more than 300 feet without reaching the water table. The shallow ground water is tapped almost exclusively by dug wells, numbering several thousand, that supply the villages with their small domestic and livestock needs. Although the water is usually low in dissolved solids, its commonly high nitrate content suggests pollution from human and animal wastes.

The chemical quality of water in all the artesian aquifers of the basin is generally good to excellent; however, high iron concentrations are common, particularly in the vicinity of Sokoto. Waters high in sodium, undesirable for irrigation, also occur in the Gundumi Formation near its contact with bedrock. Mineralized waters, relatively high in dissolved solids, are found at depth in the basin, particularly in the Rima Group at Balle (1,090 mg/l) and in the Gundumi Formation at Kaloye (2,980 mg/l). Water in the Gwandu artesian aquifer changes progressively from a calcium sulfate type in the recharge area to a mixed calcium magnesium bicarbonate type and then to a sodium bicarbonate type in downdip extensions of the aquifer. The water in limestone of the Kalambaina Formation is hard, slightly alkaline, and of calcium bicarbonate type. Moreover, because the Kalambaina water body is shallow and contained in cavernous rock, it is readily subject to pollution from human and animal wastes.

RECOMMENDATIONS

The observation-well network should be continued, at least on an interim basis, with water-level or pressure measurements made about every 3 months, preferably in early October, January, April, and July, or if possible at shorter intervals.

Shallow test holes should be drilled or augered in the outcrop areas of the major aquifers and confining beds primarily to obtain better definition of their surface extent, contact relations, thickness, and physical properties, particularly of the confining clay layer in the lower Rima Group and the artesian aquifers in the basal part of the Gwandu Formation and in the Rima Group. Similar subsurface testing is also needed to determine the stratigraphic relationships between the Gundumi Formation and the Rima and Illo Groups where they appear to merge in the southern part of the basin.

When new boreholes are drilled for water supply in areas of artesian flow, each installation should include automatic shutoff devices, for cattle-trough fixtures and domestic water-supply faucets, and recording flow meters, to measure the quantity and rate of water use from boreholes tapping the various aquifers. Boreholes should not be allowed to flow uncontrolled. In addition chemical analyses of water should be made for all new boreholes put down in the basin.

When new boreholes are drilled in already proven subartesian areas, only one borehole may need to be drilled, and it can be screened for production. In these areas the savings from elimination of an exploratory or test borehole could be applied to larger diameter casing and screens. In artesian areas, however, at least two boreholes are generally required to foresee and prevent blowouts: a small-diameter exploratory hole put down first to define the depth and position of the artesian aquifer and a second larger diameter production borehole to be cased and screened for permanent water supply. The procedure employed by Balakhany (Overseas), Ltd., on production wells is to drill first into the overlying confining clay and seat the casing. Then drilling is continued into the aquifer, so that if an artesian blowout does occur the screen can still be set and wedged into a secure casing.

For the improvement of Birnin Kebbi's water supply, new boreholes should be put down and screened in the productive Rima aquifer at a spacing that is considerably distant from existing boreholes. The existing boreholes screened in the Gwandu aquifer, whose flow is presently (1967) declining in this area, can then be shut down for several months to recover. By this procedure the withdrawals for municipal use can be alternated between the aquifers to conserve the artesian pressure and flow. A similar method of water-supply development is possible at Argungu, seat of the emirate. Here artesian flow has already been proved from the Gwandu aquifer and probably can also be obtained from the Rima aquifer. At both Birnin Kebbi and Argungu, boreholes should be tightly cemented around casings to retard corrosion and prevent concurrent leakage and loss of confined water. Defective or leaking boreholes should be plugged and sealed with cement.

At the sites (Karfin Sarki, Kurdula, Balle, and Yeldu) of the test boreholes put down for the first-phase study of the present project, the existing unused artesian boreholes can be turned over to the villages for domestic water supply, after being fitted with appropriate trough-control fixtures, domestic water-supply faucets, and water meters. A water rate-of-use study could then be conducted and the effects of any pressure decline noted in the nearby recorder installations.

With respect to poorly drained tracts in the perched-water area of the Kalambaina outcrop, often a problem in construction or agricultural development schemes, drainage can be achieved by digging or boring holes through the clay of the Dange Formation to permit the perched water to move down to the permanent water table. A similar procedure could be used to recharge the Rima aquifer artificially, if desirable.

In order to obtain additional information on natural ground-water discharge, it would be desirable to gage selected streams during the dry season. For example, to measure ground-water discharge from the perched water body in the Kalambaina Formation, the River Kware should be measured where it enters the River Rima, and the Rivers Sokoto and Rima where they cross the upper and lower geologic contacts of the Kalambaina. Natural ground-water discharge from aquifers in the Gundumi, Illo, Rima, and Gwandu Formations could be measured by selective stream gaging along the River Zamfara and lower River Sokoto at the aquifer or formation boundaries.

With time, some of the borehole waters low in pH and high in iron may cause corrosion to existing casings or riser pipes. To anticipate this problem, water quality should be periodically monitored and, if signs of corrosion do occur, the borehole casings and screens in the affected areas can be selected from more resistant materials.

Around the tops of dug wells, provision should be made for adequate surface drainage to carry away the more common pollutants of animal and human wastes and laundry drainage. This problem is particularly acute in very shallow wells in the perched water area of the Kalambaina.

The proposed irrigation dams to be built in the crystalline-rock terrane near the headwaters of the River Sokoto are to provide enough storage to maintain year-round flow downstream, thus enabling the farmers to cultivate the normally unused lands in the fadama during the dry season. Should these diversions materially reduce surface flow in the lower reaches of the River Sokoto, say, below Sokoto city, ground water from the artesian aquifers of the Gwandu and Rima or the unconfined water of the fadama alluvium could be developed to provide supplemental water for irrigation.

Except for exploratory purposes, boreholes should not be drilled deeper than the base of the Rima Group in western Sokoto Province. Generally, the water in aquifers in this region, below the River Rima and even in the Rima aquifer itself below 1,000 feet, is moderately to highly mineralized and may be undesirable for most uses.

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TABLES 8-12

TABLE 8.—*Log of deep exploration borehole GSN 3053 at Balle, Sokoto Emirate, Sokoto Province*

[Elev 782 ft. Total depth 1,972 ft. Test well drilled in 1963 by Balakhany (Overseas), Ltd. Log by William Ogilbee, geologist, U.S. Geol. Survey]

Lithologic description	Thickness of unit (feet)	Depth (feet)
Gwandu Formation:		
Topsoil, sandy	1	1
Sand, red clayey	9	10
Sand, brown, fine to medium	27	37
Sand; and gray-brown clay; becomes very clayey near bottom. Traces of ironstone	26	63
Clay, gray-brown, mottled, sticky	14	77
Clay, gray and red, silty; and ironstone	4	81
Clay, brown and red, sandy; has bands of sand and ironstone gravel	4	85
Clay, gray, sandy; includes traces of limestone	10	95
Clay, brown, sandy; becomes sandier with depth	33	128
Clay, red-brown, mottled, indurated	4	132
Clay, red and brown, sandy; has traces of laterite	5	137
Clay, red and brown, mottled, sticky	6	143
Subartesian aquifer		
Sand, brown to red, fine to medium and coarse; quartz subrounded, red sand 182–182.5 ft, very coarse 182.5–185 ft. Water bearing; subartesian	42	185
Sandstone, hard, fine-grained, cemented; includes oolitic limonite nodules and lignite	1	186
Lignite; has containing soft sand bands	2	188
Sandstone, fine-grained, loosely cemented; has lignite bands	14	202
Confining layer		
Clay, gray, silty; and traces of lignite	3	205
Clay, light-blue; plastic, sticky	26	231
Clay, blue; harder than units above; slightly indurated, includes mudstone at 235 ft	5	236
Clay, blue, soft, slightly indurated	37	273
Clay, gray, sandy	3	276
Clay, blue, sandy; has lignite bands	7	283
Clay, dark-gray, soft, very sandy	11	294
Siltstone or mudstone, dark-gray; includes lignite	17	311
Mudstone, dark-gray, silty	5	316
Lignite or peat	1	317
Mudstone; includes clay and silt	4	321
Artesian aquifer		
Sand, white, very fine, homogeneous; becomes loosely cemented at 330 ft. Water bearing; artesian	11	333
Clay, gray, sandy	4	337
Clay, gray, silty	3	340
Sand, gray, very fine; becomes clayey at 345 ft	7	347

TABLE 8.—*Log of deep exploration borehole GSN 3053 at Balle, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Artesian aquifer—Continued		
Gwandu Formation—Continued		
Clay, black, silty; and lignite	5	352
Sand, gray, fine, free. Artesian water; flow 5,000 gph. Head 46 ft above land surface	26	378
Sand; has hard clay bands	2	380
Sand, gray, very fine, silty	6	386
Clay blue; has alternating sand bands	5	391
Sand, gray, fine, free; has thin clay bands from 392 to 394 ft	5	396
Clay, gray, sandy; and lignite	6	402
Sand, gray, very fine; has silty bands	5	407
Sand, gray, fine to medium; clayey near bottom	68	475
Clay, gray; very sandy to clayey sand	9	484
Sand; alternates with bands of clay	17	501
Sand, gray, fine, free	4	505
Sandstone, gray, fine-grained, loosely cemented; includes some clay	1	506
Sand, gray, quartz, coarse to very coarse, free. Artesian water; flow 7,000 gph. Head 46 ft above land surface	34	540
Sand, gray, quartz, loosely cemented; includes some clay	6	546
Sand, gray, quartz, medium to coarse, free; has firm bands	24	570
Sand, gray, medium; includes thin clay bands	5	575
Sand, gray, medium to coarse; includes hard and soft bands	29	604
Peat or lignite, black, sandy, carbonaceous	2	606
Sand, fine to medium, quartz; has cemented bands	8	614
Sand, fine, very clayey; becomes sandy clay	11	625
Clay; has thin sand bands	14	639
Confining layer		
Kalambaina Formation:		
Clay, blue-black, soft; has thin white limestone bands	12	651
Shale, blue, hard, indurated; has thin limestone bands	11	662
Shale, blue, soft	16	678
Shale, gray-blue	10	683
Shale, light-blue; and white clay	6	694
Shale, blue and gray; has white clay bands	5	699
Clay, blue, silty	6	705
Mudstone	5	710
Limestone, gray, soft; has hard streaks (samples contaminated with shale)	65	775
Limestone, gray; has soft shale bands	15	790

TABLE 8.—*Log of deep exploration borehole GSN 3053 at Palle, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Confining layer—Continued		
Dange Formation:		
Shale, light-blue; becomes darker at 199 ft	66	856
Shale, dark-blue, soft	19	875
Shale, blue; has limestone bands	5	880
Shale, dark-blue	13	893
Clay, black, silty, soft	11	904
Clay, black, silty, soft; becomes sandy near bottom	31	935
Subartesian aquifer		
Wurno Formation:		
Sand, gray and pink, fine to very coarse, quartz, feldspar, pyrite, free; has hard and soft bands from 1,028 to 1,040 ft, becoming finer near bottom. Free from 1,000 to 1,025 ft, fine from 1,050 to 1,083 ft. Water bearing; subartesian. Water level 30 ft below land surface	148	1,083
Confining layer		
Dukamaje Formation:		
Shale, black, hard, silty; becomes harder with depth	61	1,144
Sandstone, gray, fine-grained, hard, tight	3	1,147
Shale, dark-gray, sandy, hard	4	1,151
Shale, gray, hard; has limestone bands	3	1,154
Shale, gray, black, soft, carbonaceous; becomes harder with depth; has thin sand bands	17	1,171
Subartesian aquifer		
Taloka Formation:		
Sand, gray, fine, dirty; has shale bands; becomes coarser with depth	21	1,192
Sand, gray, fine to coarse, quartz. Free to 1,341 ft; tight bands to 1,352 ft. Fine to 1,220 ft, medium to coarse to 1,315 ft. Water bearing; subartesian. Water level 30 ft below land surface	160	1,352
Sand, dark-gray, fine, clayey; has clay bands	24	1,376
Sand, gray-white, fine to coarse, quartz; fine to medium to 1,390 ft; fine to 1,405 ft; medium to coarse from 1,405 to 1,451 ft; thin clay bands from 1,399 to 1,422 ft	75	1,451
Shale, dark-gray, plastic, silty	4	1,455
Sand, clayey, fine to medium, dirty	15	1,470
Sand, clayey, fine to medium, gray; becomes very clayey at 1,515 ft and increasingly clayey with depth	132	1,602
Shale, plastic, hard, gray and brown, mottled	47	1,649

TABLE 8.—*Log of deep exploration borehole GSN 3053 at Balle, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Subartesian aquifer—Continued		
Taloka Formation—Continued		
Shale, hard, silty, gray-red-brown, mottled	7	1,656
Sand, very fine, brown, hard	1	1,657
Shale, hard, plastic, silty, blue-brown and red, mottled	18	1,675
Sand, quartz, fine to coarse, white to pink	13	1,688
Shale, hard, sandy, brown	16	1,704
Shale, sandy, gray-blue-red, mottled	36	1,740
Clay, soft, yellow-gray; and fine sand bands	31	1,771
Shale, hard, brown; has thin limestone bands	15	1,786
Shale, soft, sandy; has limestone bands	7	1,793
Sand, quartz, medium to coarse, free	10	1,803
Sand, medium, clayey; includes hard clay bands	7	1,810
Shale, sandy, gray; has sand bands	12	1,822
Shale, plastic, gray-red, mottled	3	1,825
Sand, white-gray, quartz, fine to coarse	25	1,850
Shale, brown, sandy	7	1,857
Sand, quartz, medium to coarse, free	37	1,894
Shale, gray, hard	2	1,896
Sand, quartz, fine to medium	4	1,900
Shale, gray, sandy	5	1,905
Sand, quartz, fine to medium	19	1,924
Shale, gray, sandy	16	1,940
Shale, yellow, hard, plastic	2	1,942
Gundumi(?) Formation:		
Shale, hard; multicolored fragments (shale conglomerate	18	1,960
Shale, reddish-brown, hard, plastic	12	1,972

TABLE 9.—*Log of deep exploration borehole GSN 3704 at Girawsi, Sokoto Emirate, Sokoto Province*

[Elev 805 ft. Total depth 1,600 ft. Observation well drilled in 1966 by Balakhany (Overseas), Ltd. Log by H. R. Anderson, U.S. Geol. Survey]

Lithologic description	Thickness of unit (feet)	Depth (feet)
Holocene deposits:		
Soil, sandy clay, brownish-gray	4	4
Sand, ironstone-quartz, medium to coarse, red-brown; water table	6	10
Ironstone, red-brown	3	13

TABLE 9.—*Log of deep exploration borehole GSN 3704 at Girawsi, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Confining layer		
Dange Formation:		
Clay, light-greenish-gray, soft, flakey; has fibrous gypsum-phosphate nodules and quartz pebbles in lower part	17	30
Clay, yellowish-gray, calcareous; includes gypsum and phosphate nodules	10	40
Clay, light-gray, calcareous	3	43
Clay, calcareous, yellow	4	47
Clay, bright-green, silty; has a peppery appearance	3	50
Clay, light-gray, sandy; and interbedded fine sand; dark-red spots at base	15	65
Clay, gray; and mottled dark-red siltstone	5	70
Subartesian aquifer		
Rima Group:		
Sand, quartz, fine, uniform, brownish-white	59	129
Clay, black, silty, peaty, consolidated	24	153
Consolidated bed—claystone or pyrite	2	155
Clay, black, silty, peaty	10	165
Sand, fine, light-gray; has black clay bands	5	170
Sand, fine, light-gray	34	204
Sand, fine, light-gray	6	210
Clay, black; and gray sand	7	217
Clay, very dark brown to black	13	230
Clay, dark-brown; and fine gray sand	6	236
Sand, fine and very fine, gray	10	246
Clay, dark-brown, lignitic	1	247
Sand, fine to medium, quartz, light-gray; has scattered coarse grains. Water bearing; subartesian. Water level 2.5 ft below land surface	36	283
Clay, gray	3	286
Sand, fine, uniform, light-gray; includes some medium grains and cemented bands	24	310
Sand, fine, light-gray; includes interbedded gray clay bands	33	343
Sand, fine, light-gray, uniform; has thin cemented bands; medium toward base	67	410
Clay, gray	2	412
Sand, fine, light-gray; has clay bands	13	425
Clay, gray, sticky, tough; and claystone bands	12	437
Sand, light-gray, very fine to fine, uniform	104	541
Confining layer		
Clay, medium-gray, sticky, tough; has consolidated bands near base	53	594

TABLE 9.—*Log of deep exploration borehole GSN 3704 at Girawsi, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Confining layer—Continued		
Rima Group—Continued		
Sand, fine, light-gray; includes some medium grains	4	598
Clay, medium-gray, plastic and sticky	29	527
Sand, fine to coarse, light-gray	2	629
Clay, plastic, light-gray, sticky	18	647
Limestone, clayey, light-gray	3	650
Clay, yellow and gray	53	703
Sand, coarse, light-gray, quartz	2	705
Clay, sticky, pliable, medium-gray to brown	27	732
Sand, medium to coarse, gray	1	733
Clay, gray	1	734
Sand, medium to coarse, quartz	5	739
Clay, medium-gray	1	740
Artesian aquifer		
Gundumi Formation:		
Sand; medium to coarse light-gray firm subangular quartz	25	765
Clay, medium-gray, sticky	8	773
Sand, quartz, coarse, uniform, clean, grayish-white, subangular	17	790
Clay, medium-gray, sticky	3	793
Sand, coarse, clean, white	2	795
Clay, brownish-gray; changes to mottled yellow, gray, and red brown with depth	19	814
Sand, fine, clayey, brownish-gray	11	825
Clay, red-brown, yellow, and gray	5	830
Sand, medium to coarse, gray	3	833
Clay, gray	1	834
Sand, fine to coarse, light-gray	17	851
Clay, light-gray	5	856
Clay, red-brown and gray	5	861
Clay, yellow and gray	8	869
Sand, fine to coarse, gray	5	874
Clay, brownish-gray, stiff; becomes sandy and consolidated with depth	11	885
Sand, fine to coarse, gray	8	893
Sand, fine to very coarse, gray	12	905
Sand, coarse to granule-grained sized, brownish-white. Water bearing; artesian flow 2,500 gph. Head 22 feet above land surface	17	922
Confining layer		
Clay, very light gray, soft	7	929
Clay, cocoa-colored, sticky, soft	15	944

TABLE 9.—*Log of deep exploration borehole GSN 3704 at Girawsi, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Confining layer—Continued		
Gundumi Formation—Continued		
Clay, brown and yellow, sticky	25	969
Clay, yellow and reddish-gray	11	980
Clay, yellowish-gray	6	986
Sand, fine to coarse, firm, gray-brown	10	996
Clay, yellow and gray	2	998
Sand, fine to coarse, firm, gray-brown	4	1,002
Clay, red-brown and gray, sticky	13	1,015
Clay, yellowish-gray	35	1,050
Clay, red-brown	8	1,058
Sand, very fine and fine, gray and brown, clayey	8	1,066
Sandstone	2	1,068
Clay, medium-gray; stone at 1,075 ft	20	1,088
Clay, medium-gray and red-brown	9	1,097
Clay, light-gray, tough, sticky	18	1,115
Sand, fine to coarse, brown	3	1,118
Clay, light-gray, slightly sandy	13	1,131
Sand, fine and medium, brown; has interbedded gray sandy clay	12	1,143
Clay, light-gray, micaceous, tough, sticky	4	1,147
Gravel; medium-sand to fine-pebble size, gray and brown, firm	7	1,154
Clay, purple and gray, sandy, tough	4	1,158
Sand; medium to granule size, gray and brown	16	1,174
Clay, medium-gray, somewhat sandy	12	1,186
Conglomerate; coarse-sand to medium-pebble size; yellow and red-stained pebbles. Also clear, white, and smoky quartz, subangular and subrounded shapes, cemented	25	1,211
Clay, gray-brown, sandy, tough	10	1,221
Clay, light-gray, sandy, includes trace of mica	19	1,240
Clay, sandy, red-brown	5	1,246
Clay, sandy, light-gray	17	1,262
Sand; coarse to fine feldspathic gravel	12	1,264
Clay, sandy, tough, light-gray and pink	37	1,301
Clay, yellow	7	1,308
Clay, light-gray, gray, and white	40	1,348
Clay, brown	4	1,352
Gravel, fine to medium, white	10	1,362
Clay, sandy	15	1,377
Sandstone, shaly, light-gray	10	1,387
Clay, sandy, gray and white	14	1,401
Gravel, light-gray; contains white clay, firm	23	1,424
Clay, sandy, pink and white	5	1,429
Sand, fine to very coarse, light-brown, firm	17	1,446

TABLE 9.—*Log of deep exploration borehole GSN 3704 at Girawsi, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Confining layer—Continued		
Gundumi Formation—Continued		
Clay, sandy, pink and white, tough	39	1,485
Sand, fine to very coarse, brownish-gray	7	1,492
Clay, sandy, pink, tough	14	1,506
Claystone, red and white, micaceous, rock-hard	11	1,517
Clay, sandy, pink and brown; has indurated bands	48	1,565
Clay, sandy, pink and lavender; includes some free gravel bands	15	1,580
Claystone, yellow-brown, micaceous; (rottenstone?)	5	1,585
Clay, sandy, pink; has thin free gravel bands	15	1,600

TABLE 10.—*Log of deep exploration borehole GSN 3707 at Mungadi, Gwandu Emirate, Sokoto Province*

[Elev 625 ft. Total depth 1,305 ft. Test hole drilled in 1966 by Balakhany (Overseas), Ltd. Composite of log by F. Beltaro, geologist, Geological Survey of Nigeria]

Lithologic description	Thickness of unit (feet)	Depth (feet)
Holocene deposits and Gwandu Formation:		
Topsoil	6	6
Sand, brown, clayey, medium	8	14
Same as above unit except has traces of peat; water table	11	25
Confining layer		
Sokoto Group:		
Limestone; has some clay contamination. White at the top, gray in the middle, and brown at the bottom	35	60
Clay, gray, sandy; has fragments of limestone	4	64
Subartesian aquifer		
Rima Group:		
Peat	4	68
Sand, dark-gray, medium, unsorted; includes grit	20	88
Illo Group:		
Unsorted sand and grit, generally medium, light-gray-brown; includes a few semiconsolidated bands. Water bearing; subartesian. Water level 13 ft below land surface	134	222
Sand, coarse, light-gray-white, clean	80	302
Sand, light-gray-brown, medium to very coarse	120	422
Sand, light-gray, generally coarse, unsorted	80	502
Gravel, well-sorted; includes a few bands of fine sand	42	544

TABLE 10.—*Log of deep exploration borehole GSN 3707 at Mungadi, Gwandu Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Subartesian aquifer—Continued		
Illo Group—Continued		
Gravel; and medium to coarse-gray sand; pyrite grains	38	582
Sand, coarse, pebbly; and white clay	58	640
Confining layer		
Clay, gravelly, white and light-yellow; has dark pyritiferous concretions	80	720
Clay, light-green, sandy	20	740
Gravel; and some coarse sand	7	747
Clay, sandy, light-green	35	782
Gravel, pebble; includes some coarse white sand	100	882
Clay, pinkish-purple; includes some gravel	8	890
Clay, white, sandy; includes some gravel	14	904
Clay, purple, sandy; and some gravel	21	925
Clay, light-gray, sandy; and some gravel	40	965
Clay, light-green-gray, coarse, sandy	40	1,005
Clay, white, silty, gritty	30	1,035
Clay, light-gray-green, gritty	52	1,087
Clay, dark-violet, massively bedded	13	1,100
Clay, light-green and dark-violet	8	1,108
Gravel; and white gritty clay	11	1,119
Clay, light-gray-white, silty	31	1,150
Clay; has light-green, gray, and dark violet bands	16	1,166
Same as above unit except includes white, silty clay	14	1,180
Clay, light-green-gray, slightly silty	10	1,190
Sand, coarse; and gravel mixed with silty clay	34	1,224
Clay, purple and light-gray; and white sandy clay	20	1,244
Clay, purple; and some coarse-grained sand (calcareous?)	25	1,269
Quartzitic rubble	7	1,276
Pre-Cretaceous crystalline rocks:		
Rock, disintegrated, pink, white, and light-green	19	1,295
Schist, gray and yellow	10	1,305

TABLE 11.—*Log of deep exploration borehole GSN 3708 at Kaloye, Argungu Emirate, Sokoto Province*

[Elev 673 ft. Total depth 1,560 ft. Observation well drilled in 1967 by Balakhany (Overseas), Ltd. Log from description by F. Beltaro, geologist, Geological Survey of Nigeria]

Lithologic description	Thickness of unit (feet)	Depth (feet)
Gwandu Formation:		
Clay, red-brown, silty	11	11
Clay, light-brown, silty	7	18

TABLE 11.—*Log of deep exploration borehole GSN 3708 at Kaloye, Argungu Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Gwandu Formation—Continued		
Clay, yellow, silty; has laterite nodules	22	40
Clay, pink, yellow, and white, silty	25	65
Hard laterite band	1	66
Clay, light-yellow and white, silty	44	110
Clay, white, silty	28	138
Clay, white, kaolinitic	10	148
Sand, light-brown, fine; includes laterite nodules	41	189
Confining layer		
Hard ironstone band	1	190
Clay, white, slightly silty, massively bedded	8	198
Clay, gray, silty, massively bedded	7	205
Clay, black, peatty	5	210
Clay, light-gray, massive	10	220
Clay, light-brown	10	230
Clay, white; mottled with pink and red	17	247
Variegated clay	2	249
Clay, light-gray, slightly silty, massive; has two hard bands at 274 ft and 283 ft	71	320
Sandstone, fine-grained, light-brown, soft	2	322
Clay, gray-black, silty; includes a band of peat	9	331
Sand, light-brown, very fine	4	335
Clay, dark-gray-black, silty; has traces of carbonaceous material and pyritiferous fine-grained sandstone	45	380
Sand, gray, fine, slightly clayey	5	385
Clay, gray, variegated, slightly silty; has carbonaceous inclusions	19	404
Subartesian aquifer		
Sand, very fine, brown	3	407
Clay, gray; has carbonaceous stains	2	409
Sand, very fine, brown	11	420
Clay, gray; has carbonaceous stains	1	421
Sand, very fine, brown	8	429
Clay, black, silty; and peat having pyritiferous concretions	4	433
Sand, white, fine to coarse; includes traces of pyritiferous concretions	8	441
Clay, black, silty; and peat	1	442
Sand, white, fine to coarse; has traces of pyritiferous concretions	3	445
Clay, dark-gray, silty; includes carbonaceous layers	8	453
Sand, gray, fine to coarse; and grit; includes muscovite and traces of pyritiferous concretions. Water bearing; subartesian. Water level 10 ft below land surface	27	480

TABLE 11.—*Log of deep exploration borehole GSN 3708 at Kaloye, Argungu Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Confining layer		
Gwandu Formation—Continued		
Clay, dark-green-brown, earthy, probably glauconitic; includes pyritiferous grains	3	483
Clay, gray; includes carbonaceous fragments	17	500
Clay, light-gray, slightly silty, massive; has pyritiferous concretions	12	512
Kalambaina Formation:		
Limestone, light-gray, fossiliferous	38	550
Dange Formation:		
Shale, black; includes bands of white limestone	28	578
Rima Group:		
Sand, medium-gray; and a band of black, nonmetallic, hard minerals and traces of pyrites	2	580
Artesian aquifer		
Sand, gray, medium, unsorted; includes traces of pyrites	20	600
Sand, light-gray, fine to medium, unsorted; and grit having traces of pyrites and black shale	100	700
Sand, white, very coarse, unsorted; and medium grit. Water bearing; artesian flow 1,050 gph. Head 23 ft above land surface	20	720
Sand; and white medium and coarse unsorted grit	20	740
Sand, light-gray, medium, unsorted; includes a few traces of black shale	40	780
Same as above unit except includes several fragments of black shale and gray sandy clay	20	800
Sand, light-gray-brown, fine to medium, unsorted; includes a few fragments of black shale	60	860
Sand, light-gray, very unsorted; includes a few fragments of black shale	50	910
Sand, light-gray, unsorted; includes fragments of black shale and gray sand clay	131	1,041
Clay, gray, hard, silty	4	1,045
Sand, light-gray; and medium and coarse unsorted grit, having traces of black shale	41	1,086
Clay, gray, hard, silty	4	1,090
Sand, light-gray, medium to coarse, unsorted, clean	20	1,110
Clay, dark-gray, sandy; includes coarse grit	20	1,130
Sand, white, unsorted, clean mostly medium to coarse	30	1,160
Same as above unit but chiefly fine to medium size	25	1,185
Sandstone, pyritiferous	3	1,188
Sand, light-gray, unsorted	12	1,200
Clay, gray, sandy	30	1,230

TABLE 11.—*Log of deep exploration borehole GSN 3708 at Kaloye, Argungu Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Artesian aquifer—Continued		
Rima Group—Continued		
Sand, light-gray, medium and coarse, clean	10	1,240
Gundumi(?) Formation:		
Sand; and gray clayey gravel	10	1,250
Clay, gray, silty	15	1,265
Gravel, clayey	5	1,270
Sand, gray, unsorted, mostly medium. Water bearing; artesian flow 360 gph. Head 19 ft above land surface	40	1,310
Sand, gray, coarse; and gravel having bands of soft sandstone	15	1,325
Clay, gray and light-gray, silty	25	1,350
Clay, red, mottled	9	1,359
Clay, white and yellow, silty	29	1,388
Clay, gray, silty	14	1,402
Clay, variegated, massive	16	1.422
Sand, brown-red and gray, medium, unsorted; and grit having traces of silty clay	22	1.444
Pre-Cretaceous crystalline rocks:		
Rock, disintegrated; includes kaolin	74	1,518
Pegmatite(?)	10	1,528
Schist, disintegrated	4	1,532
Schist	28	1.560

TABLE 12.—*Log of deep exploration borehole GSN 3709 at Sainyinan Daji, Sokoto Emirate, Sokoto Province*

[Elev 800 ft. Total depth 900 ft. Test hole drilled in 1967 by Balakhany (Overseas), Ltd. Composite of log by F. Beltaro, geologist, Geological Survey of Nigeria, and M. I. Slatter, driller]

Lithologic description	Thickness of unit (feet)	Depth (feet)
Gwandu Formation:		
Soil, brown, sandy	7	7
Ironstone, hard; water table	8	15
Clay, brown; and ironstone	2	17
Kalambaina Formation:		
Limestone, white, soft has ironstone bands at 25 and 35 ft	28	45
Confining layer		
Dange Formation:		
Clay, gray, massive, plastic	23	68
Clay, gray, plastic; and white and brown silt having irregular fragments of ironstone	30	98

TABLE 12.—*Log of deep exploration borehole GSN 3709 at Sainyinan Daji, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Subartesian aquifer		
Rima Group:		
Sand, white, mainly fine, unsorted; has fragments of light-gray clay and crumbs of ironstone	27	125
Same as above unit but medium	30	155
Same as above unit but medium to coarse and including abundant fragments of ironstone	13	168
Peat	1	169
Sand, white, medium to coarse, unsorted. Fragments of gray clay	15	184
Clay, black, carbonaceous	4	188
Sand, light-gray, unsorted; and fragments of light-gray clay and peat	32	220
Clay, black, carbonaceous	44	264
Sand, light-gray, very fine	6	270
Clay, black, carbonaceous	22	292
Sand, white, very fine and fine, clean	28	320
Sand, fine and medium, white; includes bands of dark-green pyritiferous sandstone	60	380
Sand, gray, fine; and clay fragments	10	390
Clay, gray, silty	10	400
Sand, fine, gray; and grit	20	420
Sand, white, medium; includes traces of white and black clay and pyrite	40	460
Clay, gray; and pyritiferous sandstone	3	463
Sand, white, fine; and fragments of white clay and dark pyritiferous sandstone	77	540
Same as above unit but has a band of peaty clay	10	550
Same as above unit but has less clay	10	560
Confining layer		
Clay, black, silty; includes a band of peat between 580 and 590 ft	40	600
Mudstone and pyrite	2	602
Clay, black, silty; and pyrite	28	630
Sand, white, loose	10	640
Clay, dark-gray, silty	25	665
Sand, white, fine	4	669
Clay, gray, silty	15	684
Subartesian aquifer		
Sand, light-gray, medium	43	727
Clay, light-gray	13	740

TABLE 12.—*Log of deep exploration borehole GSN 3709 at Sainyinar Daji, Sokoto Emirate, Sokoto Province*—Continued

Lithologic description	Thickness of unit (feet)	Depth (feet)
Subartesian aquifer—Continued		
Gundumi Formation:		
Sand, white, medium to coarse, unsorted. Water bearing; subartesian. Water level 5 ft below land surface	94	834
Siltstone, black, clayey	32	866
Sand, white, fine to medium, firm	34	900

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