Ground Water in the Teresina-Campo Maior Area, Piauí, Brazil

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1663-G

Prepared in cooperation with the Superintendência do Desenvolvimento do Nordeste of Brazil under the auspices of the U.S. Agency for International Development

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By HARRY G. RODIS *and* EDSON F. SUSZCZYNSKI

CONTRIBUTIONS TO HYDROLOGY OF LATIN AMERICA AND THE ANTILLES

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CONTENTS

ILLUSTRATIONS

TABLES

CONTRIBUTIONS TO HYDROLOGY OF LATIN AMERICA AND THE ANTILLES

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By Harry G. Rodis and Edson F. Suszczynski

ABSTRACT

The Teresina-Campo Maior area lies in a presently developing farming and grazing region near the margin of drought-prone northeast Brazil where irrigated farming offers the best potential for economic development. The area comprises 9,700 square kilometers largely of catinga-covered tabular uplands which are drained by the perennial Rio Parnaíba. The climate is hot and humid most of the year but with distinct wet and dry seasons. Temperature extremes range from 20°C to 39°C and the annual rainfall averages 1,200 millimeters.

The area's ground-water reservoir is contained chiefly in sandstone aquifers of six westward-dipping sedimentary rock formations, all part of the Maranhão sedimentary basin. The youngest of these formations, namely the Piauí (Pennsylvanian), Potí (Mississippian), Longá (Upper Devonian), and Cabeças (Middle Devonian), contain the principal aquifers. Precipitation is the primary source of recharge to these aquifers and is more than sufficient to replenish current withdrawals from wells. Underlying the principal aquifers are the untapped Pimenteiras and Serra Grande Formations (both Lower Devonian) which in areas adjacent to the report area are moderately good to excellent water producers. These aquifers are recharged principally by lateral inflow from the east. Water also occurs in the alluvial deposits (Quaternary) underlying the flood plain of the Rio Parnaíba but recurrent and uncontrolled flooding at present (1966) precludes their development. Of little economic importance, because they lie above the zone of saturation, are the thin erosional remnants of the Pastos Bons (Upper Triassic), Matuca, and Pedra de Fogo (both Permian) Formations.

There are in the report area about 200 drilled wells most of which are pumped with power-driven engines. The wells range from 40 to 500 meters deep but most do not exceed 150 meters, and practically all are completed open hole. Yields range from 500 liters per day for 6-inch-diameter domestic wells to 240,000 liters per hour for 10-inch high-capacity municipal wells. Although there are many more dug wells than drilled wells, dug wells account for less than 1 percent of the current (1966) draft.

The current annual withdrawal from the principal aquifers is approximately 5 million cubic meters of which almost half is used for municipal supply and the rest for rural household and irrigation uses. Additional water for public supply is available from aquifers now being pumped, and larger yields probably could be obtained from rural wells designed to take full advantage of the aquifer.

Analyses of 28 samples show that the chemical quality of the water is well below the accepted limits of mineral concentration for most uses. Water from the Longá Formation averages 842 milligrams per liter in total dissolved solids and is more mineralized than that in the Piauí and Potí Formations which contain water averaging less than 300 milligrams per liter. The water in the Piauí and Potí aquifers is the most suitable in the area for irrigation and has SAR values of C1–S1 and C2–S1.

The quantities of water currently being used for irrigation are relatively small (600,000 cubic meters annually) but will increase substantially when intensive irrigation becomes a reality. Divisão de Hydrogeologia da Superintendência do Desenvolvimento do Nordeste estimates that about 2,500 million cubic meters of water per year would be needed to irrigate about 250,000 hectares in the Teresina-Campo Maior area (about 25 percent of the total area). This goal, however, is not likely to be realized as the water requirement is five times the estimated natural recharge to the aquifers of the area.

Most of the water-bearing formations in the report area have barely been tapped and can be developed a great deal more. In fact, the current annual withdrawal from the principal aquifers is less than 0.0025 percent of a conservative estimate of annual replenishment from rainfall. Additionally, only the upper one-third of the principle water-bearing formations have been penetrated by wells. Development of water from the deeper formations, however, will lag behind that of the shallower aquifers because well construction and pumping costs will inhibit their development under current (1966) economic conditions.

INTRODUCTION

PURPOSE AND SCOPE OF REPORT

The Teresina-Campo Maior area is part of a traditionally subsistance-level farming and grazing region but has ample rainfall and an abundance of virtually untapped ground water. This report points out opportunities for enhancement of the welfare of the people living in the area by developing this ground-water resource for irrigation, industrial, and stock use. The purpose of this report is to describe the basic features of the regional occurrence, availability, and chemical quality of the ground water for those who will eventually develop and manage the resource. The report should also be of interest to economists, government officials, and others who are actively engaged in the agricultural and industrial development planning for the region. The surface-water resources, although they are important and offer great potential, are beyond the scope of this report.

The study of the geology and ground-water resources of the Teresina-Campo Maior area was made by Divisão de Hidrogeologia da SUDENE (Divisão de Hidrogeologia da Superintendência do Desenvolvimento do Nordeste) in cooperation with USAID (U.S. Agency for International Development) as part of a general program to evaluate the ground-water resources of selected areas in northeast Brazil. The program was under the general supervision of Geraldo Gusmão, Chief of the Divisão de Hidrogeologia da SUDENE and Stuart L. Schoff, U.S. Geological Survey, who was in charge of the ground-water program in northeast Brazil for USAID. This investigation was carried out by Harry G. Rodis, U.S. Geological

Survey, who was assigned to work with SUDENE under the auspices of USAID, and by Edson F. Suszczynski, geologist of the Divisão de Hidrogeologia da SUDENE. Technical, administrative, and drafting support to the program were provided through the offices of George C. Taylor, Jr., U.S. Geological Survey.

LOCATION OF AREA

The Teresina-Campo Maior area lies in northeast Brazil, about 900 km (kilometers) northwest of Recife in the northwestern part of the State of Piauí (fig. 1). Its geographic boundary on the west is formed by the Rio Parnaíba and on the north, south, and east the boundaries are arbitrarily marked by lines of latitude and longitude shown on plate 1. Geologically, the report area is on the eastern flank of the Maranhão sedimentary basin which extends over an area of about 185,000 sq km

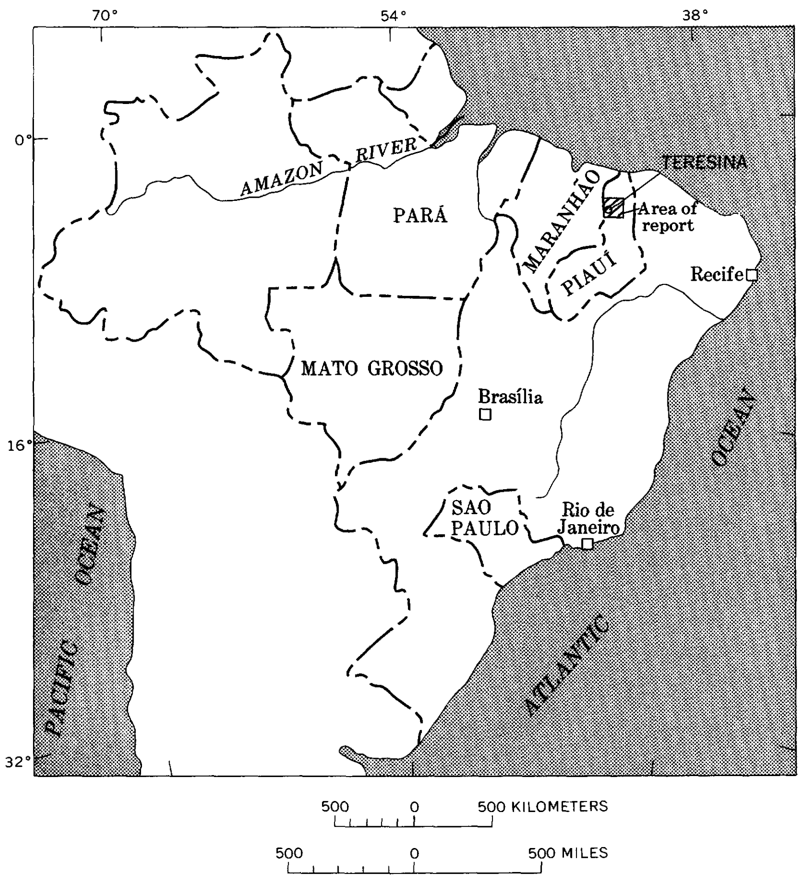

FIGURE 1.—Location of report area.

(square kilometers). It comprises about 9,700 sq km and includes most of the municipalities of Teresina, Altos, Campo Maior, União, and José de Freitas and parts of the municipalities of Barras, Demerval Lobão, Beneditinos, and Mosenhor Gil. Teresina, the principal city, commercial center, and capital of Piauí, had a population estimated at 90,000 persons in 1966.

PREVIOUS REPORTS

Several geologists have studied the geology and ground-water resources of the Maranhão basin, but most of the work has been of a reconnaissance nature and none has dealt with the particular problems of the Teresina-Campo Maior area. The major contributions are described in the following paragraphs, but a more complete listing is offered in the "Selected References" at the end of this report.

The first regional geologic studies of the Maranhão basin were completed in 1909 by Lisboa (1914). Later, the stratigraphic and structural relationships of the rocks of the basin were systematically studied and described by such workers as Small (1914), Campbell, Almeida, and Silva (1949), Albuquerque and Dequech (1950), and by Kegel (1953). A geologic map of the Maranhão basin, published by Pétrobras in 1963 at a scale of 1:1,000,000 summarizes the contributions of these workers and includes new data obtained from deep oil test wells.

The first significant ground-water study of the Maranhâo basin was made by Small (1914). More recently comprehensive regional investigations were undertaken by Kegel (1955 and 1961), Blankennagel (1952, 1955, and 1962) and Figueiredo, Chaves, Dalia, and Vasconcelos (1964). In a report on Campo Maior, Mente and Duarte (1962) contributed data on new water wells.

METHODS OF INVESTIGATION

Field hydrologic and geologic data used for this report were collected during 22 days of field reconnaissance made intermittently between October 1965 and January 1966. Antecedent hydrogeologic and related supplementary data previously obtained by others were assembled, compiled, and evaluated from existing reports and maps. Most important were well records furnished by the Teresina offices of DNOCS (Departamento National de Obras Contra as Secas) and DNPM (Departamento Nacional da Producão Mineral).

More than 70 wells were visited by the writers during field reconnaissance, and measurements of well yields and water levels were made wherever possible. Information on the recent performance of many of the wells and changes in the taste or physical appearance of the water was obtained from well owners and users. Firsthand information on the physical characteristics of the several aquifers was obtained by examining cuttings from wells under construction. Water samples for laboratory chemical analyses were collected at selected wells, and water temperatures were measured at wellheads. During the latter part of the field reconnaissance, altitudes of selected wells were determined by a barometric survey using bench-mark data established by the Second Army Battalion of Teresina.

ACKNOWLEDGMENTS

Acknowledgment is made to the many farmers and government officials who provided data on wells and other relevant information. The willing cooperation of Dr. Mamede of DNPM and the administrative staff of DNOCS in furnishing data on wells is greatly appreciated. Acknowledgment is also made to Captain Ferreira of the Second Army Battalion of Teresina for his valuable assistance in furnishing bench-mark data.

GEOGRAPHY

TOPOGRAPHY, DRAINAGE, AND VEGETATION

The Teresina-Campo Maior area is a part of the tabular uplands, a physiographic division of eastern Brazil, that extends from Piauí, Maranhão, and Pará in the north, to eastern Mato Grosso and São Paulo in the south (James, 1959, p. 25).

Except for the Rio Parnaíba valley with its broad sloping terraces, the report area is a gently undulating upland interrupted locally by moderately incised stream valleys and isolated hills. Altitudes over most of the uplands range from 75 to 175 meters above mean sea level. The highest point in the area with an altitude of more than 200 meters is in Serra Grande, 10 km (kilometers) south of Campo Maior, whereas the lowest point, about 45 meters, is on the Rio Parnaíba flood plain north of União.

The report area lies entirely within the Rio Parnaíba basin of which the northward flowing Rio Parnaíba is the only perennial stream. In the report area, the basin includes three watersheds, that of the Rio Parnaíba proper, the Rio Potí which drains into the Parnaíba several kilometers north of Teresina, and the Rio Longá which drains northward and finally empties into the Rio Parnaíba about 250 km northeast of Teresina.

The type and density of vegetation in the area is clearly related to both topography and drainage. Catinga, a tropical scrub woodland consisting of low thorny deciduous trees and a mixture of coarse savannah-type grasses, covers most of the upland east of the Rio Parnaíba valley. On the broad, well-drained slopes of the upland the catinga is low, usually less than 3 meters high, and the trees are widely spaced. In poorly drained areas, however, such as in the bottoms of broad or incised stream valleys and in topographic lows, the catinga is dense and the trees stand as much as 10 meters high. Dense and luxuriant vegetation consisting of a variety of palms, high savannah grass, and giant ferns cover the bottom lands and sloping terraces of the Rio Parnaíba valley.

CLIMATE

The climate in the Teresina-Campo Maior area is hot and humid, and according to Köppen and Trewartha's classification of climates, the area is "Tropical Savanna" with a distinct dry season but without a cool season (Trewartha, 1943, p. 517). The mean annual rainfall as shown in figure 2 ranges from a high of 1,404 mm (millimeters) at José de Freitas in the north-central part of the area to 1,147 mm at Campo Maior in the east. Over most of the area more than 90 percent of the rain occurs between December and May and usually falls in high-intensity storms of short duration.

Figure 2 compares graphically the average monthly rainfall for José de Freitas, Teresina, União, and Campo Maior where the highest rainfall occurs in March and the lowest in August. Although it lies near the edge of the drought polygon of northeast Brazil (Freise, 1937), the report area is little affected by gross variations in annual rainfall which create frequent droughts in other parts of northeast Brazil.

The mean annual air temperature in the area is 28°C and with temperature extremes of 20°C and 39°C common to most localities. The relative humidity is generally 75 percent or more most of the year.

ECONOMIC AND CULTURAL FEATURES

The population of the report area is 225,000 (1960 estimate) of which 40 percent live in urban areas and 60 percent live on farms. In recent years, the percentage of people living in rural areas has declined because of the comparatively higher wages offered in the towns of Teresina, Campo Maior, José de Freitas, Altos, and União.

The economy of the area is dependent predominantly on dry farming and cattle raising and much less on agriculture based on irrigation. Rice, cotton, corn, mandioca, and beans are the principal crops raised and consumed locally, whereas nuts from the carnauba tree provide a wax which is exported. Nuts of the Babacú and Burití palms are used for making vegetable oils and sweets, much of which are also exported. Irrigated agriculture although expanding in recent years still provides only subsistence quantities of bananas, oranges, lemons, and papayas for local urban markets. Less than 1 percent of about 250,000 hectares (25 percent of the total report area) of potentially irrigable land is now being irrigated (SUDENE, 1963). A growing number of small manufacturing and food-processing plants depend almost entirely on local agriculture for raw materials.

Roads and transportation facilities in the area and to other points in northeast Brazil are now barely adequate and must be improved to support economic development. Most major towns are connected by a network of all-weather roads, and twice-weekly rail service is available from Teresina to Altos, Campo Maior, and São Luís in Maranhão. The

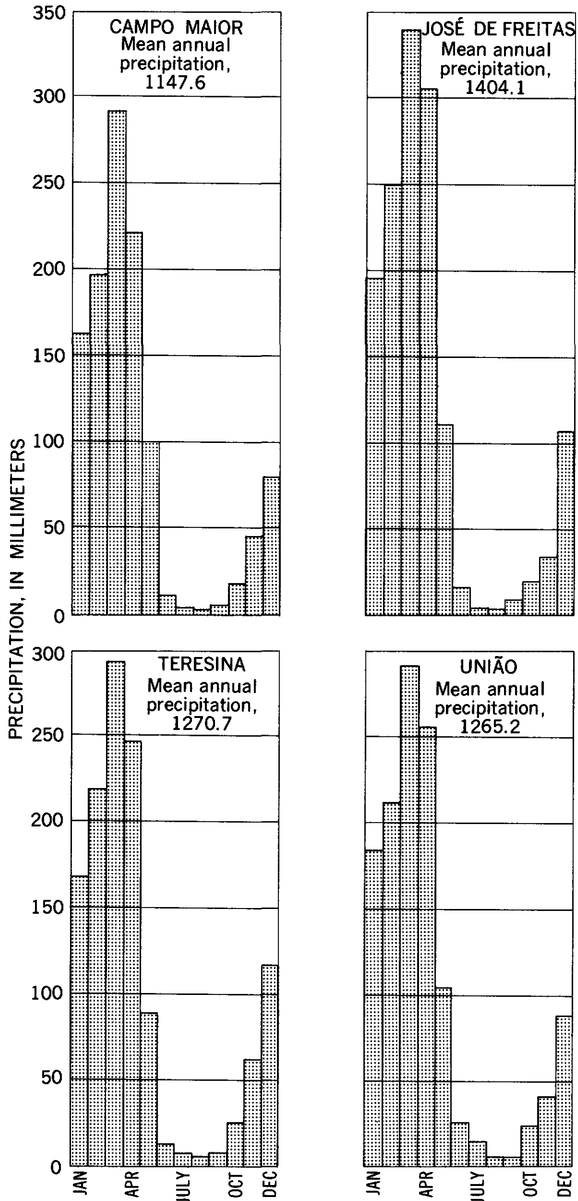

FIGURE 2—Average monthly precipitation, 1930–58, for Campo Maior, José de Freitas, Teresina, and União.

Rio Parnaíba, which is navigable by small boats to nearby ports on the Atlantic Ocean, provides means for inexpensive haulage of agricultural products.

GEOLOGY

REGIONAL GEOLOGIC SETTING

The Teresina-Campo Maior area lies on the eastern flank of the Maranhão basin, one of the most extensive sedimentary-rock basins in northeast Brazil. The basin underlies an area of more than 400,000 sq km with the sedimentary sequence approximately 3,000 meters thick near its center. The sedimentary-rock formations of the basin range from Devonian to Cretaceous in age and consist mostly of clastic sediments deposited in cyclic environments ranging from shallow marine to brackish and fresh-water conditions. The formations have an average initial dip of less than 1 degree and show no evidence of major deformation, although normal gravity faults are common especially in association with Jurassic diabase intrusions.

SUMMARY OF STRATIGRAPHY AND AREAL GEOLOGY

All the sedimentary formations of the Maranhão basin, except those of the Cretaceous, are represented in the report area. The stratigraphic sequence of the units is well established and summarized in table 1. The subsurface stratigraphic relationships are shown in the geologic section on plate 1. The rocks were formed during the Devonian, Mississippian, Pennsylvanian, Permian, and Late Triassic Periods and as indicated on plate 1 all are transected by Jurassic diabase dikes and sills. The lowermost formation, the Serra Grande, rests unconformably on an irregular and westward sloping Precambrian rock surface. The sedimentary sequence has a combined thickness of approximately 2,000 meters in the report area and a regional westerly dip of about 1 degree.

The generalized geologic map on plate 1 shows the extent and distribution of formations exposed in the report area. All formations underlying the area are exposed at the surface except for the Serra Grande and the Pimenteiras. Beginning with the Cabeças Formation in the northeast and extending southwestward over most of the area are successively younger rocks of the Longá, Potí, Piauí and Pedra de Fogo Formations. All these have a pronounced northwest lineation. Contrasting with the older formations, the younger Matuca and Pastos Bons Formations are irregularly distributed in the western part of the report area where they form the south side of a northwest-trending gravity fault. Quaternary alluvial deposits underlie the flood plain of the Rio Parnaíba and tributary valleys, however, their extent cannot be shown owing to the small map scale on plate 1.

ROCK FORMATIONS AND THEIR WATER-BEARING PROPERTIES

The principal aquifers now supplying the Teresina-Campo Maior area with water are in the Longá, the Potí, and the Piauí Formations. The Cabeças Formation contains an important aquifer only in the extreme northeast corner of the report area. Although the underlying Pimenteiras and Serra Grande Formations are probably water bearing, they have not as yet been explored by wells because of their relatively great depth in the report area. The Pedra de Fogo, Matuca, and Pastos Bons Formations are in most places very thin and sporadically distributed and are not considered important sources of water. The Quaternary alluvium is locally water bearing, however, recurrent flooding in stream and river valleys inhibit ground-water development in the flood plains.

In the following discussion, ground-water conditions in each of the several formations are described in more detail. The diabase of Jurassic age is not described here because little is known about its subsurface extent or its water-bearing character in the report area.

IGNEOUS AND METAMORPHIC ROCKS (PRECAMBRIAN)

Igneous and metamorphic (crystalline) rocks of Precambrian age form the broad pre-Devonian surface that floors the Maranhão sedimentary basin and in the report area unconformably underlie the Serra Grande Formation at a depth of approximately 2,000 meters below land surface. Where they are exposed to the east of the edge of the Maranhão basin, the Precambrian rocks consist principally of schist and gneiss with some granite, quartzite, limestone, and pegmatite. Because of their inherent, impermeable character and their great depth, the crystalline and metamorphic rocks are not considered an important source of ground water in the Teresina-Campo Maior area.

SERRA GRANDE FORMATION (LOWER DEVONIAN)

In the report area, the Serra Grande Formation rests on Precambrian crystalline rocks, but is not exposed at the surface, nor has it been penetrated by wells at depth. The formation does, however, crop out at the surface some 90 km east of the report area where it forms the eastern edge of the Maranhão basin. There it consists of medium to thick-bedded and massive permeable sandstone which in some places is interbedded with thin strata of shale and siltstone. The sandstone is composed of fine to coarse subangular and uncemented quartz grains, is commonly cross-bedded and jointed, and ranges in color from tan to reddish brown. Both the shale and siltstone are sandy, are generally soft, and range in color from brown to reddish brown. In the eastern part of the Teresina-Campo Maior area the depth to the top of the Serra Grande Formation is esti-

TABLE 1.—*Generalized stratigraphic section for the Teresina-Campo Maior area*

Geologic age			Formation or rock unit (pl. 1)	Approximate thickness (meters)	Lithologic characteristics	Water-bearing properties
Cenozoic	Quaternary	Holocene and Pleistocene	Alluvial deposits	0–70	Unconsolidated sand, silt, clay, and gravel in flood plains and terraces of Rio Parnaíba and larger tributaries.	Ground water occurs in permeable sand and gravel beneath flood plains. Small bodies of perched ground water occur locally in alluvial terraces.
Mesozoic	Jurassic		Diabase	?	Extent and character in report area unknown.	Ground-water potential largely unknown.
Mesozoic	Triassic	Late Triassic	Pastos Bons	0–20	Consolidated massive and crossbedded fine- to coarse-grained light-gray sandstone.	Generally above the zone of saturation and not water bearing.
	Permian		Matuca	0–50	Soft reddish claystone and siltstone.	Virtually not water bearing.
	Permian		Pedra de Fogo	0–50	Consolidated and thin interbedded siltstone, sandstone, and chert in upper part. Consolidated fine- to medium-grained crossbedded light-gray sandstone. Locally friable.	Generally not water bearing except locally in tabular partings in siltstone in zone of saturation.
	Pennsylvanian		Piauí	0–250	Consolidated sandstone, shale, and siltstone with some interbedded limestone.	Ground water occurs in permeable sandstone beds throughout formation. Basal sandstone is best aquifer.

Paleozoic	Mississippian		Poti	0–250	Predominantly consolidated fine-grained sandstone with some interbedded siltstone, shale, and low-grade coal.	Ground water occurs in permeable sandstone beds in zone of saturation.
	Devonian	Late Devonian	Longá	0–120	Predominantly shale interbedded with siltstone and sandstone.	Ground water occurs in sandstone beds and tabular partings in shale in zone of saturation.
		Middle Devonian	Cabeças	450–500	Predominantly well-consolidated medium to massively bedded sandstone with some interbedded siltstone and shale.	Ground water occurs in permeable sandstone beds in zone of saturation.
		Early Devonian	Pimenteiras	250–300	Lithology unknown in report area, but where exposed to east of report area consists of argillaceous sandstone, siltstone, and shale.	Water potential largely unknown, but to east of report area, wells produce modest amounts of water from sandstone aquifers.
			Serra Grande	750	Lithology unknown in report area, but where exposed to east of report area consists mostly of thick bedded and massive permeable sandstone with some thin beds of shale and siltstone.	Water potential largely unknown but to east of report area wells produce moderate to large quantities of water from sandstone aquifers.
Precambrian			Igneous and metamorphic rocks	?	Lithology unknown in report area, but where exposed to east of report area consists chiefly of schist and gneiss with some granite, quartzite, limestone, and pegmatite.	Water potential unknown.

mated at 600 meters but downdip and on the west side of the area it lies at a depth of about 1,200 meters (pl. 1).

Because of its relatively high permeability, numerous joints, and large intake or recharge area, the Serra Grande Formation forms an excellent aquifer where penetrated by wells. The wells east of the report area are highly productive and yield water of excellent quality, low hardness, chloride, and total dissolved solids. It is probable that these favorable aquifer characteristics may extend to reaches of the formation underlying the report area.

PIMENTEIRAS FORMATION (LOWER DEVONIAN)

The Pimenteiras Formation conformably overlies the Serra Grande Formation but like the Serra Grande has not been penetrated by wells in the report area (pl. 1). The Pimenteiras is comprised of two members, the Itaim or the lower member and the Picoas or the upper member. The Pimenteiras averages 275 meters thick and ranges from 400 to 1,000 meters below land surface in the report area (pl. 1). The formation is exposed at the surface approximately 75 km east of the report area.

Both members of the Pimenteiras Formation have similar lithology and consist of thin- to thick-bedded argillaceous and occasionally ferruginous sandstone and thin-bedded siltstone and shale. The sandstone is composed largely of fine- to medium-grained quartz, finer grained than the underlying Serra Grande, and generally brownish red in color. Generally, the sandstone is well consolidated and locally contains an abundance of hematite concretions. The siltstone, too, is well consolidated and ranges from grayish to reddish brown in color. The shale has the same color range as the siltstone and is laminated and micaceous.

No hydrologic information is available on the Pimenteiras in the report area. Data from wells 75 km east of the report area, however, indicate that both members of the formation can produce modest amounts of water to wells from sandstone aquifers. The water there is of poor quality, especially in the Picos Member where it has been reported to be locally unfit for drinking or irrigation.

CABEÇAS FORMATION (MIDDLE DEVONIAN)

The Cabeças Formation is exposed at the surface in the northeast corner of the report area, and downdip the top underlies the surface to a maximum depth of 600 meters (pl. 1). The formation is 450–500 meters thick and consists of three members—the Ipiranga, Oeiras, and Passagen of which only the Ipiranga has been penetrated by wells in the report area.

The few wells that penetrate the Cabeças are northeast of Campo Maior. Here, medium to massively bedded sandstone is the predominant rock type, with a few thin beds of siltstone and shale interbedded with the sandstone. The sandstone is medium to coarse grained, clean, friable, and light to brownish gray in color. It is composed of compact subangular to subrounded quartz grains, is locally micaceous, and in places contains ferruginous concretions.

Available data from the few wells tapping the Ipiranga Member indicate the formation is as good an aquifer here as it has proved to be in other parts of the Maranhão basin. Typical is well 37, 15 km northeast of Campo Maior, that is reported to yield 15,000 lph (liters per hour) after more than 48 hours of steady pumping with virtually no drawdown (table 2). The water is low in total dissolved solids content (226 mg/l (milligrams per liter)) and is similar in chemical composition to other wells tapping Cabeças aquifers northeast of the report area (Kegel, 1955, p. 38 and 46).

LONGÁ FORMATION (UPPER DEVONIAN)

The Longá Formation conformably overlies the Cabeças Formation and is exposed at the surface in a northwest-trending belt in the northeast part of the report area (pl. 1). The formation consists predominantly of dark-gray shale locally interbedded with light-gray siltstone and fine-grained sandstone. The shale is generally well laminated and well jointed, and locally is light to brownish gray, calcareous, and flaggy. The sandstone is light gray, well cemented, and thin to medium bedded.

Although predominantly composed of shale, the Longá Formation is penetrated by a number of wells which tap thin-bedded sandstone aquifers and water-filled tabular partings in the shale. Often, the tabular partings are a few meters above or below the sandstone and will yield more water than an overlying sandstone. In the vicinity of Campo Maior where the formation is exposed at the surface, water levels average 10 meters below land surface and wells tapping the Longá yield from 3,000 to 9,600 lph. Specific capacity of the Longá wells averages slightly higher than those tapping the Potí or Piauí Formations. Downdip where the Longá is 500 meters below land surface, its aquifers have high artesian pressure and can yield water to individual wells at rates of approximately 1,500 lph by artesian flow. Larger yields of as much as 6,000 lph can be obtained by pumping (table 2, well 6). Ground-water temperatures range from 32° to 34°C with the higher temperatures prevailing from the flowing wells and the more heavily pumped wells.

Kegel (1955) reports that in other parts of the eastern Maranhão basin, the Longá Formation generally yields water of good chemical quality equal to approximately that of the Piauí and Potí aquifers. In the report area, however, the water from the Longá is poorer in quality (average 840 mg/l in total dissolved solids) than that of the other principal aquifers.

POTÍ FORMATION (MISSISSIPPIAN)

The Potí Formation unconformably overlies the Longá Formation and is exposed at the surface in a belt approximately 25 km wide that extends

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TABLE. 2.—*Hydrologic data on selected wells in the Teresina-Campo Maior area*

Driller: DNOCS, Departamento Nacional de Obras Contra as Secas; DNPM, Departmento Nacional da Produção Mineral.
Use of water: D, domestic; Ir, irrigation; In, industrial; Ps, public supply.
Type of pump: D, diesel or electric; W, windmill; M, manual.

Well	Owner or user	Year drilled and by whom	Altitude at land surface (meters above mean sea level)	Depth (meters)	Diameter (inches)	Approximate water level (meters below land surface)		Yield (liters per hour)	Temperature (°C)	Use	Pump	Remarks
						Static	Pumping					
1	Municipio, Posto fiscal	1966, DNOCS	137	210	6	63.0	63.0	3,500	------	D	------	
2	Socopo (in front of Tabajara Club)	DNPM	59	535	8	Flowing	------	1,200	33.3	D, Ir	------	Water sold for local consumption.
3	Boqueirão	------	60	------	4	do	------	------	------	Ps	------	
4	João de Araújo Chaves	1965	64	6	39	------	------	21	------	D	M	
5	Petrobras test hole MA-2-PI	1964, Petrobrás	98	2,029	10	------	------	------	------	------	------	Abandoned.
6	Municipal supply of União (CESP)	DNPM	50	534	8	Flowing	------	[1] 6,000	32.8	Ps	D	
7	Lucimar Sobral	1965, DNPM	54	105	6	4.0	4.5	6,000	------	D	M	
8	Fazenda São Felipe de Severino	1962, DNPM	52	60	6	------	------	------	31.1	D	M	
9	Prisco Medeiros	DNPM	68	370	6	6.0	------	25	------	D	D	
10	Aguardente factory	DNPM	68	56	6	------	------	------	------	In, D	D	Used only 2–4 months per year.
11	São João de Leite Chaves	1963, DNOCS	63	92	6	8.0	------	6,000	31.1	D	D	
12	São Paulo farm of Ricardo Moura	1965, DNPM	122	65	6	25.0	33.0	10,000	28.8	Ir, D	D	Used to irrigate 1 hectare of oranges.
13	Fazenda, Coratá de José Carvalho Oliveira.	1963, DNPM	104	118	6	13.0	------	7,000	------	Ir, D	D	
14	João Freita de Caicara [2]	------	------	1	39	------	------	1,500	31.7	D	------	
15	Fazenda Campenas, Gaioso de Almeida Freitas.	1961, DNOCS	115	72	6	2.5	------	41	31.7	D	W	
16	Prefecture of City of José de Freitas	1959, DNOCS	115	60	8	3.0	------	10,000	30.0	Ps	D	Two similar wells 70 meters away.
17	Do	------	113	1.5	------	.5	------	------	------	Ps	M	Water supply for city power station.
18	Fazenda São João	DNPM	104	240	6	17.5	21.4	5,400	28.3	D	D	
19	Fazenda Buritizinho	DNPM	165	205	6	39.0	------	------	------	------	------	Obstruction in casing.
20	São Leonardo	DNPM	77	301	6	3.0	6.0	30,000	28.8	D	M, D	Flows during rainy season.
21	Jockey Club de Teresina	DNOCS	64	------	------	9.0	20.0	50,000	32.2	Ps	D	Supplies swimming pool.
22	Escola Agro-Técnica	1961, DNPM	------	198	10	4.0	12.0	45,000	------	Ir, D	D	
23	Fazenda São Francisco	DNPM	------	146	------	11.2	16.0	4,000	------	D	------	
24	Palmares, Ministério da Agricultura.	DNPM	141	112	------	37.0	38.0	4,000	28.8	Ir, D	D	
25	Batalhão Ferroviário	DNPM	127	122	------	15.0	18.0	8,000	------	D	D	
26	Fripisa do Campo Maior	1964, DNPM	125	33	------	12.2	14.2	41,000	35.0	In, D	D	Similar well 50 meters away.
27	Fazenda Vista Alegre	1957, DNPM	148	112	------	26.3	------	------	------	Ir, D	D	Two more wells on property.

28	Abeleira de Vicente Ribeiro	DNPM	140	23	----------	12.8	12.8	4,000	32.8	D	D	
29	Fazenda Caratá de José Carvalho Oliveira.	1961	104	13	39	12.5	--------	20	--------	D	M	
30	Fazenda Campinas Gaioso de Almeida Freitas.	--------------	115	7	40	5.5	--------	8	--------	D	M	
31	Colonia de Pescadores	DNPM	65	25	6	6.0	6.0	5,000	--------	D	------	
32	Fazenda Sambaiba de Clementino Pires.	DNPM	147	246	6	9.8	21.5	5,000	--------	--------	------	Abandoned.
33	Foge Homem, Hermogenes de Carvalho.	1964, DNPM	172	40	6	11.0	11.3	5,000	--------	--------	------	Not in use.
34	Fazenda da Cascata, do Gen. Oswaldo Miranda.	1962, DNPM	179	49	6	14.3	14.3	3,000	32.2	D	D	
35	Ministry of Agriculture	1948, DNOCS	125	36	6	7.0	--------	4,000	32.2	Ir, D	W	
36	Public water supply, Teresina, well 9.	1966, DNOCS	60	55	10	1.5	2.5	180,000	--------	Ps	D	
37	Fazenda Socorro José L. Ferreira.	DNOCS	123	31	6	5.0	5.0	15,000	32.0	D	M	
38	Raimundo Rocha	1960, DNOCS	126	47	6	6.0	--------	----------	31.1	D	M	
39	Carmem de Carvalho Veras	1954, DNPM	98	316	4	Flowing	--------	1,800	34.0	D	------	Water reported to kill grass.
40	Fazenda Remanso, Sen. Matias Olimpio [2].	--------------	---------------	---------	----------	do	--------	2,000	27.7	D	------	
41	Fazenda Buriti, Antonio Martins.	1962	70	280	----------	--------	--------	4,000	30.5	D	D	
42	Do	1965	72	200	----------	12.0	14.5	5,780	--------	--------	------	
43	Do	1948, DNOCS	84	35	----------	10.0	--------	1,200	31.1	In, Ps	W	
44	Do	DNOCS	106	22	----------	18.0	--------	----------	--------	In, Ps	W	
45	Prefecture of Altos	1964, DNOCS	155	102	----------	14.0	53.3	27,000	31.1	Ps	D	
46	Fazenda São João do Leite Chaves	--------------	63	9	38	6.5	--------	16	--------	D	M	
47	Dr. Jorge P. Mandeiros	1960, DNOCS	109	77	6	4.0	4.0	8,000	--------	D	M	Water supply for the AMR restaurant.
48	Dr. João Bashta Filho	--------------	147	---------	----------	--------	--------	----------	--------	--------	------	
49	Poço dos negros	DNPM	113	71	----------	5.5	9.2	7,000	31.1	D	M	
50	Dr. Nash Ferrais	--------------	161	1	----------	.7	--------	16	--------	D	------	
51	Town of Coivaras	1962, DNOCS	166	53	----------	16.0	18.0	5,400	--------	D	M	
52	Water supply of Teresina, well 6	DNOCS	---------------	42	10	5.0	5.7	240,000	--------	Ps	D	
53	Maria Pires Ferreira	--------------	147	17	1.5	11.0	--------	41	--------	D	M	
54	Povoado do Coivara	--------------	166	13	1.5	9.0	--------	41	--------	D	M	
55	Abeleira, de João Mariano	1966, DNPM	145	---------	6	--------	--------	----------	31.1	D	M	
56	Municipal water supply of Campo Maior.	1960, DNOCS	119	75	10	5.3	10.8	9,600	34.5	Ps	------	
57	Antonio ferreira do Nascimento	1959, DNOCS	128	150	6	16.0	25.0	----------	32.8	D	------	
58	Luis Pedro Pereira	1958, DNOCS	111	110	6	6.0	14.0	6,750	32.8	D	------	

[1] Yield obtained by pumping.
[2] Developed spring.

from the north-central to the east-central part of the report area (pl. 1). More than 60 percent of the formation consists of a light-gray friable and very fine grained sandstone; the remainder is made up of light-gray siltstone, gray to greenish-gray shale, and thin seams of low-grade coal. Sandstone predominates in the lower part of the formation and finer clastics in the upper. The formation ranges in thickness from zero along its surface contact with the Longá to 250 meters in the west where its top underlies the surface to a depth of as much as 200 meters (pl. 1).

Because the lower part of the Potí lies at or close to the land surface in most of the central and western parts of the report area, the sandstone aquifers are within easy reach of shallow wells. The permeability of the aquifers, however, varies considerably and drillers report that the formation yields from 1,000 to 30,000 lph to individual wells. The specific capacity for all wells ranges from 66 to 500 lph per meter of drawdown. Water levels in the wells range from a few meters to more than 9 meters below land surface; none of the wells visited by the writers were flowing. Ground-water temperatures measured at the wellheads range from 28° to 31°C.

The water of the Potí Formation is of fair chemical quality (500–1,500 mg/l total dissolved solids) and is suitable for drinking and general irrigation use. In general, the quality of the water from Potí aquifers in the report area is better than that in the underlying Longá but not as good as that of the overlying Piauí Formation. This relationship appears to hold true in other parts of the eastern Maranhão basin.

PIAUÍ FORMATION (PENNSYLVANIAN)

The Piauí Formation rests unconformably on the Potí and in the report area underlies more of the surface than any of the other geologic units (pl. 1). The formation ranges in thickness from zero where it pinches out against the Potí to more than 200 meters in the west. In the west where it is overlain by the Pedra de Fogo Formation, its top is as much as 250 meters below land surface (pl. 1). The formation consists mostly of sandstone, shale, and siltstone; thin lenses of light-gray fossiliferous limestone, calcite geodes, and pyrite crystals occur sporadically throughout the section. The sandstone is generally light gray and fine to coarse grained and much of it occurs in a massive bed in the basal part of the formation. The shale and siltstone are reddish brown and greenish gray and are found mostly in the upper part of the formation.

Because of its areal extent, the Piauí Formation was penetrated by more wells than any of the other geologic formations in the report area. The most productive aquifer of the formation is the basal sandstone although other aquifers in the formation also yield moderate quantities of water to wells. In the uplands where the formation is exposed at the surface, individual wells range in yield from 4,000 to 27,000 lph. Near Teresina, however, where the aquifers are in close proximity to the saturated alluvium of the Rio Parnaíba valley and induced infiltration from alluvium is probable, individual wells yield as much as 240,000 lph and have specific capacities ranging from 750 to 5,700 lph per meter of drawdown. Water levels in wells tapping Piauí aquifers range down to as much as 12 meters below land surface but a few wells visited by the writers flow for 1 or 2 months following the rainy season. The water is generally of good quality and contains less than 500 mg/l in total dissolved solids.

PEDRA DE FOGO FORMATION (PERMIAN)

The Pedra de Fogo Formation is exposed at the surface in the western part of the report area where it reaches a maximum thickness of about 50 meters (pl. 1). Erosion has removed most of what once was a thicker, more extensive rock unit.

The formation is divided into two parts—the Saraiva Sandstone Member in the lower part and an unnamed member consisting of interbedded siltstone, sandstone, and chert in the upper part. The Saraiva is thin and discontinuous in the report area. Where it occurs, though, it is light gray, fine to medium grained, rather friable and in some places is crossbedded. In the unnamed member, the sandstone is generally fine grained and well consolidated, whereas the chert is often oolitic and pisolitic.

The formation in the report area is not considered an important source of ground water, as it is almost completely devoid of permeable beds at least in the zone of saturation. Locally, however, water does occur in tabular partings in the siltstone in the zone of saturation. The absence of aquifers is evinced by four wells shown on plate 1 which were begun in the Pedro de Fogo Formation and finally completed in underlying formations.

MATUCA FORMATION (PERMIAN)

The Matuca Formation unconformably overlies the Pedra de Fogo Formation and is irregularly exposed at the surface in the western part of the report area. The formation is as much as 50 meters thick, and, where it has not been extensively eroded, it is conformably overlain by the Pastos Bons. The Matuca consists almost entirely of soft reddish claystone and siltstone; sandstone is conspicuously absent.

The formation is not an important aquifer in the report area largely because of the absence of permeable beds where it lies within the zone of saturation. This is typified by well 1, 7 km southeast of Teresina (pl. 1), which penetrated 40 meters of siltstone and claystone of the Matuca and Pedro de Fogo Formations, most of which is within the zone of saturation, before it was finally completed in the Piauí Formation.

PASTOS BONS (UPPER TRIASSIC)

The Pastos Bons Formation is the least extensive of the geologic units in the report area. The formation consists mainly of the Sambaiba Sandstone Member which often is used synonymously with the formation name. The sandstone is usually massive and crossbedded, light gray, and fine to coarse grained. It is so thin (less than 20 meters thick) and discontinuous in the report area that it is not considered an important aquifer.

ALLUVIUM (QUATERNARY)

Alluvial deposits are most extensive in the Rio Parnaíba valley where they form a flood plain and a series of narrow, highly eroded terraces. In the valley, the alluvial deposits attain a width of as much as 2 km and, below the flood plain, a maximum thickness of approximately 30 meters. The alluvium forming the terraces averages 40 meters in vertical thickness and is commonly gravelly or sandy. In the upper few meters of the flood plain the alluvium is silty, but drillers report that at depth it is predominantly sand and gravel. The alluvium in other parts of the report area is thin and discontinuous and is generally associated with intermittent streams and lakes.

The alluvium beneath the flood plain in the Rio Parnaíba valley has excellent potential as a ground-water source. Recurrent and uncontrolled flooding in the valley, however, preclude exploration and utilization of the aquifers under present economic conditions. The terrace alluvium is intermittently water bearing, and the ground water is discharged locally by springs during and following the rainy season.

The principles of the occurrence and movement of ground water which are fundamental to its understanding are discussed in some length in papers by Meinzer (1923a, 1923b, and 1932). The discussion that follows is a brief résumé of the more important of these principles, as they apply in the Teresina-Campo Maior area.

GROUND WATER

OCCURRENCE

The replenishment of the ground-water reservoir in the Teresina-Campo Maior area depends ultimately on rainfall. When it rains, a part of the water runs off in streams, a part is returned to the atmosphere by evaporation and by transpiration of plants, and a small part percolates downward to the zone of saturation and becomes ground water. Ground water then is defined as all subsurface water that lies within the zone of saturation, the zone in which the interstices of all rock materials are filled with water at or greater than atmospheric pressure.

Geologic strata within the zone of saturation capable of yielding water to wells in the Teresina-Campo Maior area are called aquifers. An aquifer usually includes a bed or a series of beds of a geologic formation but may include strata of several geologic formations. Aquifers are of two types—artesian and water table. An artesian aquifer is one that is confined between relatively impermeable strata; when the aquifer is penetrated by a well, the water which is under pressure will rise above the bottom of the confining bed. Water-table aquifers are not covered by impermeable strata, and the water table is free to rise and fall with changes in ground-water storage. Although water-table conditions exist in the alluvial deposits of the Rio Parnaíba and its tributaries, most of the ground water in the sedimentary rock aquifers of the Teresina-Campo Maior area is under artesian pressure.

The rate at which an aquifer can transmit water under hydrostatic pressure is its permeability and is dependent on the degree of interconnection of pore spaces. The finer grained sedimentary rocks—siltstone, claystone, or shale—such as those of the Matuca Formation, have a high porosity, but because of lack of interconnection between pore spaces they have low permeability. In other porous rocks, such as the sandstone of the Potí Formation or the alluvial sand and gravel of the Rio Parnaíba flood plain, the pore spaces are interconnected to some degree. If the interconnected pore spaces are sufficiently large, then the material has a high permeability; if the pore spaces are small and it takes substantial pressure to transmit water, the bed has low permeability. Unweathered crystalline rocks such as the Precambrian granite or the Jurassic diabase, which have almost no interconnected pore spaces, are considered virtually impermeable. However, many rocks of this type have secondary permeability along openings or crevices formed through structural stress and enlarged by the dissolving action of water.

The potentiometric surface of a water-bearing formation or aquifer is the level at which water stands in a well tapping the aquifer. For an unconfined aquifer this level is the water-table surface. For an artesian aquifer which is confined above and below by less permeable beds, the water is under pressure and the potentiometric surface is above the base of the upper confining bed.

AQUIFER SYSTEM

The upper limits of the ground-water reservoir underlying the Teresina-Campo Maior area are defined by potentiometric contours shown on plate 1 that extend through the Cabeças, Longá, Potí, and Piauí Formations. Hydraulically connected with these water-bearing formations and part of the aquifer system are the underlying aquifers of the Serra Grande and Pimenteiras Formations. Most of the Pedra de Fogo, Motuca, and Pastos Bons Formations, however, are not part of the aquifer system because they lie above the zone of saturation.

The slope and configuration of the potentiometric surface (pl. 1) coincides approximately with that of the land surface. The potentiometric contours slope northward and then westward from a high of 160 meters in the eastern part of the report area to 60 meters near the Rio Parnaíba. As is apparent from the spacing of the contours, the hydraulic gradient is relatively flat in an extensive area between Campo Maior and José de Freitas, then it declines rather steeply toward the west where it intersects the channel of the Rio Parnaíba.

RECHARGE

The ground-water reservoir underlying the Teresina-Campo Maior area is recharged by subsurface inflow from the adjoining aquifers to the east and by local precipitation that percolates downward to the zone of saturation either directly or from surface runoff. Subsurface inflow moves mainly into the lower part of the ground-water reservoir through the Cabeças, Pimenteiras, and Serra Grande Formations and replenishes the water contained in them. Recharge by lateral underground flow from the east is difficult to measure but is probably substantial.

When water from the deeper aquifers is developed and utilized then it would become necessary to evaluate quantitatively recharge from this source. Local precipitation, on the other hand, is the principal source of recharge to the upper part of the ground-water reservoir, namely in the Piauí, Potí, and Longá Formations and the upper beds of the Cabeças Formation.

The amount of precipitation that infiltrates to the zone of saturation within the Teresina-Campo Maior area is understandably a fundamental factor in estimating the amount of annual recharge. From precipitation records at the four stations shown on plate 1, it is estimated that the annual precipitation on the area averages about 1,270 mm. If conditions in other regions having comparable climatic and hydrologic environments can be assumed to apply, recharge in the report area may be conservatively estimated to be about 15 percent of the annual rainfall or about 2,000 cu m (cubic meters) per hectare per year, although the actual recharge is probably considerably more. In the Atlantic Coastal Plain of the United States, for example, where precipitation is approximately that of the report area, recharge to the zone of saturation from rainfall ranges from about 1,600 to 3,500 cu m per hectare per year.

MOVEMENT

Although some lateral movement of ground water takes place through all the rocks within the zone of saturation, the bulk of the flow is concentrated in the more permeable beds. Lateral ground-water flow through the Precambrian rocks where weathered and creviced zones are lacking is negligible.

Ground-water movement through the Piauí, Potí, and Longá Formations and the upper part of the Cabeças Formation is in a direction at right angles to the potentiometric contours shown on plate 1. The direction of movement is predominantly to the north and west and generally follows that of the surface drainage. In the southeast, between Altos and Campo Maior and in the southwest between Rios Potí and Parnaíba, both surface drainage and subsurface flow is northerly whereas in the west, between Altos, José de Freitas, and the Rio Parnaíba, the flow is westerly.

DISCHARGE

Water is removed from the zone of saturation in the Teresina-Campo Maior area naturally by evapotranspiration, by discharge into the Rio Parnaíba, by subsurface outflow to the west, and artificially by withdrawals from wells. Among these discharge factors, evapotranspiration is quantitatively important because the depth to the zone of saturation in most of the area ranges from only 2 to 20 meters below land surface. Although sufficient observational data are not available to determine the amount of water loss through evapotranspiration, a relatively large water loss takes place in river and stream valleys and other topographic lows where the water table is near the surface. Natural discharge into rivers takes place mainly in the western part of the report area where considerable ground water is perennially discharged into the Rio Parnaíba, principally by seepage through its banks and bottom. Here, too, quantitative data is lacking because river stage and base-flow measurements have not been made. The amount of natural discharge by lateral outflow, although unknown because of insufficient data, is probably considerable because of the thickness of the saturated aquifers (more than 2,000 meters) and moderate hydraulic gradient of the potentiometric surface (pl. 1).

Ground water is also discharged artificially from aquifers of the report area by withdrawals from drilled and dug wells. Withdrawals by pumping from all wells was estimated to be 5 million cu m in 1966 of which less than 1 percent is from dug wells. Withdrawals from both drilled and dug wells in the Teresina-Campo Maior area, although increasing in the past few years, have not measurably decreased ground-water storage. Assuming that the specific yield is 5 percent and the storage capacity is about 500 cu m for each hectare-meter of saturated rock, the general water levels in the ground-water reservoir of the report area would decline only 1 meter in 97 years at the rate of withdrawal prevailing in 1966. This estimate of water-level decline is conservative because the ground-water reservoir undoubtedly receives recharge from precipitation. Drillers report that water levels in wells have remained virtually unchanged during the past decade in the report area even in the heavily pumped localities near Teresina and Campo Maior.

CHEMICAL QUALITY

Laboratory chemical analyses of water samples from 28 wells show that ground water in the Teresina-Campo Maior area is generally well within the accepted limits of concentration of mineral matter for use by man, plants, animals, and machines. The locations of the wells sampled are shown on plate 1, and the analytical data and geologic source of water are given in table 3. All samples except that for well 14, a developed spring, and well 17, a dug well, were taken from drilled wells and represent hydrologic and hydrochemical conditions that seem to be prevalent in most of the area. The laboratory analyses were supplemented by 30 field determinations of total dissolved solids, chloride, hardness, iron, and pH. These were taken from wells at intermediate locations and provide continuity of water-quality information.

RELATION TO GEOGRAPHIC AREA AND GEOLOGIC SOURCE

The geographic distribution of dissolved solids in water from wells is illustrated on plate 1 by map patterns representing four ranges in mineralization of the water. Although well data are too sparse to draw firm conclusions, the patterns do show that certain sectors in the report area tend to yield water of similar dissolved-solids content. For example in an area bounded by Teresina, Altos, and José de Freitas, most wells yield water containing less than 250 mg/l in total dissolved solids. Wells near the Rio Parnaíba yield water ranging from 250 to 500 mg/l in dissolved solids, whereas wells in the vicinity of Campo Maior yield water of 500–1,500 mg/l in total dissolved-solids content.

In the report area there is no direct relationship between the depth of wells and the total dissolved-solids content of the water, except that the deepest wells (2, 6, and 39) yield water with the highest mineral content.

Chemical analyses of water from wells listed in table 3 show there is a rather direct relation between the chemical quality and geologic source of the water. This relationship is demonstrated by comparing the water quality from each of the principal aquifers in table 4 and by the areal distribution of these waters shown on plate 1.

Water from Piauí aquifers is characterized by nearly consistent low dissolved-solids content, by low hardness, and by a slightly acidic pH (table 4). Chemical analyses of samples from 12 wells that tap Piauí aquifers show the total dissolved-solids content to range from 48 to 459 mg/l and the total hardness from 12 to 185 mg/l. The average of the other chemical constituents such as calcium, magnesium, sodium, potassium chloride, sulfate, and bicarbonate is correspondingly less than that for other principle aquifers.

Water from Potí aquifers although generally poorer in quality than that from Piauí aquifers is regarded as being of good quality. The water aver-

TABLE 3.—*Chemical analyses of water from selected wells in the Teresina-Campo Maior area*

[Results in milligrams per liter except as indicated. Analyses by the SUDENE Hydrologic Laboratory, Recife, Brazil, Feb. 5 to Mar. 15, 1966]

Well	Depth (meters)	Water-bearing formation	Total dissolved solids	pH	Total hardness as $CaCO_3$	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Chloride (Cl)	Sulfate (SO_4)	Bicarbonate (HCO_3)	Iron (Fe)	Nitrite (NO_2)	Nitrate (NO_3)
2	535	Longá	1,880	6.8	95	22	9.7	550	23	562	69	560	----	----	----
6	534	do	982	6.9	125	30	12	295	10	365	22	301	----	----	----
8	60	Piauí	245	7.1	126	19	19	10	6.0	6.5	27	148	T	----	----
9	370	do	300	6.5	185	40	21	10	11	35	107.6	73	----	----	----
11	92.5	do	459	7.1	54	13	5.3	93	5.0	13	24	268	----	----	----
12	65	do	187	6.3	68	11	10	4.0	25	13	22	83	----	----	----
13	118	do	62	6.3	23	3.6	3.4	6.5	5.0	7.0	16	19	T	----	----
14[1]	.4	do	77	6.4	23	6.8	1.4	6.4	6.4	5.0	20	26	----	----	----
15	72	Potí	213	7.2	88	18	10	15	5.9	8.0	20	120	----	----	----
16	60	do	379	6.7	151	33	16	34	9.4	37	24	190	----	----	----
17[2]	1.5	Piauí	110	6.4	29	6.8	2.9	12	6.0	6.0	18	49	----	----	T
18	240.7	Potí	140	6.9	17	12	4.1	7.1	16	25	6.7	50	----	----	----
20	301	do	447	7.2	102	26	9.2	72	4.5	12	15	288	----	----	----
21	------	------	380	7.5	60	14	5.8	115	4.5	25	18	298	----	----	----
24	112	Piauí	205	5.9	82	17	9.7	27	22	87	21	24	----	----	----
27	112.5	do	256	6.6	80	16	9.7	22	21	32	22	102	----	----	----
28	23	Longá	240	7.4	78	12	12	30	4.2	4.0	21	149	----	----	----
34	49	do	403	6.8	33	6.0	2.7	13	6.2	8.5	20	251	T	----	----
35	36	do	630	7.5	60	13	6.8	150	9.8	90	35	288	----	----	----
37	31	Cabeças	226	6.9	50	8.0	7.3	43	7.5	50	48	41	----	----	----
38	47	Potí	510	7.2	82	11	13	102	14	68	35	234	----	----	----
39	316.8	Longá	1,070	7.4	90	20	1.7	367	10	320	14	500	----	----	----
41	280	Piauí	404	7.4	60	11	7.9	135	6.2	45	16	317	----	----	----
43	35	do	48	6.0	12	3	1.2	2.9	6.0	1.3	12	17	----	----	----
45	102	do	164	7.2	59	20	2.2	12	6.4	4.0	24	76	----	----	----
49	71.7	Potí	298	6.3	121	28	12	20	6.2	8.5	23	168	----	----	----
56	75	Longá	842	7.3	68	13	8.7	217	10	150	41	354	----	----	----
57	150	do	678	7.1	72	16	7.8	162	2.4	90	41	317	----	----	----

[1] Developed spring.
[2] Dug well.

TABLE 4.—*Comparative characteristics of water quality from the Longá, Potí, and Piauí Formations*

[Results in milligrams per liter, except as indicated. Analyses made by the SUDENE Hydrologic Laboratory, Recife, Brazil. Water temperatures were measured between Jan. 17 and Feb. 2, 1966]

	Longá (eight wells)		Potí (six wells)		Piauí (12 wells)	
	Range	Median	Range	Median	Range	Median
Total dissolved solids.	240–1880	842	140–510	379	48–459	205
pH	6.8–7.5	7.3	6.3–7.2	7.2	5.9–7.4	6.5
Total hardness as $CaCO_3$.	33–125	78	17–151	82	12–185	60
Calcium (Ca)	6.0–30	16	11.3–33	26	2.8–40	13
Magnesium (Mg)	1.7–12	9	4.1–16	12	1.2–21	7.9
Sodium (Na)	13–550	217	7.1–102	34	2.9–135	12
Potassium (K)	2.4–23	10	4.5–16	9	5.0–25	6.4
Chloride (Cl)	4.0–562	150	8.0–68	25	1.3–86	13
Sulfate (SO_4)	14–69	35	6.7–35	23	12–108	22
Bicarbonate (HCO_3).	149–650	317	50–288	190	17–317	76
Temperature °C	32.2–34.5	32.8	28.3–31.7	31.1	28.8–31.7	31.1

ages 380 mg/l in total dissolved-solids content and 82 mg/l in hardness (as against 205 mg/l in total dissolved-solids and 60 mg/l in hardness for the Piauí).

As compared to Piauí and Potí aquifers where total dissolved-solids content is relatively low, the total dissolved-solids content of water from Longá aquifers is high. It averages 842 mg/l and ranges from a low of 240 mg/l to a high of more than 1,800 mg/l. Table 4 also shows that the concentrations of individual ions in the Longá water are correspondingly higher than those in water from the Piauí and Potí aquifers, especially sodium, chloride, and bicarbonate. The Longá water is, however, generally softer than that of the Potí. Presumably, the water in the Longá has been naturally softened by base exchange, but in this process the dissolved-solids content has been increased.

The relatively small amount of mineral matter dissolved in the water of the Piauí and Potí aquifers suggests that the circulation of water through these aquifers is relatively active and that the water has spent a relatively short time in transit through them. On the other hand, the larger amounts of dissolved mineral matter in the water of the Longá aquifer, especially in the west where it is the deepest, suggest a longer transit and residence of the water in its lateral movement from the intake area.

Chemical analyses of water from other formations in the report area are virtually nonexistent. The water quality of the Cabeças Formation is represented only by well 37 (table 3), however, field determination of Cabeças water quality from nearby wells verify the low mineral concentration (226 mg/l) shown by the analyses. Chemical analyses of water from the Serra Grande Formation are not available. Where penetrated by wells to the east of the report area, however, the water is reported to be of excellent chemical quality. On the other hand, where the Pimenteiras Formation has been penetrated by wells, the water is often reported to be of poor chemical quality. Also, water from the alluvium of the Rio Parnaíba valley has not been analyzed but is reported to be of good to fair chemical quality.

SUITABILITY OF WATER FOR DOMESTIC USE

With a few exceptions, the water from wells tapping aquifers in the Teresina-Campo Maior area is potable and acceptable for normal domestic use. Acceptable limits of concentration of constituents ordinarily found in water have been proposed by the U.S. Public Health Service (1962, p. 7) and are as follows for some of the constituents reported in tables 3 and4.

Constituent	*mg/l*
Chloride (Cl)	250
Sulfate (SO_4)	250
Nitrate (NO_3)	45
Iron (Fe)	.3
Total dissolved solids	500

Except for total dissolved solids, all the water analyses shown in table 3 indicate water quality within the limits suggested by the U.S. Public Health Service. Empirically, the limits of concentration of total dissolved solids tolerated by residents of the report area is about 1,500 mg/l. Many persons though, including visitors, suffer occasional organic discomfort caused by drinking water with dissolved-solids content of more than 1,000 mg/l.

Marked traces of nitrate were detected in the water from dug well 17 (table 3) but not enough to indicate pollution. The traces found in the dug well and not in the drilled wells suggest that the nitrate content in water from other dug wells should be tested before use for human consumption.

SUITABILITY OF WATER FOR IRRIGATION

Several factors in addition to mineral content determine whether the ground water of the Teresina-Campo Maior area is suitable for irrigation use. Among these are the amount of water applied to the soil, the amount and distribution of rain, the subsurface drainage, and the physical and chemical character of the soil. If concentrations are not excessive, some dissolved salts favor plant growth, but others are harmful to plants or to soils. The total concentrations of dissolved salts in water range from a few milligrams to many milligrams per liter, but in most irrigation waters are in the range of 100–1,500 mg/l.

The U.S. Salinity Laboratory Staff (1954, p. 69–81) states that the most important characteristics of water for irrigation are: (1) Total concentration of soluble salts, (2) relative proportion of sodium to other cations, (3) concentration of boron or other elements that may be toxic, and under some conditions (4) the bicarbonate concentration as related to the concentration of calcium plus magnesium. The system for classifying irrigation water on the basis of electrical conductivity and sodium content is explained in the following paragraphs.

The total concentration of soluble salts can be adequately expressed for purposes of diagnosis and classification in terms of electrical conductivity, which is useful because it can be readily and precisely determined.

Water with conductivity below 750 micromhos per centimeter at 25°C is satisfactory for irrigation insofar as salt content is concerned, although certain salt-sensitive crops may be damaged by water having conductivity in the range of 250–750 micromhos per centimeter. Water in the range of 750–2,250 micromhos per centimeter is widely used, and satisfactory crops are obtained under good management and favorable drainage conditions, but saline conditions will develop if leaching and drainage are not adequate. Successful use of water with conductivity above 2,250 micromhos per centimeter is exceptional. Only the more salt-tolerant crops can be grown with such water and then only if the water is used copiously and the subsoil drainage is good.

Four classes of water are recognized on the basis of electrical conductivity (salinity):

C1. Low-salinity water is usable for irrigation with most crops on most soils. Some leaching is required, but the leaching incidental to normal irrigation is sufficient, except in soils of extremely low permeability.

C2. Medium-salinity water can be used if there is moderate leaching. Plants having a moderate salt tolerance generally can be grown without special salinity control.

C3. High-salinity water cannot be used on soils having poor drainage. Special management for salinity control may be required, even with adequate drainage, and the plants should have good salt tolerance.

C4. Very high salinity water ordinarily is not suitable for irrigation, but may be used occasionally if the soils are permeable, the drainage is adequate, the irrigation water is applied in excess to provide considerable leaching, and very salt tolerant crops are grown.

The relative proportion of sodium is best expressed by the sodium-adsorption-ratio (SAR). The soluble inorganic constituents of irrigation waters react with soils as ions rather than as molecules, and the alkali hazard is determined by the absolute and relative concentrations of the cations. If the proportion of sodium is high, the alkali hazard is high; and, conversely, if calcium and magnesium predominate, the hazard is low.

The SAR of a soil solution has advantages as an index of the sodium or alkali hazard because it is simply related to the adsorption of sodium by the soil. This ratio is defined by the equation:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$

where Na^{+} and Ca^{++} represent concentrations in millequivalents per liter.

Four classes of water are recognized on the basis of the SAR:

S1. Low-sodium water is usable for irrigation on almost all soils with little danger of accumulating harmful quantities of exchangeable sodium. However, sodium-sensitive crops may accumulate injurious concentrations.

S2. Medium-sodium water involves an appreciable sodium hazard in fine-textured soils that have high cation-exchange-capacity, especially where leaching is inadequate, unless the soil contains gypsum; it may however be used on coarse-textured or organic soils that have good permeability.

S3. High-sodium water may lead to harmful quantities of exchangeable sodium in most soils but may be controlled by good drainage, liberal leaching, and the addition of organic matter. Gypsiferous soils, however, may accumulate harmful quantities of exchangeable sodium from such waters.

S4. Very high sodium water is generally unsatisfactory for irrigation except at low and perhaps medium salinity, where the solution of calcium from the soil, or the use of gypsum or other additives, may make these waters usable.

The quality classification of ground water in the Teresina-Campo Maior area is shown on plate 1. Waters from 20 of the 27 wells selected represent conditions prevalent in most of the area. They are classified as C1–S1 and C2–S1. Waters from the remaining wells represent local conditions and are classified as C3–S1, C3–S2, C3–S4, and C4–S4.

The suitability of water for irrigation appears to be related to its geologic source. Waters most suitable for irrigation (C1–S1 and C2–S1) are from wells tapping Piauí and Potí aquifers whereas water less suitable is contained in the Longá aquifer.

Boron was not determined in the chemical analyses of water from the Teresina-Campo Maior area. No statement, therefore, can be made with respect to the importance of boron in the water. The following paragraph suggests how boron, when present, may affect plants.

Boron is essential to the normal growth of all plants, but the quantity required is small. A deficiency of boron produces striking symptoms in many plants. On the other hand, boron is toxic to sensitive plants, and a concentration that will kill them may approximate the concentration required for normal growth of the very tolerant plants. Lemons show definite, and at times, economically important injury when irrigated with water containing 1 mg/l of boron, whereas alfalfa will make a maximum growth with 1–2 mg/l of boron.

SUITABILITY OF WATER FOR LIVESTOCK

Cattle and other domestic animals will tolerate water that is much more mineralized than man can accept. Judged by standards of the Australian Department of Agriculture, the ground water in the Teresina-Campo Maior area is well below the upper limits of acceptability for dissolved-solids concentration. The Australian standards, as given by Hem (1959, p. 241), are as follows:

	Mg/l		*Mg/l*
Poultry	2,860	Cattle (dairy)	7,150
Pigs	4,290	Cattle (beef)	10,000
Horses	6,435	Adult sheep	12,900

PRESENT UTILIZATION

The principal uses of ground water in the Teresina-Campo Maior area are for domestic, stock, municipal, and industrial supply; only a small quantity is used for irrigation and recreational activities. In all there are about 200 successful drilled wells and half again as many unsuccessful or abandoned drilled wells. Most wells were drilled by Federal agencies and some by private companies under contract to the government. Open hand-dug wells number into the hundreds but the majority of these go dry shortly after the dry season. These produce less than 1 percent of the total draft.

Domestic, stock, and irrigation wells constitute about 90 percent of the drilled wells in the area, however, they produce only slightly more than half of the total ground water withdrawn by wells. The wells usually are 6 inches in diameter and range in depth from 30 meters to more than 300 meters. Most are equipped with a 3–6 horsepower diesel or gasoline-driven piston pump and yield individually between 25 and 160 lpm (liters per minute); those equipped with only a hand pump or windmill will yield as much as 20 lpm. Practically all wells are completed open hole and use only a short section of surface casing to prevent caving. Water from most of the wells is pumped directly into a 2–4 cu m capacity concrete or steel storage tank which stands a few meters above ground level. From such tanks the water is distributed by gravity flow to nearby spigots or watering troughs. If the water is used for irrigation, then it is pumped into a much larger steel or concrete storage tank which may be set as much as 10 meters above ground.

Dug wells are used mostly to supply water to livestock, although some of the water is used for household purposes. The dug wells average about

1 meter in diameter, are as deep as 20 meters and are generally cased with cement or concrete pipe. Water is withdrawn manually with a rope and bucket or by windmill-driven pumps. Yields of dug wells range from about 200 to 1,000 lpd (liters per day).

Developed and undeveloped springs locally supply only minimal amounts of water for livestock, but most go dry shortly after the rainy season. Of those that flow all year, for example, spring 14, table 2, few yield more than 1,500 lpd.

Although they compose only about 10 percent of the total number of wells, the municipal or public-supply wells produce almost half of the ground water withdrawn in the report area. Wells supplying water to private and public swimming pools are considered in this category. The wells are generally 8, 10, and 12 inches in diameter and range from 42 meters to more than 500 meters deep. Most are finished with a gravel-packed slotted-pipe screen, and a few are constructed using manufactured shutter-type screens. The wells are generally pumped with 5- to 120-horse-power electric motors geared to turbine pumps, and some individually yield as much as 4,000 lpm. Water for municipal supply is stored in rectangular elevated steel tanks where it is then distributed by gravity flow to homes, clubs, factories, public buildings, and public spigots.

The towns of Teresina, Campo Maior, União, and José de Freitas all have public water systems supplied by large-capacity wells. Their estimated use of ground water in 1966 was as follows:

City or town	Estimated pumpage (cubic meters)	Number of wells in use	Storage (cubic meters)	Service outlets (1966 estimate)	Population (1966 estimate)
Teresina	1,650,000	5	2,000+	5,000	90,000
Campo Maior	250,000	2	570	600	25,000
José de Freitas	35,000	3	30	250	5,000
União	15,000	1	5	100	2,500

Altos, not shown above, is only now (1966) constructing a public water-distribution system to be supplied by Army-owned wells, one of which is well 45 (pl. 1 and table 2). For the smaller towns, villages, and hamlets, water is supplied by centrally located domestic and stock wells and distributed to homes by cart or on the backs of porters. Except for occasional chlorination, none of the water used for public supply is treater or filtered.

In Teresina, 80 percent of the public water supply is furnished by five wells and the rest is obtained from the Rio Parnaíba which at one time supplied all the city's water. The wells are in a well field 2 km north of the city and less than 100 meters from the Rio Parnaíba. Because of hydraulic interference between two of the wells and routine servicing on one of the others, only three wells are normally pumped simultaneously.

To alleviate the resulting water shortage from wells and to avoid using more of the turbid river water, five additional wells have been constructed but are not as yet (1966) in use. The new wells are 500 meters south of Teresina and are also adjacent to the river; their combined yield will more than double the available water supply. All nine wells tap Piauí aquifers at depths ranging from 50 meters to 75 meters and yield water of good quality. Their large yields (individually as much as 240,000 lps) is due, at least in part, to induced infiltration from the nearby saturated alluvium of the Rio Parnaíba.

The water supply of Campo Maior is obtained from two wells that tap Longá aquifers. One well is 102 meters deep, and the other (well 56, table 2) is 75 meters deep. Reportedly, the water is of good quality and has a temperature of 34.5°C; the wells yield enough to supply the present needs of the city.

Water for José de Freitas was at one time supplied by three wells that tapped Piauí aquifers; however, now (1966) only one, well 16 (table 2), is in use. The well is pumped 8 hours per day, and the water is of good chemical quality (table 3). In addition to well 16, but not listed in table 3, is a developed spring which supplies the public swimming pool and an outdoor laundry facility. The spring issues from sandstone of the Piauí Formation, and the temperature of the water at both the well and spring is 30°C.

In União, water for public supply is obtained from well 6 (table 2), which taps a Cabeças aquifer; however, the water is of such poor quality (982 mg/l in total dissolved solids) that it is not suitable for drinking. Drinking water for União is carried from the nearby Rio Parnaíba where it is stored along with rainwater in small cisterns at individual residences.

The total quantity of water used for irrigation in the report area is estimated to be slightly more than 10 percent of the total annual pumpage (about 600,000 cu m) from the ground-water reservoir. The wells used for irrigation are 6–10 inches in diameter, are equipped with 5- or 6-horsepower diesel or electric-driven pumps, and range in individual yield from 4,000 to 45,000 lph.

Typical of such wells is one (well 12) at Granja São Paulo, 18 km northeast of Teresina. This well was drilled in 1965, is 65 meters deep, is 6 inches in diameter, and has a static water level about 25 meters below the land surface and a pumping level about 33 meters (table 3). The owner reports that this well normally is pumped 7 or 8 hours per day three or four times a week at a rate of 10,000 lph (7,500 cu m per year). Its yield, he says, is more than sufficient for irrigation of 1 hectare of oranges, bananas, and papayas. Exceptionally productive wells, such as well 22 at Escola Agri-Técnica, yield as much as 45,000 lph and irrigate 4–5 hectares.

Water levels in nonflowing wells range from 0.5 to 40 meters below land surface. Well owners and users report that, since these wells were constructed, many as early as World War II, there has been no appreciable net increase or decline in water level. The discharge rate of the several flowing wells has not measurably diminished in recent years; however, some of these, such as well 6 at União, are now being pumped as the free flow cannot sustain current demand.

The specific capacities of wells, determined from well records, range from 10 to 4,000 lpm per meter of drawdown. Of wells with specific capacities greater than 250, seven (wells 26, 28, 31, 33, 34, 36, and 37) are finished in the Longá Formation and two, (wells 7 and 52) in the Piauí Formation. For most of the wells in the report area, however, including those finished in the Potí Formation, specific capacity and drawdown data indicate that the wells can produce considerably more than they now do. The data are not sufficient to show areal or stratigraphic specific-capacity variations.

The annual pumpage from the principal aquifers in the Teresina-Campo Maior area is estimated to be 5 million cu m in 1966 or about 5.2 cu m for each hectare-meter of saturated rock. Annual recharge from precipitation (estimated to be 2,000 cu m per hectare) is considerably more than enough to replenish the water currently being withdrawn.

FUTURE DEVELOPMENT

In the Teresina-Campo Maior area, the rate of replenishment to ground-water storage from precipitation is more than adequate to balance the present (1966) rate of withdrawal from wells. In fact, the present withdrawal of water from the principal aquifers is less than 0.0025 percent of a conservative estimate of the annual replenishment from rainfall. Also, the current withdrawal from wells in many areas of the uplands is so small that no perceptible change in storage would be detectible even though natural replenishment may be negligible. Thus the annual draft of 5 million cu m prevailing in 1966 from the principal aquifers could be increased several fold with no significant decrease in the amount of water in storage.

Most of the water-bearing formations underlying the uplands have barely been tapped and can be developed a great deal more. Inasmuch as the principle aquifers yield adequate quantities of good-quality water where they are within easy reach of shallow wells, they also probably contain a large and untapped supply in the central and western parts of the report area where they occur at depth. In addition, aquifers in deeper formations, notably the Serra Grande, probably contain a large but untapped supply of water.

Additional large quantities of good-quality water for all municipalities, except União, may be obtained from aquifers already being pumped. For Teresina, shallow Piauí aquifers, which when pumped induce infiltration from the saturated alluvium of the Rio Paranaíba, can probably be further developed to the greatest extent. The Longá Formation, which supplies water to Campo Maior, also can produce additional water in moderate quantity from new wells. Additional water from Piauí aquifers can be provided for José de Freitas either by repairing and cleaning existing wells or by drilling new replacement wells. For the town of Altos, Piauí aquifers here as elsewhere appear to have excellent potential for future ground-water development. In the town of União where additional water supplies are now needed, Piauí aquifers, especially where they are in close proximity to the alluvium of the Rio Parnaíba, warrant serious consideration as a water source.

Further withdrawal of ground water in the Teresina-Campo Maior area will probably come about from an increase in irrigated farming. Increasing the irrigated area and the amount of water used will induce a gradual shift from the small-diameter unscreened wells to larger capacity screened wells equipped with large turbine pumps. Such wells, although they may be deeper and more expensive to construct, will in the long run develop water at a lower unit cost than the small diameter wells now being used.

To increase the area irrigated to its full potential of 250,000 hectares according to SUDENE (1965, p. 16) would require approximately 2,500 million cu m of water per year which is several times the perennial potential yields of the ground-water reservoir. Considering the quantity available from the natural recharge and from recirculation (pumped water that infiltrates to the water table and can be pumped again) the ground-water reservoir could probably supply about 20 percent of the SUDENE estimate (or 500 million cu m). SUDENE assumed in its estimate that the duty of water (application rate) would equal a depth of about 1 meter per year, a quantity much greater than that being used at present. Although the application rate is likely to increase, especially if large-scale irrigation becomes widespread, it will probably be many years before the average approaches 1 meter per year.

The growth of irrigation and public water systems can be expected to generate an increasing demand for water in other sectors of the economy. Higher employment resulting from marketing agricultural produce, supplying seed and fertilizer, and servicing water systems, such as in pump sales, repair, spare parts, and fuel, will create additional demands for water. Other industries will be expanded or created which will require water, such as in processing of food products. The growth of irrigation would be accompanied by additional demands for water in towns and villages and on ranches and farms which supply meat, eggs, and dairy products to the people of the region.

The development of ground water from the lower Cabeças, Pimenteiras, and Serra Grande Formations will probably lag behind development of ground water from the shallower Piauí, Potí, and Longá Formations and the upper part of the Cabeças. The Cabeças, Pimenteiras, and Serra Grande, especially in the western part of the report area, lie too deep for development under prevailing (1966) economic conditions. In the future, however, a profitable industry might find no obstacle in development of water from such depth, even with attendant well construction and pumping costs.

Although the Teresina-Campo Maior area is endowed with ideal soils and climate for agriculture and with large reservoirs of ground water and ample rainfall to replenish much of the water that may be used, the problems of economic development remain complex. Even with respect to ground water, the scope of this report is general, not establishing precise limits as to the extent of possible development. To determine such limits, more data than now exist will be needed, including the following:

1. The extent, thickness, permeability, and storage coefficients of the aquifers in the geologic formations.
2. The amount and rate of natural recharge and discharge to the principal aquifers. This requires information on precipitation and measurements of streamflow to establish which reaches of the major streams receive from and which contribute to ground water.
3. The annual pumpage from wells and fluctuations in water levels, especially in heavily pumped localities, which would be established by periodic measurements of water levels in wells, correlated with precipitation (recharge) and pumpage (a factor in discharge).
4. The areal distribution of ground water of various chemical types to include analyses for boron.
5. The hydraulic relationship and extent of alluvial and Piauí aquifers along the Rio Parnaíba valley.
6. The effects of irrigation on the land, especially the accumulation of salts in the soil or water logging.

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