Ground-Water Resources of the Açu Valley Rio Grande do Norte Brazil

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1663-C

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* JONAS MARÍA DE CASTRO ARAÚJO

CONTRIBUTIONS TO HYDROLOGY OF LATIN AMERICA AND THE ANTILLES

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GROUND-WATER RESOURCES OF THE AÇU VALLEY, RIO GRANDE DO NORTE, BRAZIL

By HARRY G. RODIS and JONAS MARÍA DE CASTRO ARAÚJO

ABSTRACT

The Açu Valley is the lower part of the Rio Piranhas valley in the northwestern part of the State of Rio Grande do Norte, Brazil. It begins where the Rio Piranhas leaves the crystalline Precambrian rocks to flow across the outcrop of sedimentary rocks. The area considered in this report extends northward for about 45 kilometers; it is terminated arbitrarily where encroachment by sea water has contaminated the aquifer and imparted a disagreeable saline taste to the water in it. The boundary was not determined in the field, however, for lack of special equipment. Part of the extensive uplands on either side of the valley are included. This makes the total area approximately 2,500 square kilometers. The largest town, Açu, had a population of about 8,000 in 1960.

The area is considered to be part of the Drought Polygon of northeast Brazil because the precipitation, although averaging 448 millimeters annually at Açu, varies widely from year to year and often is deficient for many months. The precipitation has been supplemented by use of irrigation wells, but irrigated agriculture is not yet far advanced, and the quantities of water used in irrigation are small.

Geologically, the area consists of basement crystalline rocks (Precambrian), a wedge of sedimentary rocks thickening northward (Cretaceous), and alluvial sediments constituting a narrow band in the bottom of the valley (Alluvium and terrace deposits). The crystalline rocks contain water mainly in fractures and, in general, are impermeable. The sedimentary rocks of Cretaceous age comprise two units: a thick but fine-grained sandstone grading upward into siltstone and shale (Açu Sandstone), and limestone and dolomite with an included shale zone (Jandaíra Limestone). The sandstone especially and the limestone to a lesser degree are ground-water reservoirs of large capacity. The limestone has been tapped at several places, but the sandstone and its contained water are practically untested and, hence, imperfectly understood. The alluvium of the first terrace is the aquifer supplying most of the ground water being used in the area. Wells in the alluvium yield as much as 80,000 liters per hour. Larger yields probably could be obtained from wells designed to take full advantage of the aquifer.

There are in the valley about 300 dug wells which are used for irrigation. Half of these are equipped with pumps and engines. The rest, together with about 500

drive-point wells, are equipped with manual or windmill-driven pumps. In addition to irrigation, the water is used in homes and for cattle.

The quantities of water currently used in irrigation are relatively small, both per hectare and in the area as a whole, but this will probably increase substantially when intensive irrigation becomes a reality. The annual pumpage from the alluvium, nearly constant since 1959, was about 2.25 million cubic meters in 1964, which is only about 90 cubic meters from each hectare-meter of saturated alluvium. This amount would lower the water table about 1 meter in 11 years, if there were no recharge. Actually, no such decline is likely to occur, because the recharge from precipitation alone is estimated to be more than enough to replace the water currently being pumped.

Chemical analyses of eight samples show that the ground water in the aluvium is acceptable for most uses. The water in the Açu Sandstone and Jandaíra Limestone is more mineralized than that in the alluvium and at some places, at least, is not acceptable for human consumption. The available chemical data on this water, however, are not adequate to judge fully the quality of the water in these formations.

It is estimated that about 22 million cubic meters of water would be needed annually if irrigation were extended to all the bottom land, which totals about 25,000 hectares. This amount is only one-fourth to one-half the estimated recharge from precipitation alone. The present rate of application of water is very low but probably would be increased under intensive irrigation. An estimate of 350 million cubic meters per year by the U.S. Bureau of Reclamation exceeds the probable annual recharge, but this amount is not likely to be realized for a long time to come.

Although much information not presently available will be needed before the limitations of the ground-water supply can be estimated accurately, it is evident that considerable more water can be developed for irrigation than is currently being used.

INTRODUCTION

The Açu Valley is a developing farming area that has a rare combination of fertile bottom-land soils, favorable climate, and abundant ground water. It is one of the more promising areas for irrigated agriculture in Rio Grande do Norte. Water is an important factor in determining the degree and rate of development of the area, although it is not at present a limiting factor. Surface water developed and ready for use in irrigation is not at present adequate for all the irrigable area, nor can the future availability of increased surface-water supplies be predicted. The ground-water resources serve as a base for development of the area and should be fully integrated in plans for use of the water resources.

PURPOSE AND SCOPE

This report describes the results of an investigation to determine the availability and quality of ground water occurring in the Açu Valley and vicinity. It is based on data collected during 21 days of field reconnaissance made intermittently between May and July 1965 and on published and unpublished hydrogeologic data. It seeks to provide an appraisal adequate for the planning, development, and management of the ground-water resources in the present and near-future economic development of the region.

The investigation, part of the Alliance for Progress program was made cooperatively by the Divisão de Hidrogeologia of the Superintendência do Desenvolvimento do Nordeste (SUDENE) and the U.S. Agency for International Development (USAID) as part of an evaluation of the ground-water resources of northeast Brazil. The investigation was under the general supervision of Geraldo de Azevedo Gusmão, Chief of the Divisão de Hidrogeologia, and Stuart L. Schoff, of the U.S. Geological Survey, who was in charge of ground-water investigations in northeast Brazil for USAID.

LOCATION AND AREA

The Açu Valley is in the north-central part of the State of Rio Grande do Norte, about 125 km (kilometers) west of the State capital, Natal, and 200 km northwest of Recife (inset map, pl. 1). The boundaries of the area considered here are arbitrary, having been selected to include the part of the valley where the ground water is relatively abundant and of good chemical quality, together with representative segments of the upland plains on either side. The area thus delineated extends from a few kilometers south of the town of Açu northward to the latitude of the village of Pendências, a distance of about 44 km (pl. 1). Its width is 32–43 km, and its area 2,500 sq km (square kilometers). Its northern boundary is about 20 km south of the Atlantic coast.

Included in the area are parts of the municipalities of Açu, Carnaubais, Ipanguaçu, and Pendências. The largest town and principal commercial and cultural center, Açu, in the southwestern part of the mapped area, had a population in 1960 of 8,158.

The part of the area of major interest from the standpoint of possible development of irrigation by means of ground water is the alluvial bottom land in the Açu Valley. This bottom land ranges in width from 3 km near the village of Carnaubais to 17 km near the village of Ipanguaçu. This area totals about 250 sq km.

PREVIOUS REPORTS

Previous reports cover only the broader aspects of geology and hydrology in the Açu area. Petrobrás (1956) outlined the regional geology and structure, especially of the sedimentary rocks, and prepared a contour map of the surface of the crystalline basement rocks. Kegel

(1957) included the extreme northern part of the area in his description of the geology of the coastal lowlands. Blankennagel (1962), in a report on a broad area, described the occurrence of ground water in the Potiguar Basin, of which the Açu area is part. The Departmento Nacional da Producão Mineral (1963) published a photogeologic map of the Macau-Ponta do Mel quadrangle, scale 1:250,000, which covers the report area. The U.S. Bureau of Reclamation (1964) and Thompson (1964) reporting on the surface-water hydrology of the Rio Piranhas basin, of which the Açu Valley is a part, included some information on wells.

METHODS OF INVESTIGATION

The investigation summarized in this report was carried out by methods used in most reconnaissance hydrogeological investigations. The available topographic and geologic maps and reports were collected and studied, and records of wells in the area were obtained. This preliminary work was then followed by fieldwork, which consisted principally of an inventory of wells and spot verifications of available geologic maps.

The base map used in the fieldwork was an enlargement, to the scale of 1:125,000, of the west-central part of the photogeologic map of the Macau-Ponta do Mel quadrangle (SB–24L). Aerial photographs at the scale 1:40,000 were used in locating wells and in verifying the principal geologic contacts. Topographic quadrangle maps issued by the Conselho Nacional de Geografia on two scales, 1:1,000,000 (Jaguaribe) and 1:500,000 (Jaguaribe NE), were used in estimating altitudes and in identifying roads and trails in localities not covered by the aerial photographs.

Measurements of depth and static water level were made by use of a steel tape in about 50 wells. At a few wells, the discharge was estimated by the trajectory method, or by timing the rate of filling a tank or container of known capacity. Other data obtained include the year the well was constructed, diameter and type of casing or curbing, type of pump, discharge rate and drawdown, total annual water requirement, normal use to which the water is put, and annual fluctuation of static water level. Information on the number of hectares irrigated and the adequacy of wells to supply the necessary water, as well as the effect of the ground water on the crops, was especially sought. Some of this information was obtained by interviewing the well owner or his foreman, the well digger or driller, and municipal, State, and Federal officials. Not all the wells could be included in this inventory, because the number is large and would have caused needless repetition of similar data where the wells are most numerous. Irrigation wells from which pumps had been removed could not be pumped and therefore were not visited.

Water samples collected from eight representative wells were analyzed chemically in the water laboratory of the Superintendência do Desenvolvimento do Nordeste. Field tests of chloride, pH, and hardness were made of the water at many other wells.

The altitudes of selected wells and geologic contacts were determined by altimeter surveys.

ACKNOWLEDGMENTS

Much of the data for this report were obtained from well owners, municipal and Federal officials, well diggers, and private citizens. Their interest and cooperation are greatly appreciated. The authors especially thank Sr. José da Costa Leitão, Mayor of the Municipality of Açu, for providing office space and a guide.

GEOGRAPHIC FEATURES

TOPOGRAPHY AND DRAINAGE

The Açu Valley is the lower 75 km of the valley of the Rio Piranhas, which heads in the State of Paraíba, 250 km southwest of the area investigated. The Açu Valley crosses thick sedimentary rocks, in contrast with the upper Rio Piranhas Valley, which is mainly on crystalline rocks. The Açu Valley trends northward and is shallow and slightly sinuous. The riverbed at places is a kilometer wide. The valley is flanked on either side by broad, flat, nearly featureless uplands.

The valley in transverse profile has a shallow river channel, a flood plain ranging in width from 0.75 to 1 km, and two terraces. Floods easily overflow the channel onto the flood plain, which has many intermittent sloughs and small lakes. The flood plain is under water for part of the year, and only a small fraction of it is being cultivated. It is the flood plain, rather than the channel, that is shown in the middle of the valley on plate 1.

Most of the bottom land in the valley is on the first terrace above the flood plain. This terrace is poorly drained, but nevertheless offers the major opportunity in the area for agricultural development. Most of the farms in the valley, both irrigated and not irrigated, are on this terrace. The soils are principally organic silts and clays, which grade into sandy silt near the river. The vegetation outside the cultivated fields includes rank grass, weeds, shrubs, and carnaúba palms.

The second terrace has been reduced by erosion to small remnants. It generally is no more than a meter above the first terrace, and is covered with coarse, compact soils unsatisfactory for agricultural use.

The river has a gradient across the mapped area of about 0.3 meter per kilometer. Formerly intermittent, the river since about 1961 has had a continuous flow owing to the periodic release of stored water from upstream reservoirs. During floods the river overflows its banks, and reverses the flow of some of its tributaries. A notable example is the Rio Pataxós which annually reverses for 3–5 weeks and fills two lakes east of Ipanguaçu (pl. 1).

The uplands to the east and west are at places nearly 200 m above the stream. They have only a few streams in shallow valleys, but they do not have lakes, and they are not subject to being flooded as the flood plain is. Their runoff may go underground. The soils in part, at least, are sandy, and the underlying rock in much of the area is limestone. The rudimentary character of the upland drainage system may be the result of water infiltrating from the surface into solution openings in the limestone.

CLIMATE

The climate of the Açu Valley area is tropical-rainy, and most of the precipitation falls during the so-called winter, January through June (fig. 1A). There is, however, no truly cool season. The average annual precipitation recorded at Açu is 448 mm (millimeters) (fig. 1*B*), but the actual precipitation for any one year may depart widely from this (Departmento Nacional de Obras Contra as Sêcas, unpub. data). The maximum annual precipitation in the 30 years, 1931–60, was 1,085 mm (1935), and the minmum was 132 mm (1958). Thus, the climate varies from humid to semiarid, and the locality qualifies for inclusion in the Drought Polygon of northeast Brazil, which is a triangular-shaped area receiving irregular rain and subject to both floods and droughts.

The temperatures are normally high. At Açu the average temperature is 31° C, and the range is from an average maximum of 33° C to an average minimum of 29° C.

ECONOMIC DEVELOPMENT

The Açu Valley is devoted principally to dry farming and only secondarily to irrigated agriculture. Less than 10 percent of the arable land of the first terrace is under irrigation. The remainder is used for dry-farm cultivation of cotton, corn, vegetables, sweet potatoes, and beans, all of which are dry-farm crops. Part is used for grazing cattle, sheep, and goats, part lies fallow, and part is occupied by dense stands of wild carnaúba palms. Most of the farms in the valley are odd shaped narrow pieces of land extending from the river bank at right angles to the axis of the valley and average about 100 hectares each. The uplands on either side of the valley are used mainly for grazing; only small, scattered patches are in crops.

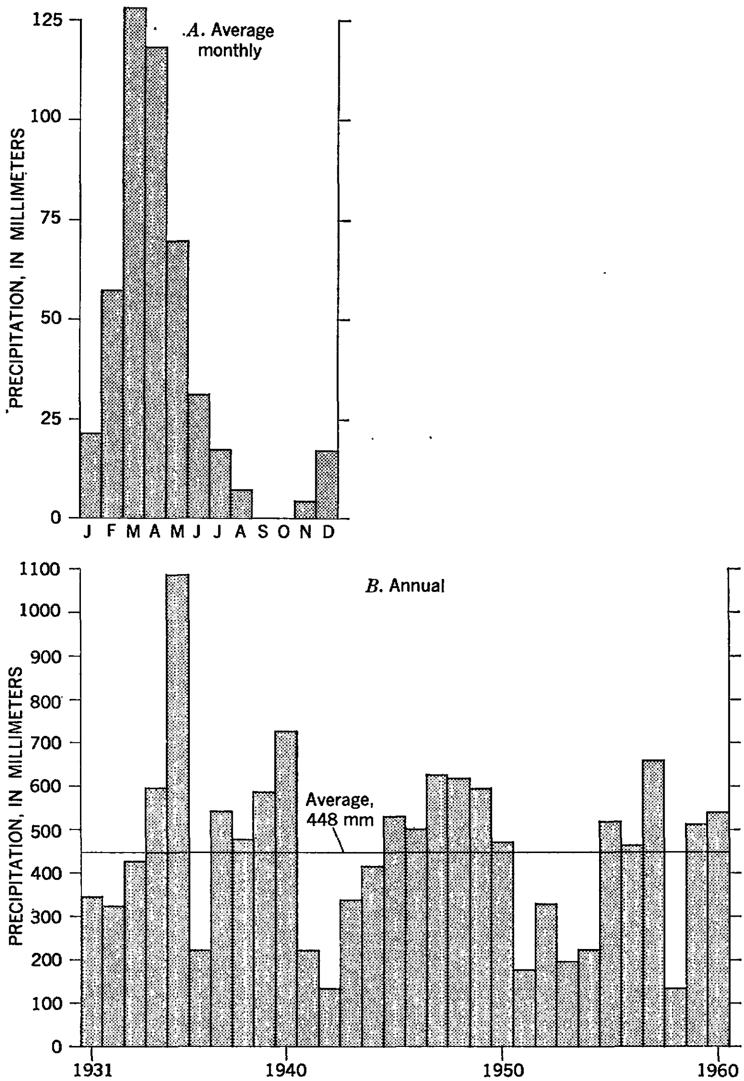


FIGURE 1.—Precipitation at town of Açu, 1931–60.

The Instituto Brasileiro de Geografia e Estatística (unpub. manuscript) reported that irrigation has increased considerably in recent years, but that cotton and carnaúba are still the largest money crops. The principal irrigated crops are banana, orange and other citrus fruit, papaya, and mango, with the first two leading in value. The irrigated fruits could be considerably increased under existing conditions of soil and water, provided, of course, that markets and transportation for them exist or could be developed.

GENERAL GEOLOGY

The rocks in the Açu area range in age from Precambrian to Recent, and from hard igneous and metamorphic types to loose unconsolidated sediments. Their areal and stratigraphic distribution are shown on plate 1. A thick sequence of marine and continental sedimentary strata containing a potentially important aquifer represents the Cretaceous System, and alluvium that already has been tapped for irrigation water at some places represents the Recent stage. A few mafic intrusive rocks occur within the area but appear to have little influence on the hydrology.

PRECAMBRIAN ROCKS

Crystalline rocks of Precambrian age are exposed in the extreme southern part of the mapped area (pl. 1) and constitute the basement upon which rests a thick sequence of sedimentary rocks. The Precambrian rocks, consisting mostly of gneiss, mica schist, and granite, are slightly to moderately weathered according to their differing susceptibilities to weathering. The schist generally has been more deeply weathered than the gneiss and granite. The surface of the crystalline rocks slopes toward the Atlantic coast, and is below sea level in most of the area considered in this report (pl. 1). In the northern part, the surface is more than 1,000 m below sea level.

CRETACEOUS SYSTEM

Strata of Cretaceous age are predominant in the sedimentary rocks of the Açu area. They constitute all the sedimentary bedrock of the area and make up more than 90 percent of the volume of all sediments, both consolidated and unconsolidated. They are more extensive than any other sedimentary unit, being present in all parts except where the Precambrian rocks are at the land surface.

The Cretaceous rocks dip north and thicken in the same direction from a few tens of meters on the outcrop to a known maximum, in an oil-test well near Macau (on the coast, north of the area investigated), of 1,177 m. A seismic-refraction survey indicated a maximum thickness of about 2,000 m of sedimentary rock (Blankennagel, 1962), most of which probably is of Cretaceous age. These strata lie unconformably on the Precambrian crystalline rocks.

The rocks of Cretaceous age have been described by Kegel (1957, p. 8–24), who states, "The coastal belt of Rio Grande do Norte, which is occupied by strata of Cretaceous and Tertiary age, is part of a great basin that extends from Bahía to Ceará. The Cretaceous strata belong to a sedimentary cycle that begins with clastic deposits—conglomerate, sandstone, and shale—and ends with sandy to pure limestone. Hence, a lower clastic sequence and an upper calcareous one can be distinguished, although they are not sharply separable". Kegel classified these rocks as the Açu Sandstone and Jandaíra Limestone of Apodi Group (table 1).

AÇU SANDSTONE

Kegel described the Açu Sandstone as observed in two outcrops and as penetrated in two exploratory wells drilled by Petrobrás. Both the wells were near the Atlantic coast, beyond the map area of this report. One well was near Macáu, about 68 km northeast of the town of Açu, and the other was west of Areia Branca, 77 km northwest of Açu.

Of the outcrop near the town of Limoeiro, Kegel wrote:

In this cut we observe a grayish sandstone, which is more or less calcareous, poorly cemented, in places conglomeratic, with intercalated, purplish-red shale. The red color is mainly in the intercalated shale or siltstone. The pebbles are distributed so that we can distinguish a lower unit composed principally of conglomeratic sandstone, a middle unit of shale and variegated siltstone with a minor thickness of sandstone, and an upper unit composed of sandstone notably more calcareous than those in the middle and lower units. In the upper unit there are, also, 6 to 8 meters of thin-bedded limestone containing numerous small shells or fragments of molluscs. The total thickness of the Açu sandstone in the Limoeiro exposure is 70 meters. At other places we measured or estimated the thickness as 50 to 80 meters.

Limoeiro is about 140 km west of Açu, but the sandy character of the unit is persistent. In an exposure near Lagoa do Piató, which is 8 km northwest of Açu, Kegel found "several intercalated purple or green shales thinner than in the exposure at Limoeiro (20 to 30 centimeters). In spite of the variations, the predominance of sandstone is evident, making the name Açu Sandstone justifiable for the whole."

From less than 100 m at the outcrop, the Açu Sandstone thickens to about 625 m in the well northeast of Açu and to more than 800 m in the well northwest of Açu. Not all of it is permeable enough to constitute a good aquifer, as Kegel's summary description suggests:

3. Upper part: calcareous sandstone with subordinate shale; intercalated limestone beds;
2. Middle part: shale, siltstone, and variegated sandstone, generally gray and purplish red;
1. Lower part: conglomeratic sandstone

Blankennagel (1962) divided the Açu into two units—an upper variegated sandstone and shale unit 320–354 m thick in the two oil-test wells and a lower sandstone unit 310–482 m thick. He regarded the upper part of the lower unit as the principal aquifer and described it (p. 10) as "composed of sandstone with minor interbeds of shale. The sandstone is medium- to coarse-grained, somewhat arkosic, and becomes more coarse-grained and arkosic toward the base." He reported

TABLE 1.—*Geologic formations of the coastal belt of Rio Grande do Norte, based on descriptions by Kegel (1957) and Blankennagel (1962)*

ERA	SYSTEM	SERIES		FORMATION	APPROXIMATE THICKNESS (METERS)	DESCRIPTION
Cenozoic	Quaternary	Recent		Alluvium	0–35	Sand, silt, and gravel
	UNCONFORMITY					
	Tertiary	?		Barreiras	0–100	Variegated orange-red clay, and more or less friable sandstone, with ferruginous crust. Occurs in the Açu area only in small outliers
UNCONFORMITY						
Cenozoic	Post-Cretaceous	?		Mafic intrusive rocks	?	Mainly dikes, sills, and plugs of deeply weathered basalt
UNCONFORMITY						
Mesozoic	Cretaceous	Upper Cretaceous	Apodi Group	Jandaíra Limestone	0–470	Calcareous limestone, light-gray to tan. Dolomitic gray or yellow, generally coarse, fossiliferous limestone with solution openings
		Lower Cretaceous(?)		Açu Sandstone	0–800+	Continental sandstone, gray, calcareous; intercalated limestone, shale, and siltstone. Sandstone is commonly variegated gray and purplish red; occasionally feldspathic with conglomeratic layers. The upper part of lower conglomeratic zone is a promising aquifer
UNCONFORMITY						
Precambrian				Crystalline rocks	?	Mainly gneiss, mica schist, granite, and crystalline limestone

it to be 166 m thick in the well northwest of Açu, and the top of it should be about 600 m below sea level at Pendências (his fig. 3).

JANDAÍRA LIMESTONE

Kegel mentions six types of rock considered by him to be characteristic of the Jandaíra Limestone, as follows: limestone with small shells, nodular limestone, flaggy limestone, dolomitic limestone, argillaceous limestone, and sandy limestone-limy sandstone. He mentions also that the limestone at several places contains beds of gypsum (or anhydrite); he notes especially the gypsum of Governador Dix-sept Rosado, which is only 67 km west-northwest of the town of Açu; and he emphasizes the solution features of the limestone:

> A notable characteristic is the karst phenomena found in all parts of the limestone, although to different degrees. They are very important in the eastern part of the coastal belt near Baixa Verde. Sinkholes, swallow holes, and caverns occur there in great numbers, and the water table is very low in the limestone, feeding karst springs of large discharge.

In his description of the limestone penetrated in the oil-test wells, Blankennagel mentions vugs, which could be due to solution and caverns. He states that one of the caverns measured 7 m vertically. He describes the Jandaíra as consisting of a clastic unit, a dolomite not everywhere present, and, at the top, a limestone. The clastic unit is composed of marine siltstone and fine sandstone alternating with dolomitic or fragmental limestone. It was 75 m thick in one well and 132 m in the other. The dolomite, found in one well but not the other, is described as porous or vuggy at the top but nonporous and argillaceous toward the base; as microcrystalline to finely sucrose in the upper part but medium to coarse grained below. The limestone is light gray to medium gray and tan and is granular to earthy. In one of the wells, the limestone has a fine vuggy porosity and in the other has vugs and caverns. The limestone was 95 m thick and the dolomite 235 m in the well where both were distinguished. This makes a total of 330 m. The limestone in the other well was 283 m thick.

TERTIARY SYSTEM

The Tertiary System is represented by the Barreiras Formation (considered to be a group by Bigarella and Andrade, 1964, and Mabessone, 1965), which occurs in small outliers on top of the Jandaíra Limestone in the extreme northeastern part of the area studied (pl. 1). This formation consists principally of dominantly reddish-orange variegated clay and of sandstone that is more or less friable. Where exposed, the sandstone has a ferriuginous crust. At most, the Barreiras Formation is less than 100 m thick (Petrobrás, 1956), and in the area of this report probably is relatively thin.

QUATERNARY SYSTEM

In the area of this report the Quaternary System is represented by alluvium, which occurs on either side of the channel of the Rio Piranhas.

ALLUVIUM

Alluvium is the sediment deposited by streams. It consists of the gravel, sand, silt, and clay that have been carried downstream by flowing water until, for one reason or another, the water has been forced to drop them. Alluvium contains fragments of the several rock types that crop out upstream in the drainage basin of the river that deposited it. Is is entirely fine-grained sediment if only fine-grained rocks are present in the basin, but ordinarily is a mixture of fine and coarse sediment because most drainage basins contain both fine- and coarse-grained rocks. The fine and coarse layers in alluvium become thicker or thinner or grade one into another in all directions because of variations in the strength of the currents. For this reason, the water-bearing layers generally cannot be correlated with certainty from one well to another, especially if wells are far apart, but a majority of wells in alluvium will penetrate enough water-bearing material to be productive, although some will be much more productive than others. The alluvium is generally thickest near the middle of a valley and thinnest at the bluffs.

The surface of the alluvium ordinarily is nearly flat, and irrigation water, therefore, can be readily and uniformly spread over it. The surface, as a rule, slopes gently and obliquely toward the stream—a feature that makes possible the drainage of excess water and, to some extent, the removal of salts from the soil.

A geologic cross section of the alluvium in the Açu Valley is shown on plate 1 and fits the general description given above. The deposits are of three ages although they are not differentiated in the cross section. The oldest deposit underlies remnants of a terrace and consists mainly of friable reddish-colored silty or clayey sand. Locally it is gravelly. This alluvium is best exposed in an abandoned canal about 10 km north of the town of Açu on the road to Carnaubais.

The alluvium underlying the first terrace above the flood plain consists mainly of unconsolidated thin-bedded brownish-colored sand and silt, which is commonly either silty or gravelly, and of firm black organic silt and clay. The upper 4–8 m in most of the valley is dominantly sand and gravel, not silt or clay as it is in many valleys. This suggests a somewhat unusual, although perhaps local, deviation from the normal alluvial sequence which may be illustrated by the record of an exploratory well that was dug about 1 km east of the city of

Açu. This well began in coarse sediments, but went through thick layers of silt and clay before ending on bedrock. The silt and clay may have been deposited in a lake, which after being filled with sediment was covered by fluvial sands and gravels.

The alluvium of the first terrace underlies most of the bottom land in the valley and is the principal source of water for irrigation by wells. It is, therefore, the main objective of this study. Its thickness at most places is unknown because only a couple of wells have passed through all of it. The log of well 35, which is in the town square of Ipanguaçu, indicates a thickness of 20 m of alluvium. This record is confirmed by an electrical-resistivity survey carried out by the Basin School of the Superintendência do Desenvolvimento do Nordeste. Summarizing this work, Cravo Barros, Feitosa, and Rijo (1966, p. 6) concluded that the thickest alluvium occurs near the middle of the valley west of Ipanguaçu and Deodoro da Fonseca. They also found evidence suggesting that the alluvium farther north in the study area is either relatively thinner or more clayey.

The alluvium underlying the flood plain of the Rio Açu is a narrow belt, at most no more than 1 km wide. It is often flooded and is poorly drained, and therefore has not been used for crops, except locally. No wells have been drilled on the flood plain, and so the lithologic character and thickness of this alluvium are not known. Probably, however, it is similar to the alluvium of the first terrace, and the two form virtually one aquifer that has good hydraulic connection with the river itself.

The red alluvium of the upper terrace is the oldest, and the flood-plain alluvium is the youngest of the alluvial deposits. Geologically there is not much difference in age from oldest to youngest, and all three probably are of Recent age.

POST-CRETACEOUS IGNEOUS ROCKS

Small areas designated as weathered mafic intrusive rocks are shown on the photogeologic map of the Macau-Ponta do Mel quadrangle (Departamento Nacional de Produção Mineral, SB 24 L, 1963) northeast of Pendências. Several of these are included on the geologic map accompanying this report (pl. 1). Although some of them are surrounded by the Barreiras Formation, the intrusives are said not to have invaded that formation, which therefore, is younger and accordingly is considered to be post-Cretaceous (post-Turonian). These rocks were not examined during this investigation, and details therefore are lacking. They probably have little or no effect on the general hydrology of the area.

HYDROLOGY

The water that enters Açu Valley and the water that leaves it are integral parts of the hydrologic cycle. Water occurs as atmospheric moisture and as precipitation, it flows in streams, is temporarily stored while slowly moving through reservoirs both on the land surface and underground, is stored likewise in lakes and oceans, and is evaporated from water and land surface into the atmosphere. Changing form and always moving, it is prisoner in the hydrologic cycle, sometimes completing the full cycle—sea to atmosphere to land to sea—but more often repeating small cycles within the major cycle. The activities of man change details in the major cycle, as by locally retarding or hastening the flow or by increasing the evaporation, but they do not destroy the cycle or the water.

The activities of man with respect to water must be adjusted to the hydrologic cycle if they are to succeed. An evaluation of the water resources of an area, therefore, should include examination of the various aspects of the hydrologic cycle that operate in the area. Among these are the precipitation, evaporation, transpiration, infiltration, and underground storage. Also important are the effect of topography and relief of the land on streams and the effect of soil and rocks on the relative magnitude of runoff. Where the demand for water is small, it is often unnecessary to measure carefully all the different parts of the cycle. It may suffice to identify the places in the cycle where water can be diverted in sufficient quantity to meet existing needs and to relate these places, in general terms, to the cycle as a whole. Where a major diversion of water is planned, however, the quantities need to be measured accurately, and the probable disturbance caused by withdrawing the water should also be appraised.

AQUIFERS IN THE AÇU VALLEY AREA

Each rock formation in the area of the Açu Valley performs a hydrologic function, either as aquifer or as aquiclude, with varying degrees of efficiency. The following paragraphs describe the hydrologic functions of the principal rock units and emphasize their importance as sources of well water.

WATER IN PRECAMBRIAN ROCKS

The Precambrian rocks are not good aquifers because they have virtually no primary permeability. Their porosity consists principally of fractures, which may be several kilometers long but generally are very narrow. Fractures may be open, or they may be filled with gouge or mineral deposits. They generally become fewer and more nearly closed with increasing depth below land surface, so that, at about 60 m, the chances of finding a large fracture ordinarily do not justify the cost of drilling a well in search of it. Wells that happen to intersect a large fracture or zone of fractures that are open and full of water will yield water abundantly, but wells drilled between fractures will go through solid rock and yield no water. Fortunately, the fractures in crystalline rocks are likely to be in the low places, that is, in the valleys, where the runoff is accumulated and therefore is available to fill the fractures. Even in valleys, however, a well may fail to intersect a fracture, or may intersect only a small one that may be quickly filled and quickly exhausted. In general, well drilling in crystalline rocks is more likely to fail than in sedimentary rocks. The crystalline rocks of the Açu area share these hydrologic characteristics with the crystalline rocks of the rest of northeast Brazil. They are more nearly aquicludes than aquifers and may be described as constituting a vast aquiclude containing small scattered aquifers.

WATER IN AÇU SANDSTONE

The Açu Sandstone is regarded by some geologists as the most promising aquifer in Rio Grande do Norte because it is very thick and extends over a large area (Blankennagel, 1962; Leite, 1963, p. 9–11), but there is little significant hydrologic information about the formation, because almost no attempt has been made to develop the water. Only one well ending in the Açu Sandstone was found in the area considered in this report (well 35, table 2). No well known to the authors of this report adequately tests the capacity of this formation to yield water. Scanty information indicates that the water is potable.

WATER IN THE JANDAÍRA LIMESTONE

The Jandaíra Limestone may at places be a significant aquifer, but hydrologic information is only slightly more abundant about it than about the Açu Sandstone. The vugs and cavities penetrated by oil-test wells could indicate a large capacity for storage of water and would permit easy movement of the water from one place to another. The scarcity of streams on the upland plains that are underlain by the Jandaíra Limestone may mean that much water from precipitation infiltrates and fills openings in the limestone instead of running off on the land surface. This water, then, would recharge the limestone. The water in the Jandaíra may be too mineralized to be potable, although available chemical analyses of water from the formation are too scarce for safe generalization. The limited chemical data suggest that the water is satisfactory for use by animals.

TABLE 2.—*Records of selected drilled wells in the vicinity of the Açu Valley*

[Pump: M, motor-driven pump; W, windmill; H, hand pump]

Well	Owner, user, or locality	Depth of well (meters)	Diameter of well (inches)	Depth where water enters (meters)	Water level (meters below land surface)		Date measurements made or reported	Well discharge (liters per hour)	Type of pump	Year completed	Remarks
					Static	Dynamic					
							1965				
28	State of Rio Grande do Norte, "Botelho" well.	94.2	10	[1] 85 95	[2] 74.6		May 19	3,300		1956	Uncased.
29	Baixa dos Adelinos, Açu Mayor's office	54	8	19.5 43	15	23	May 24	3,600		1962	Obstructed at 13.2 m, abandoned.
30	Fazenda São Lucas, Manoel Ferreira da Silva.	80	8		38					1960	Abandoned.
31	Jorge Barreto sawmill	88	8		[2] 38	77		2,800	W	1943	Reported unsatisfactory for drinking.
32	São Bento Júlio Pinheiro	40	8		[2] 14.2			2,500	W	1959	
33	Fazenda Bem Fica	83	8		10.1		May 24	2,500	W	1955	
34	Nursery Florestal, well "Cafe," Federal Dept. Agric. Botelho.	76	10	70 76	63		May 19	3,100	M	1955	
35	Mayor's office, Ipanguaçu, public well	26.6	6		[2] 2.6		May 18	3,500	H		Supplies drinking water for Ipanguaçu.
36	Talhado (beyond map border)	38	8	1.3	32	32.5	May 24	3,600	W	1936	Reported unsatisfactory for drinking.

[1] The two numbers represent the two levels at which water enters the well.

[2] Water level measured by authors; all others were reported.

WATER IN THE BARREIRAS FORMATION

The Barreiras Formation is not an important aquifer in the area covered by this report. It crops out only in the extreme northeast, in an area about 10 km long by 1–3.5 km wide, which is approximately 25 sq km. No wells are known that tap water in the formation. Its ability to yield water and the chemical quality of the water are therefore unknown. At other places, the Barreiras Formation contains so much fine-grained material that wells drilled in it will generally yield only small quantities of water.

WATER IN ALLUVIUM

The alluvium, mainly the alluvium underlying the first terrace above the flood plain of the Rio Piranhas, is the principal aquifer with respect to the present and future development of irrigation in the area investigated. All the existing irrigation wells, and many wells that supply water for domestic use and for cattle, tap the alluvium, yet the withdrawal remains only a small fraction of the supply perennially available.

The bottom land, measured along the valley between the towns of Açu and Pendências, is about 42 km long (pl. 1). It totals about 250 sq km. The average thickness of the aquifer in this area, estimated mainly from depths and water levels in wells, is about 8 m. If this thickness is accepted as an average for the water-bearing material and if the specific yield is 10 percent, the storage capacity in the alluvium would be 200 million cu m. The average quantity of water in storage per hectare would be 8,000 cu m. This is 1,000 cu m per hectare of saturated sand and gravel.

Not enough measurements were made of the altitude of static water levels in wells so that a water-table map could be prepared, but the available altitudes show, as expected, that the water table slopes downstream along the axis of the valley, that is, roughly north-northeast. In detail, the slopes of the water table probably are obliquely downstream from the bluff on either side to the channel where during most of the year there is a shallow trough in the water table of about 1.5 ms deep (pl. 1). This trough persists so long as ground water is being discharged into the river channel. The trough disappears during the rainy season and is replaced by a ridge about 1 m high, which is built up under the channel because at this season the heavy flows in the river are recharging the aquifer. This condition probably lasts about a month.

The altitude of the water table adjacent to the river in the dry season ranges from 19 m above sea level near the town of Açu to 7 m near Pendências. This is an average gradient of 0.28 meter per kilometer (0.03 percent).

RECHARGE AND DISCHARGE OF GROUND WATER

The water that fills the aquifers of the Açu area comes from precipitation. This is mainly the precipitation that falls within the area, although the Rio Piranhas introduces water that falls as rain in the upper part of its basin. This water from outside may recharge fractures in the Precambrian rocks in the extreme southern part of the mapped area, but mainly it recharges the alluvium. The Rio Piranhas may also recharge the Açu Sandstone and Jandaíra Limestone along and under the valley, first passing through the alluvium on its way to places where permeable alluvium is in contact with the older rocks. Most of the water entering the Cretaceous rocks, however, is water that falls on the uplands, which are too high topographically to receive river water. Some of the water from the uplands may be discharged into the alluvium and ultimately into the river in a reversal of the process just described. Available data do not suffice to show where the alluvium contributes water to the Cretaceous rocks and where it receives water from them. The recharge to the Barreiras Formation comes from precipitation on its outcrop area.

Ground water normally is being depleted at the same time that it is being replenished, although both processes cannot be simultaneous at precisely the same place. Ground water is depleted by discharge into the river during most of the year, by evaporation where the water table is near the land surface, by transpiration where the roots of plants can reach it, and by pumping from wells. All these forms of discharge deplete the water supply stored in the alluvium, but some have only small effect on the water supply in the Cretaceous rocks. Evaporation and transpiration, for example, will take water from the Açu Sandstone of the upland plains only in a small part of the outcrop where the water is only a few meters below the land surface.

In general, the quantities involved in these ground-water transactions are not known and some are virtually not measurable. The inflow and outflow of water between the Açu River and the aquifer, for example, cannot be estimated because streamflow records are not available. Records are needed for periods of both effluent and influent seepage, preferably extending over several years. The measurment of evaporation and transpiration usually requires costly instruments and much time. The movement of water between aquifers is a philosophical possibility, hard to prove or measure. Hence, although it is easy to describe how recharge and discharge are accomplished, it is difficult to measure them.

The average annual recharge over a period of several years will, under natural conditions, approximately equal the average annual discharge. In a single year, however, one may considerably exceed the other, and in a single season one may predominate to the exclusion of the other. It is the long-term average, however, that is important to water users because they can borrow from a large underground reservoir in dry years knowing that the water withdrawn will be replaced in a subsequent wet year.

The removal of water by pumping tends to upset the natural balance between recharge and discharge, but may in some situations increase the quantity of water recharged to an aquifer because the removal of water makes storage space available in the aquifer. If the pumpage exceeds the recharge by a large amount, water levels in aquifers not only will decline in response to pumping, but they will fail to rise to their original position in response to subsequent recharge. This condition has not occurred in the Açu Valley. Reports of well owners indicate that static water levels annually return in the rainy season to approximately their original positions. Hence, current withdrawals of ground water are causing no permanent depletion of the ground-water supply. Instead, they probably are only a small fraction of the quantity that could be pumped without ill effect.

The present annual pumpage from the alluvium, which on page C30 of this report is estimated as 2.25 million cu m, can be compared with the possibilities for recharge. The area of the alluvial plain is about 250 sq km, and the average annual precipitation (448 mm at Açu) on this area would amount to 112 million cu m. Most of this, of course, runs off, evaporates, or is transpired, but only a tiny fraction would be needed to offset the pumpage: 9 mm of the precipitation or about 2 percent. If 5–10 percent of the average precipitation goes underground, the amount of recharge would be approximately, 5–10 million cu m not counting water introduced from upstream by river infiltration or received from adjacent aquifers. Hence, the withdrawal of ground water from the alluvium by pumping probably can be increased by 2½–5 times, although at the moment rigorous proof for this estimate is lacking.

The quantities of water recharged per square kilometer to the Cretaceous formations on the uplands and to the Barreiras Formation may be smaller than the amount recharged per square kilometer to the alluvium. More or less precipitation than the 448 mm assumed for the above estimate would increase or decrease the amount of water available for recharging. A clay or shale layer just below the land surface would reduce or prevent infiltration of water, but a cavernous limestone might take in nearly all the rain that falls. Whatever the exact quantity of recharge to these formations may be, it is sure to be more than enough to offset the current withdrawal, which in relation to the capacity of the ground-water reservoir in the Cretaceous rocks is negligible.

CHEMICAL QUALITY OF WATER

Chemical analyses of eight samples show that the ground water in the alluvium of the Açu Valley is generally well below the accepted limits of concentration of mineral matter for use by man, plant, beast, and machine. The locations represented by the samples are shown on plate 1, and the analytical data are given in table 3. Wells 8, 13, 18, 23, and 24 were sampled because they represent hydrologic and hydrochemical conditions that seem to be prevalent in most of the valley. Wells 16, 26, and 27, on the other hand, represent localities where the ground water was reported to be of poor quality. The laboratory analyses are supplemented by 35 field determinations of total dissolved solids, chloride, hardness, iron, and pH. These provide information on many intermediate locations and confirm the conclusions based on the laboratory analyses.

The water from the alluvium is characterized by generally low dissolved solids content, low hardness, and a neutral or near-neutral pH. The total dissolved-solids content ordinarily ranges from 225 to 275 ppm (parts per million), the hardness from 65 to 110 ppm, and the pH from 6.7 to 7.3. Except locally, most of the water in the uppermost 8 m of the saturated alluvium is of usable quality. Where the water had been reported as inferior, the dissolved-solids content ranges from about 580 to 1,200 ppm, owing principally to the presence of large amounts of sodium and chloride. These places may have a predominance in the alluvium of fine-grained relatively impermeable sediments, perhaps partly enclosing a lesser amount of coarse water-bearing strata. This type of sediment retards the movement of ground water. Because retardation would lengthen the period of contact of water with sediment, the opportunity for solution to occur would be increased. Where the water contains more than 500 ppm of dissolved solids, the possible ill effects that might be caused by the water should be considered before it is used in large quantities.

The relatively small amount of mineral matter dissolved in the water throughout most of the valley suggests that not much soluble materials is present in the alluvium, or that the flow of water through the alluvium is relatively rapid, or both. It could also mean that the water received as recharge to the alluvium consists mainly of rain that falls on the flood plain.

In spite of the generally favorable results of the chemical analyses, there is a possibility that the ground water in some parts of the study area, or the water at depth in the alluvium, is relatively mineralized. Reporting on an electrical-resistivity survey, Cravo Barros, Feitosa, and Rijo (1966, p. 5–6) concluded that encroachment by marine water had extended up the valley to about 7 km southwest of Pendências. The same authors found also a locality a few kilometers to the north where a possible fresh-water overlies salty water, but they concluded that it would not justify development, both because it is thin and because it has salty water under it.

SUITABILITY OF WATER FOR DOMESTIC USE

With a few exceptions, the water from wells tapping the alluvium in the Açu Valley is potable and acceptable for normal home use. Acceptable limits of concentration of some 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 table 3.

Constituent	*Parts per million*
Chloride	250
Sulfate	250
Nitrate	45
Total dissolved solids	500
Hardness (soft water)	70

Marked traces of nitrate were detected in the water from wells 16, 18, and 27, but not enough to indicate a hazardous condition. The traces suggest the desirability of testing the nitrate content of the water periodically in order to detect a hazardous condition, if it should occur. Nitrate in excess of 45 ppm is an indication of organic contamination of the water, which at wells 16 and 27 could be derived from fresh protein waste, inasmuch as these wells are in a public market.

TABLE 3.—*Chemical analyses of water from the alluvium of the Açu Valley*

[Results in parts per million, except as indicated. Analyses made by Superintendency for Development of the Northeast, Recife, Brazil]

Well number [1]	8	13	16	18	23	24	26	27
Date of collection	7–14–65	7–13–65	7–13–65	7–12–65	7–10–65	7–12–65	7–12–65	7–14–65
Calcium (Ca)	21	26	56	18	24	15	61	80
Magnesium (Mg)	7.4	7.8	12.0	10.0	13.0	6.3	31.0	39.0
Sodium (Na)	34	33	290	25	20	30	68	100
Potassium (K)	4.9	4.9	16.0	3.8	7.8	4.4	9.5	14.0
Chloride (Cl)	64	36	370	50	29	26	220	232
Sulfate (SO_4)	16	10	31	14	19	16	35	115
Bicarbonate (HCO_3)	68	137	373	72	132	105	112	166
Nitrite (NO_2)	0	0	0	0	0	0	0	0
Nitrate (NO_3)	Tr.	Tr.	Tr.	Tr.	0	0	0	Tr.
Dry residue (110°C)	237	276	1,206	226	263	224	583	880
Total solids (calculated)	216	255	1,147	198	244	203	532	747
Total hardness ($CaCO_3$)	82	96	210	86	110	64	280	360
Specific conductance (micromhos at 25°C)	340	380	1,680	270	290	290	880	1,250
pH	6.7	6.9	7.3	7.0	7.2	7.3	7.0	7.2

[1] Well location shown on plate 1 and described in table 4.

SUITABILITY OF WATER FOR IRRIGATION

Several factors in addition to mineral content determine whether water is suitable for irrigation use. Among them are the amount of water applied to the soil, the amount and distribution of rain, the drainage, and the physical and chemical character of the soil. If the concentration is 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 parts to many thousand parts per million, but in most irrigation waters range from 100 to 1,500 ppm.

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) 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 generally are satisfactory for irrigation insofar as salt content is concerned, although certain salt-sensitive crops may be damaged by waters having conductivity in the range of 250–750 micromhos per centimeter. Waters in the range of 750–2,250 micromhos per centimeter are widely used, and satisfactory crops are obtained under good management and favorable drainage conditions, but saline conditions will result if leaching and drainage are not adequate. Successful use of waters with conductivity above 2,250 micromhos per centimeter is exceptional. Only the more salt-tolerant crops can be grown with such waters, 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 that have 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 proportion of sodium is best expressed by the sodium-absorption ratio (SAR). The soluble inorganic constitutents 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 sodium-absorption ratio of a soil solution has advantages as an index of the sodium or alkali hazard because it is simply related to the absorption of sodium by the soil. This ratio is defined by the equation:

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

where Na^+ and Ca^{++} represent concentrations in milliequivalents 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 having 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 having 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.

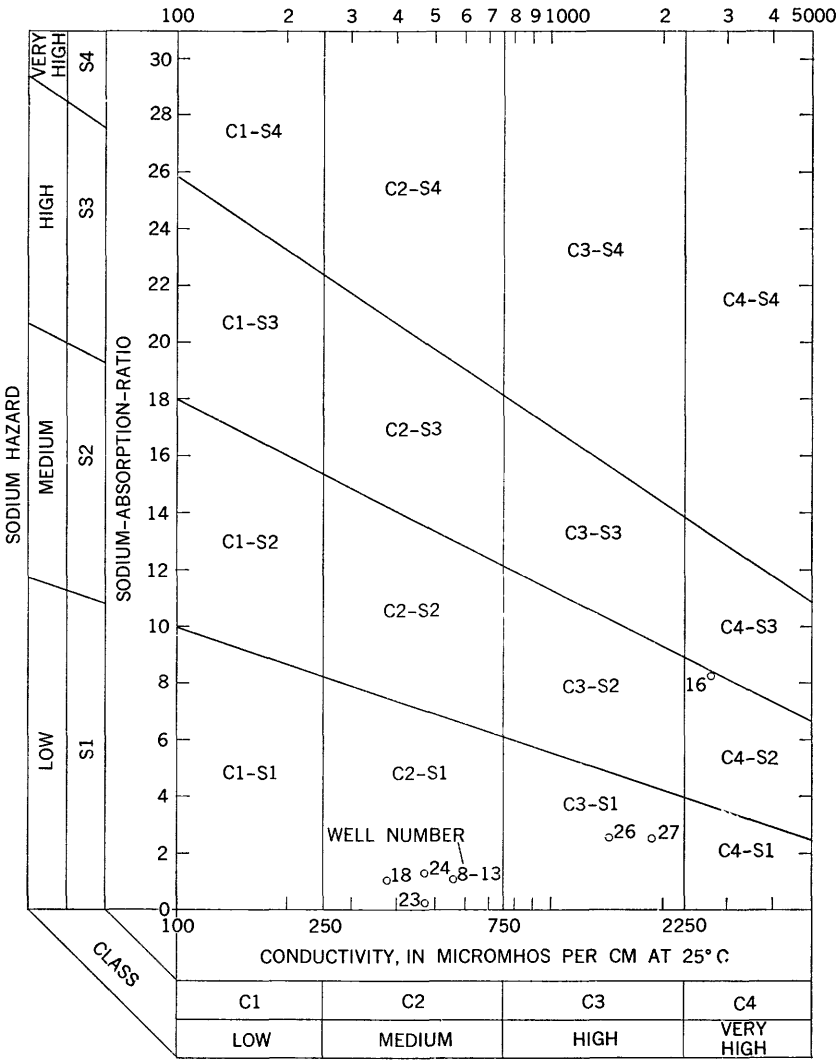


FIGURE 2.—Classification of irrigation waters from wells in the Açu Valley. Diagram from U.S. Salinity Laboratory (1954).

Combining the four SAR classes with the four conductivity (salinity) classes makes a total of 16 possible classes, as shown in figure 2. From the SAR and electrical-conductivity values used as coordinates, a point showing the quality classification of a water from wells listed in table 3 is found on the diagram. Waters from wells 8, 13, 18, 23, and 24 represent the chemical condition prevalent generally in the valley. They are classified as C2–S1. Waters from wells 16, 26, and 27 represent local situations and fall in categories C3–S1 and C4–S2.

Boron was not determined in the chemical analyses of water from the Açu Valley. 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 ppm of boron, whereas alfalfa will make a maximum growth with 1–2 ppm of boron.

SUITABILITY OF WATER FOR LIVESTOCK

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

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

QUALITY OF WATER IN CRETACEOUS ROCKS

Ground water sampled at several wells that tap the Açu and Jandaíra formations, both in and outside the report area, was found to be generally of poor quality. Some of it is unfit for human consumption. Field tests show the total dissolved solids to range from 1,100 to 5,200 ppm and the hardness, chloride, and iron to be considerably higher than in water from the alluvium. Exceptions occur where the water from the alluvium infiltrates into the underlying permeable Açu Sandstone. An example is the public-supply well in the city of Ipanguaçu (well 35), which penetrates 18 m of saturated alluvium over the Açu

Sandstone. At this well, the total dissolved-solids content is 440 ppm, considerably lower than for other wells in the Cretaceous rocks and slightly higher than for most wells in alluvium.

TEMPERATURE OF GROUND WATER

The temperature of the ground water as it comes from wells in the Açu area is not important in the present stage of economic development of the locality, but it could become important in the future. Because the prevailing temperatures are in the ordinary range, no difficulties are created in using the water. When water is used for cooling or in industrial processes requiring a specific temperature, the temperature of the water from a well can affect the cost of operation. The temperature of water used in irrigation, on the other hand, is unimportant so long as the water is neither exceptionally warm nor exceptionally cold.

The temperature of ground water fluctuates seasonally where the water table is less than 10 m below the land surface, and there is a strong contrast between the hot and the cold season. The seasons are not pronounced in the Açu area, however, and the fluctuations of ground-water temperature probably are small. The fluctuations of water temperature in the Açu area probably do not extend as much as 10 m below the land surface.

The temperature of the ground water at depths somewhat greater than about 10 m—perhaps less in the Açu area—is likely to be about 1°C higher than the mean annual air temperature for a locality (Van Orstrand, 1935, p. 88). The temperature of water from wells in the alluvium of the Açu Valley was measured only once in this investigation. It ranged from 28 to 31°C.

The temperature of ground water below a depth of about 30 m normally increases gradually as the depth increases, because the rocks deep in the earth are warmer than those at the surface. The wells that tap the Açu Sandstone and the Jandaíra Limestone are considerably deeper and have deeper static water levels than wells in the alluvium. The water from these wells should be slightly warmer than water from the wells in the valley, but too few temperatures were measured for a plausible average. The temperatures measured at these wells were generally 30–31°C.

PRESENT DEVELOPMENT OF GROUND WATER

Ground water from the alluvium is used in homes throughout the Açu Valley for drinking, washing, and cooking and is used for cattle and irrigation. Several wells are used as a principal source of water for people living in urban areas. Much of the drinking water for the town of Açu comes from the privately owned "Poço das Carroças" (well 23, table 4), from which water is hauled in barrels mounted on donkey-drawn two-wheeled carts. A large part of the drinking water for Ipanguaçu comes from a centrally located publicly owned drilled well (well 35, table 2). Even Macau, which is about 10 km north of the area studied, gets part of its drinking water from a well near Pendências (well 21, table 4). The consumption of water per capita is low, even in the towns, because no town in the area has either a public water-distribution system or water-borne sewerage system. Urban citizens, like rural citizens, carry water by hand, or at best have it delivered by cart or donkey.

There are in the valley about 300 dug wells, half of which are equipped with pumps and 5- or 6-horsepower diesel engines for irrigation use. The other half have only manual or windmill-driven pumps, or a rope and bucket. There are, in addition, about 500 drive-point wells equipped with manual or windmill-driven pumps.

The dug wells range in depth from 2 to 8 m and in diameter from 1 to 2.5 m. Typically, these wells are lined with bricks that are supported with flat steel rings at vertical intervals of 1–2 m. The bricks above the water table are cemented together, but those below are loosely fitted and uncemented and form a screen through which water can enter the well. The wells with diesel-power pumps, it is reported, yield an average of about 50,000 lph (liters per hour) and are pumped about 50 hours per month during the 6-month dry season. Typical of such wells is one at Fazenda Santo Antonio, 10 km north of the town of Açu (well 4, pl. 1). This well was dug in 1958, is 7.8 m deep, 2.25 m in diameter, and has a static water level about 4.5 m below the land surface and a pumping level of about 6.5 m (table 4). The foreman reported that this well normally is pumped 3 or 4 hours a day, 3 days a week, at a rate of about 60,000 lph (6,300 cu m per week). Its yield, he says, is more than sufficient for the irrigation of 1 hectare of banana, mango, orange, and coconut. Exceptionally productive wells, such as the one at Fazenda Córrego do Maia (well 13, pl. 1), are pumped with electricity and yield as much as 80,000 lph. Dug wells that have only manual or windmill-driven pumps, or rope and bucket, probably yield only about 500 lpd (liters per day) throughout the year.

The drive-point wells range in depth from 3 to 8 m and in diameter from 1.25 to 2 inches and generally have a screen about half a meter long. The wells equipped with hand pump or windmill probably yield an average of about 500 lpd, which is only enough for house use, for cattle, and for irrigation of a small garden. When pumped continuously, however, a good drive-point well will yield 600–2,000 lph. Typical is well 18, 3 km east of Ipanguaçu, which is 5 m deep, 1.5 inches in

TABLE 4.—*Records of selected dug and driven wells in the Açu Valley*

Type of well: D, dug well; Dr, driven well.
Depth: referred to land surface; measured in dug wells, reported in driven wells.
Pump: M, motor driven; E, electric power; H, hand pump; W, windmill.
Water level: referred to land surface; measured in dug wells, reported in driven wells.
Use: I, irrigation; D, domestic.

Well	Owner, user, or locality	Type of well	Depth (meters)	Diameter of well		Type of pump	Water level (meters)		Date	Well discharge (liters per hour)	Use	Year completed	Area irrigated (hectares)	Remarks
				(meters)	(inches)		Static	Dynamic						
									1965					
1	Joaquim Alfredo, Fazenda Puaçá.	D	7.9	2.2		M	5.8	7.0	May 13	60,000	I	1959	7.0	
2	Francisco Morais Sobrinho, Fazenda Santa Clara.	D	11.0	3.0		H	7.8		do	200	D	1957		Pumps an average of 600 lpd., however, well goes dry after 0.5 hr of pumping in dry season.
3	José Rodrigues da Silva, Fazenda Santo Antônio.	D	7.4	2.3		M	2.5		do	[1] 40,000	I	1959	1.0	
4	Sebastião Rodrigues de Madeiros, Fazenda Santo Antônio.	D	7.8	2.3		M	4.5	6.5	May 21	60,000	I	1958	4.0	0.75 hr pumping test.
5	Pedro Borges, Fazenda Canto do Umuri.	D	6.5	2.5		M	4.1	5.24	July 22	45,000	I, D	1957		
6	Eliodoro C. Costa, Fazenda Estevão.	D	8.4	2.3		M	2.6		May 13	35,000	I	1958	4.0	
7	João Severo de Moura	D	4.5	2.0		M	2.0		July 14	30,000	I, D	1956	2.0	Water considered unsuitable for drinking.
8	Tarcísio Moura Fernandes	Dr	5.0		1.5	H	3.0		do	[1] 900	D		.2	Pumps an average of 700 lpd.
9	Luis Cortez Sobrinho, Carnaubais.	Dr	6.6		2.0	H	5.0		May 20	600	D	1960		Pumps an average of 500 lpd.
10	Antônio Rodrigues da Silva, Carnaubais.	Dr	6.0		1.5	H	4.0		May 19	1,200	D	1964		Pumps an average of 3,000 lpd.
11	Antônio Vicente de Lemos, Fazenda Tabatinga.	Dr	6.6		1.2	H	4.4		do	[1] 750	D	1951		Pumps an average of 750 lpd.
12	Mariano Farias	Dr	3.5		1.5	H			July 14	550	D	1961		Pumps an average of 100 lpd.

13	Valter Sá Leitão, Fazenda Corrego do Maia.	D	8.0	2.5		E	4.1	5.24	May 13	[1] 50,000	I	1952	4.0	0.5 hr pumping test.
14	Ministério da Agricultura, Posto Agro-Pecuário.	D	8.1	2.2		M	3.4	4.43	May 14	[1] 90,000	I	1954	5	Do.
15	Ray Lewis	Dr	6.0		1.5	H	4.0		May 18	850	D	1960		Pumps an average of 200 lpd.
16	Ipanguaçu market	Dr	6.0		1.5	H	2.0		July 12	[1] 1,500	D	1964		Pumps an average of 1,000 lpd.
17	Fazenda Ubarana	D	6.8	3.0		M	1.3	4.26	May 15	[1] 54,000	I	1957	3.0	0.5 hr pumping test.
18	Francisco Irineu Sobrinho	Dr	5.0		1.5	H	2.0		July 12	[1] 1,350	I	1957	.3	Pumps an average of 1,000 lpd.
19	Manuel Montenegro, Fazenda Picada.	D	10.0		1.5	W			July 11	400	D	1919		Pumps an average of 500 lpd.
20	Antes do Alto Rodrigues	D	4.9	1.3		W	.85		May 21	650	I		.5	Pumps an average of 1,000 lpd.
21	João Rocha Bezerra, Fazenda Bamburral.	D	5.9	3.0		M	1.5		May 22	50,000	D	1958		Supplies drinking water in dry season for Macau.
22	Sebastião, Pendências	Dr	7.0		2.0	W	3.0		do	700	I	1962	.2	Pumps an average of 1,500 lpd.
23	Poço das Carroças	D	6.0	2.0		M	3.9		May 17	[1] 20,000	D			Supplies 80,000 l (liters) of drinking water for Açu per day.
24	Francisco Soares	Dr	6.0		1.5	H	3.0		May 18	[1] 600	D	1964		Pumps an average of 300 lpd.
25	Grupo Escolar JK	D	27.6	2.6		H	21.8		May 17	[1] 800	D	1958		Pumps an average of 400 lpd.
26	Valter Sá Leitão Fazenda Córrego do Maia.	D	4.1	1.0		W	3.1		July 12	650	D			Pumps an average of 500 lpd. Pumps an average of 500 lpd.
27	Carnaubais market	Dr	5.0		2.0	H	2.5		July 14	1,000	D	1963		Pumps an average of 700 lpd.

[1] Measured by authors.

diameter, and is equipped with a manual suction pump (table 3). The static water level is about 2 m below the land surface. The owner reports that this well yields from 500 to 1,000 lpd, and has never been dry. The water is used for irrigation of about 0.33 hectare planted in banana, orange, and mango. A second driven well on the same property is equipped with a windmill-driven pump, and is said to supply enough water for irrigation 0.75 hectare of citrus fruits and bananas.

The annual pumpage from the principal aquifer in the valley has been nearly constant since 1959. It is estimated to have been about 2.25 million cu m in 1964, or only about 90 cu m from each hectare-meter of saturated alluvium. If no recharge were received, this pumping rate would lower the water table about 1 m in 11 years. Actually, no such decline is likely to occur, because the recharge from precipitation alone is estimated to be more than enough to replace the water currently being pumped out.

WATER DEMAND

The total quantity of water needed for irrigation in the Açu Valley depends on the number of hectares being irrigated and the amount of water applied to each hectare. The area of irrigable bottom land between Açu and Pendências is about 25,000 hectares, but only 10 percent is being irrigated. The quantity of water currently applied to irrigated crops is very small compared with the quantities used in highly developed irrigated areas. As stated in the section "Present Development of Ground Water," one irrigator was using only 630 cu m per week per hectare and another was using 500–1,000 lpd on one-third hectare. These quantities probably would be ineffective if the water were being spread uniformly over the land. The first of these irrigators, however, conducts the water by lined canal to citrus trees and other plants, which thus are being watered individually. Intervening areas get little or no irrigation water. The other irrigator was carrying water by hand to each plant, a procedure that in itself tends to limit drastically the amount of water used and would be impractical for large-scale irrigation. If the average quantity of water applied by these methods is extended to the total area, the total water requirement would be about 22 million cu m per year.

At the other extreme, perhaps, is an estimate by the U.S. Bureau of Reclamation (1963, p. 43; 1964, p. 79) that irrigation of 22,400 hectares in the valley would require 278 million cu m per year. Adding 25 percent for water lost in distribution and in operation would bring the total to about 350 million cu m per year. The Bureau assumed in its estimate that the annual application rate would equal a depth of 1.24 m, 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 probably will be many years before the average throughout the valley approaches 1.24 m. The total annual demand for water, therefore, will be considerably below the Bureau's estimate for a long time.

FURTHER DEVELOPMENT OF GROUND WATER

The ground water of the Açu Valley can be developed further. In fact, the present withdrawal of water is only a fraction of the quantity that probably could be withdrawn without permanently depleting the supply of water stored in the alluvium. The estimate of the annual replenishment, although far from precise, suggests that the withdrawal might be 2½–5 times greater than at present. In addition, aquifers in the rocks of Cretaceous age, notably the Açu Sandstone, contain a large but practically untapped supply of water.

Further development of ground water is likely to stem from slow expansion of the area being irrigated and an increase in the number of wells being pumped for irrigation. It will probably include, also, a gradual shift from large-diameter dug wells to drilled wells equipped with turbine pumps, and when electric power becomes generally available in the area, a shift from diesel and gasoline engines to electric motors for driving the pumps. Such wells, although more costly to construct than dug wells, may be constructed more quickly and often will yield more water. The drilled wells will have to be cased, and for maximum efficiency they ultimately will have well screens designed and manufactured especially to admit water to wells. Increasing the area irrigated and the quantity of water employed is likely to require a change from the present piecemeal plant by plant method of distributing water to a general soaking of whole fields by spreading water from ditches or by sprinklers. This change probably will result in an increase in the quantity of water used per hectare.

The growth envisioned in the preceding paragraph will necessarily depend on a strong and growing demand for the crops produced. At the same time, it will itself generate a part of that demand, by creating employment for suppliers of pumps, fuel, equipment, repair parts, seeds, fertilizers, and for those who buy, sell, process, and transport the products. The growth of irrigation can be expected to be accompanied by an increasingly insistent demand for additional water in towns, accompanied by new water-distribution systems that will make it possible and easy for the citizens to use much more water than now. Industries will be established, and some of them will require water, which they will obtain either from the public supply or from their own wells.

The further development of the ground water in the Açu Sandstone and Jandaíra Limestone is likely to lag behind the development of ground water in the alluvium (which as yet has not gone far), partly because in these formations, especially at locations on the uplands, the depth to water is greater than in the valley. Greater depth means greater cost in construction of a well and also in pumping water from it, and, therefore, will deter or prevent the irrigation of the uplands with well water. A profitable industry, on the other hand, might find depth to be no obstacle.

ADDITIONAL HYDROGEOLOGIC INVESTIGATION

This report outlines an opportunity for economic development of the Açu area on the basis of a single resource, ground water. Other resources also are involved, as are geographic, climatic, economic, and even political factors. The problems of development, here as elsewhere, are complex. Even in respect to ground water, this report is in general terms, not establishing precise limits to the extent of the possible development. To determine such limits, more data than now exist will be needed, including the following:

1. The extent and thickness of the alluvium, and especially the thickness and distribution of water-bearing sand and gravel in the alluvium. This information could be determined by drilling test wells, or by geophysical exploration.
2. The transmissibility and storage coefficients of the aluvium, determined by making aquifer tests in which wells are pumped under controlled conditions; such tests should be made at several representative locations in the Açu Valley.
3. The amount of natural recharge and discharge to the aquifer. This would require information on precipitation at many locations and the measurement of streamflow, including measurements to determine which reaches of the river receive from and which contribute to ground water; several years of records are needed to make valid averages.
4. The amount of artificial discharge, principally the pumpage from wells, determined over a period of several years by annually surveying the wells being used on the areas being irrigated.
5. Fluctuations of water levels, determined by periodic measurements of water level in wells, correlated with precipitation (recharge) and pumpage (a factor in the discharge).
6. The areal distribution of ground waters of various chemical types, determined by sampling and analyzing water from many different wells and from different depths; identifying, if possible, the sources of objectionable chemical constituents.
7. Effects of irrigation on the land, especially the accumulation of salts in the soil, or the water logging of intensively irrigated areas.

8. The quantity and quality of the ground water in the rocks of Cretaceous age, determined by appraising items 1–6 with respect to these rocks.

The investigative work suggested above need not all be done immediately, but it should not be postponed until the reservoir is nearly exhausted. Development of the ground water in the Açu area, if it proceeds at the same moderate pace as in the past, does not require immediate answers to all the problems suggested above, but, sooner or later, mistakes can be made if the hydrologic system is not well understood. Hydrologic studies made concurrently with the development of the water resource would mainly serve to guide the development, prevent most of the mistakes, and lead ultimately to a rational and practical utilization of the water. Local problems created by locally intensive demand and development could be solved through intensive investigation of the limited areas involved.

CONCLUSIONS

The ground-water reservoir underlying the Açu Valley can supply much additional water. The estimated natural recharge alone is probably 2½ to 5 times as much as the quantity of water pumped from wells in 1964 and may be augmented by water introduced from upstream by the river, or by water moving underground from other adjacent aquifers. If additional water were to be developed, it probably would be destined first to irrigation use.

Recirculated water—pumped water that infiltrates to the water table and can be pumped again—would increase the total quantity of water available.

The quality of the ground water is generally good. The mineral matter dissolved in the water will not limit the extension of irrigation in the Açu Valley for a long time to come. The relatively rapid circulation and renewal of water in the aquifer preclude rapid deterioration of water quality.

Recirculation will gradually cause an increase in dissolved solids in the water. Such an increase is normal in irrigated areas where recirculation occurs, but ordinarily requires years to become serious.

Evapotranspiration will also tend to increase the amount of dissolved substances in the water, as well as the salts accumulated in the soil. This, too, is a natural process normally occurring in irrigated area, and the increase in salinity will take place slowly.

Water logging could become an acute problem in some parts of the area if excessive amounts of surface water should be introduced in irrigation. In general, however, the vertical drainage between the land surface and the water table is relatively rapid, and the problem of water logging probably will be unimportant where ground water is the principal or only source of water for irrigation and the pumping lowers the water table.

The water from the alluvium is generally potable and can be used for municipal water supplies. It could also be used by industries, except those having special requirements with respect to certain chemical ingredients.

The Açu Sandstone is an aquifer having great capacity for water, but is practically untapped. The water probably contains more dissolved mineral matter, on the average, than the water in the alluvium. The Jandaíra Limestone also contains considerable quantities of water, which, however, seems to be of inferior chemical quality.

REFERENCES CITED

Bigarella, J. J., and Andrade, G. O. de, 1964, Considerações sôbre a estratigrafia dos sedimentos cenozoicós em Pernambuco (grupo Barreiras): Arquivo do Inst, de Cienc. da Terra, Univ. Fed. Pernambuco, no. 2, p. 2–15.

Blankennagel, R. K., 1962, Geologic summary and ground-water potential of the Potiguar Basin in Rio Grande do Norte: Petrobŕas report, 1579, Rio de Janeiro, 24 p., 2 pls., 1 fig.

Cravo Barros, J. G. do, Feitosa, Editosa, Edilton, e Rijo, Luiz, 1966, Vale do Rio Açu, reconhecimento hidrogeológico por prospeção elétrica: Supt. Desenv. do Nordeste (Brazil) open-file report, 9 p., 2 maps.

Departamento Nacional de Produção Mineral. 1963. Reconhecimento foto-geológico da região nordeste do Brasil: map SB 24 L.

Hem, J. D., 1959, Study and interpretation of chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 269 p., 40 figs.

Kegel, Wilhelm, 1957, Contribuição ao estudo bacia costeira do Rio Grande do Norte: Div. Geol. Min. (DNPM), Bull. 170, 52 p.

Leite, D. C., 1963, A colaboração da Petrobrãs no problema de águas subterrâneas para o nordeste; XVII Congresso Bras. de Geol. mimeographed report, 17 p.

Mabessone, J. M., 1965, Observações sôbre os sedimentos do grupo Barreiras nos estados de Pernambuco, Paraíba e Rio Grande do Norte: Resumos dos trabalhos apresentados, I Simposio, Geologia do Nordeste (Maceió), p. 6.

Petrobrás, 1956, Sumário geológico e potencial de água do sub-solo da bacia Potiguar, Rio Grande do Norte: mimeographed report, 20 p.

Thompson, A. N., 1964, Interim report, Piranhas River basin: U.S. Agency for Internat. Devel. open-file report, 18 p.

U.S. Bureau of Reclamation, 1964, Um estudo da bacia do Rio Piranhas: SUDENE Bol. Rec. Nat., vol. 2, no. 1/4, p. 27–136. (Translated from Piranhas River basin study: U.S. Agency for Internat. Devel. open-file report, 1963, 87 p.).

U.S. Public Health Service, 1962, Drinking water standards: Pub. no. 956, 61 p.

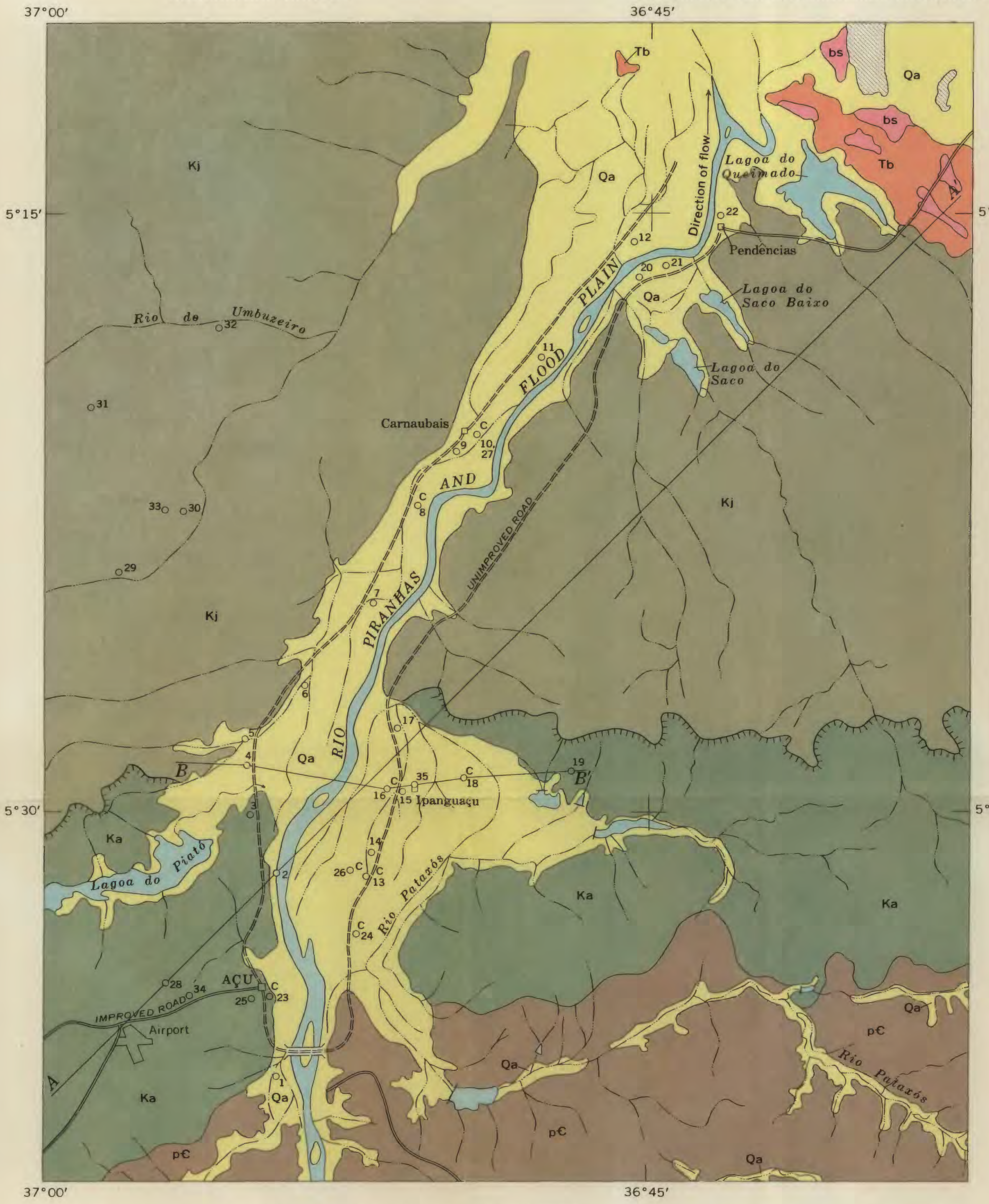
U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Dept. Agriculture Handbook, no. 60, 160 p., 33 figs.

Van Ostrand, C. E., 1935, Normal geothermal gradient in United States: Am. Assoc. Petroleum Geologists Bull., v. 19, p. 78–115.

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
SUPERINTENDÊNCIA DO DESENVOLVIMENTO DO NORDESTE OF BRAZIL
UNDER THE AUSPICES OF THE
U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT

WATER-SUPPLY PAPER 1663-C
PLATE 1



EXPLANATION

Soil not shown on geologic map

Qa	Alluvium	QUATERNARY
Tb	Barreiras Formation	TERTIARY
bs	Mafic intrusive rocks	POST-CRETACEOUS
Kj	Jandaíra Limestone	CRETACEOUS
Ka	Açu Sandstone	CRETACEOUS
pЄ	Crystalline rocks	PRECAMBRIAN
	Salt flats	

8○C Well

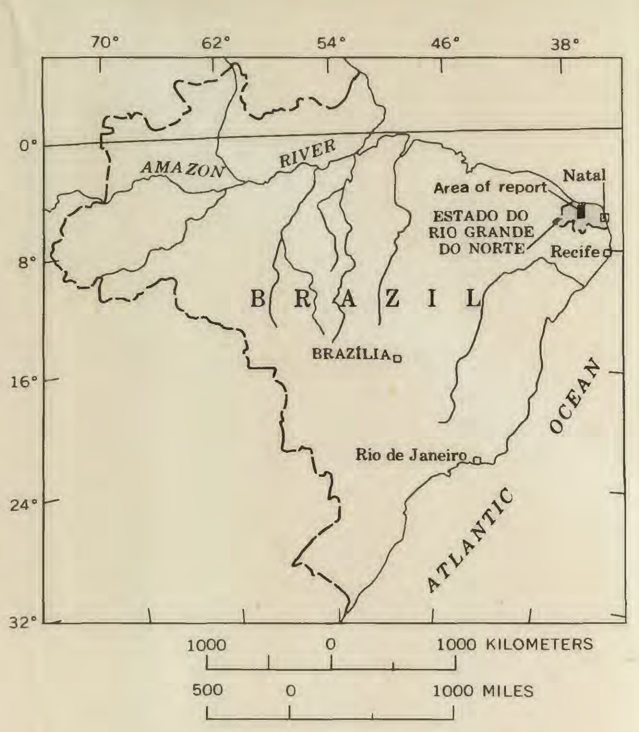
Number referred to in table 3. Letter "C" indicates chemical analysis available

Contact

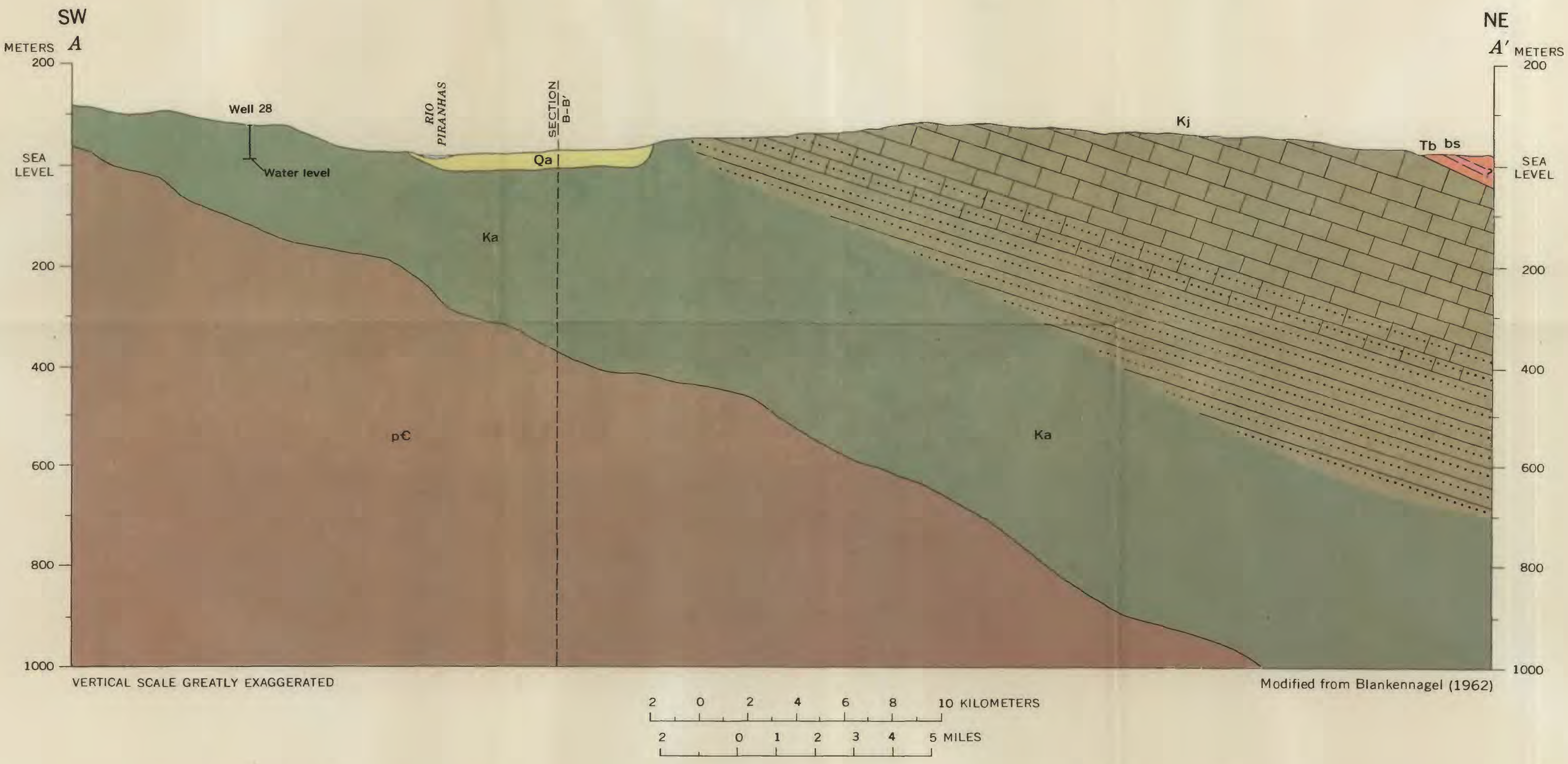
Escarpment

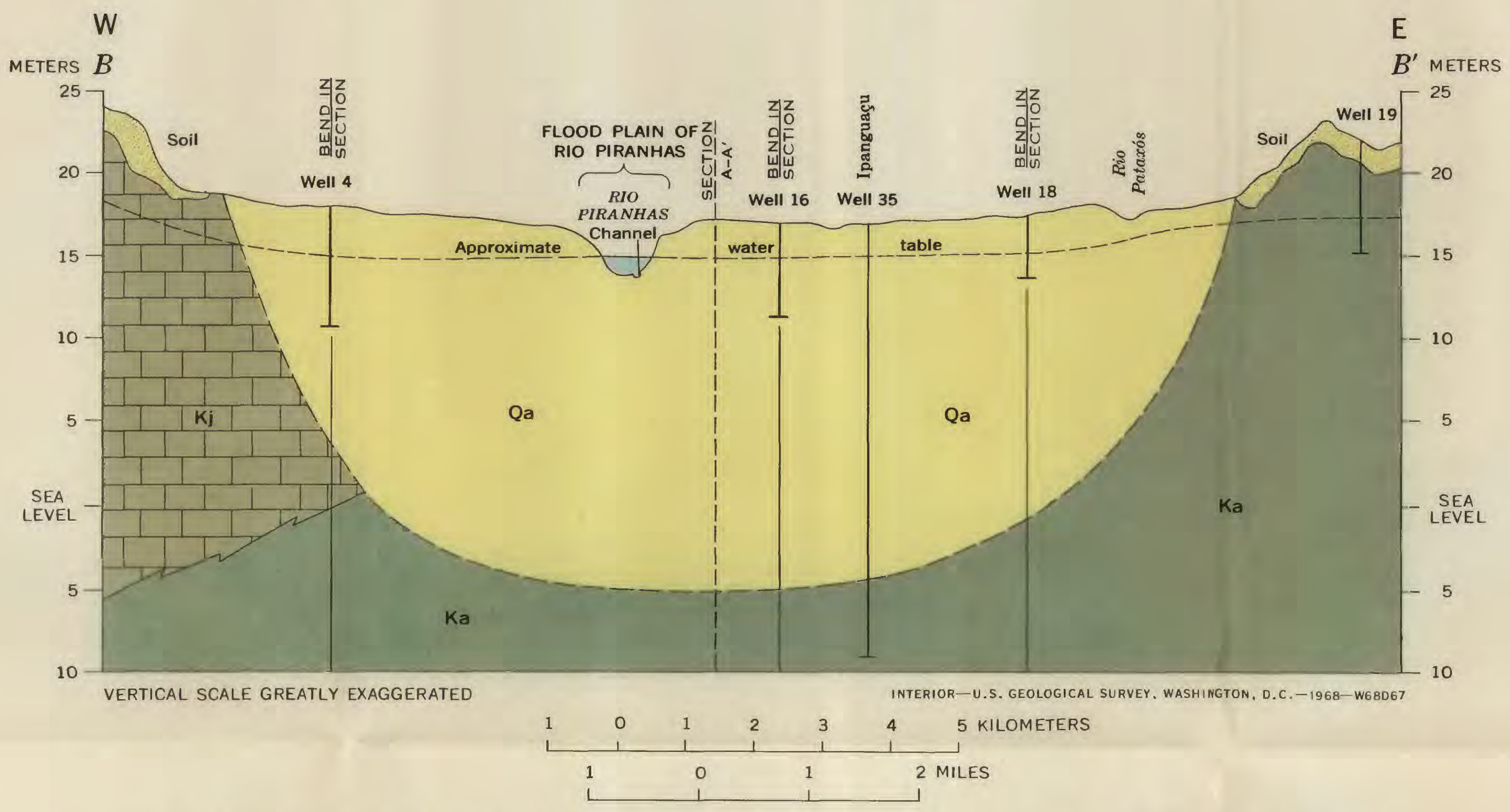
2 0 2 4 6 8 10 KILOMETERS
2 0 1 2 3 4 5 MILES

Geology from photogeologic map of the Macau–Ponta do Mel quadrangles, SB-24L and SB-24F, by Departamento Nacional de Producão Mineral, Ministerio Minas e Energia (1963)



INDEX MAP OF BRAZIL SHOWING LOCATION OF REPORT AREA





GEOLOGIC MAP SHOWING LOCATIONS OF WELLS, AÇU VALLEY RIO GRANDE DO NORTE, NORTHEASTERN BRAZIL