EVALUATION of POTENTIAL IMPACT of PHOSPHATE MINING on GROUND-WATER RESOURCES of EASTERN NORTH CAROLINA

By Board of Consultants: R.J.M. DeWiest, A. Nelson Sayre, C.E. Jacob, Chairman

STATE OF NORTH CAROLINA
DEPARTMENT OF WATER RESOURCES

January 1967

LETTER OF TRANSMITTAL

Raleigh, North Carolina
March 14, 1967

Mr. J. R. Townsend, Chairman
Board of Water Resources
Raleigh, North Carolina

Dear Mr. Townsend:

On behalf of Dr. DeWiest, Dr. Sayre, and myself, I am pleased to transmit herewith our report titled "Evaluation of Potential Impact of Phosphate Mining on Ground-Water Resources of Eastern North Carolina."

This report, while emphasizing the urgent problem of the ground-water supply of the coastal plain, is concerned with the broader issue of the management of all the ground-water resources of the state. We trust that it will prove helpful to the people of North Carolina and particularly to the General Assembly.

May we express our appreciation for the excellent cooperation of all concerned, especially official agencies, municipalities and industries of the state. It has been a pleasure to be of service. We stand ready to discuss our findings and recommendations with you and the General Assembly and with industrial and other interests.

Respectfully submitted,

C. E. Jacob

C. E. Jacob, Chairman
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Honorable Dan K. Moore
Governor of North Carolina
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Dear Governor Moore:

I am submitting herewith Evaluation of Potential Impact of Phosphate Mining on Ground-Water Resources of Eastern North Carolina prepared by the Board of Consultants.

Conflicting views regarding the effect of open pit phosphate mining on the ground-water resources of the Coastal Plain region of North Carolina prompted the Board of Water Resources, in the fall of 1965, to request that an evaluation of potential impact of phosphate mining on ground-water resources of Eastern North Carolina be conducted by an independent board of consultants.

You as Governor and the Council of State made funds available to engage a three-man board of internationally-recognized consultants to make this evaluation to resolve the divergent views.

With the full cooperation of the phosphate industry, a study involving on-the-site investigations, numerous conferences with State and industry officials, and detailed analysis of large volumes of technical data, was carried out in 1966. From the beginning of this study, the primary objective of all concerned has been to insure the maximum feasible development of the phosphate industry while safeguarding the natural resources for Total Development.

The report of the Board of Consultants supports the original contention of the Board of Water Resources that heavy withdrawals of water from the underground aquifers of the Coastal Plain can, unless properly controlled, adversely affect the quality and quantity of water available in the region for other present and future uses.

Sincerely,

J. R. Townsend

J. R. Townsend
Chairman

Enclosure

SYNOPSIS

The Castle Hayne limestone underlying part of the Coastal Plain of eastern North Carolina is the most prolific and most permeable water-bearing formation or aquifer in that area. It dips eastward beneath the Coastal Plain and at greater depths east of the phosphate area contains salty water that is unusable. Fortunately, in the area of interest it has been flushed out by freely circulating ground waters that discharged naturally by slow percolation through overlying formations into the estuaries of the rivers crossing the Coastal Plain.

In order to dewater an open-pit phosphate mine at Lee Creek on the Pamlico River a number of wells surrounding that pit and tapping the Castle Hayne have been pumped since July 1965. The influence of this pumping has extended more than 25 miles in all directions and has reduced artesian pressures. This has caused a reversal of the natural seepage, so that in some places, especially in the estuary of the Pamlico River upstream from the pit, where the protective cover on the limestone is thin and ineffective, salty or brackish water from the river has moved and will continue to move into and contaminate the fresh water in the Castle Hayne aquifer. The Beaufort formation, immediately underlying the Castle Hayne limestone at the mine, contains brackish water and it also is a nearby source of contamination by salty water.

Natural replenishment in the outcrop of the Castle Hayne limestone west and southwest of the pit, about 20 miles away on the average, is not close enough to the pit to overshadow, or to overcome the ill effects of, the downward leakage through the estuary of the river.

The Coastal Plain of North Carolina is on the threshold of a period of rapid and extensive development, but the course of this development will depend upon the continued availability of abundant supplies of potable water. We recommend that steps be taken by the State Legislature immediately to establish controls that will provide for the optimum utilization of the ground water resources without incurring the risks that attend over-development and to provide equitable treatment for all potential users. The State Department of Water Resources has outlined the options available to North Carolina and the need for further regulation and we endorse the objectives outlined by that Department. It is not the purpose of the consulting board to suggest the precise form that management and control of ground-water development should take; however, we do recommend a thorough study of the laws of the States of New York and New Jersey, where salt water already has ruined some productive aquifers. The regulation and control of ground-water withdrawals have been effective for many years in those states.

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INTRODUCTION

This report is concerned with the management of the coastal water supply of eastern North Carolina. An immediate problem is the recovery of valuable deposits of phosphate without impairment of the ground-water supply. A long-range goal should be the balanced economic development of the area through the wisest use of all resources--mineral, agricultural, and water. Water supply will figure pre-eminently in such development. Hence the need for accurate appraisal of the resource, wise planning for its full use, and effective legislation for its management.

Terms of Reference

The scope of this study was outlined in a written memorandum and orally during a conference in Raleigh, January 10, 1966 as follows:

> The study and conclusions on the ground-water conditions in eastern North Carolina should be limited to evaluating the present conditions and the effects that may result from prolonged withdrawal of large quantities of **ground water.**
>
> The report should present the technical findings and conclusions and recommendations based on those findings.
>
> An opinion is requested on the legal classification of the water in the Castle Hayne aquifer, that is, whether it is percolating water that filters, oozes, percolates or flows, or is a subterranean stream flowing in a known and defined channel.

Advice is sought on the adequacy or inadequacy of existing legislation to enable the State of North Carolina to administer the development and conservation of the ground-water resources of the Coastal Plain.

Specifically, the report was to accomplish the following:

Review existing data and reports pertaining to ground-water conditions in the area and the current and proposed mining operations that may affect ground-water conditions.

Determine, on the basis of available data, whether mining operations have created or may create significant ground-water problems, and the probable scope and magnitude of such problems.

Delineate the fresh water-salt water contact in the major water-bearing formations.

Determine the actual depth to salt or brackish water over the area.

Determine whether salt or brackish surface water might be drawn into the fresh-water formations, and if so, where.

Determine the rate at which saline water would enter and migrate through the formations.

Outline remedial measures to prevent or retard salt-water encroachment.

Review current and proposed programs of investigations and data collection to determine their adequacy, and recommend any needed modifications or expansion of these programs to provide a sound basis for conclusions on the effects of mining on ground-water conditions.

Previous Investigations

Surface water. A small program of surface-water investigations was initiated by the U. S. Geological Survey in cooperation with the State Geologist of North Carolina in 1895 and was continued until 1909. The number of stream-gaging stations included in the program never exceeded thirty. Systematic stream-discharge measurements were begun again in 1918 by the Survey in cooperation with the North Carolina Geological and Economic Survey. In 1920 the total expenditure from State and Federal sources was $830. At about this time Dr. Thorndike Saville, an enthusiastic proponent of hydro-power, became Chief Hydraulic Engineer of the North Carolina Survey. Largely because of his interest the stream-gaging program was rapidly expanded, and in 1928 the combined annual expenditure for stream gaging was a little over $22,000. In 1929 the U. S. Army Corps of Engineers, owing to its interest in flood control, augmented the money available for the stream-gaging programs by transfers of funds. There has since been still further growth in the program through increased appropriations and by transfers of funds from other agencies. Thus, investigations of stream flow are reasonably adequate at the present time.

Ground water. Early in the Twentieth Century a study of the geology and water resources of the Coastal Plain of North Carolina was begun by the U. S. Geological Survey in cooperation with the North Carolina Geologic and Economic Survey. This reconnaissance report by Clark and others [1912] was published by the State. In 1932-34, the U. S. Geological Survey made a study of the Elizabeth City area in cooperation with the Division of Water Resources of the North Carolina Department of Conservation and Development.

The results of this investigation were published in reports by Lohman [1934, 1936].

The investigations of ground-water resources in the State have generally lagged behind the stream-gaging program. As late as 1937 the North Carolina State Planning Board noted no shortage in water supply but recommended comprehensive ground-water investigations. In 1941, the State Geologist entered into an agreement with the U. S. Geological Survey and a small program of ground-water investigations was started. However, the staff was small and only slow progress was made. As a by-product of the program, P. M. Brown [1958] called attention to the wide extent and richness of the phosphate deposits in the Coastal Plain. These deposits were previously known, and several test wells had been drilled through them by commercial interests in 1952.

In 1959, the responsibility for investigations of both surface-water and ground-water resources was transferred to the newly organized Department of Water Resources. Since that time the professional staff engaged in ground-water studies has been increased about tenfold, and a substantial number of areal reports on ground-water resources have been published.

Texas Gulf Sulphur Company began to explore further the extent of the phosphate deposits and to determine the grade of the ore some time before 1961, also to evaluate the several methods by which the phosphate at Lee Creek, near Aurora, could be recovered. The Company carried out extensive tests on the feasibility of slurry pumping and of dredging. These tests were successful but the methods were considered too costly. Dry-pit mining was decided upon as the best method of mining. (Dry-pit mining requires that the ore body be dewatered.)

The Company made extensive engineering and geological studies of the

formations above the ore body and of the ore body itself. Numerous test wells were drilled and pumping tests were made to determine the hydraulic characteristics of the formations, including the Castle Hayne aquifer, which underlies the ore body and is also the principal source of water supply for the inhabitants of Beaufort and Pamlico Counties. Tests were made to explore the potential threat of salt-water intrusion that might be induced by the mining operation. These investigations and the conclusions drawn from them by consulting firms and by the experts of the Company are described in a report titled "Report of Investigations on the Castle Hayne Aquifer as Affected by Phosphate Mining Operations" which was released to the Department of Water Resources in May 1966.

In brief, the conclusions reached by the Company were:

(1) Dry-pit mining is the best method of recovering the phosphate at the Lee Creek site.

(2) Dewatering an open pit to a depth of 150 feet below the land surface (133 feet below sea level) would require pumping water from the Castle Hayne aquifer at the rate of 60 to 65 million gallons a day.

(3) As a result of pumping this quantity of water from the Castle Hayne aquifer, the water levels in farm and municipal wells would be lowered appreciably within a distance of twenty miles from the mine.

(4) Thick strata of impermeable clay above and below the aquifer and ore body would effectively prevent vertical movement of salty water. The impermeable heavy muck in the trench of the Pamlico River would inhibit movement of salty water into the aquifer from that source. The only known source of brackish water within the Castle Hayne itself is near Belhaven which is some 25 miles distant. Since the calculated rate of movement of ground water in that vicinity is 75 feet a year, the danger of salt-water

intrusion from that source was considered to be negligible.

Since completing their initial investigations, the Company has cooperated with the Department of Water Resources in carrying out a number of investigations suggested by the Division of Ground Water and by the Board of Consultants.

Other mining companies also have been interested in the feasibility of recovering phosphates in Beaufort and Pamlico Counties. Magnet Cove Mining Company has been experimenting with a hydraulic method of mining beneath Pungo River, but at this time the process is still experimental. Bear Creek Mining Company conducted pumping tests on the Yorktown formation, which overlies the phosphate beds, and on the Castle Hayne aquifer, which underlies the phosphate beds. The report on these pumping tests, which were conducted in December 1962 about three miles north of Aurora, was made available to the Board of Ground-Water Consultants. The conclusion was reached that both the Yorktown formation and the Castle Hayne carry water under artesian pressure and that the Castle Hayne is about ten times as productive as the Yorktown. The test on the Castle Hayne was terminated after 28 hours because of complaints that a nearby well had ceased to flow.

Department of Water Resources. In 1962 the State Stream Sanitation Committee and the Board of Water Resources became alarmed over the possibility that leases for rights to mine phosphate deposits beneath State-owned land in the Pamlico River and its tributaries might not provide sufficient protection against possible pollution of surface waters. Accordingly, the options to lease submerged lands thereafter specified that the State Stream Sanitation Committee would have the right to inspect operations at all times as well as the right to intervene and halt any operations that resulted in

violations of the State Stream Sanitation Laws.

With these provisions it was believed that the problems of compliance with stream sanitation laws were not insuperable. Operations on land could be carried on without seriously affecting the quality of the river water, but mining within the Pamlico River would create problems that could not be clearly foreseen. However, early in 1964 the Chief of the Division of Ground Water presented evidence that test-mining operations had lowered water levels over a considerable area and expressed the opinion that salt-water intrusion was almost inevitable. In July, 1964, Ground-Water Circular No. 2 [Nelson and Peek, 1964] was released. This report recommended the following protective measures:

"(1) Determination of the depth of saline water at the site of withdrawal before pumping begins.

(2) Installation and maintenance of an adequate system of water-level observation stations and water-quality monitoring stations at each withdrawal site to provide records of any changes in water levels or quality resulting from pumping.

(3) Restriction of significant effects of pumping to the immediate vicinity of the pumping site.

(4) Maintenance of water levels and artesian pressures of principal aquifers at sufficient elevation above sea level outside the immediate area of ground-water withdrawal to prevent encroachment of salt water into the aquifers."

The authors stated (p. 21) that: "The mining of the phosphate deposits that lie beneath the area must be accompanied by adequate protective measures, or a large part of ground-water resources will be permanently damaged or

destroyed." They suggested that the effects of dewatering the ore body might be restricted to the immediate area of mining by using the pumped water to recharge the aquifers through a system of wells or pits.

The Division of Ground Water established its own system of observation wells to monitor water levels and water quality. It also procured a well-drilling rig with which it could carry out its own exploratory program. The staff of the Division has cooperated fully with the Board of Consultants in securing additional data relating to the problem of recovering the phosphate while at the same time conserving, insofar as possible, the valuable resource of underground water.

Definitions and Notations

In this report the standards of the Soil Science Society of America and of the American Petroleum Institute are accepted, and the following definitions of technical terms are adhered to.

Permeability. The property of a porous water-bearing material that is related to its ability to conduct water under a hydraulic gradient is known as its permeability. The Board uses the definition of this term accepted in the petroleum industry. Thus, the permeability is the horizontal volume-flow per unit area per unit time per unit horizontal pressure gradient of a fluid of a unit viscosity. The flow may be expressed in cubic centimeters per square centimeter per second, the horizontal pressure gradient in atmospheres per centimeter, and the viscosity in centipoises. With this choice of units, the unit of permeability is called the "darcy" (American Petroleum Institute, Recommended Practice for Determining Permeability of Porous Media, RP 27, Sept. 1952.)

Hydraulic conductivity. In soil mechanics and foundation engineering the term "permeability" is often applied to another constant. This second constant or characteristic typifies not only the porous material but also the fluid flowing through it and includes, in addition to the permeability as defined above, the fluid factors viscosity and specific weight. In this report this product is termed "hydraulic conductivity" (Soil Science Society of America, Subcommittee on Permeability and Infiltration, August 31, 1951). In terms of the hydraulic conductivity

$$\frac{Q}{A} = (H_c)(H_G) = \frac{H}{L}$$

Darcy's law of flow may be expressed as follows: The volume-flow per unit area is equal to the product of the hydraulic conductivity by the hydraulic gradient, or loss of head per unit distance in the direction of flow. The hydraulic conductivity is the permeability multiplied by the specific weight of fluid and divided by its viscosity.

Transmissivity. A convenient term used to describe the ability of a uniformly thick bed or aquifer to transmit water is its transmissivity. This is the same as the "transmissibility" of Theis, but since the water in the aquifer is transmissible while the aquifer itself is transmissive, we prefer the word "transmissivity" to describe the aquifer. The transmissivity is the hydraulic conductivity multiplied by the thickness of the transmissive formation.

Storage coefficient. The ability of an aquifer to store water is expressed by a nondimensional coefficient defined as the volume of water removed from storage under a unit surface area by a unit decline of head. In confined aquifers the storage coefficient ranges from about 10^{-5} to 10^{-3}; in unconfined aquifers from about .05 to about .40. Intermediate values imply semi-confinement.

Hydraulic diffusivity is the ratio of the transmissivity to the storage coefficient.

Pumping level is the water level observed inside a well when it is discharging.

Standing level is the level observed inside a well when its pump is idle.

Static level is the water level that would have been observed at any time in a well if it had never been pumped.

Specific capacity is the ratio of the discharge to the drawdown it produces, measured inside the well and expressed in gpm/ft or in cfs/ft.

Specific drawdown is the ratio of drawdown to the discharge that produces it. It is the reciprocal of specific capacity and may be expressed in ft/gpm or in ft/cfs.

Leakance is the ratio of the hydraulic conductivity to the thickness of a semi-permeable confining layer enclosing a "leaky" confined aquifer.

Runoff is that part of the precipitation which reaches a stream.

Surface runoff is water which either reaches stream channels essentially as overland flow or falls directly into the stream channels.

Subsurface storm runoff (interflow) is water which enters the soil but returns to the surface or appears in channels at a lower level without entering the zone of saturation (beneath the water table).

Ground-water runoff is water that has passed into the earth and entered the zone of saturation, and has later been discharged into a stream channel as spring or seepage water.

The aquifer characteristics defined above are summarized in the following tabulation:

Characteristic	Symbol	Dimensions l	t	f	Unit
Hydraulic diffusivity	D	2	-1	0	US gal/day/ft = gpd/ft
Permeability	K	2	0	0	darcy
Hydraulic conductivity	K	1	-1	0	US gal/day/ft^2 = gpd/ft^2
Leakance	L	0	-1	0	ft/day/ft = day^{-1}
Storage coefficient	S	0	0	0	cu ft/sq ft/ft = 1
Transmissivity	T	2	-1	0	US gal/day/ft = gpd/ft

The storage coefficient recently has been the subject of renewed discussion ((DeWiest, 1966a; Cooper, 1966)).

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GEOLOGY

Physiographic Provinces

North Carolina includes parts of three major physiographic provinces. The Mountain area, the Piedmont, and the Coastal Plain. (See Fig. 1.) These provinces differ in topography, in the character of the underlying rocks, and in the mode of occurence and relative abundance of ground water.

The Mountain area is an extremely rugged area of high relief that comprises the extreme western part of the State. It is a part of the Blue Ridge province, which extends northeastward into Pennsylvania and southwestward into Georgia. It is characterized by a series of ridges and valleys elongated in a northeasterly direction. The average elevation of the crests is about 3,000 feet [Eardley, 1951, p. 73], but many of the peaks rise above 5,000 feet and a few, including Mt. Mitchell (6,711 feet in elevation) rise above 6,000 feet. The Mountain area is the most sparsely populated part of the State.

The Piedmont province is separated from the Mountain province by an escarpment 1,000 to 2,000 feet high from the base of which it slopes gently to the southeast at a rate of 12 to 15 feet per mile. It occupies a belt 150 to 170 miles wide in the middle of the State and extends northeastward to the lowlands of New Jersey and southwestward into Alabama. Its aspect, as seen across the horizon, suggests a broad smooth plain. However, it has been dissected by streams during the present cycle of erosion to low rolling hills and it has a local relief of a few hundred feet. Numerous

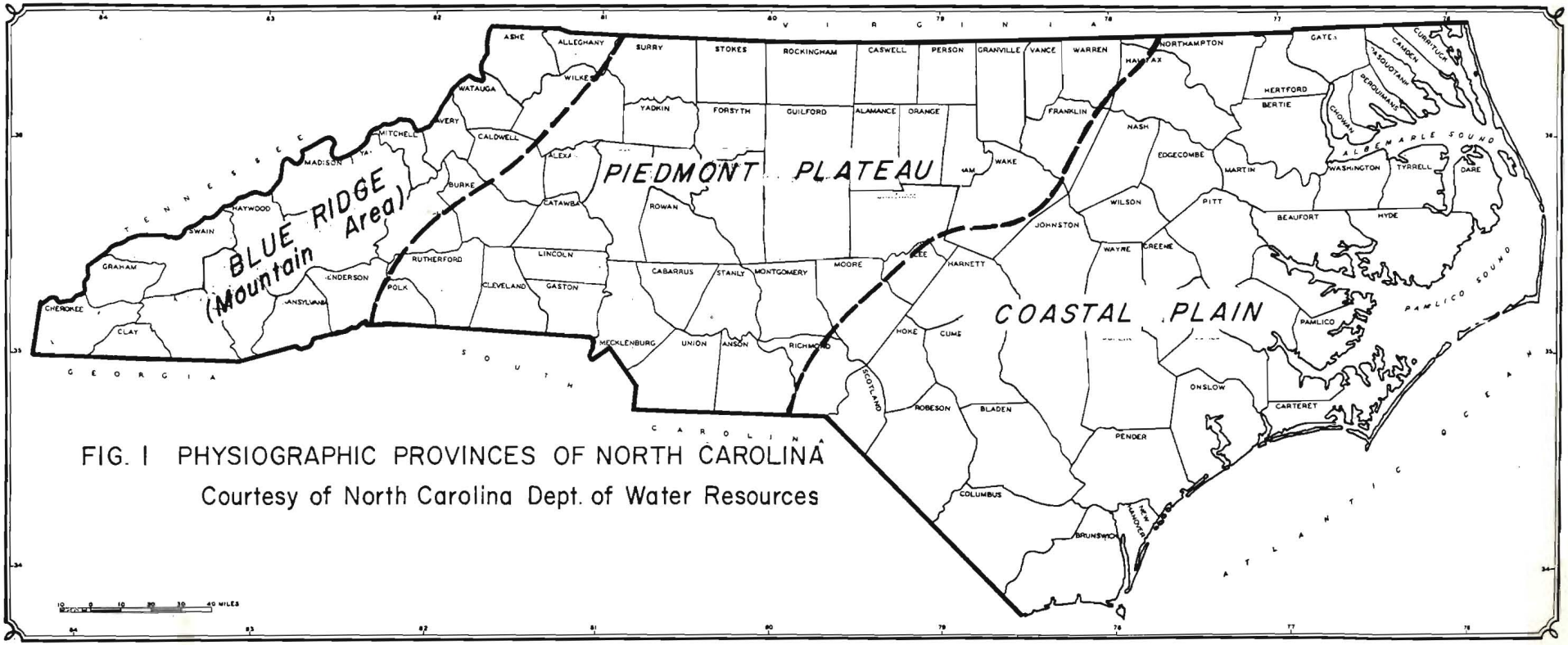


FIG. I PHYSIOGRAPHIC PROVINCES OF NORTH CAROLINA

Courtesy of North Carolina Dept. of Water Resources

FIG. I

hills rise as monadnocks from the smooth plain to a height of 200 to 1,000 feet. The Piedmont is the most highly industrialized and the most populous part of the State.

The Coastal Plain occupies about 45 percent of the area of the State. It is a broad low-lying plain that extends northeastward to New England and southwestward into Georgia and Alabama, where it merges into the Gulf Coastal Plain. For the most part the Coastal Plain is less than 100 feet above sea level. Its eastern margin is indented by long tidal estuaries. From the ocean the land surface rises very gently at a rate of three feet per mile or less until it nears the western boundary of the province, where the slope steepens, and near the fall zone the relief may be 150 to 200 feet near the larger streams. The Coastal Plain is much less populous than the Piedmont. Near the coast a large part of the land is swampy.

Structure and Stratigraphy

Piedmont Province. The rocks underlying the Piedmont province are of sedimentary, volcanic and igneous origin. The older rocks have been intensely folded and faulted and metamorphosed into gneisses, schists, slate, marble, quartzite and granite. Rocks of Triassic age occur in two belts -- one extending from Anson County in the southwest to near Oxford, Granville County in the northeast, the other extending northeastward through Stokes and Rockingham Counties into Virginia. Another small area of Triassic rocks is found in Davie and Yadkin Counties. The Triassic rocks consist of red, brown, purple and gray sandstone, siltstone, shale and conglomerate. The eastern belt contains the first coal that was mined in America, in 1750 [Eardley, 1951]. The Triassic rocks have been indurated to some extent by

cementation and compaction and have been cut by diabase dikes and sills. They have been gently tilted, but have not been metamorphosed as the older rocks have.

The rocks of the Piedmont have not been studied in sufficient detail to permit meaningful discussion of structural and age relationships. As a result, the State geologic map [Stuckey and Conrad, 1958] shows only a few faults of regional significance. The rocks are believed to be mainly pre-Cambrian and Paleozoic in age. Since Triassic time the surface of the Piedmont has been more or less continuously eroded. The present surface slopes eastward at a rate of 12 to 15 feet per mile. However, at the fall zone, where the ancient surface plunges beneath Cretaceous and younger sediments, the slope increases to about 35 feet per mile. In central Washington County a well drilled by the Davidson Oil Co. encountered the basement rock at a depth of 2,693 feet. Eastward of this well the slope increases to over 100 feet per mile, and in the Hatteras Light well Spangler [1950] reports deeply weathered basement rock at a depth of 9,878 ft. (Fig. 2). In southern North Carolina there is a broad arch or nose where the basement rock is reached in southern Onslow County at a depth of 1,335 feet. This arch is called the Great Carolina Arch [Spangler, 1950] or the Cape Fear Arch [LeGrand, 1961]. Toward the northeast the basement slopes downward to a depth of 2,822 feet in the Weyerhauser No. 1 well in Camden County (Fig. 3).

Mountain area. The rocks of the Mountain area are lithologically similar to those of the Piedmont and consist of highly folded gneiss, marble, schist and slate. Some of them are harder and more resistant to erosion than others so that the relief is much greater than in the Piedmont. The geology of the area has been very little studied and is imperfectly known.

FIG. 2

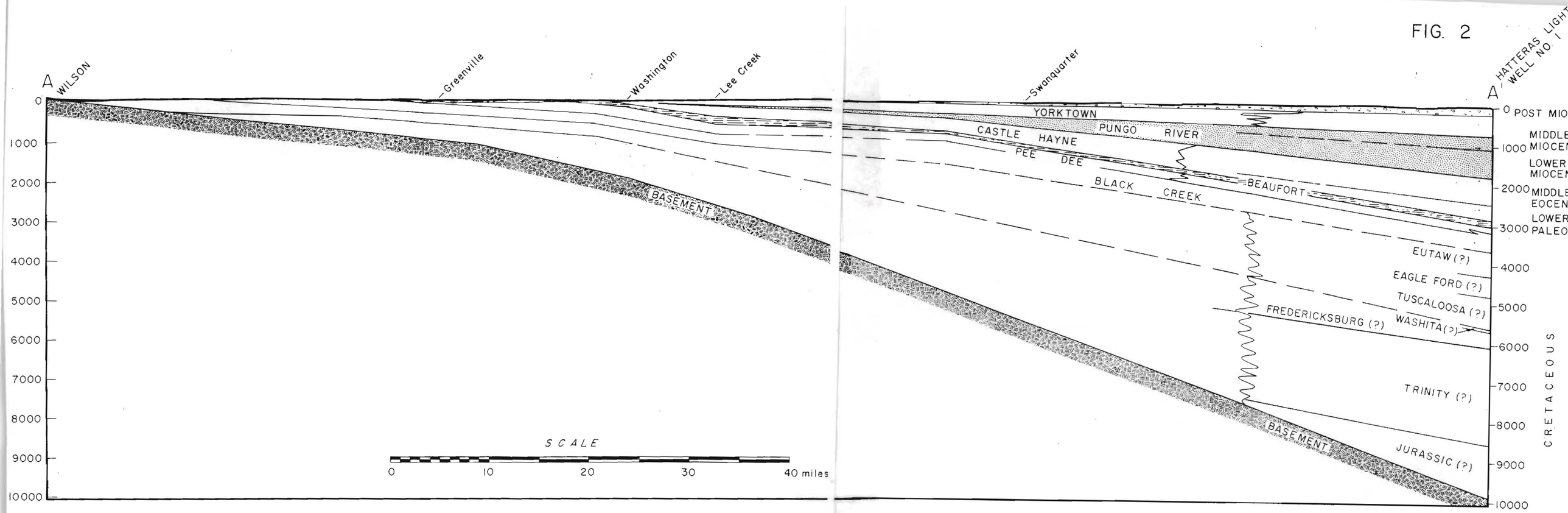


FIG. 2 GENERALIZED GEOLOGIC CROSS-SECTION FROM WILSON, N.C. TO APE HATTERAS, N.C. (Line A-A', Pl. 1)

Sources; Spangler (1950), Swain (1952), Stuckey and Conrad (1958), N.C. Department of Water Resources (1966)

FIG. 3

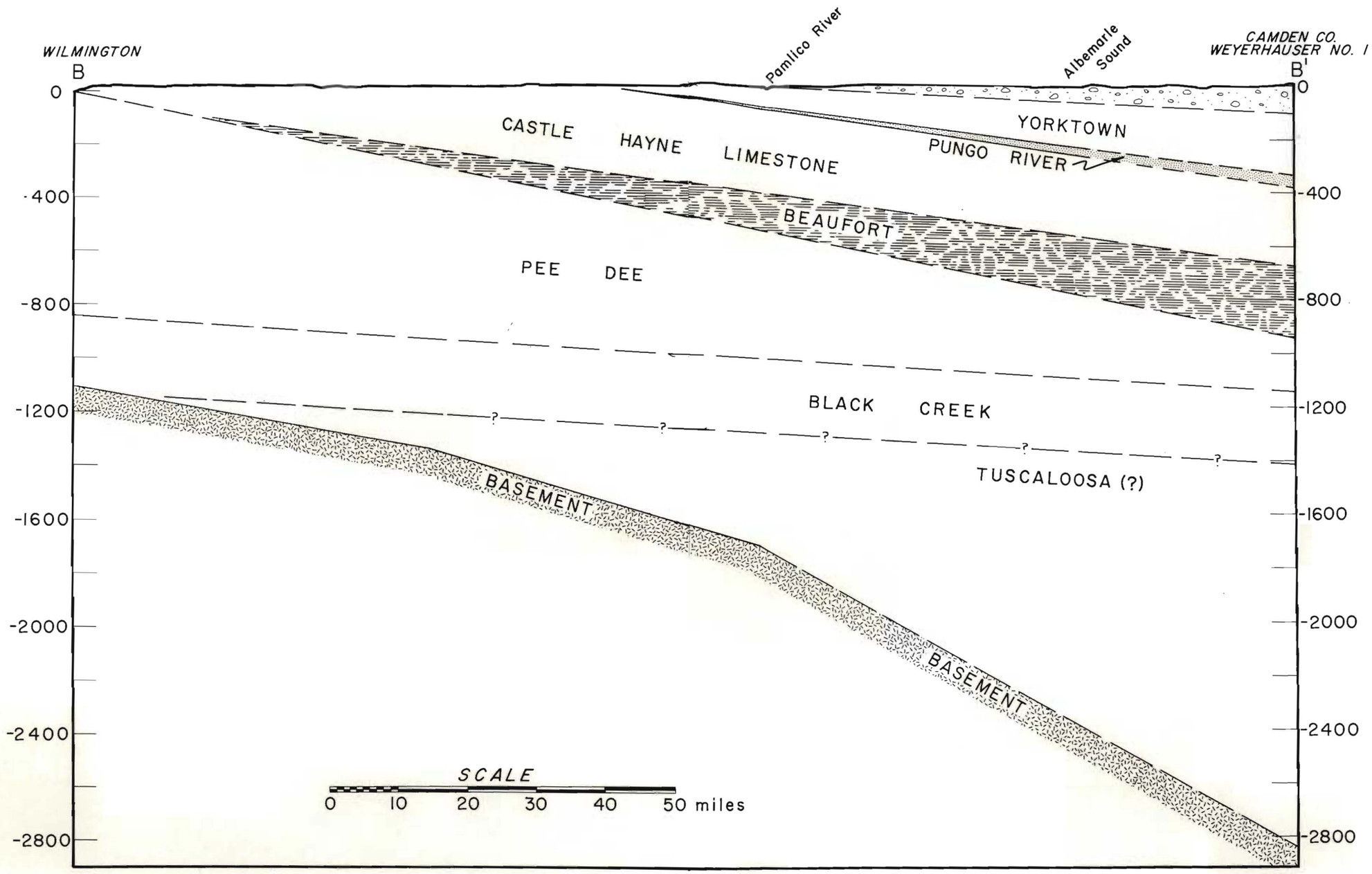


FIG. 3 GENERALIZED GEOLOGIC CROSS-SECTION FROM WILMINGTON N.C. TO CAMDEN CO. N.C. (Line B-B', Pl. 1)

Sources; Brown (1958a), Swain (1952), N.C. Department of Water Resources (1966).

Coastal Plain. The Coastal Plain is underlain by a wedge of sedimentary rocks which thickens from a feather edge at the fall zone to nearly 10,000 feet at the Cape Hatteras Light well. The oldest strata that crop out in North Carolina are of Upper Cretaceous age. However, in the Cape Hatteras Light well Swain [1952] has identified rocks, some 4,200 feet thick, of probable Jurassic and Lower Cretaceous age. (See Fig. 2)

The formations that have been recognized in surface outcrops are described by Clark et al [1912], by Stephenson [1923], and by many later workers, chiefly in connection with the investigation of ground-water resources of the State, in reports issued by the North Carolina Division of Mineral Resources and by the Department of Water Resources.

The oldest formation cropping out in the Coastal Plain is the Tuscaloosa formation of upper Cretaceous age which extends northeastward from the state line to about Johnston County (see Plate 1). Toward the north it is overlapped, by successively younger formations. In the northern half of the Coastal Plain the Yorktown formation of Miocene age overlaps all of the older formations. However, along the Tar River near Greenville and farther north along the Roanoke River, erosion has exposed elongated strips of Cretaceous rocks in the river valleys.

A thin veneer of post-Miocene deposits consisting of sand and clay with some shell beds conceals the older formations throughout the Coastal Plain except along stream beds and in recently opened road cuts. These deposits range in thickness from a few feet to 30 or 40 feet in the central part of the Coastal Plain, and they may be as much as 120 feet thick in the Hatteras Light well. They are arranged in belts 10 to 15 miles wide and are bounded on the east by more or less pronounced scarps. Cooke [1931] believed

these to be marine terraces marking former stands of the sea. He identified the highest as the 270-foot terrace and recognized other, lower terraces at 215, 170, 100, 70, 42 and 25 feet above sea level. Only the lowest terrace is shown on the geologic map, with the symbol Qpl.

Lower Cretaceous

Unnamed unit. Brown [1959] recently established the presence of sediments of Lower Cretaceous age in a well at Greenville, Pitt County. On the basis of a well-preserved ostracode fauna he considers these strata to be roughly equivalent to sediments of Trinity age and older as recognized in the Gulf Coast province. These beds were encountered at a depth of 608 feet, and the well was continued to a depth of 754 feet. The sediments consist chiefly of chocolate-colored argillaceous quartz sand and green calcareous clay. These beds are not known to crop out at the surface, but it is likely that they extend over a broad area in the subsurface.

Upper Cretaceous

Tuscaloosa formation. The Tuscaloosa formation crops out in a belt that trends northeastward from Hoke County to Johnston County, where it is overlapped by the Black Creek formation, which in turn is overlapped by the Yorktown formation. It is exposed in an elongate window in the valley of the Tar River in Edgecombe County and again in the valley of the Roanake River. The Tuscaloosa formation appears to be partly alluvial in origin. The

lithology varies greatly from place to place. In general the strata consist of interbedded lenses of pinkish to drab-gray micaceous sand and clay. Coarse to medium-grained sand and gravel occur at all horizons, but are generally more prevalent below the upper 150 feet of the formation. The uppermost 150 feet invariably is composed of layers of compact lenticular clay [Brown, 1959]. In eastern Scotland County the Tuscaloosa is 300 feet thick, and in Sampson County it is 80 feet thick [Brown, 1958a, pp. 50-52]. The formation thickens eastward to several hundred feet [Spangler, 1950, pp. 118-119].

The Black Creek formation overlies the Tuscaloosa unconformably. It crops out in a belt about 50 miles wide in Robeson and Scotland Counties along the South Carolina border and extends northeastward to about Pitt County, where it is overlapped by the Yorktown formation. The Black Creek consists of two members: the upper member is called the Snow Hill marl; the lower is unnamed. The Snow Hill marl is composed of gray to black clay and marl which in places is indurated to thin limestone. The unnamed member is composed of gray to black clay and interbedded sand [LeGrand, 1960, p. 15]. In a well at Kinston the Snow Hill member is 141 feet thick and the unnamed member is 245 feet thick [Brown, 1958a, pp. 30-31]. These beds thicken rapidly toward the southeast and are probably the equivalent of the beds identified by Swain [1952, p. 61] in the Hatteras Light well as Black Creek (?) and Eutaw (?), which were encountered at depths of 3,148 to 3,655 feet and 3,655 to 4,453 feet respectively.

The Peedee formation lies conformably on the Black Creek formation. It crops out in a belt about 25 miles wide in Columbus County on the

South Carolina border and extends northeastward to the vicinity of Greenville. At the State line it is overlain by the beds of Pleistocene and Recent age, but a few miles to the northeast it is overlapped by the Castle Hayne, and in the vicinity of the Neuse River it is overlapped by the Yorktown formation, so that the outcrop area becomes progressively narrower until it is only one or two miles wide southwest of Greenville. The Peedee formation consists chiefly of layers of dark gray sandy clay alternating with layers of dark green to gray glauconitic sand. Beds of impure limestone, generally in layers a few inches thick, are commonly penetrated in wells and may be observed in many outcrops [LeGrand, 1960, p. 16]. In Onslow County more than 500 feet of the formation was recognized in a well at Richlands [Brown, 1959, p. 12]. LeGrand [1960, p. 16] reports that 710 feet of the formation was penetrated in a well at the Riegal Paper Co. about five miles south of the Bladen County line. The formation apparently thins toward the east. In the Hatteras Light well Swain [1952] assigns only 165 feet of the section to the Peedee.

Paleocene

Beaufort formation. The existence of beds of Paleocene age beneath the Coastal Plain in North Carolina was first suggested by Spangler [1950, p. 131]. Brown [1959, p. 13] proposed the name Beaufort for these beds and described the type section in a well at Chocowinity between the depths of 150 to 215 feet, which he had described in 1958 [Brown, 1958a, p. 7]. The strata consist chiefly of glauconitic and calcareous sand and of limestone, some of which is dolomitic. In the Hatteras Light well Swain [1952, p.11] identified

the strata from 2,870 feet to 3,033 feet as Paleocene and described them as light gray and white shale.

Eocene

Castle Hayne limestone. The Castle Hayne limestone overlies the Beaufort formation unconformably where that formation is present or, where it is absent, it lies unconformably on the Peedee formation. It crops out in a belt of variable width from Brunswick County to southwestern Beaufort County, where it is completely covered by the Yorktown formation. Scattered remnants of the Castle Hayne are recognized on the stream divides as far west as Raleigh. The formation dips gently to the east and also becomes thicker. It is absent in wells in the extreme western part of Beaufort County. At the Lee Creek mine of Texas Gulf Sulphur Co. it is 230 feet thick. However, it has not been definitely identified in the thick Eocene section of the Hatteras Light well.

The formation typically consists of very permeable gray to white shell limestones and dolomitic shell limestones interbedded with and underlain by fine to medium-grained calcareous sands and clays.

Miocene

Pungo River formation. Phosphatic beds above the Castle Hayne limestone had been reported, and several test wells were drilled in Beaufort County by commercial interests, prior to 1952. Ground-water investigations in the County led to critical examination of the cuttings from numerous wells and showed that these beds extended over a large area. As a result,

Brown [1958b] formally described the phosphorite beds as a unit and assigned it to the Middle Miocene. Subsequently Kimrey [1964] proposed the name "Pungo River formation" for the unit. The following year Kimrey [1965] published the results of a detailed study of gamma-ray logs of existing water wells and gamma-ray and resistivity logs of core holes. The formation does not crop out at the surface and is known only from subsurface investigations. It is composed of interbedded phosphatic sands, silts and clays, phosphatic and non-phosphatic limestones and silty claystones.

The recovery of phosphate from the Pungo River formation has required the pumping of a large volume of water from the Castle Hayne limestone and has raised pressing questions as to the possible effects of this pumping on the availability of fresh ground water for domestic, municipal, industrial and agricultural developments in the years to come. The following description of the Pungo River formation is condensed from the composite section prepared by Kimrey [1965, pp. 9-10]:

Zone 1. Ten to 15 feet of clay.

Zone 2. Ten to 12 feet of high-grade phosphatic sand. The P_2O_5 content of this zone ranges between 15 and 20 percent.

Zone 3. Nine to 11 feet of phosphatic limestone. There are cast and mold limestones in this zone that are permeable enough to cause loss of circulation of the drilling mud.

Zone 4. Ten to 15 feet of phosphatic sand. This zone is lower in P_2O_5 than Zone 2. It ranges from 10 to 14 percent and averages about 12 percent P_2O_5. The high percentage of quartz sand in this zone makes a high rate of core recovery difficult.

Zone 5. Six to 10 feet of clay; in part diatomaceous, phosphatic clay.

Zone 6. Two to 10 feet of phosphatic limestone that contains thin beds of phosphatic sand.

The above zones are horizons that make up the Pungo River formation throughout Beaufort County. They extend to and beyond the boundaries of the County toward the east, although in some areas they have pinched out, have been removed by erosion, or have undergone facies changes.

Toward the west, erosion has removed Zones 1 and 2 and the top of the formation is the phosphatic limestone of Zone 3. In Beaufort County, the Pungo River formation ranges in thickness from 15 feet in the west to about 115 feet in the east.

Yorktown formation. This formation overlies the Pungo River formation unconformably, and from the vicinity of the Tar River northward it overlaps successively the Castle Hayne limestone, the Peedee formation, the Black Creek and the Tuscaloosa formations. In the northern half of the Coastal Plain it extends westward to and beyond the fall zone. The formation consists chiefly of gray shell marl, indurated shell beds, and massive interbedded sand beds. The beds are lenticular, and individual beds have not been traced laterally for any distance. The formation thickens from a feather edge near the fall zone to several hundred feet along the coast. In Bertie County it is 195 feet thick [Brown, 1959, p. 15] and in the Hatteras Light well it is believed to be several hundred feet thick.

Post Miocene

Undifferentiated sediments. Throughout the Coastal Plain and much of the Piedmont a thin veneer of soil, sand and clay underlies the land surface and covers the rocks previously described. The origin and age of these deposits is not everywhere the same, and attempts to differentiate them have met with indifferent success. In some places they represent the weathered soil zones overlying older rocks. In other places they appear to represent sediments of Pleistocene age deposited during the most recent marine occupation of the Coastal Plain. In the Hatteras Light well these sediments attain a thickness of 160 feet, and the lower portion of them may be of Pleistocene age.

The flood plains of the streams in the Piedmont and in the Mountain area are in many places underlain by deposits of sand and gravel that are probably of Recent origin.

GROUND WATER--
ORIGIN, OCCURRENCE AND MOVEMENT

Piedmont Province

The rocks of the Piedmont province are highly folded, faulted and fractured. In most parts of the province domestic and farm supplies of water are available from relatively shallow wells. Municipal and industrial wells are common. They yield up to 200 gallons per minute (gpm) in general; some of them yield larger supplies. Most wells are less than 300 feet deep as the water-bearing fractures in the rock become fewer and smaller below the weathered zone, which is about 150 feet deep.

Mountain Area

Very little information is available on the ground-water supplies of the Mountain area. Domestic supplies are obtained chiefly from shallow wells or springs. Most municipal and industrial supplies are obtained from surface reservoirs. In general the mountain ridges are composed of hard, dense rocks that have few fractures. Moreover, they occur on steep slopes and ground water drains away rapidly. However, in the valleys the rocks are similar to most of the rocks in the Piedmont, and conditions for retention of ground water are more favorable. In the Clyde area in Haywood County, Duncan [1965] reports wells yielding up to 45 gpm. However, some wells failed to reach any water. In the Hays area, Wilkes County, Peace [1965] concluded that in favorable locations wells may yield as much as 55 gpm.

Coastal Plain

The stratified sand, gravel and limestone formations of the Coastal Plain are potentially the most productive sources of ground water in North Carolina. The water is generally acceptable for most purposes although some wells yield waters that contain objectionable amounts of iron, hydrogen sulfide or hardness. Some of the waters are corrosive. In general, the best water from each formation is obtained from wells drilled in or near the outcrop area of the formation. As the formation dips toward the east, the water in it tends to become progressively more saline. Where wells are drilled too close to each other, - especially in coastal areas, - where they are drilled too deep, or where they are pumped too heavily, there is a possibility that brackish or saline water may be drawn into the wells from the numerous tidal estuaries or from deeper formations that contain saline water.

Tuscaloosa formation. The Tuscaloosa formation contains large amounts of clay, but wells that penetrate the lenticular beds of sand in the formation yield from 10 to 300 gpm. East of Lenoir County the Tuscaloosa carries saline water.

Black Creek formation. The Black Creek is a very productive aquifer in Bertie, Martin, Pitt, Greene, Lenoir, Duplin and western Pender Counties. Gravel-packed wells yield up to 1,000 gpm. Eastward from these counties the water in the aquifer becomes increasingly saline with depth. In the deep test well drilled by the Department of Water Resources at the Lee Creek mine of Texas Gulf Sulphur Co., water from a depth of 918 to 922 feet is thought to come from the Black Creek aquifer. The water contained 9,700 ppm (parts

per million) of chloride, and the static level of the water was 20.9 feet above mean sea level. This is substantially higher than the water level of the Castle Hayne aquifer before the mining operation was started.

Peedee formation. The Peedee formation is a major aquifer from Hertford County southwestward to Brunswick County. Most of the municipal and industrial wells that tap this aquifer also tap sand in the Black Creek formation so that the potential yield of wells in the Peedee alone is not known.

Beaufort formation. The Beaufort formation is used as an aquifer in Gates, Hertford, Bertie, Martin, Chowan, Pitt and Beaufort Counties. "Most of the wells tapping the Beaufort formation are single-screen or open-end wells that yield from 15 to 150 gpm. In addition, several gravel-wall wells obtain all or part of their water from this aquifer and yield as much as 750 gpm" [Brown, 1959, p. 25]. In the test well at the Lee Creek mine the Beaufort was identified in the section from 400 to about 565 feet. A sample of the water from 466 feet contained 3,000 ppm of chloride. The static level of the water was -89.9 feet. This level is much lower than one would expect by comparison with other areas, and the low head may reflect the heavy pumping from the overlying aquifer.

Castle Hayne limestone. The Castle Hayne limestone is the most productive aquifer in the Coastal Plain. Small-diameter wells in the upper part of the formation yield from 5 to 150 gpm. Large-diameter wells (10 to 12 inches) yield from 1,000 to 3,000 gpm. In many parts of the area the wells flow. In the deep test at the Lee Creek mine the water from the Castle Hayne contained 200 ppm of chloride. The static water level was 98.3 feet below mean sea level. North of the Pamlico River

near Belhaven, fresh water was found at the top of the Castle Hayne. However, the chloride concentration increased with depth in the formation. The chloride content at various depths in a test well drilled by the Department of Water Resources is given below:

Multi-well station N-13, near Belhaven, N. C.

Formation	Depth (ft)	Chloride (ppm)	Water Level (ft)
Pleistocene	19- 24	20	- 3.5
Yorktown	100-150	33	- 3.4
Castle Hayne	335-340	100 (?)	-11.2
do	375-370	820	do
do	405-410	1,520	do
do	462-467	3,540	do

Yorktown formation. The Yorktown formation is predominantly marine clay interbedded with lenticular sands, shell beds, and shell limestone. In general, wells yield from 5 to 300 gpm. However, the municipal supply at Edenton obtains its water from gravel-packed wells that yield from 500 to 700 gpm.

Undifferentiated sediments or the Pleistocene and Recent formations yield water to wells used for domestic supplies throughout most of the area. The water is soft but generally corrosive and it may contain objectionable amounts of iron.

Origin of Ground Water

Water on and beneath the land surface has its origin in precipitation that falls on the land as rain or snow. Although the annual precipitation in the Mountain area of North Carolina may, in some places, average as much as 100 inches, in the Coastal Plain and the Piedmont province, which comprise about 95 percent of the State, it averages between 45 and 50 inches. Of this amount, about two-thirds is returned to the atmosphere by evaporation or by the transpiration of plants, about one-sixth is direct runoff into the streams, and the remainder (about 8 inches) sinks into the pores and other openings in the soil and the underlying rocks and becomes "subterranean water". Subterranean water can be divided into two parts; the water that is found in the "zone of saturation", where all the voids are filled and from which wells and springs are supplied, is commonly called "ground water". The water that occurs between the zone of saturation and the land surface has been called "suspended water", although this term is not particularly appropriate because a large part of the suspended water simply may be moving downward into the zone of saturation.

Water-Bearing Properties of Rocks

Porosity is the property of a material for containing voids or pore spaces. It is usually expressed as the percentage of openings in a given volume of the material. The porosities of silt, sand and gravel depend largely upon the shapes and sizes of the particles, the degree of sorting

and the amount of compaction to which they have been subjected. The porosities of igneous and metamorphic rocks depend chiefly upon the number and sizes of fractures and the degree of weathering involved. Limestone and other soluble rocks may be fractured, and these openings may be enlarged by solution.

Permeability is the property of a rock that governs the ease with which water or other liquids pass through it. Permeability depends on the sizes of the openings in the rock and the degree to which they are interconnected. Well-sorted sands and gravels are usually very permeable. Many limestones, especially those that have been subjected to solution by ground water, are usually very permeable, as are jointed, fractured and deeply weathered igneous and metamorphic rocks. Materials such as silt and clay may be porous and saturated with water, but the openings are so small that they do not transmit water readily and are apparently impermeable under the pressures normally encountered in nature. However, there is evidence that water may move slowly through these fine-grained materials under pressure.

Permeable soils and rocks readily permit infiltration of rainfall. The water moves downward to the zone of saturation or until it encounters less permeable rock, and then it moves laterally toward points of discharge in springs or seeps in stream valleys, into marshes, ponds and tidal estuaries, and to wells. The slow but constant flow of water from the zone of saturation maintains the flow of streams during dry weather and accounts for the persistent lakes, ponds and swamps that are common in the Coastal Plain.

In the zone of saturation permeable geologic formations that transmit water in sufficient quantities to supply wells and springs are known as

aquifers. They are commonly overlain or underlain by formations that, although porous and capable of absorbing water slowly, will not transmit it rapidly enough to supply appreciable amounts of water to wells or springs. Such formations are called aquicludes.

Permeable formations that are not overlain by an aquiclude may receive water by vertical transmission from above, and the water may move in the direction of the hydraulic gradient (slope of the water table) after it reaches the water table. (The water table is that warped and inclined geometric surface at atmospheric pressure, below which all the rocks are saturated with water.) Since it moves freely downward, the water in the zone of saturation is said to be unconfined. In the Piedmont, water may move freely from the land surface down to the water table. Hence the ground water there is unconfined. The ground water in the outcrop areas of the water-bearing formations in the Coastal Plain also may be unconfined. However, as they dip eastward these formations pass beneath younger formations, which are less permeable aquicludes, the vertical movement of the water is greatly retarded, and the aquifer is said to be confined. Because the land also slopes to the east, the head of the unconfined water in the outcrop area is higher than the top of the aquifer at any point downdip. Consequently, if a well is drilled into the aquifer at some point downdip, the ground water will rise in the well above the top of the aquifer. That is, because of the hydraulic head, the confined water exerts an upward pressure against the confining aquiclude. Since aquicludes are not strictly impermeable, there is a certain amount of leakage from the aquifer through the confining beds. In nature, leaky aquifers are so common that hydrologists have developed many solutions of leaky-aquifer problems.

Hydrologic History of the Coastal Plain

Before the beginning of Jurassic time a nearly smooth surface had been developed by planation of the land surface that had existed where the Coastal Plain now is. This surface was tilted toward the east, and marine sediments were deposited in the area that is now the Continental Shelf. These sediments were the products of weathering of the land mass to the west, carried into the sea by streams and deposited there as sand or silt. Some of them were formed by marine organisms that took calcium carbonate from the sea water to form their shells. However, deposition of sediments was not a continuous process, for the geologic record shows that from time to time the area was raised above sea level and that the sediments deposited previously were partially eroded. As sediments accumulated, the old land surface was further tilted, until now it is nearly 10,000 feet below sea level at the coast.

Because the sediments contain fossils of marine organisms, we can be sure that at the time they were deposited they probably contained sea water similar to the chemical composition of water in modern oceans. Ocean water is remarkably similar the world over. It contains about 35,000 parts per million of dissolved solids, of which about 55 percent (19,500 ppm) is chloride [Clarke, 1924, p. 127]. By contrast, the maximum chloride content of water considered by the U. S. Public Health Service [1928] to be suitable for drinking on interstate carriers is 250 ppm.

Ground water that meets or approximates these standards can be found in most parts of the Coastal Plain [Blankenship, 1965; Brown, 1959; LeGrand, 1960; Mundorff, 1946; Nelson, 1964; Pusey, 1960]. Therefore,

it is evident that the sea water originally contained in these aquifers must have been diluted or flushed out by fresh water that circulated through them after they were deposited. Since the area was alternately elevated and depressed relative to the ocean, it seems likely that there were many periods when fresh water could and did enter the marine sediments. The clearest part of the record is, of course, found in Tertiary and Recent time.

During Eocene time, when the Castle Hayne limestone was deposited, the sea covered all of the Coastal Plain and also the eastern part of the Piedmont, as is clearly shown by the remnants of Castle Hayne which form "outliers" almost as far inland as Raleigh. The unconformity between the Castle Hayne and the Yorktown indicates that the sea retreated and that there was a period of erosion. This episode was followed by another advance of the sea during which time the Yorktown formation of Miocene age was deposited. The Yorktown sea appears to have covered nearly as much of the land as the Castle Hayne sea. After it retreated, fresh water again could enter the Cretaceous and Tertiary formations. According to Cooke [1931], the final advance of the sea occurred during Pleistocene time when the marine terraces were formed. At this time the sea is believed to have risen to at least 270 feet above the present strand line.

Periodically, during the Pleistocene (glacial) epoch vast quantities of water were locked in the continental glaciers that covered much of the northern hemisphere. At these times sea level must have been substantially lowered. During the last glacial stage, which is probably between

10,000 and 20,000 years ago, sea level was about 400 feet lower than it is at present [Tanner, 1965]. At that time fresh water would be circulating through the aquifers of the Coastal Plain with a hydrostatic head of more than 400 feet.

There are records of a number of wells in the Coastal Plain which have found water that was too highly mineralized for any beneficial use. LeGrand [1960, p. 66] reports a chloride concentration of 7,050 ppm in a test well 1,330 feet deep at Wilmington, and the deep test at Lee Creek mine yielded water containing 9,700 ppm of chloride from a depth 918 feet. However, these waters do not approach the salinity of ocean water. So it must be concluded that flushing or dilution of the original water extended to a considerable depth.

Spangler [1950, p. 106] reports that samples of water taken from depths of 6,473 and 7,018 feet in the Hatteras Light well contained 71,335 and 79,460 ppm of chloride respectively. The occurrence of brines in deep wells is a subject beyond the scope of this report.

In general, the aquifers of the Coastal Plain have been flushed of sea water throughout their areas of outcrop and the flushing extends for some distance downdip where they are covered by younger sediments. LeGrand [1960] found that, in most of the Wilmington-New Bern area, ground water that contained less than 250 ppm of chloride could be obtained at depths of more than 400 feet and in nearly half of the county it could be found at depths greater than 500 feet. The principal aquifers in this area are Cretaceous in age. In the Swanquarter area, where the land is low and flat and the principal aquifers are Miocene and younger, Nelson [1964] reports water with high chloride content at much shallower depths.

Ground-Water Movement

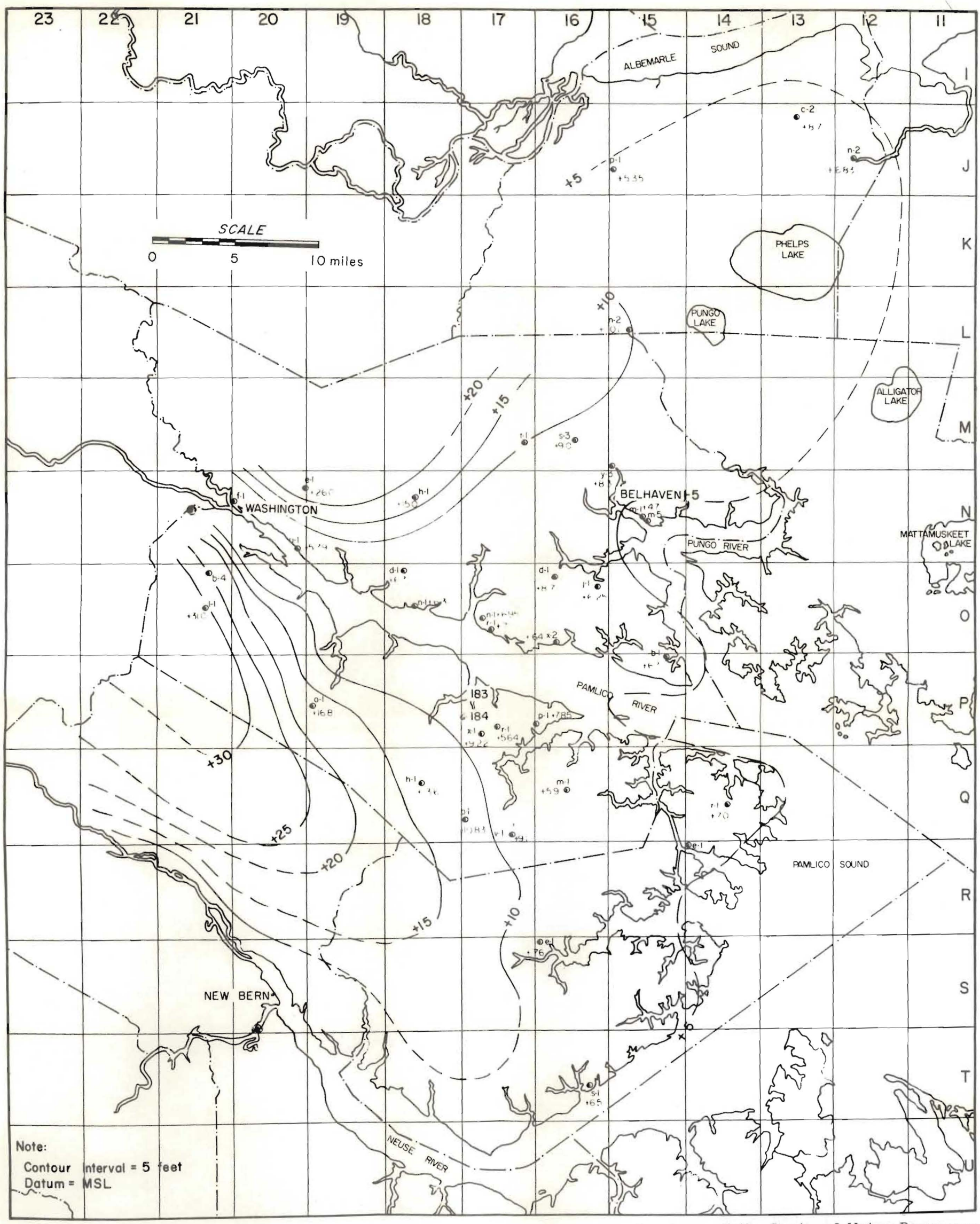
In the preceding section it was established that the sediments of the Coastal Plain are chiefly marine and that originally the aquifers contained sea water. Much of the saline water they contained has been flushed out or diluted by fresh water since they were deposited. Consequently, at present the aquifers contain fresh water for a considerable distance downdip from their areas of outcrop. Visual evidence that fresh water entering an aquifer on land may move down the dip and be discharged in submarine is demonstrated dramatically in a number of places throughout the world. In the Persian Gulf "boils" marking submarine springs may be seen on the surface of the Gulf and it is reported divers descend into the Gulf to fill goatskin bags with drinking water. Similar "boils" are observed off the coast of Florida, and, more recently, aerial photographs taken with infra-red film have shown large fresh water springs off the Island of Hawaii. No such dramatic evidence of submarine discharge can be seen off the shores of North Carolina. Nevertheless, in addition to the freshening of the aquifers, there is evidence that submarine discharge in fact does occur in the estuaries.

A map showing the water levels of wells tapping the Castle Hayne aquifer in June, 1965, before the pumping at Lee Creek Mine began, was prepared by the Division of Ground Water of the Department of Water Resources. (See Fig. 4.) From these data, lines were drawn showing the approximate position of contours on the piezometric surface of the Castle Hayne aquifer. It will be noted that the highest contour is in an area that lies along the boundary between Beaufort and Craven

Counties near its intersection with the Pitt County line. This is also near the outcrop area of the Castle Hayne aquifer. From this "high" the piezometric surface slopes rapidly northward toward the Pamlico River and more gently southeastward toward Pamlico Sound. The map clearly indicates a difference in hydraulic head in the Castle Hayne of 25 feet in a distance of about seven miles (between wells 1-1 south of Washington and u-1 southeast of Washington). This can only mean that Castle Hayne water is moving northward toward the Pamlico River in this area.

Figure 5 is a cross section of the materials encountered in a series of test wells drilled along U. S. Highway 17 southwest of Washington. It shows that in the Pamlico River the Castle Hayne is overlain by medium to coarse sand which presumably is permeable. Thus discharge from the Castle Hayne into the bed of the river is not only possible, but likely, as there is a positive head of over five feet along the river.

Figure 4 also shows a broad southeastward-trending "high" on the piezometric surface of the Castle Hayne aquifer north of Pamlico River. It is not nearly so pronounced as that south of the river. This fact, together with the occurrence of saline water at Belhaven, suggests that water has not moved as freely through the Castle Hayne aquifer in this area as it has in the area south of Pamlico River. It should be noted that to the west of Belhaven the Castle Hayne is overlapped by the Yorktown, which is considerably less permeable. Consequently, the opportunity for flushing by fresh water is considerably reduced in this area.

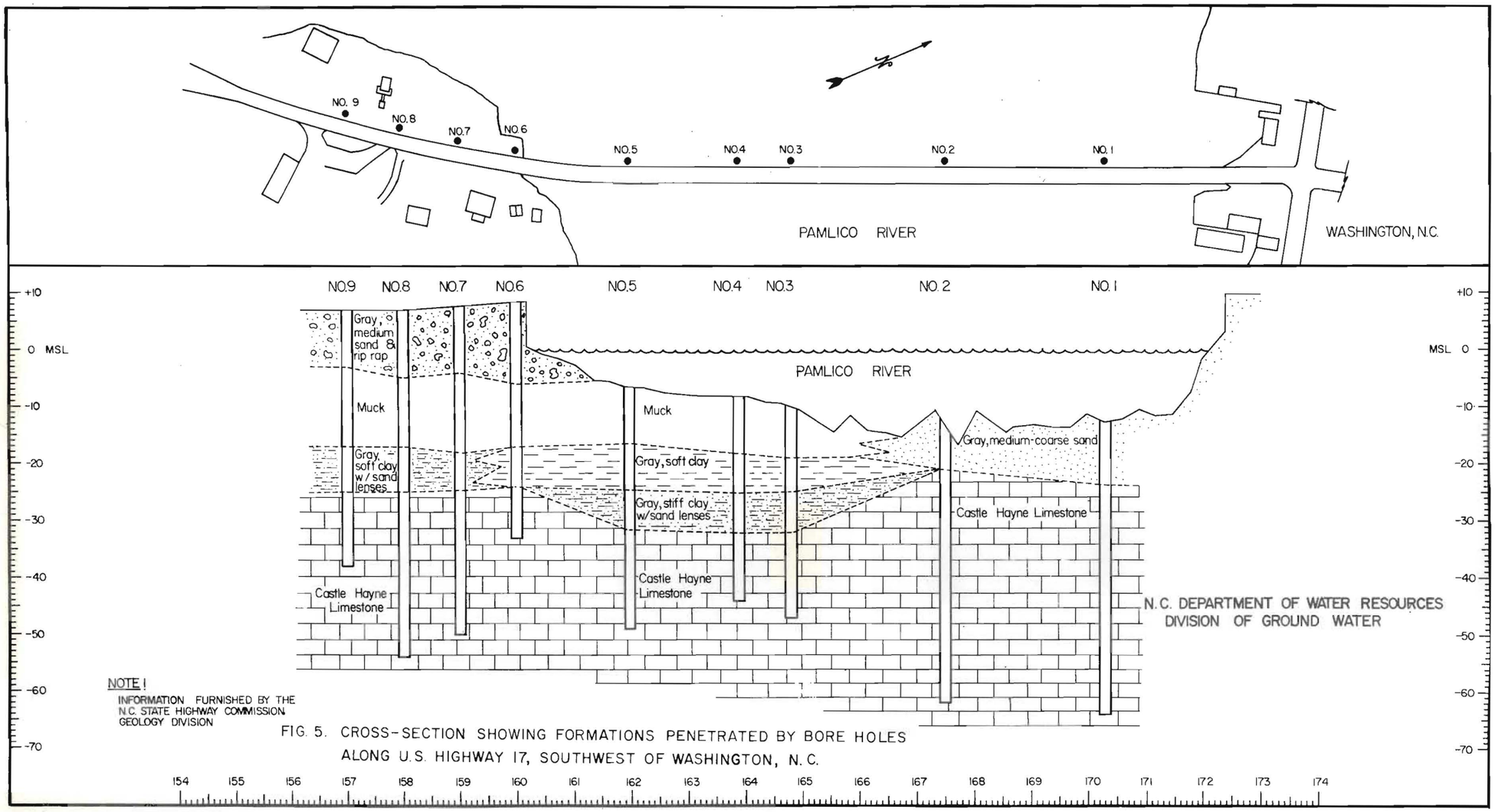


Courtesy of the Dept. of Water Resources

FIG. 4. MAP SHOWING PIEZOMETRIC SURFACE OF THE CASTLE HAYNE AQUIFER JUNE, 1965

FIG. 4

FIG. 5



NOTE 1
INFORMATION FURNISHED BY THE N.C. STATE HIGHWAY COMMISSION GEOLOGY DIVISION

FIG. 5. CROSS-SECTION SHOWING FORMATIONS PENETRATED BY BORE HOLES ALONG U.S. HIGHWAY 17, SOUTHWEST OF WASHINGTON, N.C.

HYDROLOGY

Introduction

Ground water and surface water are related through the hydrologic cycle, the path traveled by the waters of the earth, of which they are interdependent components.

The oceans are the immense reservoirs in which most water originates and to which it returns. This statement is somewhat oversimplified because not all water particles are in the process of completing the entire hydrologic cycle at all times. There are built-in loops, for example, when water evaporates from land and returns to land as precipitation, only to evaporate again, etc. But in its most elaborate cycle (Fig. 6), water evaporates from the oceans and forms clouds, which move inland, then it condenses, and falls to the earth as precipitation. From the land, through river channels and under ground, the water runs off to the oceans. So far there is no evidence that water decreases in quantity at a global level. No water is destroyed but none is generated either, to paraphrase a well-known principle of physics. For human usage, however, the physical state of water (that is, whether liquid, solid or gaseous) is important, and so is its quality (chemical and bacterial content). While its available quantity is limited, the need for water is ever increasing, and consumption is bound to exceed supply in the not-too-distant future.

A large amount of the water that is precipitated upon the earth is returned to the atmosphere as vapor through the combined actions of evaporation, transpiration and sublimation. These three processes

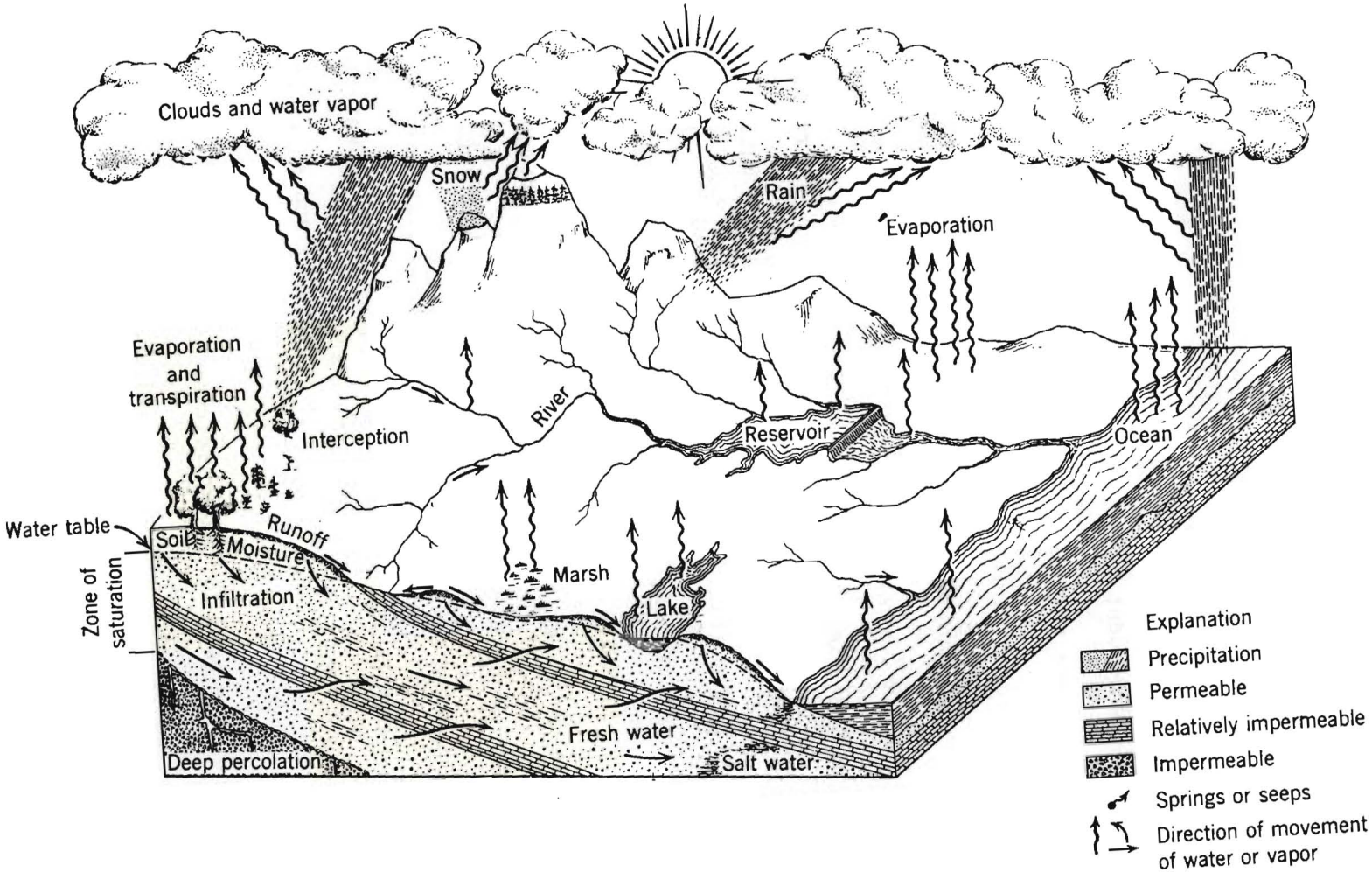


Fig. 6 The hydrologic cycle. (Courtesy of Texas Water Commission.)

essentially are modifications of a single process, owing to the energy of the solar engine that keeps the hydrologic cycle running.

On a global basis, the total amount of precipitation on the continents, P_c, and on the oceans, P_0, is equal to the total amount of evapotranspiration from the continents, E_c, and from the oceans, E_0. On a continental basis, the total precipitation, P_c, is equal to the evapotranspiration from the continents, E_c, and the runoff, R, from the continents.

$$P_c = E_c + R \tag{1}$$

On a global basis, Eq. 1 has the following annual values:

26.5 in. of precip. = 16.5 in. of evapo-trans. + 10.0 in. of runoff.

In the United States, Eq. 1 is numerically expressed as:

30 in. of precip. = 21 in. of evapo-trans. + 9 in. of runoff.

In the United States, the atmosphere makes up the difference between precipitation and evapotranspiration by providing a net transport of moisture from the oceans to rainfall over the land in the amount of 9 in., thus balancing the discharge of rivers to the sea. [De Wiest, 1965]

For the State of North Carolina, Eq. 1 is expressed as follows:

48 in. of precip. = 32 in. of evapo-trans. + 16 in. of runoff.

Of the total runoff of 16 in. for North Carolina, about 12.5 in. flows into the Atlantic Ocean and about 3.5 in. flows into the Gulf of Mexico [Goddard, 1963].

Inasmuch as the total amount of runoff determines the total quantity of water that is available to man for his use as he sees fit to use it, it can be said that North Carolina is fortunate to have 60 percent more water for its use than the average world allotment.

The total runoff or streamflow can be subdivided (Fig. 7) into ground-water flow, surface water flow, and interflow. We are interested in the total amount of streamflow and its subdivision roughly into surface-water flow and ground-water flow because overland flow, apart from its role in navigation, usually ends up as a loss to the ocean once it reaches the stream. Ground-water flow likewise, after it becomes stream flow, runs off to the ocean, but occasions to tap it and use it before it reaches the streams are plentiful. In the following we study the total amount of runoff and the breakdown into its components.

The Monthly Water Balance

Although streamflow records for the State of North Carolina have been published in annual series of the U. S. Geological Survey Water-Supply Papers, a clear picture of the distribution of precipitation, evapotranspiration and runoff over the year is obtained by the computation of a monthly water balance. Such a budget study yields runoff values that compare very well with published streamflow records [Thornthwaite and Mather, 1955].

The computation of a monthly water balance has the advantages that it can be done for small watersheds for which no streamflow records are available and that it requires only temperature and

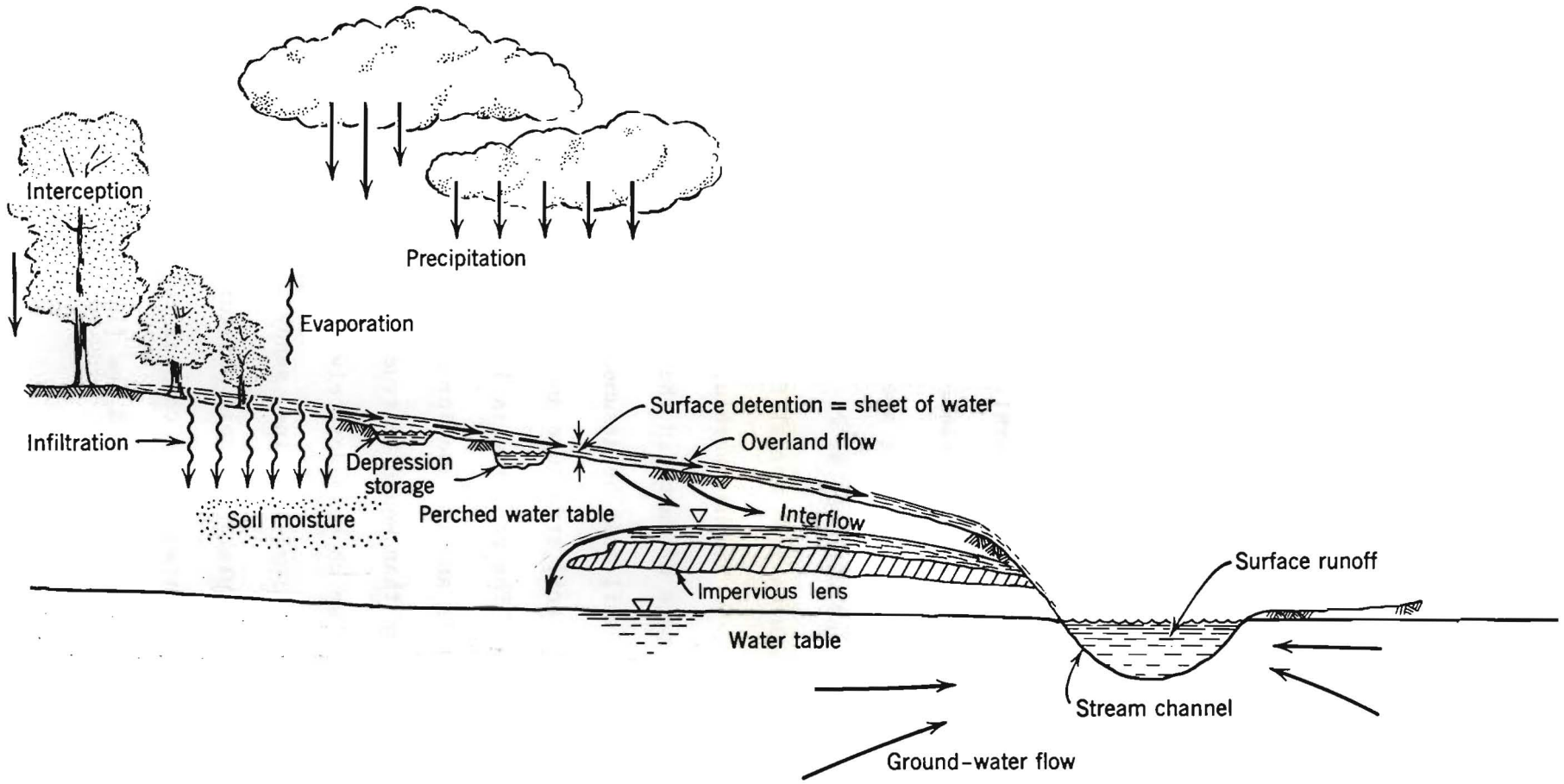


Fig. 7 Simple picture of runoff cycle.

(Modified after DeWiest [1965])

(From Geohydrology by R. J. M. DeWiest)

precipitation records which in general are more readily available and which cover longer periods than streamflow records.

Table 1 and Figure 8 give the monthly water balance for Aurora, N. C. All quantities, except temperatures and heat index, are expressed in inches. The computations are based on climatological data for New Bern, N. C.: average temperatures, total precipitation and departures from normal from start of record through 1964, all courtesy of U. S. Weather Bureau.

Table 2 and Figure 9 give the monthly water balance for Castle Hayne, N. C. All quantities, except temperatures and heat index, are expressed in inches. The computations are based on climatological data for Wilmington, N. C., and Willard, N. C.: average temperatures, total precipitation and departures from normal from start of record through 1964, all courtesy of U. S. Weather Bureau.

To compute the storage of water in the soil, a value of the water-holding capacity of the soil must be assumed. This value depends on the type of soil, on the soil structure and on the kind of vegetation that covers the surface. The capacity is larger for silty or clayey soils than for sandy soils and is also larger for vegetation like trees and pasture grasses than would be true of vegetable crops.

For Beaufort County we chose moderately deep rooted crops (corn, cotton, tobacco, cereal grains) and fine, sandy loam to silt-loam and clay-loam soils, with an appreciable soil moisture retention value of 8 inches. It is estimated that in the coastal region not more than 25 percent of the area is forest covered now (1967).

TABLE 1. MONTHLY WATER BALANCE--AURORA, N. C.

	J	F	M	A	M	J	J	A	S	O	N	D	Sum
Temperature °F	46.6	47.7	53.5	62.8	70.8	77.8	80.2	79.3	74.7	64.7	54.7	46.8	
Heat Index	2.08	2.32	3.73	6.44	9.13	11.74	12.69	12.33	10.56	7.05	4.06	2.13	84.26
Unadj. Pot. Evapo-Trans.	0.02	0.02	0.04	0.08	0.13	0.17	0.18	0.18	0.15	0.09	0.04	0.02	
Pot. Evapo-Trans.	0.52	0.51	1.23	2.62	4.72	6.18	6.48	6.25	4.14	2.62	1.03	0.51	
Precipitation	3.27	3.85	3.96	3.10	3.91	4.54	8.17	6.98	6.68	3.17	3.65	4.13	55.41
Precip.-Pot. Evap. Trans.	2.75	3.34	2.73	0.48	-0.81	-1.64	1.69	0.73	2.54	0.55	2.62	3.62	
Accum. Pot. Water Loss					-0.81	-2.45							
Storage	8	8	8	8	7.23	5.88	7.57	8	8	8	8	8	
Change in Storage	0	0	0	0	-0.77	-1.35	1.69	0.43	0	0	0	0	
Actual Evaporation	0.52	0.51	1.23	2.62	4.68	5.89	6.48	6.25	4.14	2.62	1.03	0.51	36.48
Moisture Deficit	0	0	0	0	0.04	0.29	0	0	0	0	0	0	
Moisture Surplus	2.75	3.34	2.73	0.48	0	0	0	0.30	2.54	0.55	2.62	3.62	18.93
Runoff	2.72	3.03	2.88	1.68	0.84	0.42	0.21	0.26	1.40	0.98	1.81	2.70	18.93

Note: All quantities, except temperatures and heat index, are expressed in inches. Computations are based on climatological data for New Bern, N. C.; average temperatures, total precipitation and departures from normal from start of record through 1964, courtesy of U. S. Weather Bureau.

FIG. 8

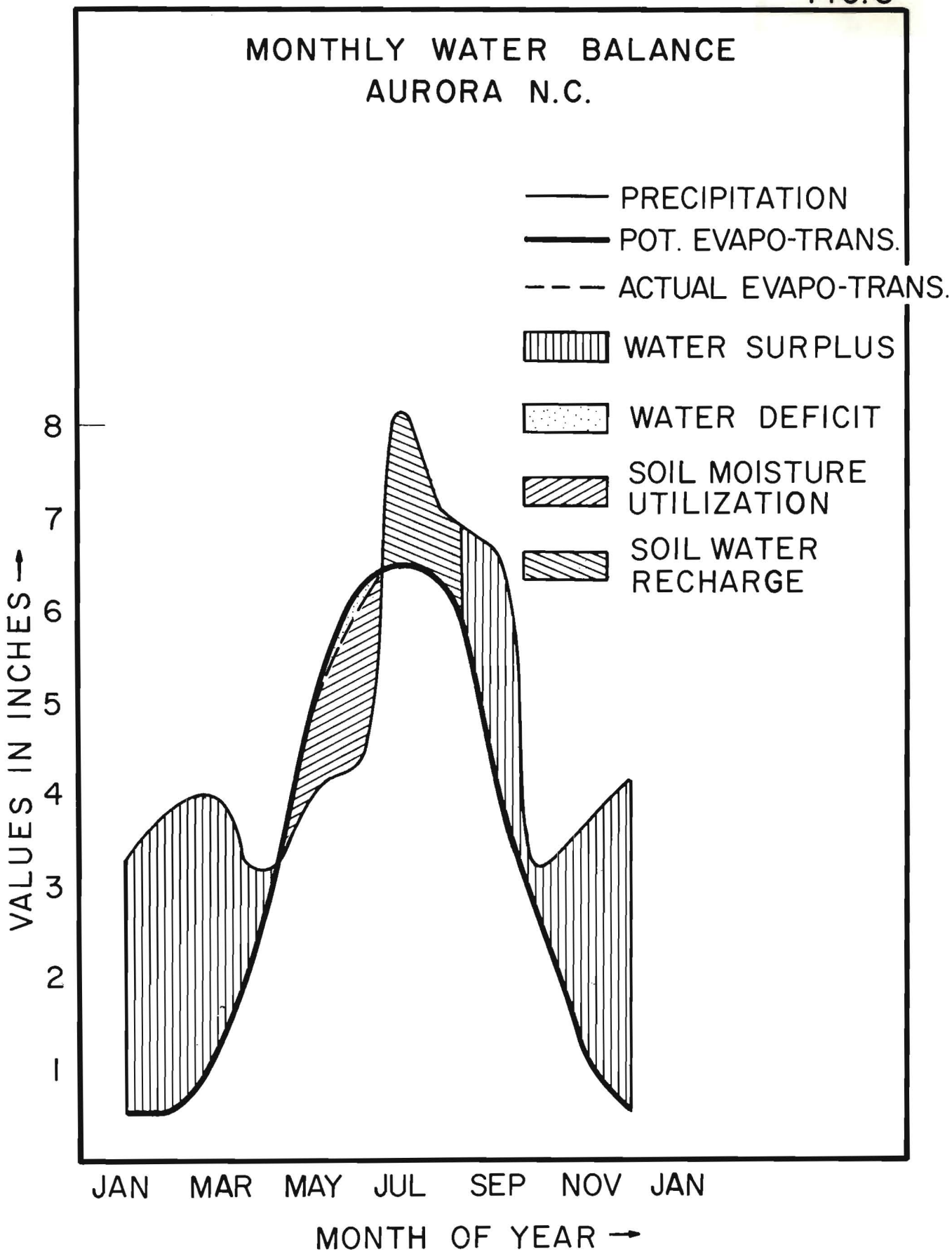
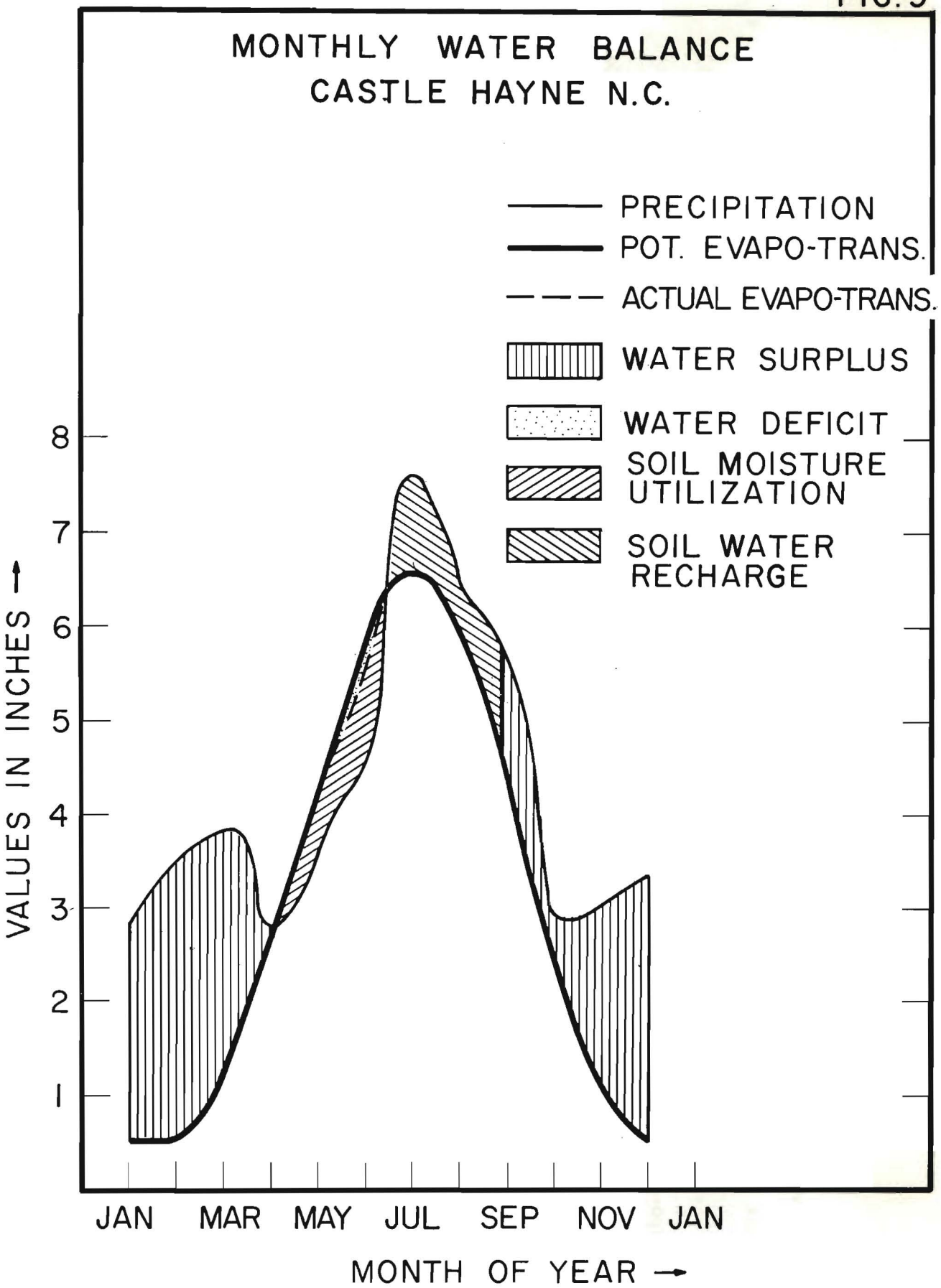

MONTHLY WATER BALANCE
AURORA N.C.
PRECIPITATION
POT. EVAPO-TRANS.
ACTUAL EVAPO-TRANS.
WATER SURPLUS
WATER DEFICIT
SOIL MOISTURE UTILIZATION
SOIL WATER RECHARGE
VALUES IN INCHES
8
7
6
5
4
3
2
1
JAN
MAR
MAY
JUL
SEP
NOV
JAN
MONTH OF YEAR

TABLE 2. MONTHLY WATER BALANCE--CASTLE HAYNE, N. C.

	J	F	M	A	M	J	J	A	S	O	N	D	Sum
Temperature °F	47.6	48.5	54.1	62.5	70.3	77.2	79.6	78.6	74.1	64.0	54.3	47.0	
Heat Index	2.30	2.50	3.89	6.34	8.96	11.51	12.45	12.01	10.34	6.82	3.95	2.17	83.24
Unadj. Pot. Evapo-Trans.	0.02	0.02	0.04	0.08	0.12	0.16	0.18	0.17	0.14	0.09	0.04	0.02	
Pot. Evapo-Trans.	0.52	0.51	1.23	2.62	4.33	5.77	6.60	5.92	4.33	2.62	1.03	0.51	
Precipitation	2.86	3.48	3.85	2.81	3.59	4.50	7.62	6.43	5.78	2.88	2.98	3.34	51.12
Precip-Pot. Evap. Trans.	2.34	2.97	2.62	0.19	-0.74	-1.27	1.02	0.51	1.45	0.26	1.95	2.83	
Accum. Pot. Water Loss					-0.74	-2.01							
Storage	12	12	12	12	11.28	10.14	11.16	11.66	12	12	12	12	
Change in Storage	0	0	0	0	-0.72	-1.14	+1.02	+0.50	+0.34	0	0	0	
Actual Evaporation	0.52	0.51	1.23	2.62	4.31	5.64	6.60	5.92	4.33	2.62	1.03	0.51	35.84
Moisture Deficit	0	0	0	0	0.02	0.13	0	0	0	0	0	0	
Moisture Surplus	2.34	2.97	2.62	0.19	0	0	1.00	0.01	1.11	0.26	1.95	2.83	15.28
Runoff	2.18	2.58	2.60	1.40	0.70	0.35	0.67	0.34	0.73	0.49	1.22	2.02	15.28

Note: All quantities, except temperatures and heat index, are expressed in inches. Computations are based on climatological data for Wilmington, N. C. and Willard, N. C.; average temperatures, total precipitation and departures from normal from start of record through 1964, courtesy of U. S. Weather Bureau.

FIG. 9


MONTHLY WATER BALANCE
CASTLE HAYNE N.C.
PRECIPITATION
POT. EVAPO-TRANS.
ACTUAL EVAPO-TRANS.
WATER SURPLUS
WATER DEFICIT
SOIL MOISTURE UTILIZATION
SOIL WATER RECHARGE
VALUES IN INCHES →
8
7
6
5
4
3
2
1
JAN
MAR
MAY
JUL
SEP
NOV
JAN
MONTH OF YEAR →

For computation of the water balance in the Castle Hayne area, we assume a somewhat larger coverage with forest, fine sandy loam, and an applicable soil-moisture retention value of 12 inches.

The runoff values computed by means of the water balance and the observed values compare favorably as follows:

Annual Runoff

Castle Hayne (calculated, water balance)	15.3 inches
Northeast Cape Fear River, near Chinquapin, N. C. (observed)	15.9 inches
Aurora (calculated, water balance)	18.9 inches
Swift Creek, near Vanceboro, N. C. (observed)	14.9 inches

The graphs of Figures 8 and 9 show that there is a surplus of water from September until April and that less water is available for runoff in the Castle Hayne region than in Beaufort County. Approximately 30 percent of the precipitation runs off in the Castle Hayne region, compared to 34 percent for Beaufort County.

Thornthwaite's method of computing the monthly water balance is based on simplifying assumptions which should be understood in the interpretation of the numerical results. Since the numbers are average values for individual months, they represent steady-state conditions. It is assumed that equal volumes of water are added to and extracted from the ground-water basin. In other words, no account is taken of the change in storage inside the ground-water reservoir. Nor is there taken into account the change in storage in the unsaturated-flow zone of the ground.

Hydrograph Separation

A hydrograph is a plot of the discharge from a hydraulic or hydrologic unit or system such as a river or drainage basin, or it may depict the time variation of the runoff component of a storm.

In the case of perennial streams, in periods of drought when no direct overland flow reaches the river, the hydrograph is a line which slopes gently down. The streamflow is made up entirely of ground-water flow, sometimes called "base flow".

In general however, as in the case of a storm with a rainfall intensity larger than the rate of infiltration and with a volume of infiltrated water exceeding the soil moisture deficiency, the hydrograph has the form of Figure 10. This figure shows as flow contributions the surface runoff (a), the direct channel precipitation (d), the interflow (b), and the base flow or ground-water flow (c).

Actually, it is very difficult to separate the base flow from the surface runoff because stream-flow measurements do not reveal the times when a stream becomes influent, that is, contributes water to the adjacent aquifers. In such cases the contributions to base flow are <u>negative</u>.

In spite of this difficulty, it is possible to make an approximate hydrograph separation which is acceptable for most purposes. The simplest separation consists in drawing a horizontal line through the point where the rising limb starts and in finding the intersection point with the recession curve. The surface runoff component is the volume of water given by the area under the curve and above the horizontal line. This procedure has been applied to the monthly hydrographs of

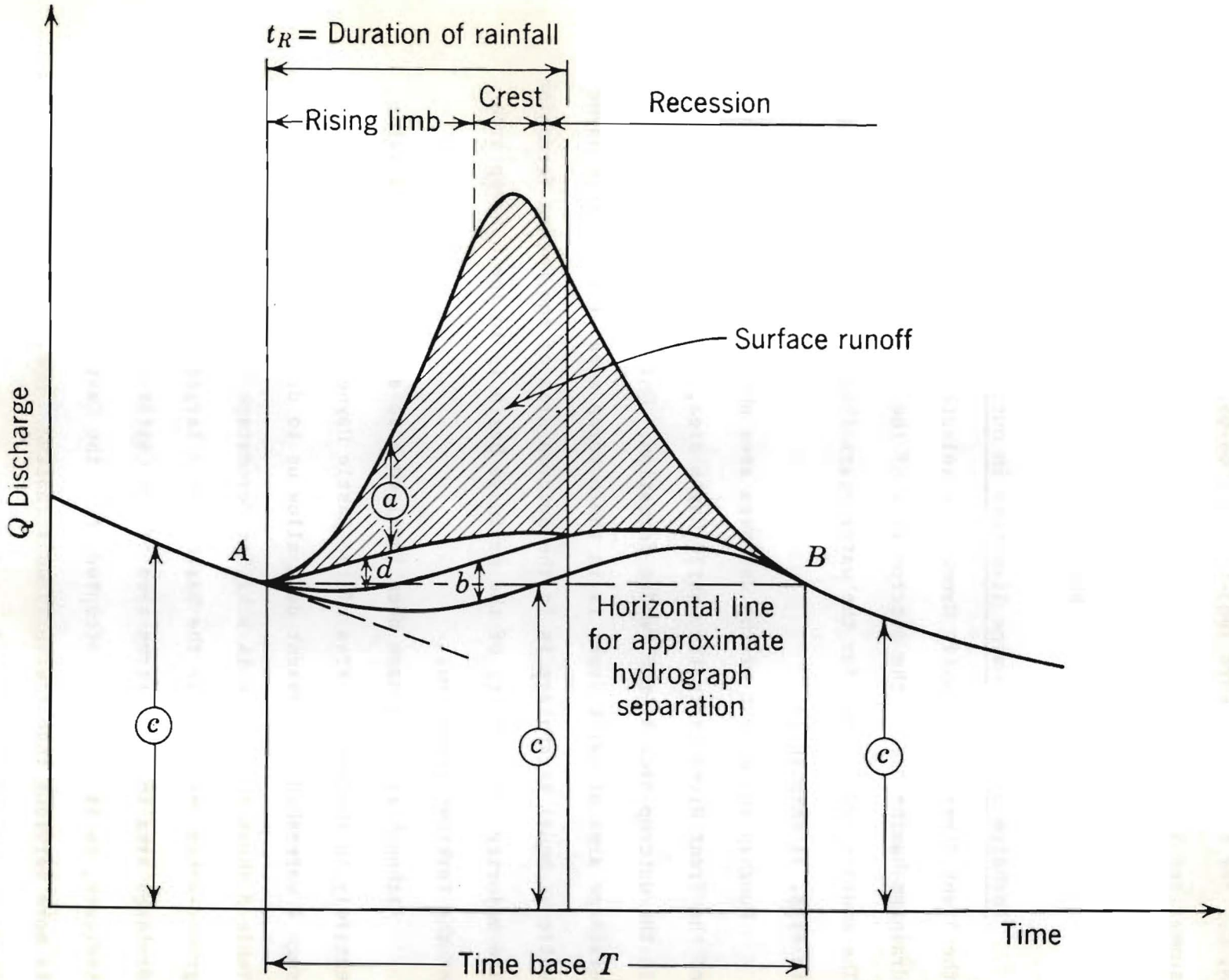


Fig. 10 Hydrograph parts and flow contributions.
(From Geohydrology by R.J.M. DeWiest)

Trent River, near Trenton, N. C., and of Swift Creek near Vanceboro, N. C., for the water years 1963-64 and 1964-65. The results are summarized in Tables 3 and 4.

Recharge

Recharge of Castle Hayne limestone in outcrop area. The records of the Trent River and of Swift Creek were selected because parts of their drainage basins are in the outcrop area of the Castle Hayne limestone. The monthly hydrographs for the water years 1963-64 and 1964-65 are given in Figs. 11 through 14.

Roughly 40 percent of the drainage area above the gaging station of the Trent River is in the Castle Hayne area, while the remainder is in the outcrop area of the Peedee formation. Only 15 percent of the drainage area of Swift Creek is in the outcrop area of the Castle Hayne, while an equal percentage is in the outcrop area of the Peedee formation. The majority (70 percent) of the drainage basin is in the outcrop area of the Yorktown formation.

Although it would have been ideal to have a gaged watershed lying entirely in the outcrop area of the Castle Hayne, in the absence of such a watershed the present data allow us to draw valuable conclusions. Table 3 shows that there is a higher percentage of recharge to the ground-water reservoir in the basin with a larger fraction of its drainage area in the outcrop area of the Castle Hayne. This would indicate, as is generally accepted, that the Castle Hayne formation is more pervious than the Yorktown formation. However, the difference in percentage of total runoff is less than 10, while the

TABLE 3. HYDROGRAPH SEPARATION,
MONTHLY FLOWS, WATER YEAR 1963-1964

(In Inches)

	Trent River near Trenton, N. C.		Swift Creek near Vanceboro, N. C.	
	Base flow	Surface runoff	Base flow	Surface runoff
October	0.07	0.24	0.11	0.24
November	0.30	0.35	0.39	0.88
December	0.84	0.46	1.21	0.78
January	2.28	1.19	1.98	1.96
February	2.30	1.17	1.67	1.66
March	1.09	0.95	1.50	1.61
April	0.69	0.94	1.00	0.89
May	0.27	0.26	0.08	0.21
June	0.07	0.26	0.03	0.22
July	0.88	0.43	0.08	0.01
August	0.40	1.62	0.04	0.25
September	0.40	3.42	0.55	4.35
Sum	9.49	11.29	8.64	13.06
Percent of total runoff	45.7	54.3	39.8	60.2
Percent of total precip.	14.2	17.0	14.5	22.2

TABLE 4. HYDROGRAPH SEPARATION,
MONTHLY FLOWS, WATER YEAR 1964-1965

(In Inches)

	Trent River near Trenton, N. C.		Swift Creek near Vanceboro, N. C.	
	Base flow	Surface runoff	Base flow	Surface runoff
October	1.15	1.78	1.60	3.69
November	0.34	0.03	0.43	0.14
December	0.64	0.45	0.84	0.39
January	0.82	0.52	0.96	0.44
February	1.83	1.05	2.25	0.57
March	1.60	1.39	1.26	0.63
April	0.52	0.33	0.36	0.24
May	0.24	0.12	0.19	0.19
June	0.94	3.22	0.67	0.90
July	2.14	1.52	1.36	1.71
August	0.44	0.69	0.86	1.09
September	0.14	0.02	0.14	0.02
Sum	10.80	11.12	10.92	10.01
Percent of total runoff	49.2	50.8	52.2	47.8
Percent of total precip.	20.1	20.6	21.3	19.4

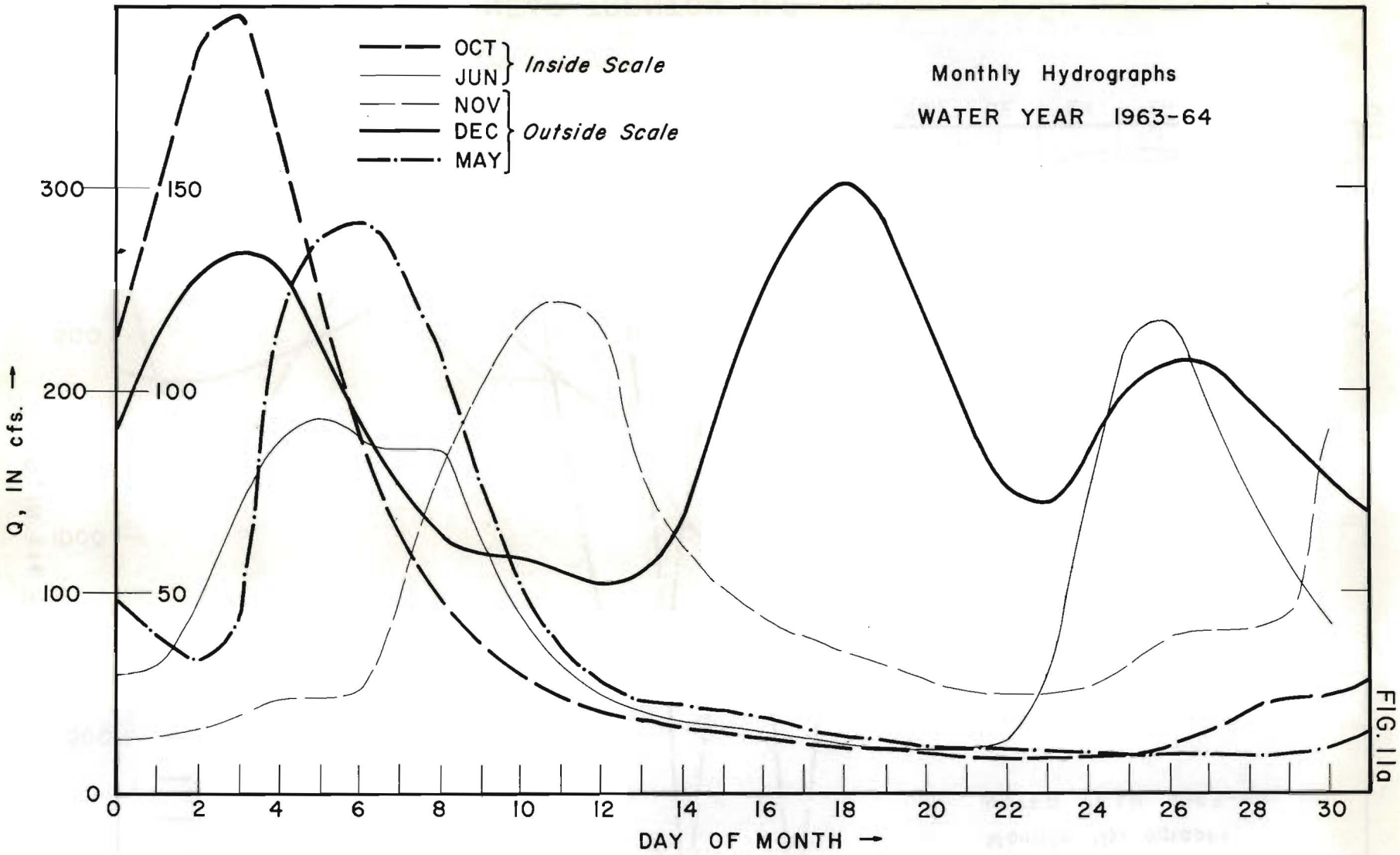


FIG. 11a TRENT RIVER NEAR TRENTON N. C.

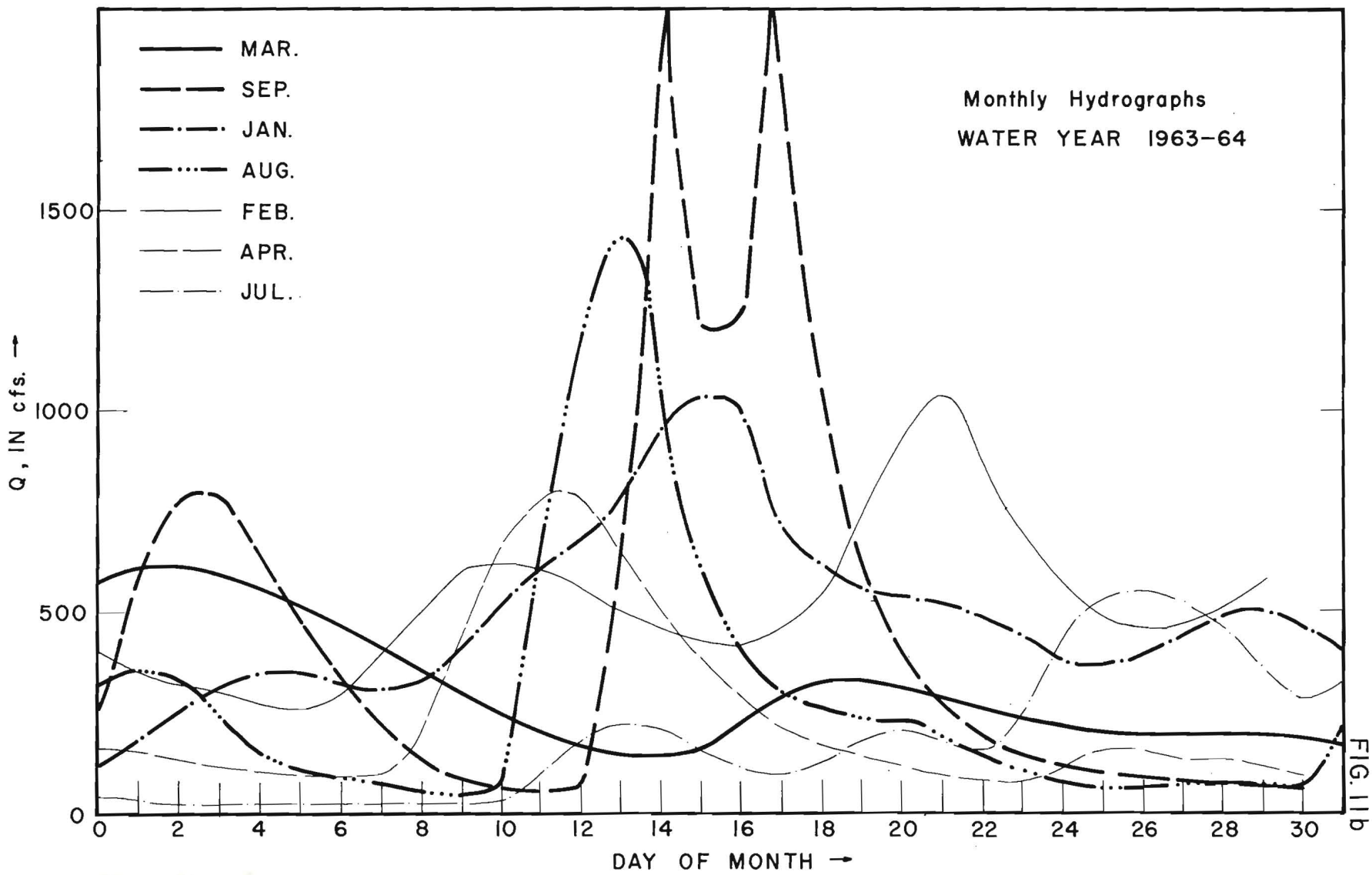


FIG. 11b TRENT RIVER NEAR TRENTON N.C.

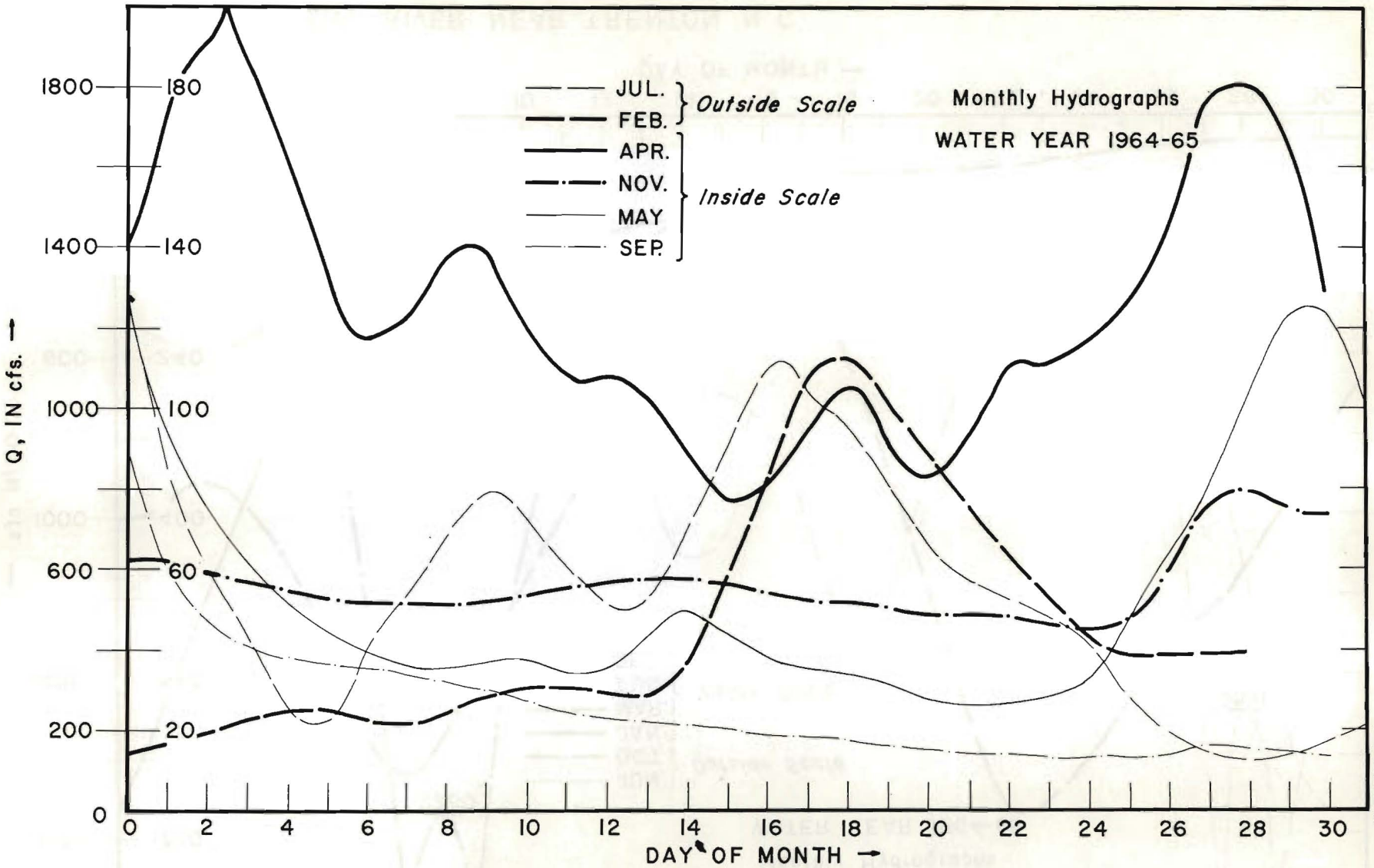


FIG. 12a

FIG. 12a TRENT RIVER NEAR TRENTON N.C.

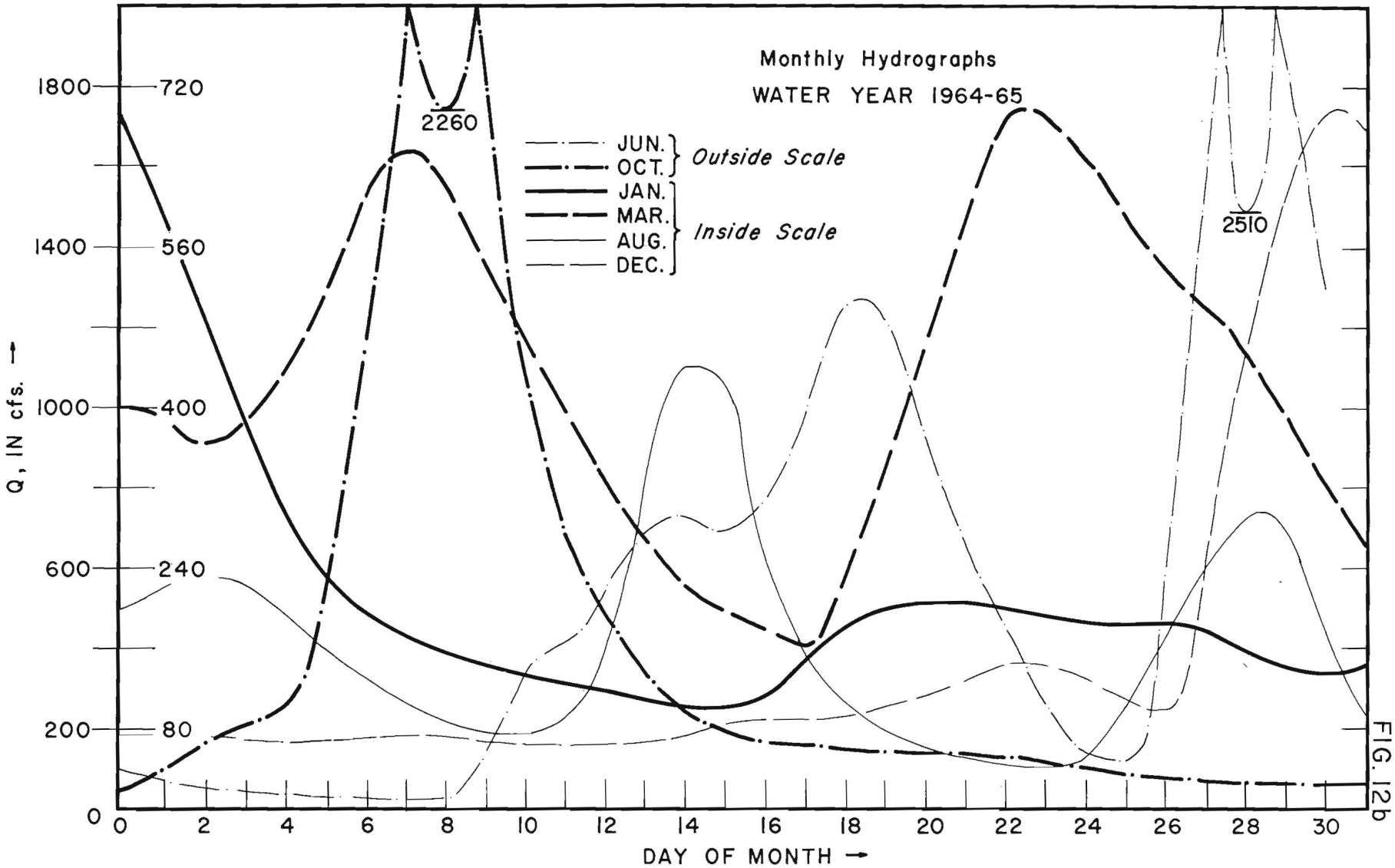


FIG. 12b TRENT RIVER NEAR TRENTON N. C.

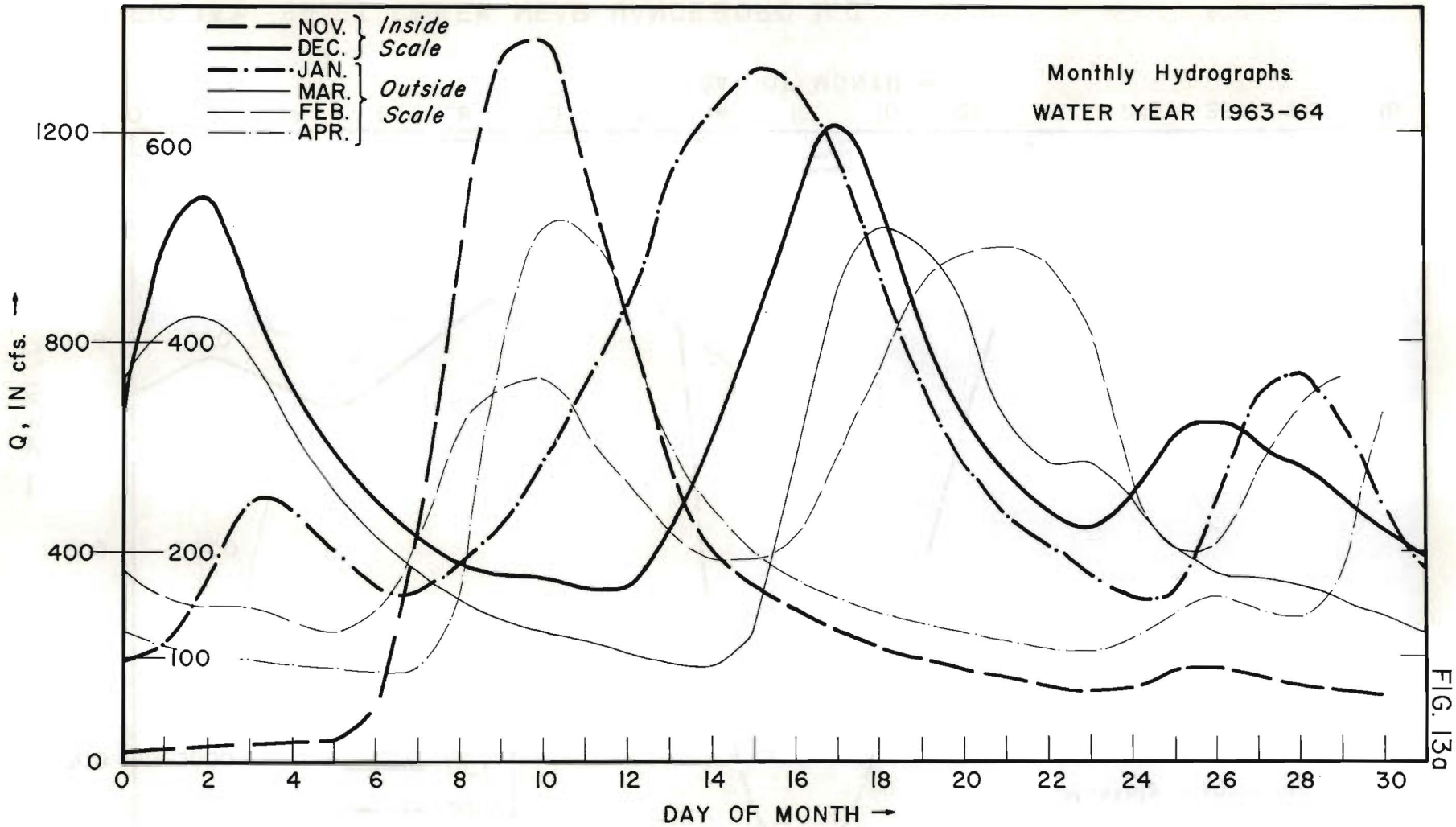


FIG. 13a SWIFT CREEK NEAR VANCEBORO N.C.

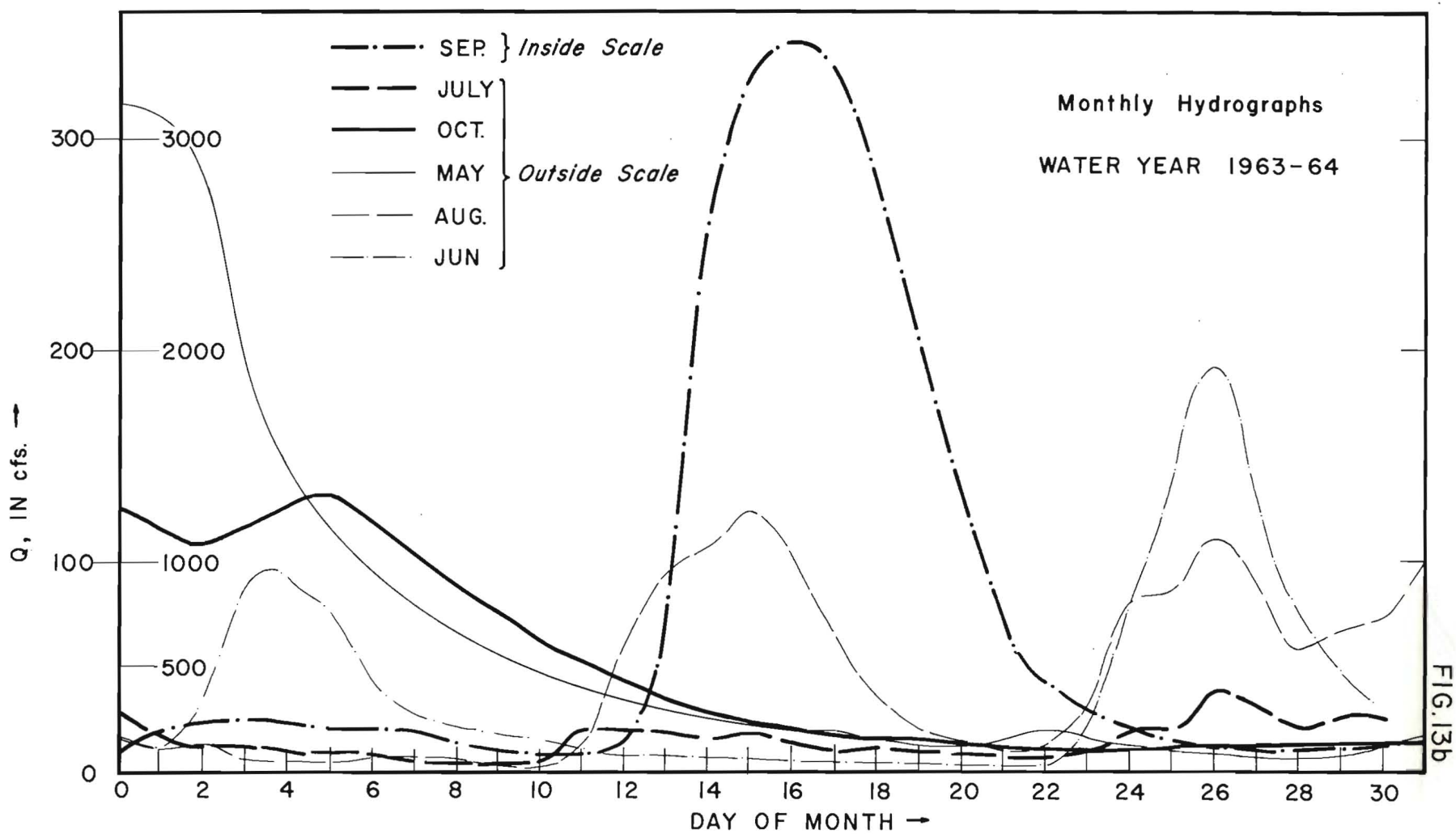


FIG. 13 b SWIFT CREEK NEAR VANCEBORO N.C.

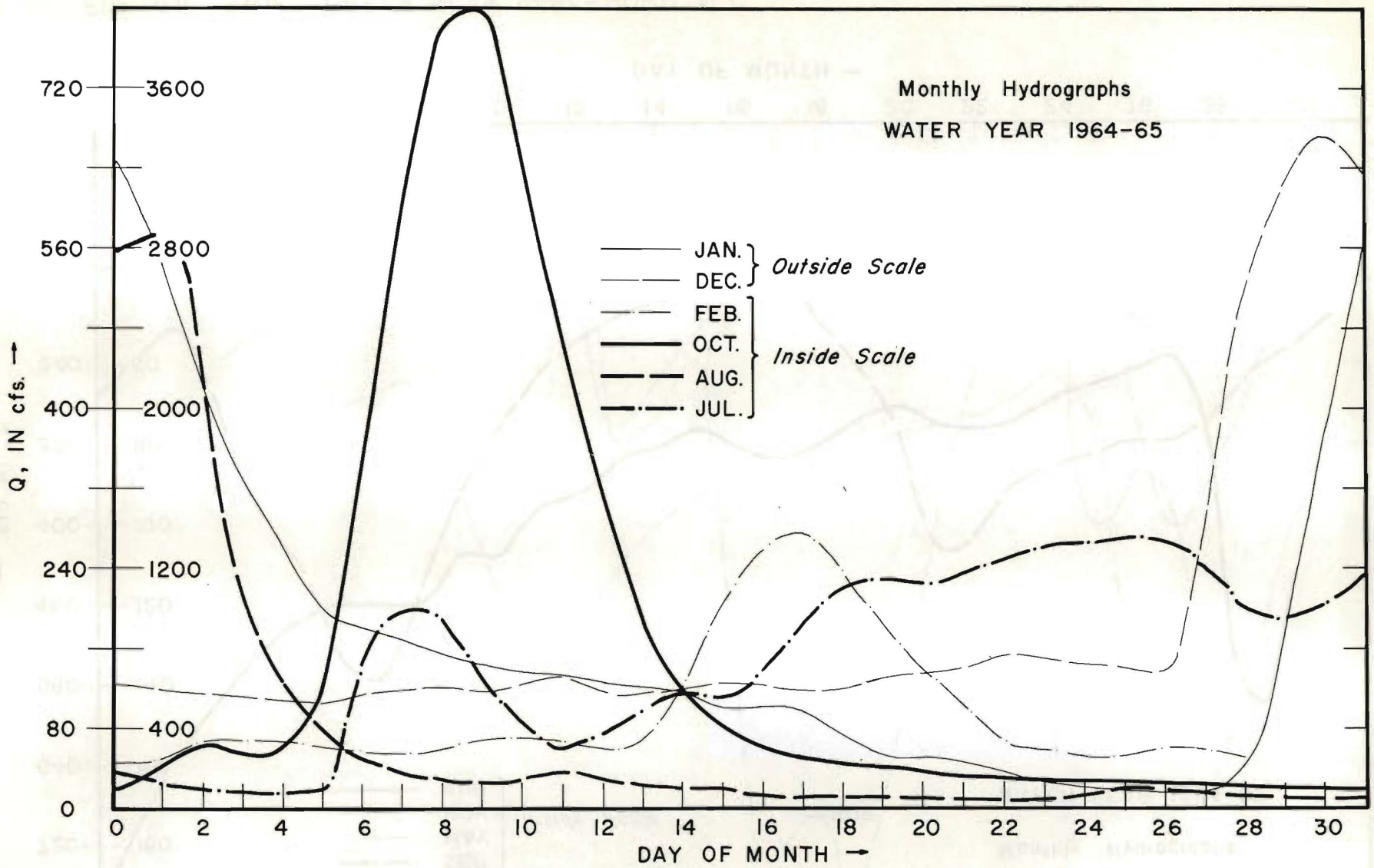


FIG. 14a

FIG. 14a SWIFT CREEK NEAR VANCEBORO N.C.

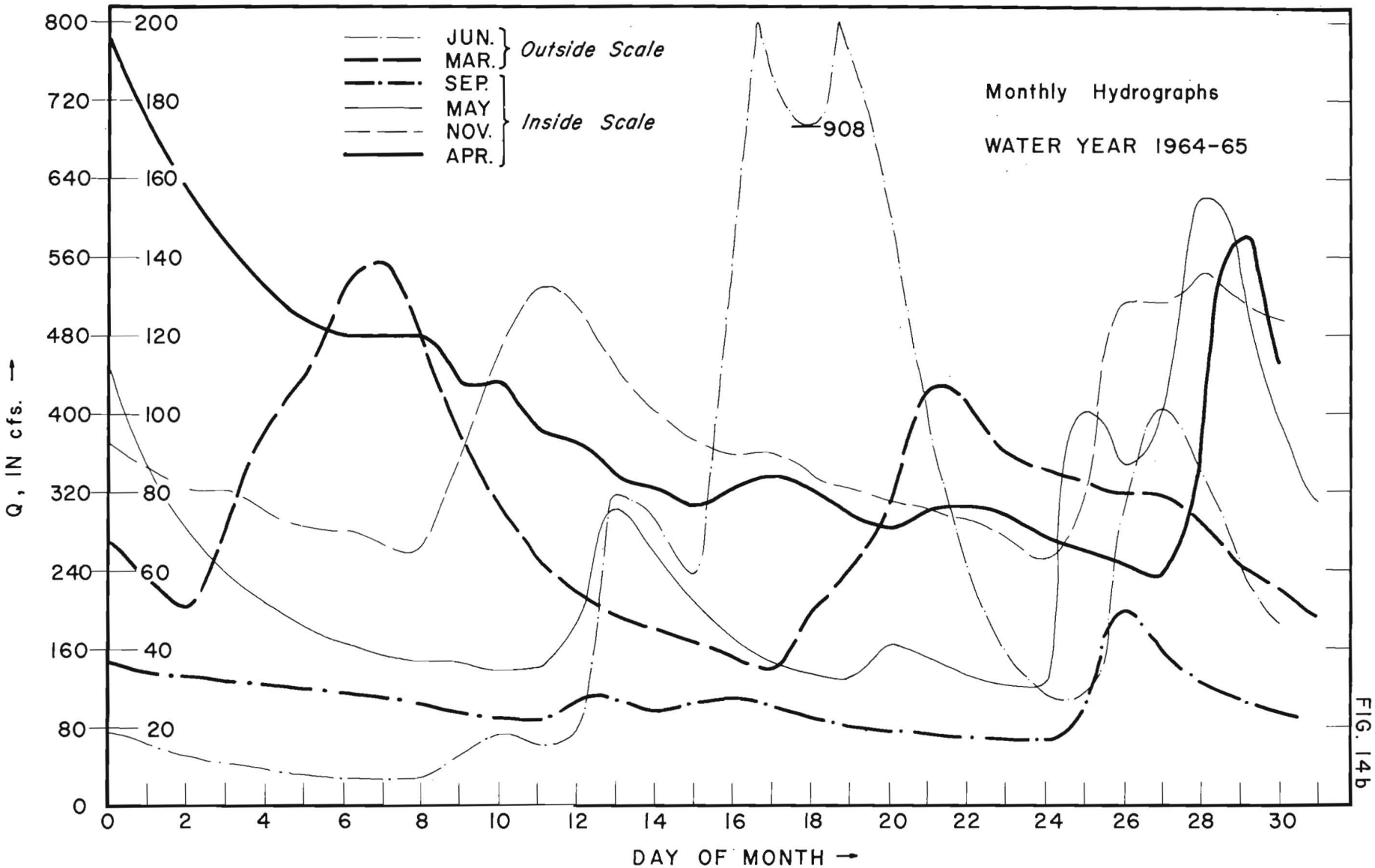


FIG. 14b

FIG. 14b SWIFT CREEK NEAR VANCEBORO N.C.

difference in percentage of total precipitation is insignificant as far as base flow is concerned.

The precipitation figures used are respectively 66.59 in. for Trenton during water year 1963-64 and 59.10 in. for New Bern during the same water year. It should be said that precipitation measurements at only one point of a basin or in the vicinity of a basin cannot be extrapolated to give average basin-wide precipitation. The figures for base flow as percentage of precipitation may therefore be somewhat in error, although they certainly are of the correct order of magnitude.

Table 4 gives the results of the hydrograph separation for the water year 1964-1965. This year is characterized by a higher percentage of base flow than the previous year, and this effect is even more pronounced for Swift Creek basin than for Trent River basin, against the normal expectation. This phenomenon may be explained by the fact that the precipitation-runoff relationship depends on many factors such as antecedent precipitation and duration of storm, etc., which give a different amount of runoff for a given amount of precipitation in a certain basin. The precipitation figures used are respectively 51.46 in. for New Bern during water year 1964-65 and 53.84 in. for Trenton during the same water year. It is remarkable that the total runoff for water year 1964-65 is nearly the same as that of the previous year, although the precipitation in that year was about 10 in. below the precipitation of the previous year, which was close to the mean precipitation on record. This explains the high percentage of precipitation (on the order of 20 percent) that is available for recharge.

For practical computations, however, it may be assumed that roughly 15 percent of the precipitation percolates through the soil and joins the water in the aquifers. The average annual precipitation for the outcrop area of the Castle Hayne may be taken as the average of the figures of Tables 1 and 2, say 53.3 in. or 4.44 ft.

An estimate of the annual recharge in the outcrop area of the Castle Hayne that could, under the most favorable circumstances (in an ultimate steady state), become tributary to the Texas Gulf Sulphur site near Lee Creek, is made as follows:

The Castle Hayne outcrop area northeast of Neuse River equals 170 square miles or about 4,740 million square feet, as taken from the Geologic Map of North Carolina. (Unconfined ground water in the outcrop area southwest of Neuse River is "shielded" by the river.)

Recharge rate: 0.15×4.44 ft/yr $\times\ 4.74 \times 10^9$ ft^2 $\times$

7.48 gal/ft^3 $\times$ yr/365 day $= 65 \times 10^6$ gpd.

Coincidentally, this about equals the rate of pumpage at Lee Creek. In other words, in the hypothetical case in which <u>all</u> the recharge in the Neuse River drainage basin northeast of Neuse River within the outcrop of the Castle Hayne were to be steadily diverted to the Texas Gulf Sulphur site, there would be enough ground water to satisfy the daily demand of 65 million gallons now pumped by Texas Gulf Sulphur. However, that diversion of outflow would entail a reduction of the natural outflow that occurred by upward leakage into the estuary of Pamlico River, especially at the head of that estuary, near Washington. (See p. 43) In other words, whereas the natural flow was from the "nose" on the piezometric surface between the Neuse and Pamlico Rivers toward the estuaries of those streams, in this

hypothetical case part of that natural flow would be diverted toward the Lee Creek site with the possibility even of reversal of flow. Brackish waters in the estuary would be pulled downward into the Castle Hayne aquifer. (See p. 44 and Fig. 5.)

Actually, in spite of the extensive and deep cone of depression created by the Texas Gulf Sulphur operation, a large fraction of the nearly 65 million gallons per day that recharges the Castle Hayne aquifer through its outcrop area northeast of the Neuse remains in the Neuse River basin and still discharges into the Neuse River.* It is precisely this large fraction of Texas Gulf Sulphur's daily pumpage that therefore has to reach the Lee Creek site within the Castle Hayne aquifer through leakage from the overlying and underlying formations, through ground-water inflow laterally from distances more remote than the outcrop, and from reduction of storage. It shall be our purpose hereafter to determine what proportions of the Lee Creek pumpage have come and are coming from these several sources.

Rejected recharge. That part of the direct recharge to the Castle Hayne and of the indirect recharge through the overlying Yorktown to the Castle Hayne that flows laterally to the stream channels is called "rejected recharge." As the Castle Hayne is filled to overflowing,

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*The runoff of two possibly affected tributaries of Neuse River and the precipitation at neighboring stations during the last three water years were as follows, in inches:

	1963-64	1964-65	1965-66
Swift Creek near Vanceboro	21.7	20.9	14.0
Precipitation at New Bern	59.5	49.8	51.0
Trent River near Trenton	20.8	21.9	13.4
Precipitation at Trenton	59.1	49.5	54.6

it may be said to "reject" some recharge in that area where it is unconfined. Where confined, it flows full. A heavy draft within the area of confinement (as at Lee Creek) has the effect of diverting some water from the area of unconfinement (e.g. outcrop area), but not without a progressive lowering of head within that area of unconfinement. In other words, despite the rejection of recharge, the area of unconfinement does not behave as a "distributed constant-head source." Rather, as seen from, or behind, the center of withdrawal it will appear as a distributed source with declining head, and as such is distinguishable from vertical leakage driven by constant or nearly constant head.

Hydrography of Estuaries

The distance to which tides travel upstream in the estuaries depends, of course, upon the stage and discharge of the stream and upon the height of the tide. Sea water encroaches up each estuary as a wedge on the bottom. Hurricanes and other violent storms with strong onshore winds drive sea water far inland. The water in the Pamlico estuary near Washington is therefore often brackish, sometimes running from about 6,000 to 8,000 ppm of chloride. At low or even moderate flow rates this stream must be freshened notably by the seepage of ground water, estimated below to be on the order of 30 mgd over a 16-mile reach. Obviously, with a reversal of the direction of seepage occasioned by the heavy draft on the Castle Hayne aquifer at Lee Creek, the upward leakage may be changed to downward leakage, and the quality of the water in the estuary may thereby be worsened, especially in dry weather.

Natural Discharge

Upward leakage from aquifers. As already pointed out (p. 39), the shallower marine sediments underlying the area of interest have been flushed of their salt water in the geologic past. Farther inland, older and deeper sediments have also been flushed. Seaward gradients of the head in all of these sediments indicate that there is an over-all component of flow toward the sea. The sediments become much finer grained and less permeable proceeding seaward. Moreover, they are buried too deeply to permit direct discharge of fresh water into the sea. Hence the fresh water must rise to successive higher beds and eventually find exit in the estuaries of the rivers.

Not only is upward leakage significant in the estuary of Pamlico River, especially in its upper reaches, but also in the estuaries of the other major streams of North Carolina. These are, from south to north, Cape Fear River, New River, Neuse River, Roanoke River, and Chowan River. Referring to the North Carolina Department of Water Resources report entitled "Wise Management of North Carolina Water Resources through Law" [1966], the generalized piezometric surface of the principal aquifers of the Coastal Plain (See Plate 2) shows indentations in the contours for 1964 as they cross each of these streams.

In the southern part of the Coastal Plain the ground-water contours are drawn on the Castle Hayne piezometric surface; farther north they represent a composite of water levels in beds of comparable depths. Despite some minor stratigraphic discontinuities that intervene, these generalized contours faithfully represent the distribution of head that governs the seaward flow of ground water in a regional sense, and the upward leakage into the estuaries in a local sense.

The average gradients between the 10- and 20-foot contours on the one hand and the 20- and 40-foot contours on the other hand were measured at 12 sections and were found to average about 2.5 ft/mi. Seaward gradients on four of these sections, remote from but between the estuaries, averaged only about 1.5 ft/mi. Taking the average transmissivity to be 300,000 gpd/ft, as determined from the response of the aquifer to continued dewatering at the Lee Creek site (See p. 96), the average intensity of seaward flow is by calculation 0.75 mgd/mi. The total seaward flow toward the 200 miles of coast line is by calculation about 150 mgd.

The foregoing estimates are based upon 12 sections, eight of which are near estuaries and therefore reflect, in part at least, the flow upstream from and parallel to those estuaries. The four sections remote from the estuaries are generally downstream from the heads of the estuaries and reflect, therefore, intensity of flow that escapes those estuaries and rises rather in the sounds or embayments along the coast. The intensity of this flow varies but is on the order of only 0.45 mgd/mi.

Estimate of upward leakage into estuary of Pamlico River. Referring to Fig. 4, an estimate may be made of the components of piezometric gradient normal to Pamlico River in a 16-mile stretch running downstream from the vicinity of Washington. The indentation in the piezometric contours suggests strong upward leakage, [Nelson and Peek, p. 8, 1964], as might be expected to occur in this reach of the estuary because of the thinness of the cover on the Castle Hayne limestone and because of the relative perviousness of that cover in places (see Fig. 5). The cosine of the angle of incidence of the streamlines is about 0.62 on the average. The average gradient is 5 ft/mi. Assuming the transmissivity is

300,000 gpd/ft, the intensity of flow is about 0.93 mgd/mi (from each side of the estuary). Thus the upward leakage into the 16-mile reach of the estuary is about 30 mgd. It is emphasized that this estimate of leakage is for conditions before pit dewatering began at Lee Creek.

Because local transmissivities are not as well known near the heads of the other estuaries, we shall not attempt an estimate of the magnitudes of upward leakages in those estuaries. The upward leakage into Neuse River from the Castle Hayne limestone is, however, probably of the same order of magnitude as that into the Pamlico. The upward leakage into each of the other four estuaries referred to earlier is probably somewhat smaller.

Miller [1966, p. 19] says, "The nature of water discharge from the Castle Hayne aquifer is unknown" (emphasis added). He correctly remarks further that there is insufficient head available to flush out connate water from the Castle Hayne aquifer into Pamlico Sound or the Atlantic Ocean. We believe that the nature of the discharge not only is known but its magnitude is determinable within reasonable limits. If the nature of discharge from the Castle Hayne aquifer is known, then the nature of inflow upon reversal of head would more likely be known. On the other hand, if the nature of the natural discharge were really unknown, then possibly the artificially induced inflow might remain unknown.

Alternative explanation of indented piezometric contours. Miller [1966, p. 17] prefers to relate the indentations in the piezometric surface to casings that "were not sealed to the aquifer." Speaking of the domestic wells drilled into the Castle Hayne formation and used for water-level observations both by Texas Gulf Sulphur Company and the Department of Water Resources, he admits that "all of the wells are cased . . . ." But, he continues, "Many of the piezometric levels measured may represent ground water hydrostatic pressures rather than piezometric levels of the deeper Castle Hayne." Continuing the quotation: "It is important to note that the contours of Fig. B-1 (Piezometric Surface of Castle Hayne Aquifer Prior to Mine Pumping) correspond to the topography of the region. The Department of Water Resources interprets this correlation to be indicative of recharge of the Castle Hayne by leakage from above. Texas Gulf Sulphur geologists prefer to relate the topographical association to leaky well casings."

In regard to the foregoing explanation, it should be remembered first that several of these observation wells flowed naturally before mine dewatering began at Lee Creek. It would appear that there are three possibilities besides the one traditionally taken [Nelson and Peek, 1964, p. 8]. First, it might be assumed that a few of the observation wells have casings that are rusted out or collapsed in the Yorktown and plugged in the underlying Castle Hayne limestone. Such wells could readily be eliminated from the observation well program by sounding them and by running "slug-inflow" tests to determine how tightly they may be plugged.

A second possibility is that, as Miller seems to suggest, casings may not have been sealed tightly to the rock hole at or near the top of the Castle Hayne. The inference to be drawn from this, it would appear, is that Castle Hayne water may be leaking from the casing into the Yorktown sand at its

contact with the underlying Castle Hayne limestone. However, unless the hole in the limestone were tightly mudded-up or otherwise sealed, the high head and high transmissivity of the Castle Hayne relative to the head and transmissivity of the Yorktown would dominate the situation and the water level measured inside the unsealed casing would still reflect quite closely the head in the Castle Hayne. Such a well, allowed to stand idle, would soon build up the water table in the Yorktown so as to equalize the head in the two formations at the well, the internal flow in the well gradually diminishing to a minimum.

A third possible interpretation, and one not ruled out by Miller's arguments, is that the casings not only are not sealed into the rock but that the casings are defective at higher levels, permitting leakage into the Yorktown formation more freely than could occur just at the contact as under the first interpretation above. However, this argument is no more valid than the others because the effect of leaky casings would be to measure the weighted average head in the two formations rather than to measure the head in either one of the two formations. The Castle Hayne, being both more transmissive and having higher head, would certainly dominate the average head. Moreover, the pattern of a piezometric surface based upon such average heads would indicate the same vertical leakage from the Castle Hayne into the upper Pamlico estuary.

If one claims that somehow the defective wells permit the Yorktown to "damp out" the strong head variations in the Castle Hayne, he is faced with the equally unexplainable possibility that, since the head relations have been reversed over a large area by the dewatering operation at Lee Creek,

those same observation wells fail to measure the full drawdown that has occurred in the Castle Hayne, and therefore both the extent and the magnitude of that drawdown is greater than depicted on piezometric-contour maps based upon water-level observations made in the supposedly defective wells. It would seem to be a test of credulity to think that, by coincidence, the defective wells might be distributed in a pattern matching the relief of the topography as this would require large numbers of such defective wells to bleed off the Castle Hayne head and still somehow remain undetected.

EVALUATION OF TESTS

Theory of Well Tests

The theory of well tests is outlined in several papers and books that are listed in the Bibliography. See especially DeWiest [1965], Jacob [1950], Jacob [1947], and Cooper and Jacob [1946]. The object of these tests is three-fold---first, to determine the formation constants; second, to determine the characteristics of the pumping well; and third, to enable predictions of the future performance of the well and the response of the aquifer.

Darcy's law. The law of horizontal flow of homogeneous fluids through porous media, such as water through limestone or sandstone, known as Darcy's law, is as follows: $Q = (kA/\mu)dp/dx$, where Q is the volume-rate of flow of water through area A under a pressure gradient dp/dx. The symbol μ stands for the viscosity of the water, and the symbol k stands for the permeability of the material through which the water is flowing. By dimensional analysis it may be seen that the unit of k is length squared (l^2). The standard unit of permability is the darcy.

The foregoing equation applies only to horizontal flow. When the flow is in some general direction, the driving force producing the flow is expressed in terms of head (h). Also, it is found convenient to lump together the permeability of the material through which the water flows, the specific weight of water and also its viscosity, to give the following relationship: $Q = KAdh/dx$, with $K = \gamma k/\mu$ and $h = z + p/\gamma$.

Transmission of water. Many water-bearing formations in nature are of almost uniform thickness, in which case it is found convenient to lump together the factor K, hydraulic conductivity, with the thickness of the formation, b, to form the coefficient know as "transmissivity", as already stated. Thus $Q = Kabdh/dx = aTdh/dx$, where $T = Kb$. In this last equation, a is the width of a strip of the water-bearing formation or aquifer at right angles to the direction of the flow (x); b is the average thickness of the aquifer.

Storage of water. The foregoing coefficients relate to the ability of an aquifer to transmit water. Another important characteristic of an aquifer is that which relates to its ability to store water. This is called the "storage coefficient" (Theis).

Aquifers may be divided into two kinds--confined aquifers and unconfined aquifers. Water may be stored and removed from storage within an unconfined aquifer by the rising and falling of the water table. The volume of water that goes into storage and comes out of storage is a fraction of the total space occupied by the water-bearing material. In coarse-grained materials this specific volume may approach the porosity of the material. In fine-grained materials, owing to capillary action, the volume of water going into and coming out of storage may be somewhat less than the actual porosity. The ratio between the volume of stored water and the volume of space it occupies, known as the storage coefficient is defined by the following equation: $S = dV/Adh$, where V is the volume of stored water under a surface area A, and where dh is the differential of head accompanying the storage of a differential volume dV.

In confined aquifers water is stored through the compressibility of the water and the expansibility of the solid framework of the aquifer. It comes out of storage through the expansion of the water and the concomitant compression or compaction of the solid framework.

Well Testing Procedures

Interference tests. When a well that has been idle suddenly begins pumping at a constant rate from an aquifer of uniform thickness and uniform permeability, the drawdown at some distance r away from that well and at some time t since the start of pumping is given approximately by the following equation:

$$s = (2.30\ Q/4\pi T)\ \log(2.25\ Tt/Sr^2),$$

where S and T are the storage coefficient and transmissivity of the aquifer, respectively, and Q is the discharge rate of the well. It is seen from this equation that, by plotting s against t at any constant r, the points should fall on a straight line on a semi-log paper, the linear scale of which is used for plotting drawdown (s) and the logarithmic scale of which is used for plotting time (t). Moreover, from the slope of the straight line drawn through such points plotted on such a semi-log graph, it should be possible to determine the transmissivity (T) using this relation:

$$T = 2.30\ Q\Delta\log t/4\pi\Delta s,$$

where $\Delta s/\Delta\log t$ is the slope of the straight line on the semi-log graph. For convenience, $\Delta\log t$ may be taken to be equal to 1, in which case Δs is the change of drawdown over a ten-fold variation of t, or over one "log cycle".

By extending the straight line backin time to where it intercepts the line of zero drawdown (or time axis), it is possible to determine S as follows: $S = 2.25\ Tt_o/r^2$, where t_o is the time at the intercept on the zero-drawdown line.

Drawdown tests. The drawdown inside a pumping well is made up of two components--the first, called "formation loss", is the loss of head from that great distance where the drawdown is negligible up to the face of the well, and the second, the "well loss" is the loss of head accompanying the flow of water through the perforations in the casing and upward inside the casing to the pump intake. The formation loss is given by an equation similar to that given previously except that the effective radius of the well (r_w) is substituted in place of r. Then writing the well loss as CQ^2 the drawdown in a pumping well may be expressed as follows:

$$s_w = (2.30\ Q/4\pi T)\ \log\ (2.25\ Tt/Sr_w{}^2) + CQ^2.$$

This equation may be abbreviated as follows:

$$s_w = A(t)Q + CQ^2,$$

where A(t) is the formation-loss coefficient, which varies with time, and where C is the well-loss coefficient, which is constant. [See Jacob, 1947.]

It may be seen from the last two equations that a semi-log plotting of drawdown against time should again permit the determination of T, though not of S. Observation wells at known distances are needed to get S.

Step-drawdown tests. By pumping a well at different rates over successive periods of time and observing the trend of drawdown during

each period it is possible to determine the well-loss coefficient, C, and the formation-loss coefficient, A, which is a function of the duration of each step. This kind of test is known as a "step-drawdown test".

Dividing the foregoing equation for drawdown by the discharge of the well, $s_w/Q = A(t) + CQ$, the ratio s_w/Q being the specific drawdown of the well. A plotting of specific drawdown against discharge for several steps of a test should give a straight line, the slope of which gives the well-loss coefficient, C, and the intercept of which gives the value of formation-loss coefficient for the duration of step that was used.

The formation-loss coefficient is also a function of the transmissivity, being inversely proportional to T. Thus it may be written $A = A'/T$. Then, dividing the drawdown equation by Q^2 instead of by Q, one may write $s_w/Q^2 = A'/TQ + C$. In this case, when plotting s_w/Q^2 against $1/QT$, the slope gives A' and the intercept gives C.

Not only may the foregoing plottings be used to analyze the data from step-drawdown tests of single wells, but they may be used to analyze statistically the data from simple drawdown tests (one-step drawdown tests) of many wells. Thus the average characteristics of a large number of wells of similar design may be determined.

Recovery tests. When a well that has been pumping continuously for some time is suddenly shut down, the water surface inside the casing begins to recover, and continues to recover for some time at a continuously diminishing rate. It is just as though the well were to continue discharging and a recharge well of the same strength were to

be superimposed on top of it at the time of shutdown. In other words, the position of the recovering water surface is the composite of two effects, the drawdown and the superimposed recovery. This kind of test is known as a Theis recovery test (after C. V. Theis of the U. S. Geological Survey, see paper by Theis, Trans. A.G.U., vol. 16, p. 520, 1935). The residual drawdown at time t' after shutdown and time t after the start of pumping is given by this equation: $s' = (2.30\ Q/4\pi T) \log (t/t')$. The logarithms of the square of the distance and of the constant factors S and T would appear twice in the equation for residual drawdown, but oppositely signed, and therefore they actually disappear from the equation.

Leaky aquifer tests. Often the case is that the aquifer is confined by a semi-pervious confining layer of variable thickness and variable permeability. For the purpose of analysis the aquifer may be idealized as a relatively highly transmissive bed overlain by a poorly transmissive confining bed in which the horizontal flow is negligible. The vertical flow through the confining bed, on the other hand, is appreciable and is assumedly in direct proportion to the drawdown and in inverse proportion to the thickness of the confining bed.

The theory of nonsteady flow in such aquifers is outlined by Hantush and Jacob [1955]. The differential equation governing radial flow is:

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{s}{B^2} + \frac{S}{T}\frac{\partial s}{\partial t}$$

where s is the drawdown of head at distance r and at time t,

S is the storage coefficient or storativity,

T is the transmissivity of the aquifer,

$B^2 = Tb'/K'$ with b' the thickness and K' the hydraulic conductivity of the confining bed overlying the aquifer.

The ratio K'/b' is termed "leakance" and is analogous to leakage conductance in electricity. Thus B^2 is the ratio of transmissivity to leakance.

The initial and boundary conditions for radial flow to a well of constant discharge Q beginning at t = 0 in an infinite aquifer are:

$$s(r,0) = 0 \text{ for } r \geq 0,$$

$$s(\infty,t) = 0 \text{ for } t \geq 0,$$

$$\lim_{r \to 0} r(\partial s/\partial r) = -Q/2\pi T \text{ for } t > 0.$$

The solution of the foregoing differential equation satisfying these three conditions is

$$s = \frac{Q}{4\pi T} \int_u^\infty \frac{1}{Z} \exp\left(-Z - \frac{r^2}{4B^2 Z}\right) dZ,$$

where $u = r^2 S/4Tt$

The definite integral is a function of u and of r/B, and may be symbolized W'(u,r/B), hence

$$s = \frac{Q}{4\pi T} W'(u,r/B).$$

For details see Hantush and Jacob [1955, especially Eq. 14, p. 98]. Values of this function are tabulated by Hantush [1955, pp. 114-117].

With the semi-confined aquifer thus idealized, there are three unknown quantities, S, T and B. The values of these are found by matching a logarithmic graph of observed drawdowns on a transparent overlay with a logarithmic graph of the family of curves depicting $W'(u,r/B)$, with r/B as parameter.

Evaluation of Pumping Tests

Yorktown formation near Aurora. A pumping test was run on an exploratory well penetrating the Yorktown formation in southeastern Beaufort County about three miles north of Aurora by John W. Harshbarger [1963], consultant to Bear Creek Mining Company (successors, North Carolina Phosphate Co.). At this location the surficial deposits are about 20 feet thick, the Yorktown formation is about 80 feet thick and the phosphate bed about 50 feet thick. Harshbarger [1963, p. 6] says that, "It seems clear that the upper marine clay acts as the confining layer for this system [Yorktown]."

The 10-inch well that was pumped penetrated effectively about 120 feet of productive formation. It was pumped for 50 hours from December 14 to December 16, 1962, at an average rate of 55 gpm. Observations of drawdown and subsequent recovery were made in the pumping well (10-S) and in nearby shallow observation wells (C, G and W, among others). The shallow well 10-S penetrated the Yorktown formation and the upper third of the phosphate bed to a total depth of 124 feet. Near the end of the 50-hour test the pumping level was 78 feet below the top of the casing.

The data were analyzed by the Theis graphical method, and the average transmissivity was found to be about 30,000 gpd/ft. The average storage coefficient was .0003 and the hydraulic diffusivity, therefore, 1×10^8 gpd/ft. Ascribing the transmissivity to an 120-ft thickness of formation, the average hydraulic conductivity is about 250 gpd/ft^2.

During this test water levels were monitored in Castle Hayne Well 10-D, which showed no direct influence that might be attributed to the pumping from the Yorktown formation and from the top part of the phosphate bed.

Castle Hayne limestone near Aurora. In December 1962, a pumping test was run on an exploratory well finished in the Castle Hayne limestone about 3 miles north of Aurora. At that location the top of the Castle Hayne is about 150 feet below ground. It is covered by about 50 feet of phosphate beds. Harshbarger [1963, p. 7] says that, "It appears that the basal consolidated clay and marl [of the phosphate bed] constitute the confining layer between the Yorktown and Castle Hayne artesian systems."

The pumping well for this test was 10 inches in diameter and about 225 feet deep. It was pumped for 28 hours at an average rate of 1,070 gpm. The maximum drawdown was 13.7 feet.

The drawdown and subsequent recovery were measured in the pumping well (10-D) and in nine shallow and eight deep observation wells. (The shallow wells were finished in the Yorktown or underlying phosphate bed and the deep ones in the Castle Hayne.) The wells were situated on four lines at various distances up to about a mile from the pumped well.

The data were analyzed by the Theis graphical method, and the transmissivity was found to be about 245,000 gpd/ft on the average. (See foregoing section entitled 'Interference tests.') The average storage coefficient was .0008. The hydraulic diffusivity thus averaged about 3.1×10^8 gpd/ft. Ascribing the transmissivity to a thickness of 100 feet, the average hydraulic conductivity is about 2,500 gpd/ft^2.

The piezometric surface was lowered more than 0.6 foot at the farthest observation well about a mile from the pumping well.

Harshbarger [1963, p.21] concludes that there is "no effect or hydraulic connection between the two systems [Castle Hayne and Yorktown]." He says that "long term pumping (6 months or longer) may be necessary for

FIG. 15

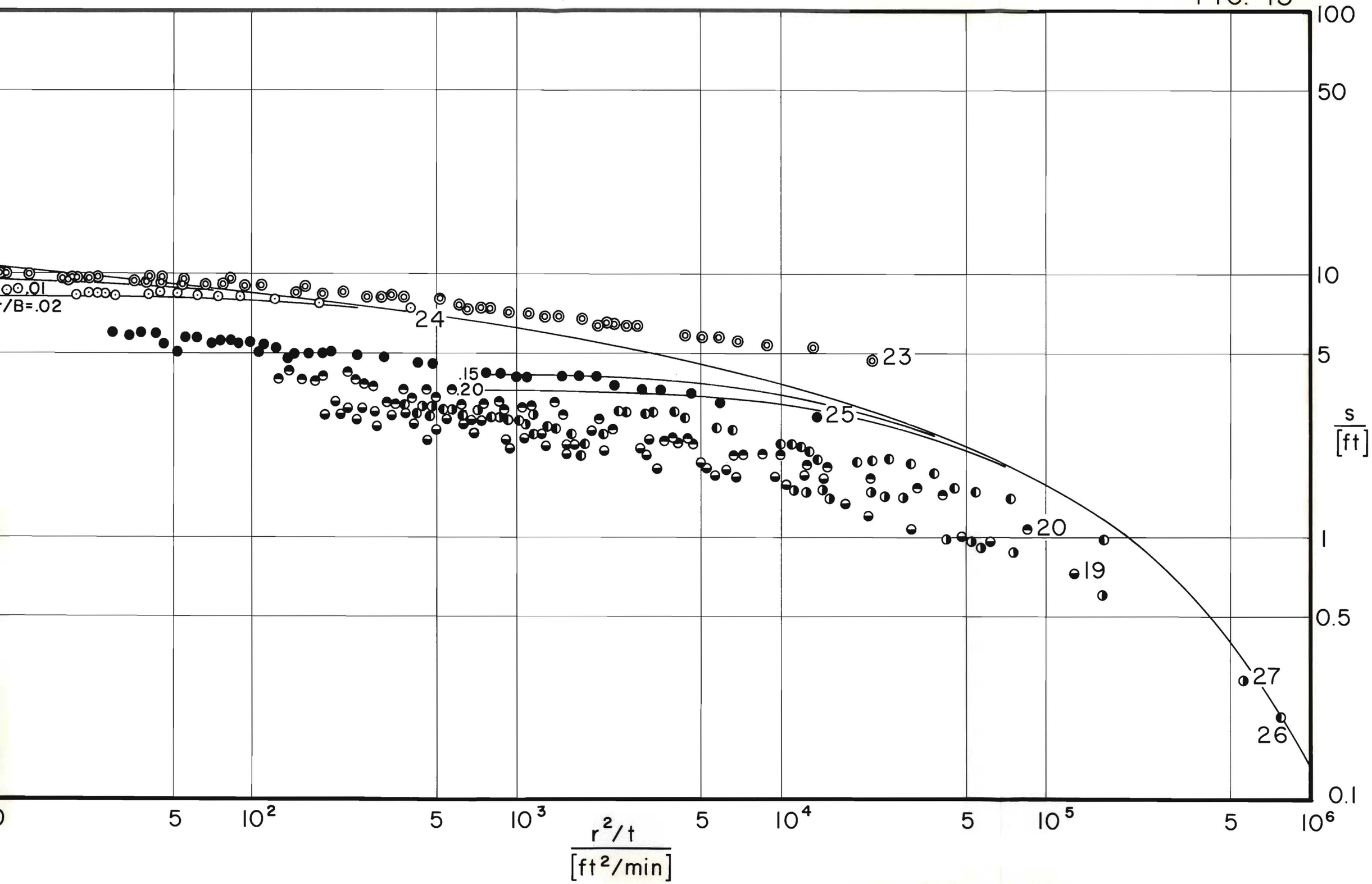


FIG. 15 COMPOSITE DRAWDOWN GRAPH FOR TGS PUMPING TEST, 1964

conditions to be reflected, if they occur." However, we believe there is graphic evidence of the influence of the Castle Hayne pumping upon the head in the Yorktown during this test near Aurora. Referring to Harshbarger's Figures 4 and 5, there is fairly strong indication of influence upon 2-inch wells numbered 170, 174, and 175 and a weak suggestion of influence upon the 2-inch well numbered 171. The maximum effect is on the order of 0.3 ft (in Well 174-2).

Castle Hayne limestone near Lee Creek. A pumping test was run on a 20-in. test well drilled in the Castle Hayne limestone near Lee Creek. Two preliminary tests were run with the well bottomed at 175 ft after encountering the Castle Hayne at a depth of 156 ft. Afterward the hole was drilled to a depth of 200 ft and a 35-day test was conducted. Observations of drawdown were made in several wells at distances from the pumped well varying from 182 to 7,200 ft. The average discharge was 3,500 gpm.

Fig. 15 is a composite drawdown graph for this test of August-September 1964. Plotted along the bottom logarithmic scale are ratios of the square of the distance in feet to the elapsed time in minutes for readings of drawdown in seven of the observation wells. The drawdown is plotted in feet on the vertical logarithmic scale. Also shown on Fig. 15 are four typical theoretical drawdown curves for different values of r/B to which the experimental data were matched by a curve-fitting technique similar to the Theis graphical method. (See foregoing section on 'Leaky aquifer tests'.)

From the best fit of the suite of data to the family of curves (with r/B as parameter) three unknown coefficients are determined. The

transmissivity is found to be about 390,000 gpd/ft and the storage coefficient about .00019. By matching the several sets of data to different curves of the same family, the factor B is found to average about 14,000 feet. The hydraulic diffusivity is 2.0×10^9 gpd/ft. Ascribing the transmissivity to a formation thickness of 300 ft we get 1,300 gpd/ft^2 for the hydraulic conductivity. The leakance, being the ratio of transmissivity to the square of the B-factor is calculated to be 2.0×10^{-3} gpd/ft^3.

In the analysis of this same test in Miller [1966, Figs. A-17 through A-24], the data for each well were fitted singly to the Theis curve (the envelope of the other four curves on our Fig. 15) and various apparent values of T and S were thus determined. This procedure was followed on the assumption that the Castle Hayne aquifer is completely confined and meets other idealized conditions relating to homogeneity, isotropy and extent of the aquifer, to its complete penetration by the well and to the concomitant release of storage. Thus, <u>by assumption</u> the fact of leakage is excluded from discovery. However, the possibility of leakage was admitted on Fig. A-18, where the data were matched to a leaky-aquifer curve for r/B = 0.001. (This ratio would appear too low by a factor exceeding 10.) The transmissivities obtained by separate trials at curve fitting ranged from 370,000 to 410,000 gpd/ft and the storage coefficient ranged between .004 and .009. This high apparent storage coefficient for confined flow in a limestone is suspect, and it undoubtedly includes leakage. These high values of S are erroneously attributed [Miller, 1966, p. 15] to "delayed yield from storage." It should be pointed out, however, that the rate of release from artesian storage is initially maximal following any step-impulse such as a well discharge. If

the storage were delayed and were not maximal initially, the curvature of the perturbation in the drawdown curve would be reversed from that which is observed.

It is not possible to divide the leakance into upward leakance and downward leakance. The average value determined from our analysis of the Texas Gulf Sulphur test when multiplied by the head differences assumed for the test is equal to the sum of the two leakances (upward and downward) each weighted by its true or effective head difference. Nevertheless, we know from other evidence that leakage does occur downward into the Castle Hayne (p. 75) and upward from the Beaufort (p. 109).

Evaluation of Sustained Dewatering Operation

Not only is it possible to get the characteristics of the Castle Hayne aquifer from pumping tests such as were run by Texas Gulf Sulphur in August and September of 1964, but also from the response of the aquifer to the sustained dewatering operation beginning July 1965. The pit now being dewatered is surrounded by twenty-four 20-inch wells withdrawing water from 65 ft of Castle Hayne formation between elevations -155 and -220. Each well has a pump capacity of 3,000 gpm or 4.3 mgd. Dewatering began July 1, 1965. By early August there were 11 wells in operation, and by mid-September, 16 or 17. The number of wells operating has since been decreased and has averaged about 15 over the last several months.

Observations of the decline of head caused by this pumping have been made by the Department of Water Resources, by Texas Gulf Sulphur, and by other operators in the area. Fig. 16 is a composite logarithmic drawdown graph showing the influence of the Texas Gulf Sulphur mine-

dewatering operation upon eight wells at distances from the pit ranging from about 1.7 mi to about 23.7 mi and in various directions from the pit. The bottom logarithmic scale gives the ratio of the square of the distance in feet to the elapsed time in days. The vertical logarithmic scale gives the specific drawdown, expressed as drawdown in feet divided by the number of dewatering wells in operation at any time.

Also drawn on Fig. 16 is a family of curves with r/B as parameter. By the simultaneous best fit of the data for the several wells to the family of curves, values of three characteristics of the aquifer are determined. (See foregoing section on 'Leaky aquifer tests.')

From the vertical fit of the drawdown data to the family of curves the transmissivity is found to average quite closely 300,000 gpd/ft. From the horizontal fit of the data the hydraulic diffusivity is found to be 3.3×10^8 gpd/ft. Thus by the ratio of the transmissivity to the diffusivity the storage coefficient is calculated to be 9×10^{-4}. Also from the vertical fit of the data to the family of curves the B-factor appears to range from 63,000 to 76,000, and average 70,000 ft. This factor may be considered to be a "leakage thickness," high values of which suggest low leakage and low values of which suggest high leakage.

The analysis of the data for the first year of the dewatering operation out to a distance of nearly 24 miles gives a much higher B than the analysis of the 35-day test, whose strong influence only reached out about 2.7 miles. In other words, the aquifer appears more leaky on a small radial scale than on a large one. This strongly suggests an area of more concentrated leakage fairly near the pit.

FIG. 16

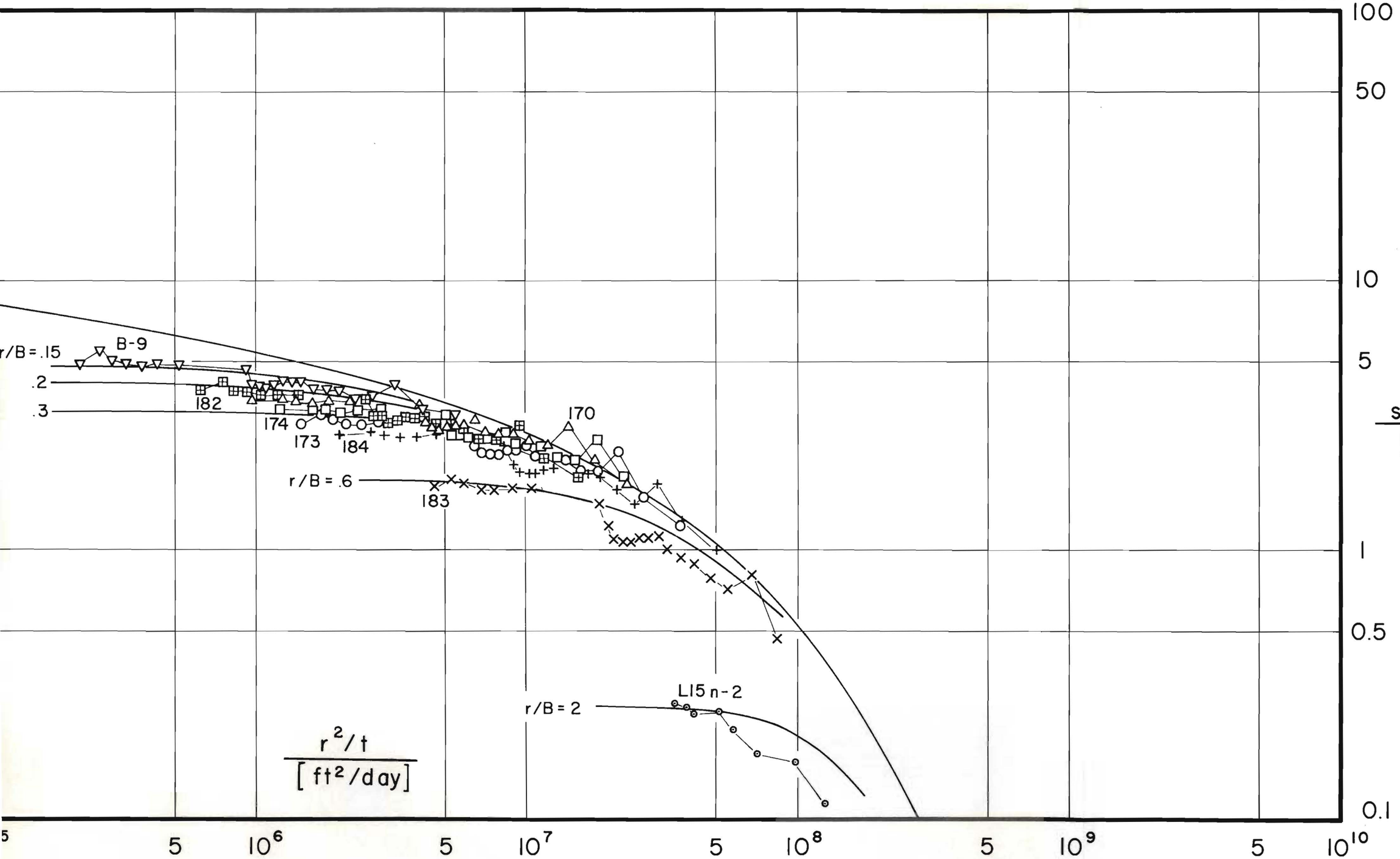


FIG. 16 COMPOSITE DRAWDOWN GRAPH FOR TGS MINE-DEWATERING OPERATION

Cone of depression in Castle Hayne limestone. Near a concentrated center of pumpage, such as the pit with its surrounding 24 wells, the radial distribution of head is very nearly logarithmic. That is, the head within moderate distances varies linearly with the logarithm of the distance. The 24 wells are on a rectangle about 2,600 ft by 2,700 ft, and considered as an equivalent circular battery, the effective radius of that system is about 1,500 ft.

If the logarithmic distribution of head is extrapolated to great distances, that is to where it intersects the original piezometric surface, a measure is obtained of what we call "virtual radius of the logarithmic cone of depression" This has been determined graphically on semi-logarithmic cross sections of the cone of depression displayed on Fig. 17 and similar maps. At the end of November 1965, the virtual radius of the cone was about 19.0 mi, and by February 1966, it had increased to 23.4 mi. By May 1966, it had grown to nearly 28 mi. The logarithmic cone as defined above does not define the outer limit of the influence of the concentrated pumpage.

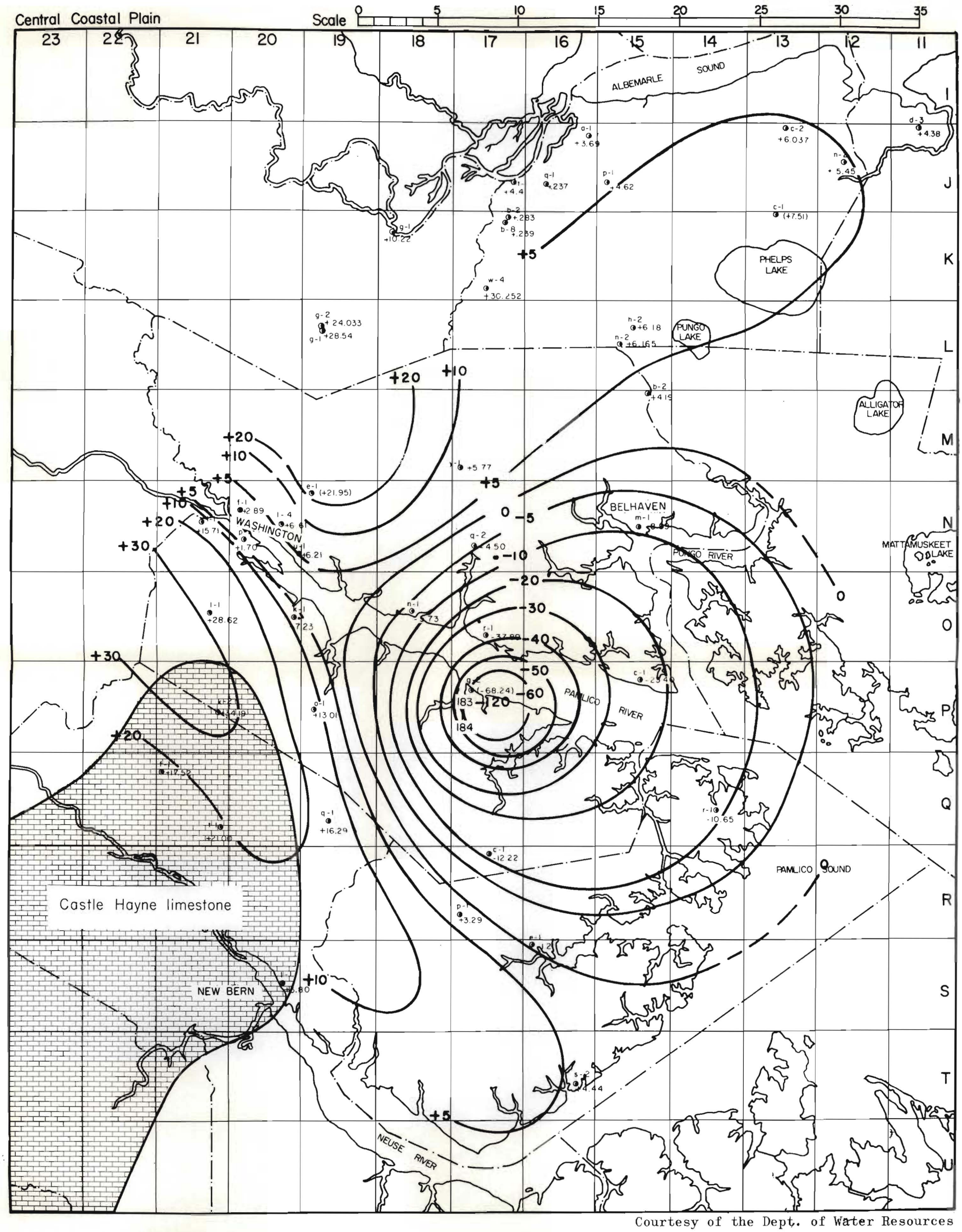
Area of influence. The area of influence of the pumpage at Lee Creek is congruent with the entire area of the Castle Hayne aquifer. At the end of one year of continuous operation we estimate that at a distance of 23.7 mi from the center of pumpage at Lee Creek (that is, at Well L15n-2) about 3 per cent of the pumpage is coming from beyond that distance, about 64 per cent of the pumpage is coming from leakage within that distance, and the remainder from salvage of rejected recharge and reduction of storage within that distance.

By comparison, in the hypothetical case of complete confinement, relied upon by Miller [1966], 57 per cent of the water comes from beyond

the virtual radius of the logarithmic cone and only 43 per cent is supplied from reduction of storage within the logarithmic cone. Thus, any attempts to place a limit on the cone of depression should be tempered by the realization that the influence of pumping is felt far beyond the apparent boundary set by this logarithmic cone. Actually, the drawdown tapers off to a "feather edge," or in technical language is asymptotic to the original piezometric surface.

Constitutive assumption of leakage. Assuming that 15 percent of the total precipitation is available for ground-water recharge, as determined in the chapter on Hydrology, the percolation rate would be on the order of 1.54×10^{-3} ft/day for an average annual precipitation of 45 inches. On the other hand, over the effective area of influence of 4.9×10^{10} ft^2 as taken from the piezometric map, the percolation rate required to produce 65 million gallons per day solely from leakage within that area would be only 0.178×10^{-3} ft/day, or only about 9 percent of the precipitation available for recharge. For each foot of drawdown this required percolation rate would be equivalent to a leakance of $0.178 \times 10^{-3} day^{-1}$. Within the effective area of influence the average drawdown was about 12 feet. As storage reduction and lateral inflow have been neglected, the leakance (L) must be less than $1.49 \times 10^{-5} day^{-1}$. Taking T to be equal to 300,000 gpd/ft, the leakage thickness (B) must be more than 52,000 ft, because $B = (T/L)^{1/2}$. For observations made at the multi-well station during the impulse tests, $r = 2500$ ft and $r/B = .047$. Thus leakage would be noticeable at that distance before the lapse of 10 days.

Quasi equilibrium. It is said in Miller [1966, p. 1] that natural recharge reached "equilibrium" with the Lee Creek discharge after six



Courtesy of the Dept. of Water Resources

MAP SHOWING PIEZOMETRIC SURFACE OF THE CASTLE HAYNE AQUIFER
SEPTEMBER, 1966

FIG. 17

months of operation. We would like to qualify the equilibrium condition by the word quasi and use the expression "quasi-steady state." A steady state can be reached in aquifers of limited extent with sufficient lateral inflow or vertical replenishment through leakage or salvage of rejected recharge. A quasi-steady state may be reached in extensive aquifers under favorable conditions of lateral inflow and/or vertical replenishment through leakage and/or rejected recharge, as is the case here.

A quasi-steady state is reached when the piezometric surface of the aquifer or the drawdown of the head of the aquifer far away from the center of pumping does not significantly change in time. It may be instructive to compute the theoretical rate of change of drawdown at Well L15n-2 at a distance of 23.7 miles from the center of pumping. By differentiation of the drawdown with respect to time, it is found that

$$\partial s/\partial t = (Q/4\pi Tt) \exp(-u) \exp(-r^2/4B^2u)$$

in which s is the drawdown, t is the time, Q is the well discharge, T is the transmissivity, r is the distance from the point of observation to the center of pumping, B is the "leakage thickness," and $u = r^2S/4Tt$ in which S is for storage coefficient and the other symbols are as defined before.

Proceeding with the computations, the following values will be used: B = 77,000 ft. $Q = 65 \times 10^6$ gpd. $S = 9 \times 10^{-4}$ and T = 300,000 gpd/ft as determined from the response of the aquifer to the first year of dewatering. Substituting in the first of the foregoing equations, $\partial s/\partial t = (17.25 \text{ ft/t}) \exp(-87.7 \text{ day/t}) \exp(-t/110 \text{ day})$. The second exponential, exp(-t/110 day) expresses the influence of leakage. It is independent of the distance of the observation well from the center

of pumping, and its numerical value becomes rapidly very small with time. Leakage, therefore, favors rapid stabilization, and any claim of rapidly established "equilibrium" or steady state is a tacit admission of leakage.

The first exponential, exp (-87.7 day/t) expresses the decay of the rate of drawdown in a perfectly confined aquifer. This factor has a numerical value of 0.89 after two years and from then on approaches the asymptotic value of unity. It can, therefore, be stated that without leakage the rate of drawdown becomes inversely proportional to the elapsed time after a pumping period of a few years.

The immediate foregoing equation permits computation of the rate of drawdown after various periods of time, as follows:

Elapsed time, days	Rate of drawdown, ft/yr
30	8.6
60	14.2
90	11.6
180	4.2
270	1.43
365	.49
730	.10

The second exponential, expressing the leakage, would very rapidly approach zero with elapsed times exceeding those in the foregoing table, meaning that a steady state could be reached in a relatively short time were there sufficient leakage. The observational data for the Texas Gulf Sulphur operation have shown that a quasi-steady state has indeed been reached within a year, and therefore support the evidence of leakage (plus a lesser proportion of rejected recharge that has been salvaged).

In the following section the drawdown in well L15n-2 is calculated taking the variable discharge into consideration and is compared with the drawdown observed during the first year of operation.

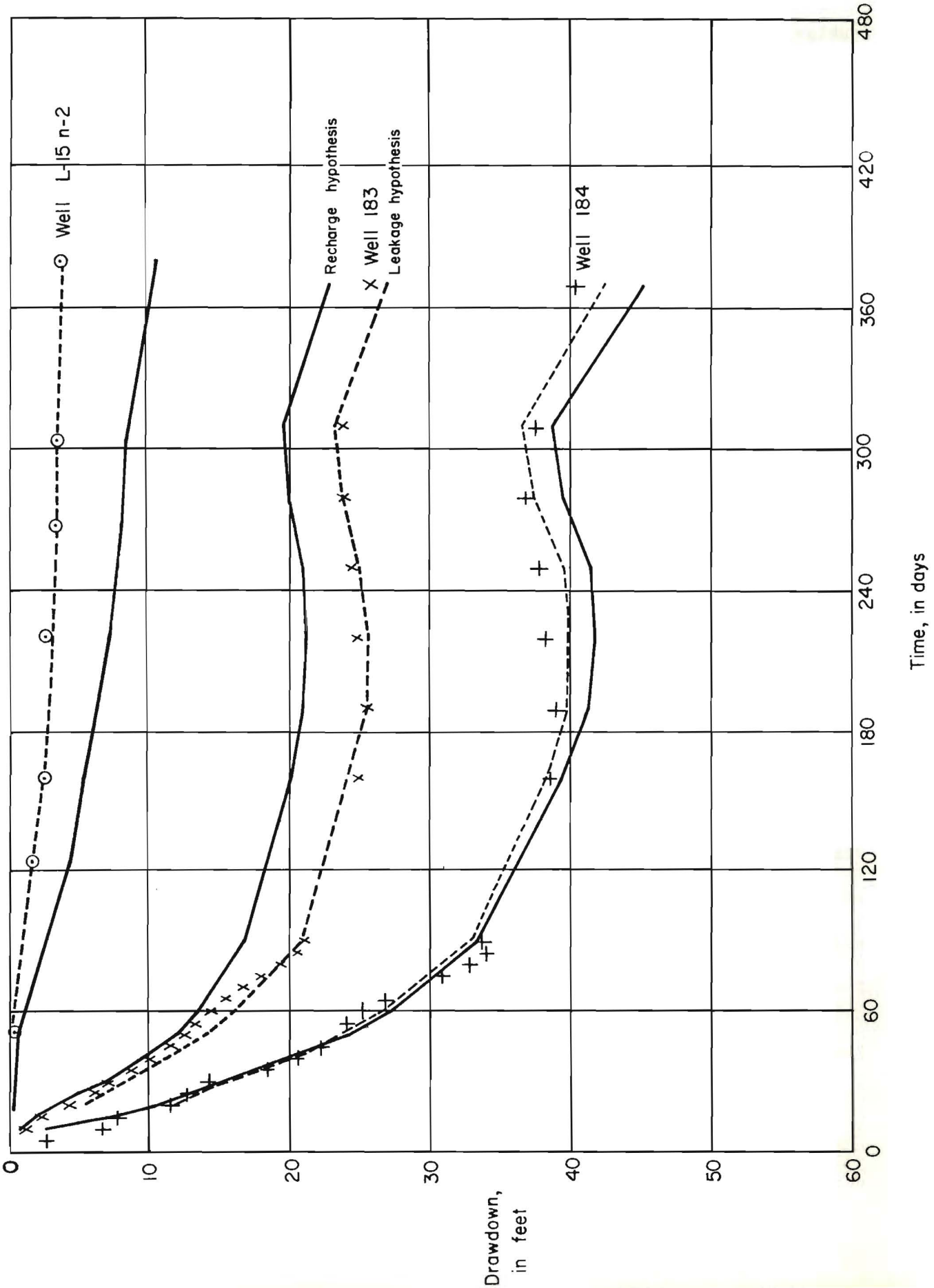
Comparison of Observed and Calculated Drawdown Under Two Hypotheses

Fig. 18 is a graph of observed and calculated drawdowns in three of the eight wells whose data are plotted on Fig. 16. Well 184 is 5.2 mi north of the pit, on the other side of Pamlico River. Well 183 is 7.7 mi south-southwest of the pit. Well L15n-2 is 23.7 mi north-northeast of the pit. The segmented dashed lines on Fig. 18 show the matching of calculated to observed drawdowns in the three wells, the calculations being based upon the assumption that the aquifer leaks. Though the leakage may be more intensive in some places than others, for the purpose of analysis we assume in effect that the leakance is more or less uniform over a rather large area influenced by the pit dewatering during the first year of operation.

The segmented full lines on Fig. 18 represent the best fit possible of observed data to drawdowns calculated on the assumption that a steady state of flow is in process of being established between the outcrop area of the Castle Hayne limestone in the Neuse River basin and the dewatering wells surrounding the pit near Lee Creek on Pamlico River. The part of the Castle Hayne outcrop northeast of Neuse River is considered, for the

FIG. 18

GRAPH OF OBSERVED AND CALCULATED DRAWDOWNS IN THREE WELLS AFFECTED BY TGS PUMPAGE STARTING JULY 1, 1965



purpose of calculation, as a constant-head source of water matching the dewatering wells in strength. (See section on 'Recharge of Castle Hayne formation in outcrop area,' p. 60.)

Actually, assuming a tendency towards a steady state of flow between the outcrop and the pit, a compromise best fit was first made of the data for Wells 183 and 184 to the corresponding curves (full segmented lines on Fig. 18). These were two curves of a family of curves with r'/r as parameter where r is the distance from a given observation well to the pit and r' is the distance of the same observation well to the center of gravity of the 170-sq mi recharge area. Then the curve for Well L15n-2 was calculated. If this "recharge hypothesis" were true, the drawdown in that latter well should have been over 10 ft after the first year of operation at the pit and should ultimately be about 19 ft. The observed drawdown in Well L15n-2 was only about 4 ft after the first year of operation.

Expressed otherwise, a comparison of calculated drawdowns based upon the recharge hypothesis and those based upon the leakage hypothesis shows the patterns of regional head distribution to be distinguishable in the two cases. Miller [1966, p. 18] remarks correctly that the piezometric surface "exhibits a relatively steep hydraulic gradient in the direction of the outcrop (westward) and a flatter gradient away from the outcrop recharge." Referring to our Fig. 17, this eccentricity is evidenced but would be much more pronounced if there were a steady state or nearly steady state of flow between the Castle Hayne outcrop and the pit. Though it is sometimes difficult to distinguish the effects of localized recharge at a distance from the effects of distributed leakage in the vicinity of an impulse on the aquifer, a study of the areal distribution of the response

to that impulse permits the two effects to be distinguished. Moreover, the time variation of the drawdown in the two cases may be distinguished if care is taken and if experimental errors are not too large. The drawdowns in an aquifer with distributed leakage and steady well discharge approach their ultimate values more rapidly than drawdowns in response to steady well discharge matched by localized recharge some distance away.

Salt-Water Intrusion

Miller [1966, p. 28 and Fig. B-9] estimates the rate of flow of ground water from beneath the west shore of Pungo River toward the Texas Gulf Sulphur pit, 12 miles away, to be about 75 ft/yr. We calculate that, irrespective of the absolute value of transmissivity, the steady velocity toward the pit at a distance of 12 miles would be 110 ft/yr in a formation of 40-percent porosity and 180-ft thickness that is constantly discharging 65 mgd into the wells surrounding the pit. This corresponds to a gradient at that distance of about 2.2 ft/mi, assuming as Miller does that the transmissivity is 400,000 gpd/ft.

It is of interest to calculate the time that would be required for the water to arrive at the pit starting from other specified radial distances. In our opinion the porosity of the Castle Hayne is probably more nearly 30 percent than 40 percent, <u>on the average</u>. Thus, we reckon that the elapsed time in years is about 1.5 times the square of the radial distance in miles. Accordingly, the elapsed time varies with the distance as follows:

Distance	r/[mi]	1	2	5	10	12
Elapsed time	t/[yrs]	1.5	6	38	150	216

The foregoing calculations are based upon the assumption that there would be no dispersion of the velocities. By that we mean that all particles of water would travel at the same speed. However, all sediments have the property known as "dispersivity." By reason of this property a fraction of the water in the limestone moves, for example, at 10 times the average speed. The size of that fraction depends upon the dispersivity of the limestone, which is believed to be high. Thus, it is likely that a fraction of the brackish water sufficient to cause deterioration of the fresh water into which it advances may traverse the respective radial distances in one-tenth the times given in the above tabulation.

Whereas the lobe of high-chloride water was about 12 miles east of the Lee Creek site, brackish waters that may threaten to degrade the quality of the Castle Hayne waters upon reversal of leakage are found within much smaller radial distances upstream from the pit. Though there is some evidence of a fairly tight cover on the Castle Hayne limestone in the immediate vicinity of the pit, elsewhere, particularly upstream, there is evidence that the cover is both thin and pervious.

Not only may salt water migrate radially toward the pit, both from downdip and from updip, it may also migrate vertically upward from the Peedee and Beaufort formations. At the multiple-well station operated by the Department of Water Resources at the Lee Creek site, the Beaufort formation has a head 8 feet higher than that of the Castle Hayne, while the chloride content of the two formations are 3,000 and 200 ppm, respectively. At the same station the Peedee formation has a chloride content of 9,700 ppm and has a head which is about 120 feet higher than that of the Castle Hayne at that location. Apart from the fact that salt water will migrate

upward from the Beaufort formation to the Castle Hayne because of the head difference, any lowering of head in the Beaufort formation will cause compression of that formation and will "squeeze" salt water from the Beaufort into the Castle Hayne aquifer.

Partial Recovery or Impulse Tests

A deep exploratory hole was drilled and a multiple-well observation station was constructed at the Lee Creek site by the Department of Water Resources in cooperation with Texas Gulf Sulphur. This work was carried out between March and June 1966 for the following purposes:

Determining the depth, thickness and lithologic character of water-bearing formations and confining layers.

Determining chemical quality of water in principal water-bearing formations and depth to brackish water.

Obtaining water-level data on the several formations.

Determining the degree of confinement between the Castle Hayne limestone and the formations above and below.

Monitoring water levels and water quality.

This project included drilling and logging an exploratory hole 954 ft deep, the construction of two observation wells in the Yorktown formation, and the installation of five observation wells at various depths down to 954 ft. The following table shows the depths and other information on the multiple-well station:

Multiple-Well Station P17

Well No.	P17h-4	P17h-5	P17h-6	P17h-7	P17h-8
Total depth, ft	954	480	323	59	18
Screen depth, ft	918-922	466-470	Open below 165	42-46	14-18
Formation	Black Creek?	Beaufort	Castle Hayne	Yorktown	Recent
Water level (Ref. MSL)	+20.91	-89.89	-98.29	+6.22	+6.07
Yield, gpm	5	15	100	15	20
Hours pumped	12	6	3	2	1
Chloride content (ppm)	9,700	3,000	200	30	150
Temperature (°F)	70	69	68	65	65

Particularly significant are the water-level and chloride data. The head in the Beaufort formation, measured at a depth between 466 and 470 ft was found to be nearly 90 ft below sea level. This is to be compared to a Castle Hayne head at the same site that is about 98 ft below sea level, or only 8 ft lower, suggesting hydraulic interconnection. (The multiple-well station is about 2,500 ft northeast of the pit.)

After installation of the several observation wells at Station P17, several opportunities arose for observing the effect upon the overlying Yorktown aquifer and the underlying Beaufort aquifer caused by intentional or unintentional shutdowns of the dewatering pumpage. These occurred several times because of power failures and twice by planned shutdowns of some of the wells. On August 2, 1966, four of the wells, with a total discharge of about 11,900 gpm, were shut off for six hours. The remaining wells gained in discharge as their pumping levels rose in response to this partial shutdown. Accordingly, the impulse was not a clean "step-impulse" but rather one with a markedly variable decrement of discharge. Without adjustments for the variability of discharge following partial

shutdown, the response of the Castle Hayne formation to the shutdown cannot be analyzed to give accurate formation constants.

The water table in the Yorktown formation showed no direct response either at the multiple-well station or at Well h-9, between the multiple-well station and the pit, or at Well h-10, on the north side of the air strip, between the multiple-well station and the Pamlico River. Sudden partial recoveries in the Castle Hayne caused by power failures on September 18 and October 9, 1966, did cause an inverse elastic effect on the order of 0.1 ft in the Yorktown recorder Well P17h-9. Similar inverse elastic effects were recorded on the same days in the Peedee Well P17h-4. These effects were caused by the redistribution of total stress between the fluid and the solid framework in those formations in response to the sudden redistribution of stress in the Castle Hayne limestone caused by the abrupt shutdown in the dewatering wells. Direct hydraulic effects of such shutdowns were observed in the Beaufort recorder Well P17h-5. Three examples occurred on the following dates with the following maximum magnitude of response and duration of pulse:

Date, 1966	Aug. 2	Aug. 17	Sept. 18
Height of response	2.5 ft	8.3 ft	5.5 ft
Duration	6 hr	24 hr	3 hr

These large fluctuations, measured at a distance of about 2,500 ft from the pit, clearly indicate that the Beaufort formation at a depth of 466 to 470 ft below ground is in hydraulic connection with the overlying Castle Hayne limestone. The chloride content is 3,000 ppm at the depth in question.

MINING METHODS

Three different methods of mining the phosphate ore have been considered and are still being considered by various companies. Each method affects the available water supply of Beaufort County in a different way and is described briefly hereafter.

Hydraulic Dredge Mining

This method was tested by the Texas Gulf Sulphur Company in 1963. A test pit 1,000 ft in diameter and 150 ft deep was established. At first it was considered to excavate the pit from sea level, but instead a 20-inch hydraulic dredge removed the water and overburden from the pit while lowering itself to 97 ft below sea level.

Although TGS achieved a successful technique to pump a phosphate slurry from the subsurface, the method was not adopted for commercial exploitation because the cost was considered too high, the ore recovery was poor and the phosphate ore became contaminated with shell.

The advantages of this method, as far as water conservation is concerned, are obvious. In the first place, the required drawdown of the piezometric surface of the Castle Hayne is significantly reduced, which means that less water has to be pumped and therefore less water has to be wasted to the Pamlico River. In the second place, a smaller head differential is established between the various formations containing fresh, brackish or salt water. This means a significant reduction of the possibilities of salt water

migration. Finally, smaller variations in the head means less subsidence of these formations and therefore less contamination of the adjacent fresh-water bodies through salt water being "squeezed" out of the compressed formations.

As far as economics are concerned, we believe the previous cost estimates for this method of mining should be revised in view of remedial measures which will have to be prescribed in order to conserve water in Beaufort County for future competitive use of water by industry other than the phosphate mines, by municipalities, and by agriculture.

Open Pit Mining

This method is adequately described in the TGS report. The mining technique consists of utilizing two large draglines which remove all of the overburden and low-grade ore to a depth of 93 ft below sea level. About 40 ft of phosphate ore is then mined to 133 ft below sea level within a dry pit. The pit is kept dry by lowering the piezometric surface of the Castle Hayne from 7 ft above sea level to about 133 ft below sea level. In August, 1966, according to TGS sources, about 45,000 gpm was pumped for dewatering purposes, of which 10,000 gpm was spilled to the Pamlico River while one third of the remainder was used for ore-slurry conveyance and the remaining two thirds were used for milling.

It seems that every effort should be made to reclaim the water spilled to the Pamlico River and that the possibility of ore-slurry conveyance by means of river water should be investigated. Artificial

recharge of the pumped water through pits or wells should be considered.

Mining by Means of Wells

At present (January 1967) this method is being considered by at least two companies which hold leases to work deposits under the Pungo River. The method, which is still in the experimental stage, involves the injection of water in wells which penetrate to depths within 10 or 12 ft above the Castle Hayne formation. A slurry is formed and is brought to the surface by airlift or pump pressure, or by a combination of both. The boreholes are provided with packers at the bottom or are cemented to prevent intrusion of brackish river water in the Castle Hayne.

The companies plan on using river water for their mining operations. No decision has been made yet as to the nature of the water that will be used for the processing of the ore in the plant. This will depend on the quality of the end product that the companies are aiming for.

In January 1967 no estimates were available yet as to the amount of water required for ore beneficiation per ton of ore.

It seems that this method, while it will achieve less ore recovery than hydraulic dredging or open pit mining, will require the usage of smaller amounts of water and therefore will be the least detrimental to the fresh-water bodies of Beaufort County, if properly applied.

Impact of Phosphate Mining on Ground-Water Supplies

The most pressing immediate problem in connection with the conservation of the ground-water resources of North Carolina arises as a result of dewatering the area surrounding the Lee Creek mine of the Texas Gulf Sulphur Company near Aurora. In order to mine the phosphate by the dry-pit method, ground water is being pumped from the Castle Hayne limestone at a rate of about 65 million gallons a day. Continued pumping of fresh water at this rate will surely result in decreasing the supply of fresh water available for the inhabitants of a large area surrounding the mine as well as the amount available for other developments in the future.

Other corporations are also interested in mining phosphate in adjoining areas. If they were to elect use of the dry-pit method, the amount of water pumped would be substantially increased, and the cone of depression would be greatly expanded. This would, in turn, increase the opportunity for salt-water encroachment, and salt-water encroachment would be evident much sooner. The net worth of the water to the State and to the inhabitants of this area, then, may be the price that eventually is paid for dry-pit mining of the phosphate.

Alternative Remedies

The closest brackish water that threatens to impair the quality of the ground water in the vicinity of the pit at Lee Creek is found in the Beaufort formation underlying the Castle Hayne limestone. Without a detailed knowledge of the distribution of vertical permeabilities and porosities in the Beaufort and in the lower part of the Castle Hayne it

would be difficult even to estimate the time of arrival of such brackish water into the dewatering wells.

The second nearest source of brackish water that threatens to encroach into the Castle Hayne limestone is that water in the estuary upstream from the pit to a distance of about 10 miles where the head has already been pulled down below sea level. Five miles upstream from the pit the head has already been pulled down over 20 ft. If mining were to continue as at present in a dewatered open pit with the pumpage of the wells averaging about 65 mgd as at present, the Castle Hayne limestone beneath this vulnerable stretch of the estuary could best be protected by an injection-well system on the opposite side of the Pamlico River about 10 miles upstream.

There are possible alternative sources of water for injection into the Castle Hayne limestone at this point. First, would be surface water piped downstream from a river intake above the head of the estuary. The water would need only minor treatment, perhaps filtration and chlorination, before injection. Another source might be water pumped from the estuary at the injection-well site or some distance upstream, which with minor treatment and chlorination could similarly be injected into the Castle Hayne limestone. A third and less promising alternative, in light of present knowledge, would be water drawn from the Peedee formation at the proposed injection-well site or some distance upstream, depending upon the salinity of the Peedee water beneath that stretch of the river. Wells might be drilled with screens or open hole both in the Peedee and Castle Hayne formations at such places where the

water in the Peedee formation is still fresh, in order to increase the leakage from the Peedee into the Castle Hayne. Until we know the relative transmissivities and absolute head distributions of these two formations, it is not possible to say whether such wells would be practicable operating with the natural energy of flow of the higher-head Peedee water, or whether the water would have to be pumped to the surface and reinjected under pressure into Castle Hayne wells.

The hydraulics of wells completed in two formations have been studied by several means including tandem horizontal Hele-Shaw or parallel-plate models ((DeWiest 1966b)) such as depicted in Fig. 19. Multi-aquifer wells are also studied with equal or greater ease and precision and at lesser cost by electronic digital computer, by resistance-capacitance network, or by electronic analog computer.

Since the Peedee formation is too brackish ease of the Lee Creek pit, wells could not economically be drilled there to create a barrier against salt-water migration updip in the Castle Hayne aquifer. Moreover, the need to protect the Castle Hayne from vertically downward encroachment of brackish estuary waters in this downstream stretch of the river is, in our opinion, not nearly as urgent. This is so because toward the east the Castle Hayne is buried more deeply and, other things being equal, it is likely that the estuarine sediments there are finer grained and less permeable. Our analysis of the response of the aquifer to the heavy pumpage required for dewatering suggests that during the first year of operation the strongest source of vertical inflow to the Castle Hayne aquifer is localized in the uppermost 16- or 20-mile stretch of the estuary. Leakage is widely distributed, but evidently less intense, in other branches of the estuaries and even on high ground in between the estuaries.

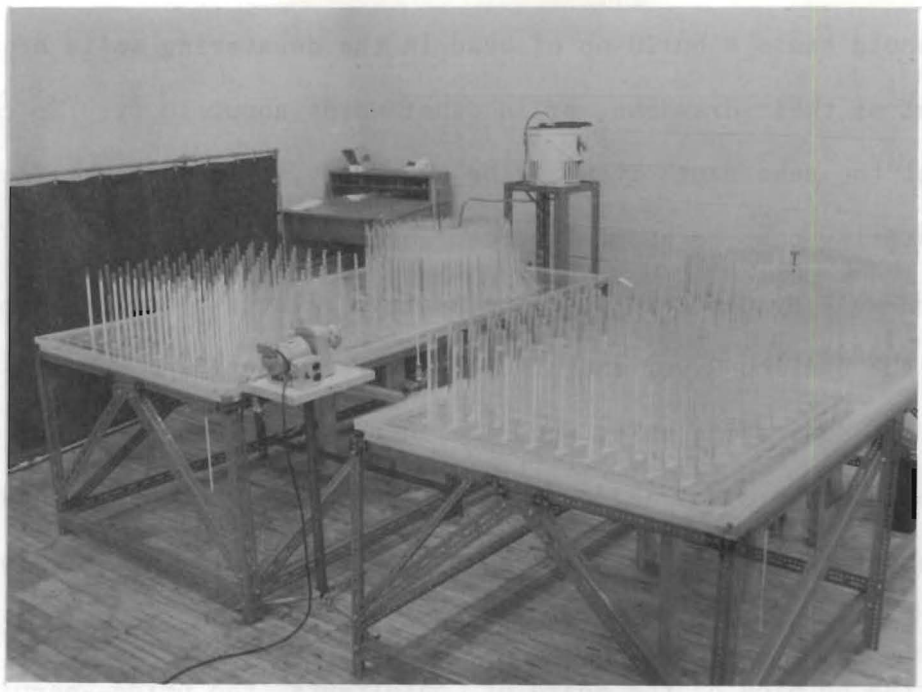


FIG. 19. CLOSE UP PHOTOGRAPH OF HORIZONTAL HELE-SHAW APPAPATUS.

The recharge area of the Castle Hayne limestone in the Neuse River basin appears to be a lesser source of vertical inflow.

A rough estimate may be made of the increased dewatering pumpage that would be caused by an injection-well system on the other side of the river. Referring to Fig. 17, if an injection-well system were installed on the other side of Pamlico River 10 miles upstream, injecting 65 mgd would cause a build-up of head in the dewatering wells of about 7 percent of their drawdown, or in other words about 10 ft. To continue mining at the same depth it would be necessary, therefore, to increase the dewatering pumping about 7 percent or to about 70 mgd. If the injection-well system were as close as five miles away on the opposite side of the Pamlico River and if 65 mgd were injected, the build-up of head in the dewatering wells would be on the order of 25 percent of the drawdown in the pit, or 35 ft. If mining were to continue with water levels at present levels, the discharge of the dewatering wells would have to be increased to over 80 mgd.

In the opinion of the Board of Consultants, the price--permanently impairing the ground-water supply of the inhabitants of so large a section of the State--may well be too high to justify the recovery of the phosphate by the dry-pit method. It is doubtless in the interest of the public and the State to mine the phosphate because of its great economic value. It is also in the interest of the public health and the public welfare to protect and conserve the ground-water supply. Therefore every effort should be made to reduce the wastage of water connected with the recovery of the phosphate, by persuasion if possible, or by the exercise of the police power of the State if necessary.

MANAGEMENT AND CONTROL OF WATER RESOURCES

Fundamental Legal Concepts

There are two basic, though fundamentally divergent, doctrines that are used in controlling the use of water in the United States: the English or common-law doctrine, which rests on the proposition that ownership of land confers on the owner the right to use any water that rests on his land, that flows past it or that lies below it; and the doctrine of appropriation, which holds that beneficial use of water is the basis, measure, and the limit of the appropriative right.

The fundamental differences between these doctrines reflect the contrasts in climate in the broad regions where they have been developed and applied.

The doctrine of appropriation was specified as the exclusive basis for the right to use water in the Constitution of the State of Colorado in 1876. It has been adopted in seven other arid or semiarid western states as the exclusive controlling doctrine permitting the use of water and it is followed in whole or in part in each of the other seventeen western states. The basic concept behind this doctrine is that water is, in its own right, of primary importance and the land owner has no inherent right to use water from sources upon, contiguous to, or underlying his land. The rights to use water from these sources are based on priority in time of beneficial use and they may be lost if the water is not used beneficially for a specified period of time.

The English rule or common-law doctrine, on the other hand, is followed in most of the eastern states. In its original form the common law entitled a land owner whose land was contiguous to a stream or was underlain by a ground-water reservoir to use as much water as he could use on his own land. Since water was used chiefly for natural purposes such as domestic consumption, for watering livestock, or perhaps for turning a water wheel, the amount of water used was not great, and disputes between water users were relatively rare. However, with the coming of the industrial age the use of water increased rapidly, and disputes over the right to use water became inevitable. The Industrial Revolution also introduced problems of disposal of wastes from factories and from cities, which have steadily grown, until today the pollution of our sources of potable water has become a matter of national concern.

One of the earliest quoted decisions relative to surface-water rights (Mason v. Hill) was handed down in England in 1833. The court abrogated the earlier custom of granting the right of use of water flowing through one's land to the first who appropriated it, and expounded the doctrine (later called "riparian") that each owner of land along a stream is entitled to have the full natural flow of the stream flow past his property undiminished in quantity and unchanged in quality. In 1843, in the case of Acton v. Blundell (12 Mees and W. 324) an English court, following the maxim that "the owner of the land owns everything above or below the surface, upward to the sky and downward to the center of the earth," ruled that a land owner is entitled to unrestricted use of water from a well dug on his property regardless of the effect that such use may have upon the property of his neighbor. This is called the common-law doctrine and is still followed in England.

American doctrine of reasonable use. The English rule relating to both surface water and ground water has been modified by decisions in numerous American courts. The earliest decision appears to be in the case (in 1862) of Bassett v. Salisbury Manufacturing Co. (43 N. H. 573; 82 Am. Dec. 180), in which case the Supreme Court of New Hampshire ruled that a man's right to use water is limited to use on his own land, and this right is restricted to a reasonable use, in view of the similar rights of others. This doctrine is known as the American doctrine of reasonable use.

However, the doctrine of reasonable use has been interpreted by the courts in different ways. In general, "reasonable use" in view of the similar rights of others, is restrictive and more properly should be called "equitable use", as adopted, for example in New Jersey. In Alabama (Sloss-Sheffield Steel v. Wilkes, 231 Ala. 511, and in other cases cited in Bayer v. Nello Teer Co. (256 N.C. 509, 124 S.E. [2d] 552) reasonable use is interpreted to mean beneficial use on one's property regardless of the effect such use may have on the ground-water supplies beneath neighboring property.

Other states were slow to follow the lead of New Hampshire, and it was not until 1900 that the doctrine of reasonable use was given support by the decision in the case of Forbell v. the City of New York (164 N. Y. 522), which held that it was not a reasonable use to take water from beneath land and sell it for use on land distant from that from which it was obtained. In 1903 the Supreme Court of California in the case of Katz v. Walkinshaw (141 Cal. 116; 70 Pac. 663; 74 Pac. 766) extended the doctrine of reasonable use to California and also introduced a further development that has become known as the doctrine of

correlative rights. Reasonable use, as there interpreted, means only the land owner's reasonable share if there is not enough water to supply the needs of all. According to Corpus Juris (67 C. J. p. 840), if the common supply is sufficient, each owner may take all he needs either for use on his own land or other lands.

Difference between ground water and surface water under common law. It should be pointed out that in most common-law jurisdictions the right to use ground water and the right to use surface water differ in one very fundamental respect. This difference lies chiefly in the interpretation by the courts of the term "reasonable use." A riparian owner may use the water in a stream to which he is riparian, only with due regard to the similar rights of other riparian owners. He may not divert enough water to substantially reduce the flow of the stream and he may not impair the quality of the water to the injury of his neighbor without exposing himself to court action. But a land owner whose property overlies a productive water-bearing formation may dig wells and pump as much water as he can use for beneficial purposes on his own land regardless of the effect such pumping has on the ground-water supplies of his neighbor. He may legally deprive his neighbor of water or render his neighbor's water unfit for consumption subject only to the conditions that the use is on his own land and that the use is beneficial to his land.

Water Law in North Carolina

In common with most of the other eastern states, North Carolina adopted most of the principles of colonial law which in turn were taken from the English rule. Its constitution embodies, either specifically or by implication, the concepts of due process of law, equal protection under the law, and just compensation for the taking of private property. This is the common law. Under the common law a water right is a property right and hence it is entitled to the same protection as other property rights. However, in North Carolina as in the other eastern states, the common-law doctrine is modified by the American doctrine of reasonable use.

Surface water falls into two major classifications; diffused surface water, and water flowing in well defined channels. Diffused surface water falls as rain or snow and is generally considered to be the property of the owner of the land on which it falls. It is not generally a source of water supply and litigation in which it is involved is usually related to damage suits. Therefore it is not discussed in this report.

When diffused waters reach a well defined stream channel they become available for diversion and are subject to a different set of legal rules and principles. Where surface water flows in a well defined channel, the courts of North Carolina are guided by the American doctrine of reasonable use, which was restated by the North Carolina Supreme Court (Dunlap v. Carolina Power Company) (212 N. C. 814, 195 S. E. 43) (1938). Each individual riparian owner has the right to make reasonable use of water from a stream on or contiguous to his land "for manufacturing purposes as well as for domestic and agricultural purposes . . . .

[This right] is qualified only by the requirement that it must be enjoyed with reference to the similar rights of other riparian owners . . . What constitutes a reasonable use is a question of fact having regard to the subject matter and the use . . ."

However, the riparian owner is strictly liable for wrongful acts such as diverting all or a substantial part of the flow of a stream or for pollution of the stream that results in material injury to downstream riparian owners. Diversion of water from a surface stream for the purpose of supplying water to a municipality is not considered a reasonable use, either because such diversions are not considered as incidental to riparian ownership or because they may involve the transfer of water to non-riparian land.

Ground Water, in North Carolina Courts, has been classified as: (a) subterranean water flowing in well defined channels; and (b) subterranean or underground percolating waters. In cases in which ground water is considered to be flowing in a well defined channel, the same legal principles are applied as those applying to surface streams. Thus, in the 1927 case of Masten v. Texas Co. (194 N. C. 540; 140 S. E. 89) the Supreme Court ruled that the plaintiff was entitled to damages because gasoline had leaked from a storage tank into a "vein" of water that supplied the plaintiff's well. The use of the term "vein" is unfortunate since it implies that the gasoline followed an underground channel that was well defined and was ascertainable from surface indications or similar means. To conclude that the gasoline, having appeared in the plaintiff's well, must have followed a well defined underground channel is unwarranted.

As a matter of fact, underground streams or "veins of water" in the usual sense are rare in nature. On the other hand, pollution of percolating ground water by gasoline, phenols, and other substances that have been introduced into the ground accidentally or otherwise is not at all uncommon, and the courts of many jurisdictions have awarded damages for such pollution. The process by which the polluting substance travels from the source to a well or spring may be and often is precisely the same as the process by which a drop of water falling on the land surface percolates downward to the water table and thence laterally to some point of discharge that is more or less distant. In many investigations of groundwater movement, foreign substances have been deliberately introduced into wells as a means of measuring velocity and direction of flow or in studying the nature of flow of liquids through porous media.

The criteria for differentiating the classes of ground water have been stated in the decision by the Supreme Court in the case (in 1960) of Jones v. Loan Association (252 N. C. 626; 114 S. E. 2d 634-635) as follows: "Subterranean waters are generally classified as (1) streams or bodies of water flowing in fixed or definite channels, the existence and location of which are known and ascertainable from surface indications or other means without excavations for that purpose, and (2) percolating waters, which ooze, seep, or filter through the soil beneath the surface, or which flow in a course that is unknown or undefined, and not discernible from surface indications without excavation for that purpose." Thus, by classification of the court, true underground streams would be very difficult to identify and this may explain in part the fact that the

courts of North Carolina have rarely been called upon to rule with regard to the rights to the flow of underground streams.

In 1924 the North Carolina Supreme Court adopted the American rule of reasonable use with reference to use of artesian water. Although the case involved flowing wells, the Court's opinion indicated that it was adopting a uniform rule for all percolating water. Rouse v. City of Kinston (188 N. C. 1; 123 S. E. 482). The Court held that the City of Kinston had dug wells on land adjacent to the plaintiff's land and had sold this water to its inhabitants, thereby causing the flow of the plaintiff's wells to be so greatly diminished that his lands were rendered unproductive, and he and his tenants had been deprived of wholesome drinking water, etc. The decision of the lower court, to the effect that selling the water was an unreasonable use, was upheld and the plaintiff was awarded damages.

The lower court's decision was in part as follows:

> "This rule (the American rule of reasonable use) does not prevent the use by any land owner of percolating water subjacent to his soil, in manufacturing, agriculture, irrigation, or otherwise; nor does it prevent any reasonable development of his land by mining, or the like, although by such use the underground percolating waters of his neighbor may be thus interfered with or diverted; but it does prevent the withdrawal of underground waters for distribution or sale, for use not connected with any beneficial ownership or enjoyment of the land from which they were taken, it thereby follows that the owner of adjacent lands is interfered with in his right to the reasonable use of water on his own land, or if his wells, springs or streams are thereby materially diminished in flow or his land rendered less valuable for agriculture, pasturage or for legitimate uses. . .I therefore charge you that, in the absence of contract or legislative enactment, whatever is reasonable for the owner to do with his subsurface water, he may do. He may make the most of it that he reasonably can. It is not unreasonable for him to dig wells and take therefrom all of the waters

> that he reasonably needs in order to get the fullest enjoyment and usefulness from his land, for the purpose of abode, productiveness of the soil, or manufacture, or whatever else the land is capable of. He may consume it at will; but to fit it up with wells and pumps of such pervasive and potential reach that from their base he can tap the waters stored in the lands of others, and thus lead them to his own land, and by merchandising it, prevent its return, to the injury of adjoining landowners, is an unreasonable use of the soil, and in such event the injured neighbor may bring his action for damages."

Two points should be noted here: First, in reality the plaintiff suffered damage only because his well ceased to flow or the volume of the flow was greatly diminished. He could have obtained water of the same quality by installing pumps on his wells. The court may have had this point in mind when it awarded him $2,000 damages instead of the full estimated value of his land. Second, it is a characteristic of all artesian basins, that as the success of the first developer becomes known, his neighbors tend to follow his example and drill wells to the same aquifer. Hence, the quantity of water withdrawn from the aquifer increases and the artesian head declines. Consequently the yield per well diminishes and eventually all of the wells cease to flow. Thus, during the normal course of events the plaintiff's wells would have diminished in flow and in head, but since his neighbors were exercising their rights of reasonable use, he could not legally collect damages.

In a recent (1962) decision (Bayer v. Nello Teer Co.) (256 N. C. 509, 124 S.E. [2d] 552) in which the Supreme Court of North Carolina reaffirmed the American doctrine of reasonable use as it applies to ground water and cited precedents in other States, Bayer owned property near Brice's Creek which he had improved and on which he had drilled a well about 80 feet deep. The well yielded good water which was used for domestic purposes.

Several years later the defendant opened a quarry nearby on Brice's Creek and in this connection drilled a well from which he pumped 5,000 to 6,000 gallons per minute for the purpose of de-watering the quarry. The Water that was pumped by the defendant was discharged into Brice's Creek and wasted to the ocean. The plaintiff's claim that this pumping had drawn salt water into his domestic well was not disputed by the defendant. The lower court ruled for the plaintiff. However, the defendant appealed to the Supreme Court which ruled that on the basis of evidence presented "Defendant was mining or taking rock from its rock quarry in accordance with the best practices of open-pit mining, ... and that it pumped no more percolating waters therefrom than was necessary for the operation. It is true that ... an expert civil engineer testified ... 'the water was being wasted', but immediately thereafter he testified 'it was to de-water the quarry to enable them to operate'. Defendant was using its rock quarry in a legitimate and natural manner and making the only use of it for which it was reasonably adapted and was pumping no more water therefrom than was necessary for its beneficial and useful operation, and under those circumstances it was not required by law to use the percolating waters, and the fact that it did not use it under those circumstances does not make it chargeable with waste".

This ruling clearly indicates that under existing law in North Carolina "reasonable use" of ground water is interpreted as a right appertaining to the use of the land.

Although, in quarrying limestone and other similar rock, it may reasonably be considered necessary to dewater a pit, in mining phosphate and similar ores it is neither necessary nor "reasonable" to dewater a pit.

Existing statutory controls over water quality. The use of water to carry away wastes from municipalities and industrial plants in surface streams or, to a smaller extent, in permeable underground formations has long been recognized as an essential function of water. The realization that in many places the discharge of wastes into streams was injurious to downstream riparian owners resulted in the first attempts to control the use of surface waters. In 1893, the General Assembly of North Carolina enacted laws which invoked the police power of the State for the purpose of protecting sources of public water supply from pollution. Since that time the North Carolina State Board of Health has devoted much attention to the problem of waste disposal into streams that are used as a source of public water supply.

However, with the growth of population and the expansion of industry, it became evident that controls were needed also on streams used for other purposes. Uncontrolled disposal of industrial wastes in the streams was endangering the usefulness of the State's surface waters, and in order to protect the water resources of the State the General Assembly enacted the State Stream Sanitation Law in 1951. The law stated:

> "It is hereby declared to be the policy of the State that the water resources of the State shall be prudently utilized in the best interest of the people. To achieve this purpose, the government of the State shall assume responsibility for quality of said water resources. The maintenance of the quality of the water resources requires the creation of an agency charged with this duty, and authorized to establish methods designed to protect the water requirement for health, recreation, fishing, agriculture, industry, and animal life. This agency shall establish and maintain a program adequate for present needs, and designed to care for the future needs of the State."

The law established the North Carolina State Stream Sanitation Committee.

The State Stream Sanitation Committee consists of seven members having backgrounds of experience in fields prescribed by the act. They are appointed by the Governor subject to confirmation by the Senate. The responsibilities of the Committee are:

(1) To develop and adopt a series of classifications and standards appropriate to each of the waters of the State and to survey all the waters of the State and assign such classification to them.

(2) To control new sources of pollution through a permit system. The Committee shall act upon applications for permits so as to prevent, insofar as reasonably possible, any pollution of the water of the State from any additional or enlarged sources.

(3) To work toward the abatement of existing pollution by issuing special orders to any person whom it finds responsible for causing any pollution within a watershed.

This is a brief summary of the specific powers of the Committee. In addition, it has auxiliary powers including the investigating of fish kills, conducting research (through the Department of Water Resources or by contracts or grants), representing the State in all relationships with the Federal Government in matters relating to water quality,

and establishing regulations with neighboring States for protection of waters of mutual interest (subject to approval by the General Assembly).

During the fifteen years since it was established, the Committee has worked effectively toward the abatement of existing stream pollution and the prevention of future pollution. The abatement, control and prevention of pollution is based upon maintaining water quality in accordance with water quality standards applicable to assigned classifications under the assumption that critical conditions of high temperature and low flow (measured by the average minimum seven-day flow) would recur at intervals of ten years. It is recognized that any stream could, under certain conditions, be overloaded. If this situation occurs, the quality-of-water standards may well be temporarily violated in some aspects. There is at present no authority to provide storage reservoirs or other means of protecting the water quality during critical periods.

However, the problem of controlling ground water contamination is more difficult than the protection of surface-water sources because the rate of ground-water movement is slow. It is quite possible that extensive pollution, accidental or otherwise, might occur long before it is recognized. The elimination of pollution that already exists may prove very difficult if not impossible within reasonable time limits. Intrusion of brackish water that may be induced by heavy pumping from wells would almost certainly render the water in the aquifer unfit for domestic and municipal uses, as has been demonstrated on the western end of Long Island.

Although the Committee has the authority under the Stream Sanitation laws to classify and establish water quality standards for the protection of ground water, its program has not developed to the extent of assigning classification and water standards to ground water. This action, when

taken, will provide authority for protection of ground-water reservoirs as they may be affected by the disposal of waste. However there appears to be a need for protection of such water from contamination such as salt-water intrusion brought about by over pumping.

Regulatory Bodies and their Jurisdiction

The Federal Government has wide powers in the water resources field through its constitutional authority to control commerce, provide for the common defense, enter into treaties, control interstate relations, manage Federal property and provide for the general welfare. However, the State has the power to create property rights and the police powers to regulate those property rights. Federal agencies are extremely active in planning water resources projects and in providing grants for selected works. There is, therefore, need for active participation by State agencies both in planning and in surveillance to assure that the interests of the State will be served to the maximum degree and that State laws will provide the most favorable climate for State-Federal cooperation.

The North Carolina State Board of Health is the oldest State agency that has authority over water resources. This authority relates only to the sanitary quality of water used for public supplies.

The State Stream Sanitation Committee was established in 1951 with responsibility for establishing and maintaining a program to protect the water requirements of surface water and ground water for health, recreation, fishing, agriculture, industry, and animal life.

There has been a growing concern among State officials and influential citizens over the possibility that the rapid growth in population and

industry within the State, especially since World War II, and the great increase in the use of water that has accompanied this growth would result in shortages of water, unless prompt remedial measures were taken. Formal proposals for statutory reforms that would enable the State to regulate and control the use of water were made in 1955 and again in 1965. These proposals were coolly received.

It is true that the State Stream Sanitation Committee may exercise indirect control of water use and withdrawal through its power to issue permits for waste disposal facilities. However, there is not at the present time any state agency that has direct control over with withdrawal and use of water resources generally within the state.

State Board of Water Commissioners. The severe drought of 1952 to 1954 focused attention on the need for a State agency with emergency powers to allocate water to drought-stricken areas. In 1955 the General Assembly enacted a law creating the State Board of Water Commissioners with emergency powers to temporarily allocate water under certain emergency conditions. The Board was also given the responsibility of carrying on a program of education and conservation in the use of water, and of giving consideration of the role of the State in relation to the water problem. In its report for the biennium ending June 30, 1958, the Board concluded that in order to meet effectively the growing need for water data and to reduce the duplication of responsibility among certain agencies, a single State agency should be created which would have the responsibility for all activities relating to water resources within the State. This report

was favorably considered and the Commission on Reorganization of the State Government, in its Eleventh Report (Nov. 21, 1958), recommended:

"(1) The creation of a Department of Water Resources to which would be transferred the existing functions of the State Board of Water Commissioners; the Division of Water Resources, Inlets and Coastal Waterways of the Department of Conservation and Development.

"(2) (a) The State Stream Sanitation Committee be transferred to the Department of Water Resources and (b) the Department of Water Resources to be designated to act as the administrative agent of the State Stream Sanitation Committee to investigate the Waters of the State, and to issue permits and certificates of approval in accordance with the policies established by the State Stream Sanitation Committee."

The Board of Water Commissioners, in its final report (1958) made seven recommendations which called directly or indirectly for legislative action:

1) Accelerate the program of topographic mapping by the U. S. Geological survey.

2) Improve the irrigation law.

3) Provide authorizing legislation for establishing Watershed Improvement Districts in connection with Public Law 566.

4) Make funds available to permit the State to finance additional storage in flood control projects for use as water supply.

5) Study the need for capping free flowing but unused artesian wells.

6) Make provisions to assure that no structure that would reduce minimum flow would be placed in a stream.

7) Establish State grants-in-aid to supplement the Federal program of grants for waste-treatment plant construction.

Board of Water Resources and Department of Water Resources. The present Board of Water Resources and the Department of Water Resources were created by the General Assembly of 1959 (Chapter 779, Session Laws 1959) through legislation entitled "An Act to Create a State Department of Water Resources." The purpose of this act is "to create a state agency to coordinate the State's water resources activities; to devise plans and policies and to perform the research and administrative functions necessary for a more beneficial use of the water resources of the State, in order to insure improvements in the methods of conserving, developing and using those resources."

The Act creates a Board of Water Resources which is to appoint a full-time Director of the Department of Water Resources; to organize the work of the department into two or more Divisions which shall include: (1) a Division of Water Pollution Control; (2) a Division of Navigable Waterways and (3) such other divisions and units as the Board deems necessary. Other divisions that have been established are: Division of Ground Water, Division of Planning, Division of Water Management, and Division of Staff Services.

The Department of Water Resources was assigned the responsibility for the administrative duties of the State Stream Sanitation Committee when the Committee was transferred to the Department in accordance with the Act. However, the power to issue permits and certificates of approval for waste disposal facilities was retained by the Committee.

The Department of Water Resources has been active and its accomplishments have been considerable as detailed in its biennial reports. In addition to the special reports which it has issued as Circulars, it has

engaged in two studies with the assistance and support of the Tennessee Valley Authority and the Institute of Government. These were entitled "Flood Damage Prevention in North Carolina" and "North Carolina Water Resources Planning."

The Board of Water Resources, convinced of the need for additional authority to regulate water resources, proposed in 1965 an amendment to its enabling act. The amendment was designed to give the Board authority to establish rules and regulations relating to water resources which would be enforceable by action in the Superior Court of North Carolina. However, the General Assembly passed a resolution directing the Board of Water Resources to study further the proposed amendment and the necessity for it and to submit a report and proposed legislation to the General Assembly of 1967.

Classifications of Water

Quality classification. Perhaps the best known classification of water is based on its suitability for drinking and culinary purposes. Although the knowledge that water may carry pathogenic organisms is only a little over a century old, most civilized nations enforce strict regulations on the sanitary quality of water that is used for public water supplies. Most of our states had established agencies for the inspection and control of public water supplies before the turn of the century. It was recognized also that the dissolved chemicals in water had physiological effects when used for drinking. A person who drinks moderately mineralized water develops a tolerance for mineral substances over a period of time, but abrupt changes in drinking water cause him

considerable discomfort. The United States Public Health Service [1928] issued minimum standards for the sanitary and chemical quality of water used for drinking on common carriers engaged in interstate commerce. These standards, with minor revisions, are now generally accepted throughout the nation for sanitary and chemical quality of water used for public water supplies.

The sanitary and chemical quality of water also determines its suitability for aquatic life and for industrial uses. North Carolina was one of the first states to undertake the abatement and control of sanitary and industrial pollution of its streams and underground water resources. The State Stream Sanitation Committee, established in 1951 for the abatement of pollution, adopted water quality standards applicable to surface waters. The Committee classified the waters of the state with regard to highest acceptable usage as follows: (1) drinking; (2) bathing; (3) fishing; (4) agriculture, industrial cooling and processing supply; (5) navigation and disposal of sewage and other wastes. Tidal salt water is classified as suitable for: (1) shellfishing for market purposes; (2) bathing; (3) fishing; and (4) navigation.

Legal classification. The courts have recognized a tri-partite classification of waters: (1) Waters flowing in natural water courses and lakes. These include waters of natural origin flowing constantly or recurrently in a reasonably definite channel. The surface stream is the most common example. The courts of North Carolina appear to recognize,

at least in principle, "underground streams," and these are treated under the same riparian rule that governs decisions in the case of surface-water courses. (2) Diffused surface waters which result from springs, rain or melting snow which lie on or flow along the surface, but which do not form a part of a natural water course. (3) Percolating waters which are subsurface waters that percolate through the soil or through the rocks, but do not follow any defined channel.

Hydrological classification. The hydrologist classifies water chiefly with regard to its position in the hydrologic cycle. This starts with the water vapor in the atmosphere and is followed by precipitation. After precipitation reaches the land surface it may return to the atmosphere by evaporation or by the transpiration of plants. It may run off overland to a stream or a lake, or may filter into the soil and rocks of the earth where it moves from a position of higher head (or specific energy content) to one of lower head, and it eventually returns to the oceans by devious routes. Water is evaporated from the oceans and the cycle starts all over again.

The hydrological classification is dual: (1) surface water, and (2) ground water. It should be emphasized that these categories are mutually interdependent. Ground water maintains the low flow of streams and, under certain conditions, streams serve to recharge the ground-water reservoirs. Ground water may emerge at the surface in low-lying areas and cause swamps or lakes. But, on the other hand, wet or swampy land may provide

recharge for a highly productive aquifer because the precipitation may be prevented from running off while the water slowly filters into the soil.

Surface water moves more or less freely from its origin to the sea, that is from a position of higher head to one of lower head. The rate of movement of ground water is much slower. It is controlled, not only by the difference in head from one place to another but also by the permeability of the rock through which it flows. Although there are several types of rock that are permeable to a greater or lesser degree, in North Carolina the rocks which are the most permeable are the beds of sand and gravel or strata of porous to cavernous limestone. These are common chiefly to the Coastal Plain. They are generally interbedded with shale and other rocks of low permeability and are spread out beneath the Coastal Plain over areas of hundreds or thousands of square miles, somewhat like a deck of cards and tilted slightly toward the ocean. Where these permeable beds (aquifers) are exposed at the land surface the water in them is not confined and is in open vertical connection with the atmosphere. But toward the ocean the aquifers are overlain by less permeable rock and the water is confined under pressure. Where a well penetrated one of these confined aquifers, the water rises in the well, and if it rises above the land surface, the water flows and the well is said to be "artesian".

Subsurface water flowing in well-defined channels or veins and underground "lakes" of ground water, although recognized by the courts, is rare and probably does not occur in North Carolina. Underground streams do occur in limestone terranes as a result of solution of the limestone

by ground water percolating along fissures or cracks. Examples of underground streams are found in the Luray Caverns in Virginia, the Mammoth Cave in Kentucky, and Carlsbad Caverns in New Mexico. There is no evidence of these streams from any surface indications; they can be seen only by entering the caves. Even underground they can be followed only for a few hundred yards.

In some sections of the country ancient streams have cut deep gorges into relatively impervious rock and these gorges have been subsequently filled or partly filled with sand, gravel, and silt. In some cases, as in the Piedmont Plateau and in the Mountains, these ancient, partly filled valleys are now occupied by streams that flow on permeable sediments above the bedrock floor. Water is contained in these sediments, and is moving slowly more or less parallel to the direction of stream flow. However, since the present course of the stream does not necessarily follow the ancient stream course, it would seem logical to consider the water moving through such sediments as percolating rather than as following a well-defined channel.

Any artificial use of water degrades it in some way. When water is passed through turbines to generate power it is degraded only to the extent that potential energy is lost. When it is used for municipal supply it becomes polluted biologically, but pollution by chemicals is negligible. The biological pollution may be removed by treating the sewage effluent. However, Jordan [1955] estimates that about 10 percent of the water used for municipal supplies is lost (consumed) by evaporation. Many other uses of water involve actual loss of water to the atmosphere. Blaney [1955] estimates that about 60 percent of the water

used for irrigation is consumed (lost to the atmosphere). Steam generation, air conditioning, and quenching hot metals such as steel also consume large quantities of water. The water that is not consumed is degraded by concentration of the dissolved solids and it may eventually become unfit for use. The water used in many industrial processes is not actually consumed. Rather, it is degraded to such a degree by addition of various chemicals that it cannot be safely returned to a stream unless it is treated, diluted with fresh water, or both. Water that is pumped to dewater to a mine is not used in the strict sense of the word. However, if it is discharged into a tidal estuary it is wasted, or for practical purposes "consumed." Stock ponds and other reservoirs, while of great economic value, also consume water by evaporation. According to Thomas and Harbeck [1956] the total evaporation from such ponds is greater than all other withdrawals exclusive of irrigation.

Modifications of Fundamental Legal Doctrines In Other States

The fundamental doctrines relating to water use and disposal were established by the courts over a hundred years ago when this nation was predominantly agricultural. Ownership of land and the enjoyment of the benefits to be derived from the land were of primary importance in the economy of the young nation. Water, in relation to its use, was so abundant that, in humid climates at least, it was taken as a matter of course. Since that time the nation has become predominantly urban and

industrial. Tremendous quantities of water are used to supply municipalities, industries and irrigated agriculture. Waste products are discharged into the streams or collecting basins, and stream pollution has become a pressing problem in many parts of the country. Municipalities are forced to import water from great distances, and industries are increasingly moving to areas where water supply is plentiful. Thus the availability of adequate water supply has become of primary importance in the full enjoyment of the land.

This radical change has not been reflected in court decisions relating to water. Nor is it to be expected that it would be, since the function of the courts is to interpret the law, not to make it. Thus, the states have been giving increasing attention to legislation designed to permit the fullest conservation and the optimum utilization of water resources. In most of the states studies are being made or have been made of the legal, economic and technical aspects of the regulation of water resources, and of the means by which they can be used to the greatest benefit of the citizens of the state. A large number of states now have statutes that provide for partial regulation. Others have provisions for full regulation. However, in many states, these statutes are fairly recent and have not been tested in the courts.

It is not possible within the limits of this report to discuss the whole field of water-resource regulation. Nor would it be proper to attempt it. It is believed that North Carolina is so firmly committed to the common-law or riparian doctrine that the appropriation doctrine

has no application in the State except possibly where flood waters (surplus waters) are concerned. Hence the following discussion is limited to those states having the doctrine of riparian rights and the doctrine of common law. It is also limited to those states where ground-water regulation has been effected and to those states which have had ground-water laws for a sufficient period of time to be tested in the courts.

California. Parts of California have had chronic shortage of water locally since the State was first settled. Hence Californians are keenly aware of the importance of water as a prerequisite to the enjoyment of land ownership. The northern part of the State, in view of its present underdevelopment, has a surplus of water, but the populous southern half of the State has had great difficulty and has gone to great expense to keep abreast of the ever-growing need for water for public supply, for industry and for irrigation. The State Department of Water Resources maintains a large staff that is engaged in data collection, research, planning and construction. This Department has developed and, in part has constructed, dams and canal systems which will carry water from areas of surplus to areas of deficiency under the stupendous program known as the California Plan. In addition there are counties and districts that are engaged in comprehensive programs of research, experimentation and planning in problems related to water supply. The State and many of its political subdivisions support cooperative programs with the U. S. Geological Survey, the Corps of Engineers, the Bureau of Reclamation and other Federal agencies concerned with water.

al agencies concerned with water.

California water law includes recognition of rights obtained by appropriation, by prescription, and also the rights inherent in the ownership of land. In 1903 the Supreme Court of California (in Katz v. Walkinshaw) reversed earlier decisions and adopted a rule that has become known as the California doctrine of correlative rights. This rule accorded equal rights to the owners of lands overlying a common supply for use of water on or in connection with their overlying lands, each to have a fair and just proportion in cases in which the supply was not sufficient for all owners. The landowner's right extends only to the quantity of water necessary for use on his land, and if there is a surplus, this surplus may be appropriated for distant use. There is no statutory procedure for appropriating surplus waters. Such appropriations are effected as a result of diversion and use of the waters. Accordingly, surplus waters from surface or subsurface sources may be rightfully appropriated on privately owned land for such uses as public water supplies, irrigation or industrial uses beyond the limits of the basin or watershed. However, this appropriation does not constitute a prescriptive right. In case of a shortage of water the overlying right takes precedence. The exception to this rule is that, where the appropriator has gained prescriptive rights through taking of non-surplus waters, he may exercise an equal and correlative right with the owners of the overlying land. As late as 1949 (in Pasadena v. Alhambra) the Supreme Court reaffirmed the rule of correlative rights.

Texas is faced with difficult water problems, partly due to its rapid industrial growth, but considerably worsened by its geography, climate and political history. In nearly half of the State the annual precipitation is less than 20 inches, so that irrigation is necessary for growing most crops. The remainder of the State usually has ample precipitation but is subject to prolonged periods of drought followed by periods of torrential rainfall. In this part of the State, surface-water reservoirs are essential both for flood protection and for storing water against the drought that is sure to follow. A system of reservoirs has been constructed in cooperation with the Bureau of Reclamation and by State River Authorities. There are also a number of extensive ground-water reservoirs in the State. Some of these are being depleted by over-pumping. The State Legislature has enacted numerous laws aimed at conserving water resources. However, most of these have been declared invalid by the courts. The confusion as to the legal rights to use water is compounded by conflicting rules inherited from Spanish, Mexican, Republican and State land grants.

With regard to the surface water, the riparian doctrine is applied to the normal flow of the stream, but flood water and other surplus water is the property of the State and is subject to appropriation. All ground water is considered to be percolating water and is subject to the common-law doctrine. Hence a landowner is the absolute owner of the water beneath his land and he may use as much of it as he can capture, provided only that he does not waste it and that he does not use it maliciously to harm his neighbor. He may sell it for use at a distant point. In 1949 the Legislature enacted a law which authorized the establishment of underground

water districts. These districts could be established by a County Commissioner's Court or by the Texas Board of Water Engineers. The area to be included within a district had to coincide with the boundaries of a ground-water reservoir or a subdivision thereof as determined by the Texas Board of Water Engineers. These districts are political subdivisions of the State and they are authorized to promulgate and enforce rules and regulations for protecting, conserving and recharging ground-water reservoirs, to provide for spacing of wells, to require permits for drilling wells, and to regulate withdrawal of water from wells.

The High Plains Underground Water Conservation District No. 1 has been active for many years. Its main effort has been directed toward educating the water users of the District in the principles that govern the movement and occurrence of ground water; improving irrigation methods; reducing waste; encouraging recharge to the ground-water reservoir through wells and ponds; and keeping the irrigators informed on the status of depletion of the ground-water reservoir.

The District has claimed that the ground water under the High Plains is being depleted and that an allowance for depletion should be permitted in filing income-tax returns. A test case has been argued successfully before the Court of Tax Appeals.

To date no district has exercised its authority to regulate withdrawals of ground water. However, the High Plains District is now issuing notices to irrigators found wasting tail water from irrigated tracts and those who fail to stop such waste are served with court injunctions.

New Jersey has probably done more to conserve its water resources than any other eastern state. As early as 1907 the New Jersey Legislature passed the Surface Water Diversion Act which established a State Water Supply Commission with authority to equitably allocate and control the diversion of surface water for public potable supplies. In 1910 the State assumed partial control over the diversion of ground water. These acts have been ammended several times, and the present law has gradually evolved. The basic law for diversion for private use of surface and ground waters in New Jersey is the American doctrine of reasonable use. However, New Jersey interprets the term "reasonable use" not as applying to the land on which the water is used but with respect to adjacent land owners with similar water rights. The term "reasonable" then becomes "equitable" in the true sense of the term from which it is obtained. Under specific legislation the state assumes general supervision over all sources of public potable water supply.

Under the act as amended in 1953 (N.J.S.A. 58: 4A-1 et seq.) the Division of Water Policy and Supply "shall delineate from time to time such areas of the State where diversion of subsurface and percolating waters exceeds or threatens to exceed, or otherwise threatens or impairs, the natural replenishment of such waters." In areas so delineated no person, corporation or agency of the public shall hereafter divert or obtain water from subsurface sources in excess of 100,000 gallons a day for any purpose without first obtaining a permit from the Division of Water Policy and Supply. These permits are granted for a specific period of time and at the

end of this time are subject to review. The State also requires that all well drillers be licensed and that abandoned wells be sealed.

In addition to its responsibilities for equitably allocating and controlling diversions the State also has the authority to augment its natural supplies of water for all consumers. To this end it has constructed two major surface-water reservoirs and has purchased a large tract of land, called the Wharton Tract, as a ground-water preserve.

New York. In 1933 the New York State Legislature openly invoked the police power of the State in order to control the withdrawal of ground water on Long Island:

> "Facts having been presented by the Water Power and Control Commission and the United States Geological Survey indicate that the depletion of underground waters under Long Island is such as to threaten the adequacy of the supply for domestic consumption of the inhabitants thereof, this enactment is made in the exercise of the police power of the State and its purposes generally are to protect the public health and public welfare in conserving the supply of water for domestic consumption."

The law provided that no new or additional wells could be installed on Long Island for manufacturing or industrial purposes by any person, firm or corporation where the capacity of such wells singly or in aggregate exceeds 100,000 gallons a day without prior approval of the Commission. The use of ground water for agricultural purposes was excluded. An act to amend the conservation law, passed in 1960, required that all new wells on Long Island except those used for agricultural purposes, having a capacity of more than 45 gallons per minute (64,800 gallons per day), must have prior approval from the Commission. Drillers are required

to be licensed, and they are required to provide such information about each well as may be prescribed by the Commission. It should be noted that the law does not prohibit the sale of the water to residents of a community outside the area in which the wells are located.

In both New Jersey and New York the decisions of the Commission may be appealed in the courts. However, in New York an application for a permit to establish a water company or to drill wells having a capacity in excess of 45 gallons per minute is commonly approved unless there is evidence that the issuance of a permit is not in the public interest or unless objection is raised by another party. In this case a public hearing is called and the Commission receives testimony in accordance with court rules of evidence. (In New Jersey, an application to withdraw more than 100,000 gallons a day in any area delineated by the Division of Water Policy and Supply comes before the Commission, and the burden of proof is on the applicant that his proposed diversion of ground water will not create a critical depletion of the ground-water supply.)

The Need For Regulation Of Ground-Water Resources

This Board of Consultants believes the statutory regulation of withdrawals of ground water from wells in North Carolina is most urgently needed in order to protect the interests of the citizens of the State and to assure industries, and agricultural interests of the continued availability of fresh ground-water supplies.

North Carolina lies within three physiographic provinces which differ profoundly with respect to their ground-water characteristics. The extreme western part of the State is in the Blue Ridge province (called the "Mountain province" or the "Mountain area," within the State). The Piedmont comprises the middle part of the State and covers about two-fifths of its area. The Coastal Plain, which covers about 45 percent of the area of the State, comprises the lowland coastal area.

The Mountain area is underlain by dense, relatively impermeable rocks that yield only small supplies of water, generally less than 10 gpm. The rocks that underlie the Piedmont are of the same general type as those that underlie the Mountain area, but they are generally more fractured and yield larger supplies of water to wells. Municipal and industrial wells commonly yield up to 200 gpm and a few yield more. Alluvium along some stretches of the larger streams is potentially an important source of water [Mundorff, 1950]. The Coastal Plain is underlain by sedimentary rocks such as clay, sand, gravel, limestone and marl that dip generally eastward. These strata are potentially the most productive sources of ground water in the State. Yields of 1,000 gpm are not uncommon and some wells yield as much as 3,000 gpm. The eastern part of this province is deeply indented by

estuaries, and salt-water intrusion is a threat where heavy pumping is concentrated in small areas. However, thus far, salt-water intrusion has occurred only in isolated areas.

Although the pumping at Franklin, Virginia has lowered water levels in northern North Carolina, and the pumping in the vicinity of Kinston has created a noticeable cone of depression in that area, there was no large, concentrated pumping of ground water prior to the opening of the Texas Gulf Sulphur Company's mine near Aurora in 1965. Thus the ground-water resources of the Coastal Plain, except for the areas mentioned, are relatively underdeveloped.

The ready availability of ground water favors its development by individuals and groups, with resultant uncoordinated exploitation and with little or no concern for the relationship between withdrawals and replenishment. The enormous amount of ground water in storage and the slow rate at which it moves combine to give the well operator a false sense of security. and lead him to the conclusion that the resource is inexhaustible. But the history of highly developed ground-water basins reveals a common pattern. As the use of cheap water increases, artesian wells cease flowing. Pumps are installed, and useage increases. The water levels continue to decline until the well operators are faced with the stark realization that ground-water resources are not inexhaustible. Along the sea coast salt water encroaches into fresh-water aquifers. After this happens only heroic measures can save the aquifers from complete destruction. Such measures have included drastic reduction of pumpage and the exercise of police powers to control installations of new wells (for example, in New York state); construction of submarine dams in canals and moving pumping fields back from the coast (in Florida); and reduction of pumping plus the use of the

injection wells to build a fresh-water barrier in the aquifer along the coast (in California).

The ground water of the Coastal Plain of North Carolina is a resource of untold value. It will provide water almost indefinitely for industry, agriculture and municipal uses, provided its development is wisely controlled. However, this resource can be destroyed within a few decades if it is exploited unwisely, as it has been in so many areas. The State of North Carolina is fortunate that thus far there has been no serious or widespread intrusion of salt water in the Coastal Plain. Hence the State is in a position to manage the orderly development of the ground-water resources before withdrawals cause irreparable damage.

CONCLUSIONS

The Castle Hayne limestone, which underlies the phosphate ore body at the Lee Creek pit, is the most productive water-bearing formation or aquifer in the Coastal Plain of North Carolina. The ground water in the Castle Hayne is sweet water suitable for most domestic, agricultural, and industrial purposes. However, it is in hydraulic communication with brackish water in the Beaufort formation immediately underlying the Castle Hayne at the Lee Creek site.

The Castle Hayne limestone is overlain unconformably by the Yorktown formation, which is predominantly marine clay interbedded with sands, shell beds, and shell limestones. These are lenticular beds, no one of which can be traced laterally for any great distance. In the immediate vicinity of the Lee Creek pit the Castle Hayne limestone appears effectively confined by the younger beds, but elsewhere the confinement is less effective and natural leakage occurs vertically upward from the Castle Hayne through the Yorktown, as well as in the opposite direction.

Sea waters that were originally contained in the Castle Hayne limestone and underlying marine aquifers have been diluted or flushed out by fresh waters that circulated through them after they were deposited, as is shown by the fact that in the outcrop areas and for some distance down the dip the ground water is fresh, but at greater depths it becomes progressively more saline. Evidence of continuing deep circulation of fresh water is provided by the ground-water contours on Plate 2, which show that artesian waters rise from depth and are discharged into the estuaries of the major streams crossing the Coastal Plain. It is estimated from the piezometric contours on the map that before pumping began at the Texas Gulf Sulphur

pit, 30 million gallons per day (mgd) of fresh water were discharged from the Castle Hayne limestone into the estuary of Pamlico River in a 16-mile stretch just downstream from Washington, and additional volumes were discharged farther downstream at lesser flow intensities. However, since pumping began, the hydraulic gradient and the direction of flow have been reversed so that water is now flowing toward the pit from the surrounding area (see Fig. 17). Thus, whereas formerly water from the Castle Hayne aquifer was rising and discharging into the estuary of the Pamlico it is now moving downward from the Pamlico toward the Castle Hayne.

The water in the Castle Hayne limestone is water that, according to legal classification, is "percolating water that filters, oozes, percolates or flows" through the limestone. It is not water that, by legal definition, flows in well defined channels ascertainable "without excavations for that purpose."

Existing legislation is not adequate to enable the State of North Carolina to administer the development and conservation of the ground-water resources of the Coastal Plain or of any other region of the State in such a manner as to protect them from wasteful exploitation and degradation, nor to provide for their optimum equitable utilization for all the people.

Of the 50 to 55 in. of precipitation that falls annually on the outcrop area of the Castle Hayne limestone west and southwest of Lee Creek, approximately 40 percent is disposed of as runoff, of which about half occurs as direct or surface runoff, the other half as ground-water runoff or "base flow."

Natural replenishment of the Castle Hayne aquifer in that part of its outcrop centered about 20 miles west-southwest of the pit, by coincidence, runs about 65 mgd. Despite the rejected recharge in this area the outcrop does not behave as a distributed constant-head source, but rather as a distributed source with declining head, distinguishable from vertical leakage. This recharge area is not close enough to the pit to dominate the hydraulics of the system as it is over-shadowed by the leaky Pamlico estuary.

The upper Pamlico estuary evidently is freshened notably by ground-water seepage. With the reversal in the direction of seepage caused by pumping 65 mgd the quality of water in the estuary will deteriorate, especially at low flows.

The total seaward flow in the Castle Hayne limestone and in younger formations at comparable depths and at about the same distance inland between the South Carolina and the Virginia borders is about 150 mgd.

The dewatering pumpage at the Lee Creek site thus exceeds one-third of the estimated seaward ground-water flow at those depths.

The Yorktown and Castle Hayne aquifers have characteristics as summarized in Table 5.

The transmissivities of the Castle Hayne near Aurora and near Lee Creek differ, largely because of lateral variations in thickness and permeability of the Castle Hayne limestone. Differences in the magnitudes of leakage determined from the 35-day test and from the first year of continuous dewatering are ascribable to the proximity of the pit of the leakage which is concentrated in the Pamlico estuary upstream.

Table 5

Characteristics of Yorktown and Castle Hayne Aquifers

Aquifer	Yorktown	Castle Hayne	Castle Hayne	Castle Hayne
Locality	nr. Aurora	nr. Aurora	Lee Creek	Coastal Plain
Date of test	Dec. 1962	Dec. 1962	Aug.-Sep. 1964	1965-66
Duration of test	50 hrs	28 hrs	35 days	1 year
Discharge	55 gpm	1,070 gpm	3,500 gpm	65 mgd
Extent of strong influence	-	-	2.7 mi	24 mi
Transmissivity in gpd/ft	30,000	245,000	390,000	300,000
Hydr. diffusivity in gpd/ft	1.0×10^8	3.1×10^8	2.0×10^9	3.3×10^8
Storage coeff. (non-dim.)	.0003	.0008	.00019	.0009
Thickness of bed, ft	120	100	300	300
Hydraulic cond. in gpd/ft^2	250	2,500	1,300	1,000
B-factor, in ft	-	-	14,000	70,000
Leakance, gpd/ft^2/ft	-	-	2.0×10^{-3}	6.1×10^{-5}

The patterns of regional head distribution to be expected with more or less uniformly distributed leakage on the one hand and localized recharge on the other hand are distinguishable. Piezometric contour maps of the Castle Hayne aquifer favor the dominance of leakage over recharge, as does also the time variation of drawdown caused by the pit dewatering.

It is calculated that it would take about six years for brackish ground water, moving two miles downstream beneath the estuary, to reach the Lee Creek pit; that it would take about 40 years moving five miles; and about 150 years moving 10 miles, considering the average velocities of the water. For example, a small fraction of the ground water would move with velocities ten times those cited.

The Beaufort formation underlying the Castle Hayne aquifer beneath the Lee Creek pit is in hydraulic connection with that aquifer and contains water with 3,000 ppm chloride, which will gradually find its way upward to deteriorate Castle Hayne waters. Thus, from vertical and lateral encroachment there is an imminent threat of gradual chloride increase.

Continued pumping at 65 mgd will surely result in decreasing the supply available for other present and future users and impair the quality under a sizeable area.

The most feasible physical remedy is injecting fresh water from one or more of three sources - the Pamlico River upstream, the upper reaches of the Pamlico estuary, and possibly the Peedee formation - into Castle Hayne wells several miles upstream from the Lee Creek Pit.

RECOMMENDATIONS

We believe that the Coastal Plain of North Carolina is on the threshold of a period of rapid and extensive development of its industrial, mineral, woodland and agricultural resources. The course of this development will depend, to a much larger extent than is generally realized, upon the continued availability of abundant supplies of potable water. We therefore recommend that immediate steps be taken by the State to promulgate rules and regulations that will provide for the optimum utilization of the ground-water resources that is equitable for all potential water users, without incurring the risks that attend overdevelopment.

It is the purpose of this Board not to suggest the precise form that management and regulation of ground-water development should take, but rather to emphasize the necessity of protecting the ground-water resources from wasteful exploitation. Inasmuch as the existing laws afford no protection of ground-water resources *per se*, we recommend that legislation be enacted that will give the State agency concerned with ground-water resources authority to promulgate and enforce such regulations as may be necessary to accomplish these purposes.

The Department of Water Resources [1966, pp. 101-108] has outlined the options available to North Carolina and the need for further regulation, and we endorse the objectives outlined therein.

We further recommend thorough study of the laws of New York and New Jersey because regulation and control of ground-water withdrawals have been effective in those states for many years. Although the legal basis for regulation differs in the two states---on Long Island, New York it is effected through the police powers of the State, while in New Jersey it

is effected through a declaration of policy for the equitable distribution of water, especially in the eleven coastal counties---nevertheless the regulation is equally effective in both States.

Legislation is effective only when funds and manpower are available for its enforcement. We therefore recommend that, in addition to authorizing management and control, funding for such management and control be provided.

Inasmuch as there is presently insufficient data to enable us to delineate of the fresh water-salt water contact in the major water-bearing formations, we recommend that this become a prime objective of the Ground Water Division of the Department of Water Resources and that funds be made available for the necessary exploration drilling and testing.

Ground-water investigations should be continued and expanded. Studies of a more detailed nature should be carried forward as rapidly as possible. We recommend the monitoring-well program be expanded to cover the entire coastal plain on a grid of ten miles or denser.

Specifically we recommend that the legislative authorization be sufficiently inclusive to cover the following points:

> Establishment of a permit system under which no person or persons would be allowed to install and operate a well or wells to withdraw water from ground-water sources for any purpose whatsoever where the installed pumping capacity exceeds 100,000 gallons per day (gpd) without first obtaining the approval of the Board of Water Resources. The amount 100,000 gpd is perhaps an upper allowable limit. However, certain small amounts for domestic use and for watering of stock should be excepted so long as adequate standards of well construction are followed.

Persons or corporations operating or proposing to operate a well or wells having an installed pumping capacity in excess of 100,000 gpd shall be required to file with the Board of Water Resources such information regarding the well or wells as the Board of Water Resources may stipulate. This information should include as a minimum (a) an accurate log of the well, (b) samples of cuttings at each 5 feet of depth, (c) a record of the casing, screen settings and capacity of pumps installed, and (d) a record or accurate estimate of the amount of water pumped each month, to be submitted annually to the Board of Water Resources unless excepted specifically by the Board.

Well operators should be required to permit authorized employees of the State to enter any pumping site for the purpose of gaging the well or collecting samples of water.

Well owners should be required to seal all abandoned wells by effective methods such as grouting or mudding.

Any well operator who fails to comply with the regulations stipulated by the Board of Water Resources should be subject to appropriate penalties.

We further recommend that all water-well drillers operating in the State of North Carolina be licensed on the basis of an examination by a board of competent well drillers, geologists, and hydrologists appointed by the State.

Before drilling any well having a designed pumping capacity in excess of 100,000 gpd, a driller must obtain from the Board of Water Resources a permit, for which a small fee would be charged.

The Board of Water Resources should prepare and publish mandatory standard specifications for construction and maintenance of drilled wells similar to those adopted by the American Water Works Association.

It is recommended that operators on phosphate leases in the area should be urged to not consider dry pit mining but rather dredging or mining through wells as reasonable methods of ore recovery.

It is recommended that companies now operating dry pit mines be urged, or persuaded, to convert to dredging or other methods.

It is recommended that all municipalities and industries including operators of phosphate mines be required to meter accurately the total discharge of their wells and to determine the characteristics of those wells by step-drawdown tests and calibration of pumps so that more accurate forecasts can be made of well performance and aquifer response, except in those cases specifically exempted by written authority of the Board of Water Resources.

The Board of Water Resources should be empowered to prescribe the criteria to be used and the procedures to be followed to protect fresh-water aquifers from contamination by salty water in coastal areas, especially in the vicinity of tidal estuaries, bays, or other surface or subsurface bodies of saline water. Such criteria should provide for maintaining the hydraulic head at or above sea level in all areas where it is known that the Castle Hayne limestone or other productive aquifers are directly connected with brackish water or where the mantle of less pervious material is so thin that saline water has easy access to those aquifers.

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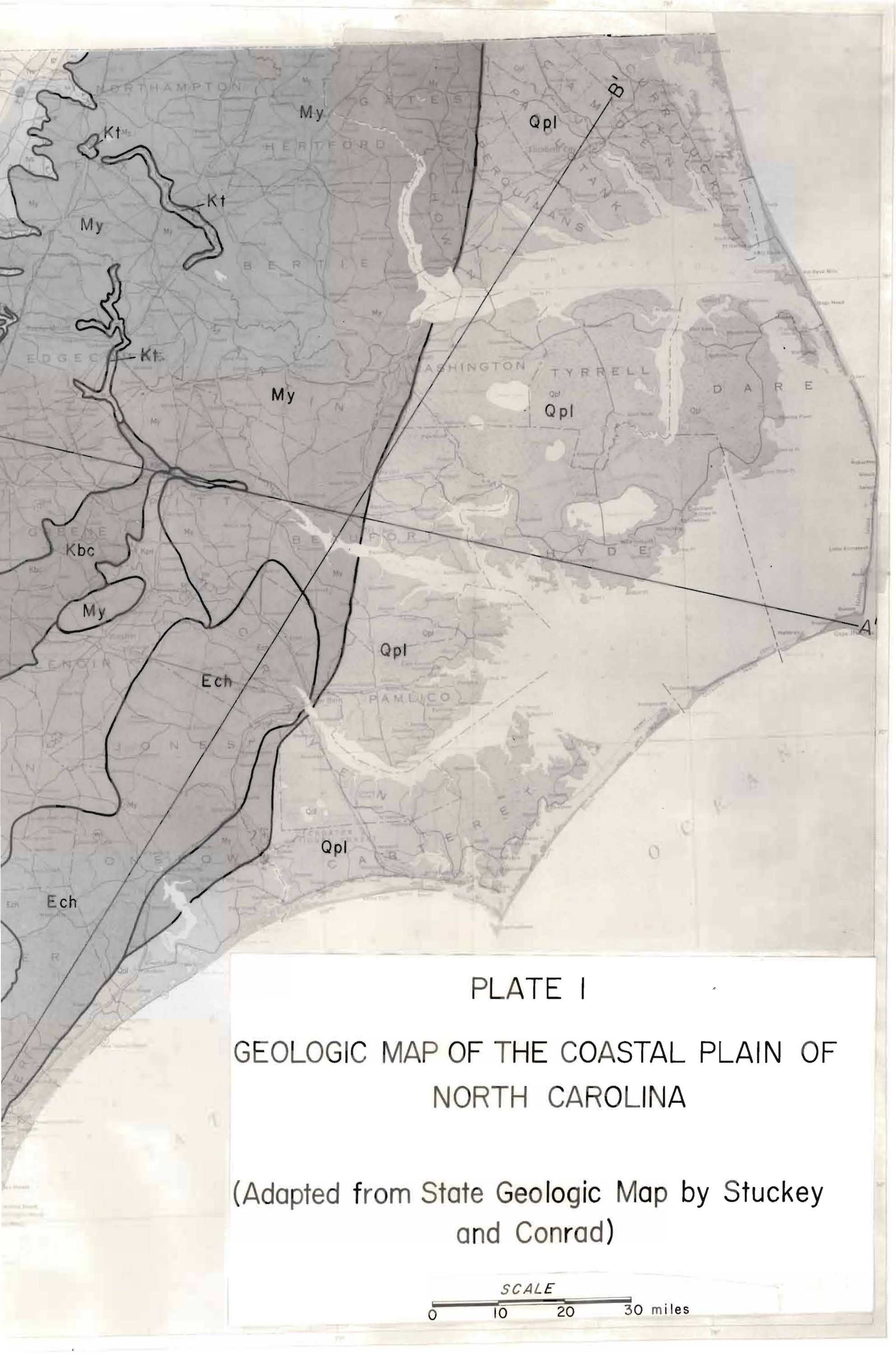


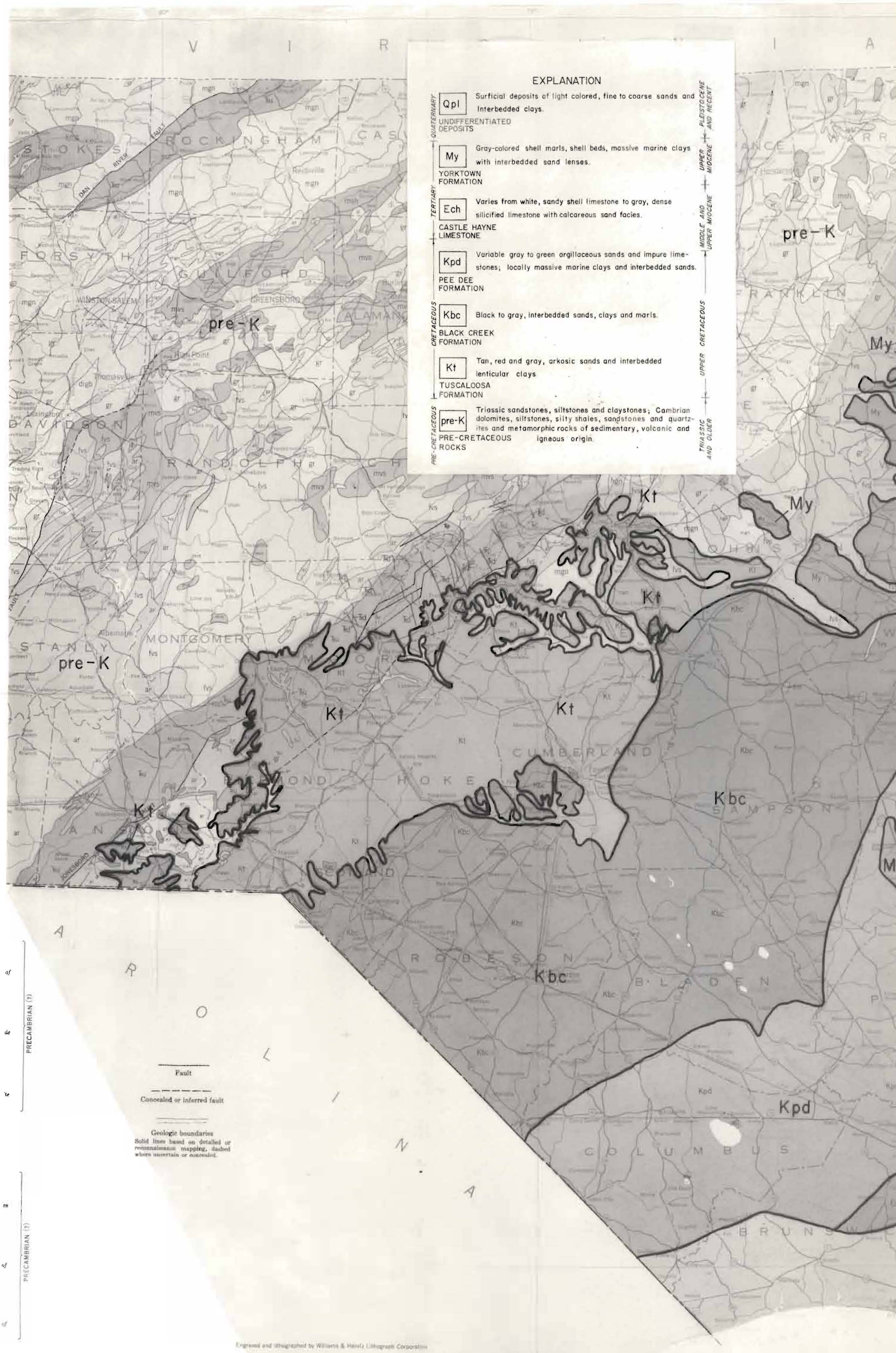
PLATE I

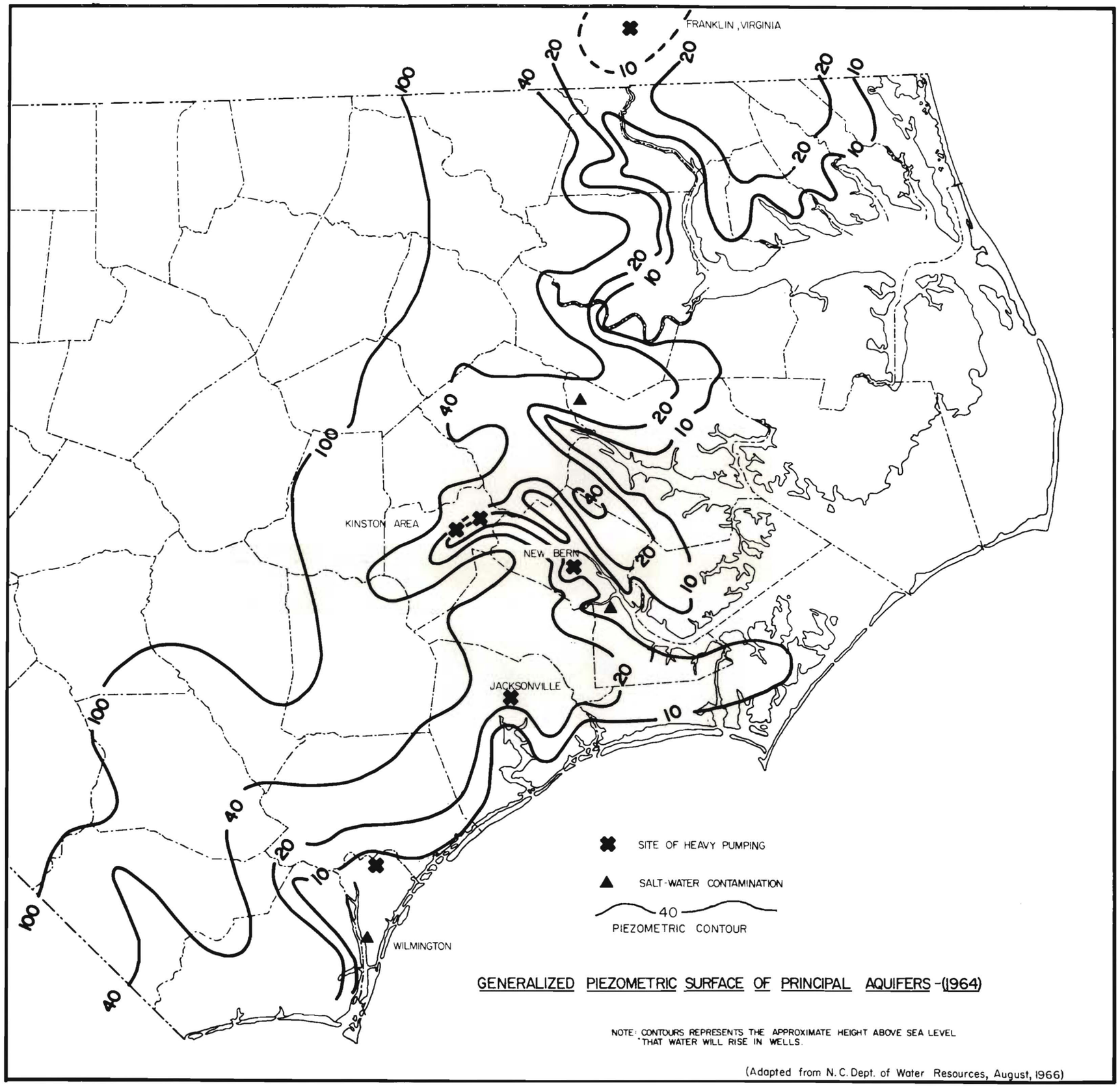
GEOLOGIC MAP OF THE COASTAL PLAIN OF NORTH CAROLINA

(Adapted from State Geologic Map by Stuckey and Conrad)

SCALE

0 10 20 30 miles


EXPLANATION
QUATERNARY
Qpl
Surficial deposits of light colored, fine to coarse sands and interbedded clays.
UNDIFFERENTIATED DEPOSITS
PLEISTOCENE AND RECENT
TERTIARY
My
Gray-colored shell marls, shell beds, massive marine clays with interbedded sand lenses.
YORKTOWN FORMATION
UPPER MIOCENE
Ech
Varies from white, sandy shell limestone to gray, dense silicified limestone with calcareous sand facies.
CASTLE HAYNE LIMESTONE
MIDDLE AND UPPER MIOCENE
CRETACEOUS
Kpd
Variable gray to green argillaceous sands and impure limestones; locally massive marine clays and interbedded sands.
PEE DEE FORMATION
Kbc
Black to gray, interbedded sands, clays and marls.
BLACK CREEK FORMATION
UPPER CRETACEOUS
Kt
Tan, red and gray, arkosic sands and interbedded lenticular clays
TUSCALOOSA FORMATION
PRE-CRETACEOUS
pre-K
Triassic sandstones, siltstones and claystones; Cambrian dolomites, siltstones, silty shales, sandstones and quartzites and metamorphic rocks of sedimentary, volcanic and igneous origin.
PRE-CRETACEOUS ROCKS
TRIASSIC AND OLDER
pre-K
Kt
My
Kbc
Kpd
STOKES
ROCKINGHAM
FORSYTH
GUILFORD
DAVIDSON
RANDOLPH
STANLY
MONTGOMERY
MOORE
CUMBERLAND
HOKE
ROBESON
BLADEN
COLUMBUS
BRUNSWICK
SAMPSON
Fault
Concealed or inferred fault
Geologic boundaries
Solid lines based on detailed or reconnaissance mapping, dashed where uncertain or concealed.
PRECAMBRIAN (?)
Engraved and lithographed by Williams & Heintz Lithograph Corporation


FRANKLIN, VIRGINIA
KINSTON AREA
NEW BERN
JACKSONVILLE
WILMINGTON
100
40
20
10
SITE OF HEAVY PUMPING
SALT-WATER CONTAMINATION
40
PIEZOMETRIC CONTOUR
GENERALIZED PIEZOMETRIC SURFACE OF PRINCIPAL AQUIFERS -(1964)
NOTE: CONTOURS REPRESENTS THE APPROXIMATE HEIGHT ABOVE SEA LEVEL THAT WATER WILL RISE IN WELLS.
(Adapted from N.C. Dept. of Water Resources, August, 1966)