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LAND-SURFACE COLLAPSE AND GROUND-WATER PROBLEMS IN THE JAMESTOWN AREA, BERKELEY COUNTY, SOUTH CAROLINA

by

B.C. Spigner
Hydrologist

Geology-Hydrology Division
South Carolina Water Resources Commission

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Open-File Report No. [redacted] 2
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CONVERSION FACTORS

English Units	Multiply by	Metric Units
ft (feet)	3.048×10^{-1}	m (meters)
ft/day (feet per day)	3.048×10^{-1}	m/day (meters per day)
ft/s (feet per second)	3.048×10^{-1}	m/s (meters per second)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3 (cubic meters per second)
ft^2/s (square feet per day)	9.290×10^{-2}	m^2/day (square meters per day)
gal (gallons)	3.785	L (liters)
gpm (gallons per minute)	6.309×10^{-2}	L/s (liters per second)
gpm/ft (gallons per minute per foot)	2.070×10^{-1}	(L/s)/m (liters per second per meter)
gpm/in^2 (gallons per minute per square inch)	$9.778 \times 10^{+1}$	$(L/s)/m^2$ (liters per second per square meter)
in (inches)	2.540	cm (centimeters)
in (inches)	2.540×10^{-1}	mm (millimeters)
in^2 (square inches)	6.452×10^{-4}	m^2 (square meters)
mi (miles)	1.609	km (kilometers)
mgd (million gallons per day)	4.381×10^{-2}	m^3/s (cubic meters per second)

CONVERSION FACTORS Cont'd

Temperature conversion

°F (degrees Fahrenheit)	5/9 (°F-32)	°C (degrees Celsius)

Hydraulic conversion

Transmissivity ft^2/day	7.48	Transmissibility gpd/ft
Hydraulic conductivity ft/day	7.48	Permeability gpd/ft^2

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ABSTRACT

Land-surface collapses and subsidence depressions have occurred in a carbonate terrane in the Jamestown area of Berkeley County, South Carolina. These collapses have occurred since the Summer of 1975, and have caused property damage, and damage to a county highway. Personal injury to one local resident reportedly occurred when the land surface suddenly collapsed.

Collapses and subsidence depressions have formed in clays and sands of the Talbot Formation overlying the Santee Limestone, a cavernous carbonate-rock aquifer. The formation of these collapses has been related to large water-level declines in the Santee aquifer. As ground-water levels decline below a cavernous, upper permeability zone in this aquifer, overlying unconsolidated sands and clays lose strength and collapse. Ground-water pumpage from two limestone quarries, estimated by the writer and reported by quarry owners to be periodically in excess of 36 mgd (million gallons per day), has caused a water-level decline of over 35 ft since the Summer of 1975. A collapse-prone area has been delineated by mapping the distribution of collapses and relating this distribution to a potentiometric map of the Santee aquifer.

In addition to land-surface collapse, water-supply problems have been caused by large ground-water pumpage from the Santee aquifer. Water levels have been lowered below the bottoms of some wells, and below the practical pumping lifts of pumps in other wells. Water levels in wells located over 1 mile from the center of pumping have been affected by the pumpage.

Several solutions are available to restore adequate drinking-water supplies to local residents. Existing wells could be deepened, and larger-diameter casing and pumps with greater lift capability installed, or water lines could be extended to the area from an existing municipal water system. However, the problem of land-surface collapse is more serious because of the possibility of personal injury. If large ground-water withdrawals from the Santee aquifer continue, land-surface collapse will probably continue and will most likely become more severe if ground-water pumpage from the Santee aquifer is increased. In all probability,

land-surface collapse will be drastically reduced or will cease entirely if ground-water levels in the Santee aquifer are allowed to recover into the upper permeability zone of the Santee aquifer. A recovery of water levels would also restore some artesian pressure in the Santee aquifer and water levels would again be within the practical pumping lift of existing pumps.

INTRODUCTION

The Jamestown area, located in Berkeley County, South Carolina (fig. 1), is underlain by less than 20 ft of sands and clays of Pleistocene age that overlie the Santee Limestone, a cavernous limestone aquifer. In 1976 local residents in the area complained of land-surface collapse, and mining officials with the S. C. Land Resources Conservation Commission were concerned that the problems could be related to a limestone quarry which had been granted a mining permit in July, 1975. During late Summer, 1975, dewatering operations commenced in order to maintain the water level below a working bench in the quarry.

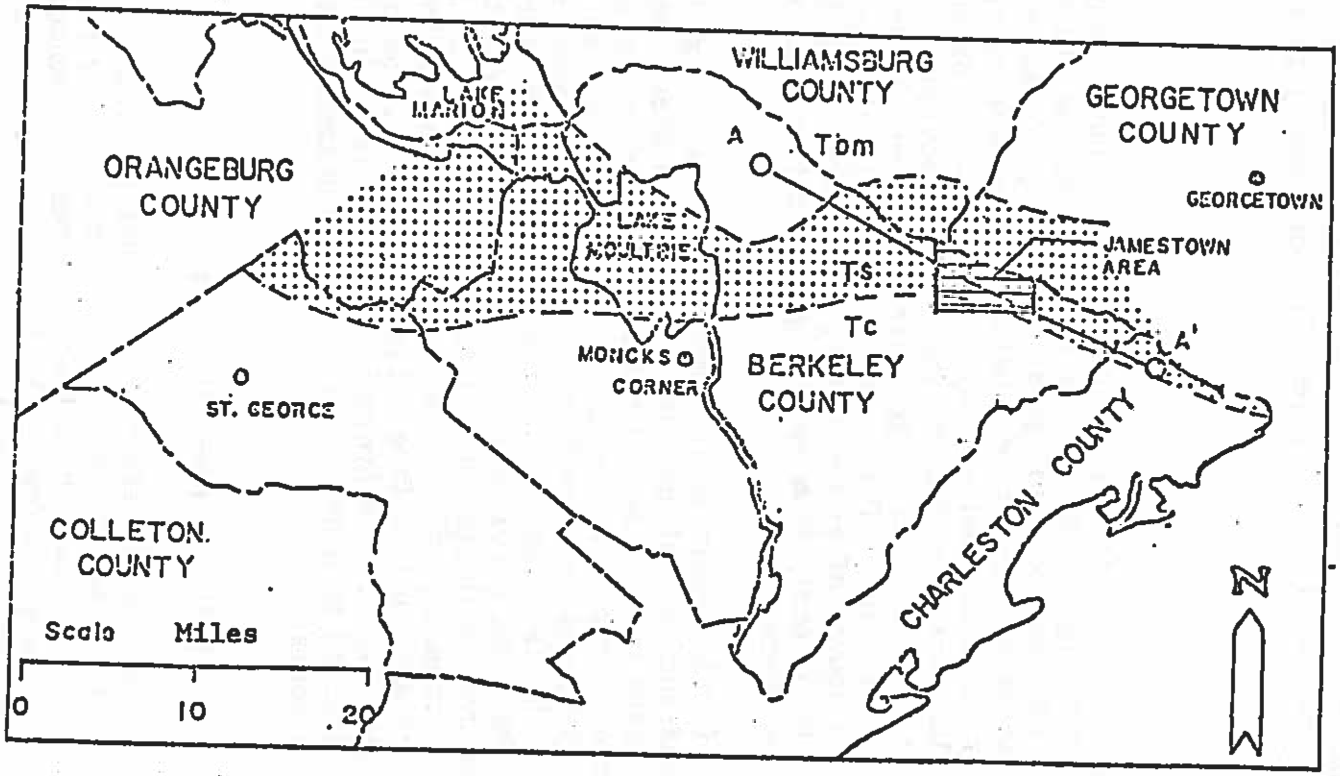
In October, 1976, a mining permit was requested by an adjacent land owner who wished to open a quarry. This second quarry operator wanted to "dry" mine the limestone and anticipated that dewatering of the quarry would be required. The first quarry operator was concerned that dewatering of a second quarry would adversely affect his mining operation, and mining officials were concerned that this additional dewatering would create more problems.

In October, 1976, mining officials requested the writer to conduct an investigation to determine the cause of land-surface collapse and evaluate the possible effects of additional dewatering operations. A reconnaissance investigation was conducted and the results were reported to mining officials in October, 1976. The reconnaissance investigation indicated that the dewatering operation was the likely cause of land-surface collapse and some water-well problems (Spigner and Cannon, 1977). Hydrogeologic data were inadequate to thoroughly evaluate the collapse problems or reliably predict the effects of additional dewatering.

The second quarry was granted a mining permit in December, 1976, and dewatering operations were begun in early February, 1977. By April, 1977, the combined pumpage from the two quarries was in excess of 10,000 gpm.

Land-surface collapse and water-well problems continued and became so severe during Summer and Fall, 1977, that on August 22, 1977, mining officials decided to alter the mining permits to prohibit dewatering of the quarries (Mr. Jack Whisnant, written communic., 1977). The writer was asked to conduct additional study and collect, if possible, sufficient hydrogeologic data to recommend solutions to the problems. Much of the information in this report was then collected, and recommendations were made to mining officials in mid-September, 1977.

FIGURE 1. MAP OF A PART OF THE SOUTH CAROLINA COASTAL PLAIN SHOWING LOCATION OF THE JAMESTOWN AREA, SUBCROP DISTRIBUTION OF THE SANTEE LIMESTONE AND LOCATION OF GEOLOGIC CROSS-SECTION A-A'.



EXPLANATION

Ts	Subcrop Distribution Of Santee Limestone
Tc	Cooper Marl
Tbm	Black Mingo Formation

In late September, 1977, mining officials decided to allow a certain amount of dewatering and quarry operators agreed to take responsibility for damages caused by dewatering (Mr. Jack Whisnant, written communic., September, 1977). In order to continue any dewatering, two solutions to the water-supply problems were considered: (1) to have existing wells deepened and pumps repaired and/or replaced, or (2) to extend water lines from the Jamestown municipal water system (free of charge) to local residents.

PURPOSE AND SCOPE

Problems such as those described in this report have occurred in the past and are occurring now in similar areas throughout the world. Unfortunately, the complex hydrogeology of fractured, carbonate-rock aquifers often prevents an adequate evaluation of the effects of ground-water pumpage prior to initiation of pumpage. Large areas of the South Carolina Coastal Plain are underlain by the Santee Limestone - an important and valuable source of construction aggregate, raw material for Portland cement, and agricultural lime. The Santee Limestone is also an important and equally valuable source of ground water. Therefore, it is imperative that ways be found to properly develop this geologic formation as a mineral and water resource.

The purpose of this report is to summarize the water-supply problems and problems of land-surface collapse in the Jamestown area. Additional hydrogeologic data have been collected since the submission of a preliminary reconnaissance report on February 17, 1977, and a more complete hydrogeologic evaluation is now possible. Because of the seri .us nature of the problems and the fact that collapse and subsidence features of carbonate terranes have not previously been described in any detail in South Carolina, the hydrogeologic data in this report should be helpful in evaluating the hydrogeology of similar areas and in preventing similar water-supply problems and land-surface collapse in other areas of the South Carolina Coastal Plain. The hydrogeologic principles in this report can also be applied to other areas in the world underlain by cavernous, carbonate rocks.

PREVIOUS INVESTIGATIONS

The hydrogeology of the Jamestown area has not previously been described in the literature except for a brief reconnaissance report (Spigner and Cannon, 1977). There have been isolated occurrences of land-surface collapse in areas underlain by the Santee Limestone in South Carolina but not of the magnitude described in this report. Ground collapse features were briefly described in an engineering geology report on the Santee-Cooper project (Lakes Marion and Moultrie) by Stephen Taber (1939). In describing potential problems of the east dike area of the Pinopolis Reservoir (Lake Moultrie), Taber (1939, p. 18) wrote, "the presence of a few small surface depressions with vertical walls indicates recent caving to fill open spaces." Taber may have been describing collapses which had occurred recently rather than the "recent" geologic past but this can not be confirmed.

Collapses which occurred in July or August, 1961, in Horry County were described by Ottie Johnson (1962). Johnson described the three collapses as "sinkholes" but gave no explanation for the cause of these collapses.

George E. Siple (1960) published a report describing limestone terranes of Tertiary age in South Carolina and he mentioned doline (sinkhole) development and the occurrence of scattered jamas, particularly south of the Santee River (in or near the Jamestown area).

WELL NUMBERING SYSTEM

The well numbering system utilized by the South Carolina Water Resources Commission is based on a latitude-longitude grid system. A grid is composed of 5 minutes of latitude and 5 minutes of longitude, and this 5-minute grid is further divided into 1-minute latitude-longitude grids. When a well is inventoried, it is given a four-part well number which consists of a number, a capital letter, a small letter and a number (e.g., 14Xp-2). The first number and capital letter refer to the 5-minute latitude-longitude grid; the small letter refers to the 1-minute latitude-longitude grid, and the last number refers to the well number in this 1-minute grid. The well grid system for the study area is shown in figure 2.

In this report, a field number given to wells during the investigation is listed with the official well number (table 2, appendix) because a previous report and field notes contain these field numbers.

The U. S. Geological Survey (USGS) utilizes a numbering system composed of a county prefix, and wells are numbered sequentially as they are inventoried. For example, the well number Brk-53 refers to the fifty-third well inventoried in Berkeley County. The USGS well number, if one has been assigned, is also listed in table 2.

ACKNOWLEDGEMENTS

The writer wishes to acknowledge the assistance of officials of the South Carolina Land Resources Conservation Commission for their assistance in the collection of much of the basic data for this report. Mr. Jack Whisnant, Geologist, formerly employed by the South Carolina Land Resources Conservation Commission, inventoried wells, made water-level measurements, and surveyed well elevations. Mr. John Hensel, Biologist, South Carolina Land Resources Conservation Commission, also collected water-level data and surveyed well elevations. Mr. Tommy Ayers, Engineer, South Carolina

Land Resources Conservation Commission, made detailed surveys of elevations in quarries and streams.

The writer wishes to acknowledge the assistance of Mr. Mark R. Cannon, formerly employed as a geologist with the South Carolina Water Resources Commission, who collected preliminary basic data on wells and mapped locations of collapses and subsidence depressions.

Special appreciation is extended to well owners who allowed the writer to collect data on their wells and spent much time and effort in directing the writer to locations of collapses. Local residents who were most helpful in this regard were Mr. and Mrs. T. E. Casselman, Mr. Joe C. Smith, Mr. Glenn Pipkin, Mr. George Pipkin, Mr. James Pipkin, and Mr. and Mrs. Curtiss Jones.

Appreciation is extended to Mr. Arthur Schirmir of B.A.S.S. Ltd. and Mr. Brian Ware of Ware Brothers Construction Company for allowing access to their property during the investigation.

The assistance of the Coastal Plains Regional Commission in providing funding support for ground and surface-water investigations in Berkeley County and other areas is gratefully acknowledged.

The writer is indebted to Mr. Ken Stevens, Mr. Drennan Park, Mr. William C. Moser, and Mrs. Janet Barclay who critically reviewed the manuscript and made many helpful suggestions. Appreciation is extended to Mrs. Doris Davis for typing and editorial review of the manuscript and Mr. Joe Mims for his assistance in drafting illustrations.

HYDROGEOLOGIC FRAMEWORK

PHYSIOGRAPHY, DRAINAGE, AND CLIMATE

The Jamestown area is located in the lower Coastal Plain subprovince of the Atlantic Coastal Plain physiographic province. The lower Coastal Plain is characterized by low relief, generally sluggish drainage of streams, and numerous swamps. Altitudes in the study area range from about 15 to 40 ft above msl (mean sea level), and local relief is rarely more than about 15 ft. The greatest local relief occurs in the northern part of the study area where the Santee River is entrenched into the Santee Limestone.

Drainage in the area is by the southeastward flowing Santee River and several northeastward flowing tributaries (fig. 2). Dutart Creek, the principal tributary, is a spring-fed stream flowing from Hellhole Bay swamp west of the study area and Little Hellhole Bay swamp on the south.

Solution (karst) features such as sinkholes (dolines) and karst springs are common but not numerous. Sinkholes occur near the Santee River and at scattered localities between the Santee River and County Highway 45. These sinkholes were formed by solution of the underlying

Santee Limestone and subsequent lowering of the overlying sands and clays of the Talbot Formation. Sinkholes are mainly of the shallow, "doline-type," but several steep-sided sinkholes occur near the Santee River. At least one small sinkhole southeast of Guillard Lake Road lies on the drainage divide between a northwest-flowing tributary of Dutart Creek and southeast-flowing tributary of Echaw Creek (fig. 2).

Several sinkhole ponds occur northwest of Dutart Creek and are used by local farmers for watering cattle. At least three of the shallow ponds are referred to as "earthquake holes" by local residents. Several of these "sinkholes" were reportedly formed several days after the Charleston earthquake of August 31, 1886. The father of Mr. James Pipkin, a local farmer, was 22 years old in 1886 and had vivid recollections of the earthquake. Heavy rains occurred several days after the earthquake and the "earthquake holes" were formed (Mr. James Pipkin, oral communic., 1976).

The Jamestown area has a humid subtropical climate that is characterized by long hot summers and relatively mild winters. The average annual precipitation is about 52 inches per year and rainfall is generally evenly distributed throughout the year.

GENERAL GEOLOGY AND AQUIFER SYSTEMS

The geologic formations in the Jamestown area consist of sedimentary clastic and carbonate rocks ranging from Late Cretaceous to Pleistocene (?) in age (table 1). Portions of the Talbot (?) Formation and the Santee Limestone outcrop along the Santee River in the northern part of the study area and are exposed in the walls of the two limestone quarries. The stratigraphy of lower formations can be studied only by analyzing geophysical logs and drillers' logs of water wells. The Cretaceous formations have been correlated with the work of Zack (1977) in adjacent Georgetown County and the Tertiary Formations with the work of Spiers (1975) in the St. Stephens area. The sands and clays of probable Pleistocene age in this portion of the lower Coastal Plain were called the Talbot Formation by Colquhoun (1965). The stratigraphic relationships of the geologic formations are shown in a geologic cross-section from St. Stephens to Hampton Plantation in Charleston County (fig. 3). The stratigraphic section is composed of a clastic-dominated Cretaceous section and a carbonate-clastic Tertiary section.

The Jamestown area lies on the southwest flank of the Cape Fear arch and the geologic formations strike southeast or almost due east in the study area (fig. 1) and dip toward the south-southwest at approximately 5 to 20 ft/mi. The structure of rock units on the southwest flank of the arch have been delineated in detailed geologic cross-sections across Horry and Georgetown Counties by Allen Zack (1977).

These geologic formations can be divided into four major aquifer systems in the Jamestown area: (1) Santee aquifer which has been called the "Tertiary limestone aquifer," "principal limestone aquifer," or

Table 1. Summary of geologic formations and water-bearing properties of the rocks in the Jamestown area.

SYSTEM	SERIES	GEOLOGIC FORMATION	HYDROGEOLOGIC UNIT	DESCRIPTION AND WATER-BEARING PROPERTIES
HOLO-CENE	PLEISTO-CENE	Talbot Formation		Unconsolidated sands and clays, 0-20 ft thick. Hydraulically connected and supplies recharge to underlying Santee aquifer.
TERTIARY	MIDDLE EOCENE	Santee Limestone	Santee Aquifer System	Light-yellow to dark-gray, thin-to-medium bedded limestone and sandy limestone or calcareous sand near bottom. Major aquifer for domestic use in study area: supplies sufficient quantities of water for domestic, stock, and light industrial use.
	LOWER EOCENE PALEOCENE	Black Mingo Formation	Black Mingo Aquifer System	Upper unit: interbedded clastics and carbonates; Middle unit: limestone; Lower unit: mainly fine-grained clastics interbedded with well-cemented, thin-bedded sandstones. Hydrologic propertie poorly known but upper and middle units should supply sufficient water for domestic, stock, and possibly light industrial use. Water may contain high concentrations of iron.
CRETACEOUS	UPPER CRETACEOUS	Peedee Formation	Peedee Aquifer System	Approximately 400 ft of alternating beds of clay, fine-grained sand, and hard sandstone or sandy limestone. No wells in study area completed in this aquifer system and hydrologic properties poorly known.
		Black Creek Formation	Black Creek Aquifer System	Alternating beds of gray-to-white sand, dark-gray clay, and sandy limestone or calcareous sandstone. Sands are good aquifers and individual wells yield several hundred gallons of water per minute
		Tuscaloosa Formation	Tuscaloosa Aquifer System	Not tapped by wells in study area and hydrologic properties unknow Good aquifer in St. Stephens area of Berkeley County and in adjace counties (Williamsburg and Orangeburg).

Note: Boundaries of hydrogeologic units may not necessarily correspond to formal geologic formation boundaries.

"principal artesian aquifer" in various areas in South Carolina: (2) the Black Mingo aquifer system which is composed primarily of the Black Mingo Formation and other lower Tertiary clastics; (3) Peedee aquifer system; and (4) Black Creek aquifer system. The Tuscaloosa (locally called "Middendorf") aquifer system underlies the Black Creek aquifer system, but has not been penetrated by wells in the Jamestown area. Each aquifer system is composed of a series of water-bearing units (aquifers) and non-water-bearing units (confining beds). Ground water in the deeper Black Mingo, Peedee, and Black Creek aquifer systems is confined and rises above the top of the aquifer tapped. Ground water in the Santee aquifer occurs under both confined and unconfined conditions. The hydrogeology of the Santee aquifer is discussed more fully in a following section.

The Black Mingo aquifer system has been penetrated by wells 15X-L1 and 15X-L5 at Jamestown and is approximately 250 ft thick (fig. 3). In the Jamestown area and to the southeast, the Black Mingo is composed of a thick clastic lower section, a middle carbonate section, and an upper clastic-carbonate section. The lower section is composed of shale (called "gumbo" by local drillers) and interbedded hard "rocks" which are probably well-cemented sandstones.

Because the lithology of rocks in the lower Black Mingo section is similar to the lithology of rocks in the underlying Peedee aquifer system, there is no well-defined lithologic separation. The contact has been chosen above an uppermost sand in the Peedee aquifer system. The Black Mingo contains a water-bearing (permeability) zone in the carbonate section and a 6-in diameter well at the Ware quarry (well 14X-y1) is completed as an open-hole well from 90 to 167 ft in this aquifer system. In much of Berkeley County and in adjacent Georgetown County the Black Mingo supplies ground water to many wells. However, the water-bearing properties of the Black Mingo aquifer have not been fully evaluated in the Jamestown area because most domestic wells are completed in the overlying Santee aquifer, and two deeper wells have been completed in the Black Creek aquifer system.

The Peedee aquifer system is composed of approximately 400 ft of interbedded clays, thin beds of fine-grained sand, and hard sandstones (called "rocks" by drillers). No wells have been screened in the Peedee in the study area and the water-bearing properties are unknown. However, geophysical and drillers' logs indicate tha 15 ft of fine sands near the bottom and an uppermost sand, about 10 ft thick at well 15X-L5, may supply ground water to wells. Several other sandy zones, generally less than 10 ft thick, occur in the middle of this aquifer system. Sand aquifers in the Peedee supply ground water to some wells in Berkeley County and in Georgetown and Williamburg Counties, but much of the Peedee is composed of fine-grained clays that act as confining beds.

The upper part of the Black Creek aquifer system contains several aquifers in the interval from 670 to 900 ft below land surface at Jamestown. Wells 15X-L1 and 15X-L5 in Jamestown are the only wells in the study area that withdraw ground water from the Black Creek aquifer system. The municipal well at Jamestown (well 15X-L1) contains 63 ft of

5 5/8-in diameter screen in the interval from 770 ft to 891 ft below land surface, and was reported by the driller to produce 127 gpm with a pumping water level of 201 ft at a specific capacity of 0.63 gpm/ft (gallons per minute per foot) of drawdown. Well 15X-L5 contains 50 ft of 6-in diameter screen in the interval from 770 ft to 880 ft below land surface. When drilled in 1954, the well was pumped at 275 gpm with a reported specific capacity of 2.5 gpm/ft. Data from these wells and wells outside the study area indicate that properly-constructed individual wells screened in sands of the Black Creek aquifer system should be capable of producing from 200 to over 400 gpm. With proper well construction, individual wells could probably be expected to have a specific capacity of approximately 4-5 gpm/ft.

WATER USE

PUBLIC, DOMESTIC, AND INDUSTRIAL SUPPLIES

At present, ground water is the source of all water for public and domestic drinking water supplies in the study area. The only municipal water system in the study area is in the City of Jamestown which is supplied by one 6-in diameter well completed in the Black Creek aquifer system (well 15X-L1). Reported water use from this system currently averages about 25,000 gpd (gallons per day) and serves 80-85 customers (275-300 people) including a day-care center and restaurant (Mayor J. Y. Clarke, oral communic., Aug. 23, 1977). A 6-inch distribution line extends along highway 45 to approximately 1,000 ft northwest of the Methodist parsonage (well 15X-t9); a 2-in line extends to the parsonage. Southeast of the parsonage, all drinking water is obtained from individual domestic wells.

The only industrial wells in the study area are at the Santee Wool Combing Plant (well 15X-L5) and at two limestone quarries (well 14X-y12, 14X-y1). Well 15X-L5 is completed in the Black Creek aquifer system and maximum daily water use from this well is reported to be approximately 25,000 gpd. Well 14X-y1 at the Ware quarry is used as a source of drinking water and some water is used in washing equipment; total water use from the well is probably less than 15,000 gpd. Well 14X-y12 at the B.A.S.S. quarry is no longer in use.

The largest number of wells inventoried in the study area supply domestic drinking water. Fifty-two domestic wells in the study area are used as a source of drinking water; three wells are used primarily for stock watering, but are occasionally used for drinking water. Sixteen wells are presently unused and 4 wells are used only occasionally for stock watering. These wells are all completed in the Santee aquifer, and the combined pumpage from the 59 domestic and stock wells probably does not exceed 10,000 gpd.

In summary, the amount of water used for public, domestic, industrial, and stock supplies within the study area is estimated to be no more than 90,000 gpd, and only about 10,000 gpd of this amount is withdrawn from the Santee aquifer.

DEWATERING OPERATIONS

The B.A.S.S. (Berkeley Agricultural Sales and Supply) Ltd. quarry began mining operations in March or April, 1975. Dewatering operations began in late Summer--early Fall, 1975, and continued intermittently through the Summer of 1977. When the quarry was in operation, from the Summer of 1975, until December, 1977, pumpage was reported to be frequently in excess of 10,000 gpm (14.4 mgd). When visited on March 25, 1977, pumpage at the quarry had been reduced because of pumpage at the adjacent Ware quarry. According to the B.A.S.S. quarry superintendent, pumpage during March, 1977, had averaged an estimated 10,000 gpm for 12 hours daily (7.2 mgd) (Mr. Thomas Mathis, oral communic., March 25, 1977).

The Ware Brothers Construction Company quarry (Ware quarry) officially opened on December 31, 1976. The Ware quarry owners opened the quarry as a "dry operation," and anticipated that complete dewatering would be necessary in order to operate. Dewatering operations at the Ware quarry began in late January--early February, 1977. When visited by the writer on February 8, 1977, approximately 500 gpm was entering the quarry from solution channels in the northeastern end of the quarry. One rotary pump was in operation at the time and approximately 1,000 gpm was being pumped from the quarry. The mine was deepened, and in April, 1977, two pumps were in operation. On April 7-8, 1977, an estimated 15,000 gpm (21.6 mgd) was being discharged from the quarry, and on April 8, 1977, the pumping water level was survey at -8.01 ft msl. On September 1, 1977, in excess of 15,000 gpm was being discharged from the quarry, and the pumping water level was surveyed at -15.2 ft msl, the lowest pumping water-level elevation surveyed by mining officials.

HYDROGEOLOGY OF THE SANTEE AQUIFER

GENERAL DESCRIPTION AND DISTRIBUTION

The Santee Limestone underlies the entire study area (fig. 1) and is composed of a light-yellow to dark-gray fine-to-coarsely-crystalline, fossiliferous limestone and a lower section of clastics, probably calcareous sand. In the northeast wall of the Ware quarry the Santee Limestone is 63 ft thick, and is interpreted to be 65 ft thick in well 15X-L5 at Jamestown. The Santee Limestone thins to a featheredge beneath younger sediments to the northwest and thickens to approximately 85 ft in the Hampton Plantation well to the southeast (fig. 3). In the Jamestown area, the Santee Limestone is unconformably overlain by the Talbot Formation and unconformably overlies the Black Mingo Formation.

The Santee aquifer, composed of the Santee Limestone, is widely used as a source of ground water in the Jamestown and surrounding areas of Berkeley County. The aquifer supplies ground water to many domestic wells in northeastern Berkeley County. However, the Santee aquifer thins northwest of the Jamestown area, and the underlying Black Mingo aquifer system is the most important source of ground water to domestic wells. South and southeast of the Jamestown area, the Santee aquifer is overlain by the Cooper Marl, a relatively impermeable formation which acts as a confining bed. Apparently, where the Cooper Marl overlies the Santee, the Santee lacks good permeability development, and aquifers within the Black Mingo are used for ground-water supplies.

WATER-BEARING PROPERTIES

Ground water in the Santee aquifer occurs in solutionally-enlarged openings, primarily along lithologic contacts within the limestone. The upper part of the aquifer is a highly-weathered zone containing solution cavities up to several feet in diameter and is the most permeable part of the aquifer. This upper permeability zone is approximately 15 ft thick in the walls of the two quarries (fig. 4). Many domestic and stock wells in the study area penetrate this upper permeability zone from 15 ft to 30 ft below land surface. Local well drillers report that the limestone becomes "sandy" at a depth of about 85 ft below land surface and they do not like to drill wells into this sandy zone because of sand problems. One well-drilling contractor and several well owners reported that open solution cavities as much as 5 ft in diameter were penetrated in their wells.

Below the upper permeability zone, the limestone is hard and compact, and solution openings are not as numerous and well developed as in the upper permeability zone. Limestone in this lower zone is being mined as a source of construction aggregate and agricultural lime at the Ware quarry, and was formerly mined for construction aggregate at the B.A.S.S. quarry.

According to the classification of carbonate-rock aquifers of White (1969), the Santee aquifer is a free-flow uncapped aquifer in the Jamestown area. However, the upper permeability zone contains extensively interconnected water-bearing solution openings. Because of this extensive permeability development, the upper permeability zone probably acts much as a confined, diffuse-flow aquifer. Therefore, properly-conducted aquifer tests on wells completed in the upper permeability zone should allow the calculation of meaningful values of transmissivity and storage. Unfortunately no wells have been available with which to conduct such tests, nor to calculate the specific capacity of wells.

WATER QUALITY

The chemical quality of ground water from the Santee aquifer is poorly known because complete chemical analyses are not available at this time. One problem reported by local residents is excessive hardness and at least one well owner has a water softener (well 14X-x11). Some well owners also report problems with excessive concentrations of iron, and the water commonly stains household fixtures.

WATER-LEVEL FLUCTUATIONS

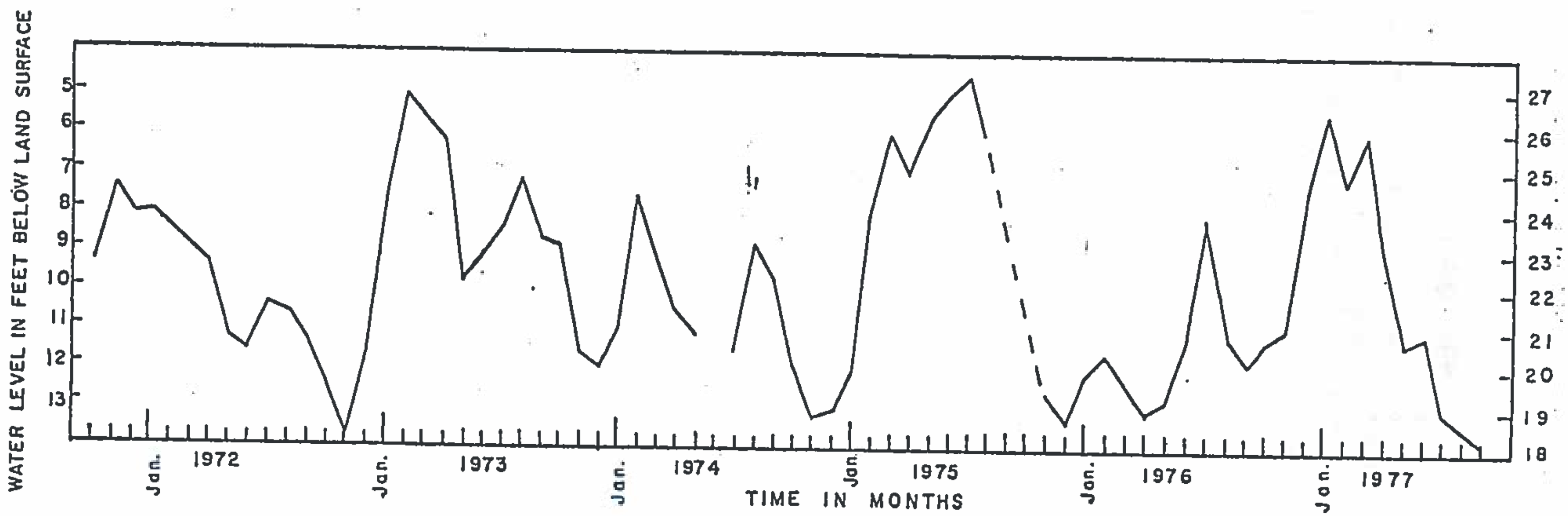
Water levels in the Santee aquifer have been recorded in a U. S. Geological Survey observation well, Brk-53 (15X-L2), at Jamestown since October, 1971, and the monthly mean hydrograph of this well is shown in figure 5. This well is completed in the upper permeability zone of the Santee aquifer from 28-32 ft below lsd (land surface datum). Water levels in this well are unaffected by local pumpage; therefore, the hydrograph represents natural water-level fluctuations in the Santee aquifer. This hydrograph indicates that water levels respond to seasonal variations in rainfall. Water levels are normally lowest during the late Fall (October) and highest following winter rains. Water levels also respond to heavy rains during the Summer, primarily during July.

GROUND-WATER RECHARGE, DISCHARGE, AND MOVEMENT

Prior to dewatering operations near Dutart Creek, the original ground-water level of the Santee aquifer in the Jamestown area was controlled mainly by the distribution of natural recharge and discharge areas. Dutart Creek was a natural discharge area, and ground water discharged through springs in and along this stream. Ground water also discharged through a series of springs along the Santee River in the northern part of the study area, and longtime, local residents report that the springs never went dry--even during prolonged dry periods. However, the natural ground-water gradient toward the Santee River and Dutart Creek has been reversed by pumpage, and flow in the springs along Dutart Creek and the Santee River has been decreased or has been stopped entirely.

A potentiometric map of the Santee aquifer was constructed from water-level measurements made in 11 unused wells and 10 temporarily unusable wells on September 7, 1977 (fig. 6). In addition, accurate elevations of the water levels in the two quarries were obtained by leveling. It was reported that there had been no pumpage at either quarry for 3 or 4 days prior to September 7, 1977 (Mr. Jack Whisnant, written communic., September, 1977). The potentiometric map shows a semi-circular cone of depression centered on the quarries, and ground water is moving toward the quarries from all directions. In addition, the map indicates that water in the B.A.S.S. quarry serves as a line-source of recharge to the Ware quarry. The swampy area along Dutart Creek northeast (downstream) of the quarries has been dewatered and is also a source of recharge to the cone of depression. Consequently,

FIGURE 5 MEAN MONTHLY HYDROGRAPH OF OBSERVATION WELL BRK-53 AT JAMESTOWN, S.C.



Source: U.S. Geological Survey, Water Resources Data for South Carolina, published annually.

the water-level contours are elongate in a northeastward direction--indicating a lower hydraulic gradient in that direction. The steepest hydraulic gradient are south and west of the quarries between the +20 and +5 water-level contours.

The potentiometric map indicates that the upper part of the Santee aquifer, at least near Dutart Creek, behaves hydraulically as a confined, diffuse-flow aquifer. The large cone of depression centered on the limestone quarries has steepened the hydraulic gradient and has caused adjustment in ground-water flow in a large area around the quaries. Therefore, the potentiometric map is believed to accurately reflect ground-water levels in the Santee aquifer in the Dutart Creek area.

WATER-SUPPLY PROBLEMS

Within an approximate radius of 1.5-mi from the quarries at Dutart Creek, 50 domestic wells are the only source of drinking water for rural residents. Three wells are used primarily for stock watering use and occasional domestic use, and 4 wells are used only occasionally for stock use. Thus, a total of 57 wells are used on a regular or periodic basis for domestic drinking-water supply or stock watering, and well owners have reported problems with 37 of these wells. The drilled, open-hole wells range from 15 ft to 110 ft deep, are of small diameter (1, 1¼, 1½, 2-in diameter casing), and are completed in the Santee aquifer (table 2, appendix).

Most wells in the study area are equipped with an electrically-powered jet pump but several shallow wells are equipped with hand-operated pitcher pumps. Most of the jet pumps are the so-called "shallow-well jet", which is located above the well and delivers water through a single pipe by suction lift. The practical lift of the shallow-well jet pump recommended by most pump manufacturers is 25 ft and a shallow-well jet, for all practical purposes, will not operate when the lowest pumping water level below the pump inlet head is greater than 25 ft. Several wells are equipped with a "deep well packer assembly" that increases the practical pumping lift of the shallow-well jet pump.

Many well owners in the area report that the static water level (as measured by the owners, water-well or pump contractors), prior to large-scale dewatering was approximately 5-15 ft below land surface. Therefore, the water levels were well within the lift capability of shallow-well jet pumps. However, large ground-water pumpage from the quarries since the Fall of 1975 has lowered water levels in some wells below the practical pumping lift of many shallow-well jet pumps.

In late Summer--early Fall, 1975, some residents began noticing reduced water pressure in wells, and at least one resident had to lower his pump intake from 21 ft to 26 ft (well 14X-y4). The problems became more severe during the Summer of 1976, and other residents had to deepen intakes or install new pumps. Some pumps had to operate for long periods in order to build adequate pressure in pressure tanks, and some residents had to manually operate pump switches in order to prevent their pumps from "burning up." On November 20, 1976, the pump on well 14X-y34 "burned out" and had to be replaced.

During the Summer of 1977, water levels were lowered below the bottom of 5 shallow wells and these well owners had to haul drinking water or obtain water from nearby neighbors (wells 14X-y9, 14X-y7, 15X-t12, 15X-t13, 14X-p6). Water levels were lowered below the pump intakes of 12 other wells (14X-p2, 14X-x1, 14X-x8, 14X-y3, 14X-y4, 14X-y8, 14X-y17, 14X-y23, 14X-y27, 14X-y29, 14X-y34, 15X-t8). In August and September, 1977, water levels were lowered below the pump intakes of 3 more wells (14X-x6, 14X-y6, 14X-y16). In addition, other residents reported that water pressure was so low that they could use their well for only one water-using activity at a time and could not wash clothes or take baths (14X-x2, 14X-x4, 14X-y13, 14X-y15, 14X-y18, 14X-y28, 15X-t11, 14Y-d3). During the Winter of 1977, the aquifer was recharged by the seasonal rains, water levels partially recovered, and some wells could again be used.

Other water-supply problems include turbidity and sand in wells. According to local residents these problems frequently occur after explosives are detonated in the nearby quarries. Solution cavities are often filled with fine clay particles that become loosened by shock waves and appear in water pumped from wells. Several well owners have installed filters on wells to remove the suspended sediment.

The limits of the reported water-supply problems are approximately defined by the +20 msl water-level contour on figure 6. Dewatering operations, first at the B.A.S.S. quarry and later at the Ware quarry, have created a large cone of depression and wells within a 1.5-mi radius of the quarries have been affected by the pumpage. Presumably, with continued dewatering operations and reduced natural recharge to the aquifer during the summer, similar well problems will occur during the Summer of 1978.

LAND-SURFACE COLLAPSE

DISTRIBUTION AND HISTORY OF DEVELOPMENT

Collapse of the land surface is a common occurrence in areas underlain by soluble carbonate rocks. Collapses have sometimes been called "sinkholes" or "sinkhole collapses." The term "sinkhole" is inappropriate for these features because the term "sinkhole," synonymous with "doline," refers to a naturally-occurring depression formed by solution of underlying rocks. Collapses, as developed in the Jamestown area, are steep-sided, closed, circular, or ovate-shaped depressions of various dimensions occurring in unconsolidated sands or clays overlying soluble Santee Limestone. The sides of collapses are often vertical, or are convex from the center of the depression resulting in a bell-shaped appearance in cross section. Subsidence depressions are generally shallow, closed depressions lacking the steep sides common to collapses. Frequently a subsidence depression preceeds a collapse, and a collapse may occur within a subsidence depression.

Collapses or sinkhole collapses have occurred in many areas of the world and have caused considerable damage. Perhaps the most notable collapses have occurred in the Far West Rand, South Africa. From 1959 through 1964, collapses occurring as a result of the dewatering of gold mines claimed the lives of 34 persons; in December, 1962, a sinkhole collapse engulfed a three-story crusher plant, and 20 lives were lost (Bezuidenhout and Enslin, 1969). In the United States, sinkhole collapses have been described from Pennsylvania (Foose, 1953; Parizek, White, and Langmuir, 1971), Florida (Stewart, 1966; Fernandez, 1969), California (Love, 1966), Alabama (Swindel, 1956; Powell and LaMoreaux, 1969; Newton and Hyde, 1971; Spigner, 1974, 1975; Warren, 1974; and Spigner and Graves, 1977), Missouri (Aley, Williams, and Massello, 1972), and other areas.

The dates of occurrence and accurate locations of collapses and subsidence depressions are important in constructing relationships between these features and probable causative mechanisms. Unfortunately, dates of occurrence and locations of some collapses could not be accurately determined in all instances because residents could not always recollect dates, and some collapses were simply covered over, especially on farmed lands. The locations of mapped sinkhole collapses and subsidence depressions are shown on figure 7, and information on these features are summarized in table 3 (appendix). Undoubtedly, other collapses and subsidence depressions exist, but have not yet been discovered or have not been reported.

Land-surface collapses in the study area first occurred as early as April or May of 1976 on the property of B.A.S.S. Ltd. When dewatering operations began in late Summer, 1975, Dutart Creek drained into a collapse in the streambed (Mr. Wildon Hucks, personal communication, October 6, 1976). Apparently, throughout late Summer and Fall of 1976, the entire flow of Dutart Creek entered the B.A.S.S. quarry through channels and cavities in the limestone. In February, 1976, the largest of 3 collapses reportedly occurred on the property of Mr. Curtiss Jones (no. 4). From June 20 to July 1, 1976, approximately 7 collapses occurred, and were discovered by Mr. T. E. Casselman on his farm property on July 1, 1976, (nos. 7-12). Several subsoil cavities were collapsed by Mr. Casselman's tractor as he plowed his farm in early July, 1976.

On the morning of September 11, 1976, a second large collapse (no. 5) was discovered on Mr. Curtiss Jones' property and a small tree or shrub is reported to have disappeared into the collapse during the night. In August or September, 1976, several collapses occurred on the apron of Highway 45, and were filled with several truck loads of soil (nos. 27, 28). During this same time period (Summer--Fall, 1976) collapses occurred at the Mt. Zion Church recreation building (no. 26), at the St. James cemetery (no. 3), and on the farms of Mr. T. E. Casselman (no. 13), Mr. Glenn Pipkin (no. 19), and Mr. Curtiss Jones (no. 6). Many collapses have occurred in the Francis Marion National Forest property and some were discovered by local residents in July--August, 1976 (nos. 16, 17, 18).

The most serious incident occurred in the Winter of 1976, when Mrs. L. D. Myers was reportedly injured by a fall into a subsoil cavity that collapsed in her back yard (no. 29). On August 31, 1977, a collapse (no. 15) occurred under a combine driven by Mr. T. E. Casselman, who escaped possible injury because the corn header caught on the rim of the collapse, probably preventing overturning of the combine. When visited by the writer on September 1, 1977, the collapse was approximately 5 ft in diameter and at least several feet deep, although the bottom of the collapse could not be observed. Several days later, on September 3 or 4, 1977, Mr. Casselman's combine fell into another collapse. In 1976, a collapse (no. 3) occurred under or near a tractor driven by Mr. Glenn Pipkin at the St. James cemetery.

Collapses are still occurring in the collapse-prone area delineated on figure 7, and they have become common on the farm property of Mr. T. E. Casselman and along Highway 45.

CAUSE AND MECHANICS OF FORMATION

It is possible for sinkhole collapses to occur in carbonate terranes as a result of naturally-occurring processes. Such collapses, however, are generally not numerous and usually occur in areas of naturally-steep ground-water gradients, often near surface streams. The previously described "earthquake holes" on the property of James Pipkin, formed by natural geologic processes a few days after the 1886 Charleston earthquake, are somewhat unique examples of naturally-occurring sinkhole collapses. However, the occurrence of numerous, previously-unrecorded collapses in a small area is usually due to artificial influences of man and is generally related to dramatic fluctuations of the ground-water table. Examples of such artificial influences are dewatering operations, large ground-water withdrawals from wells, and construction operations (such as impoundments and highways).

The artificial dewatering of quarries in karst aquifers has resulted in dramatic fluctuations of the ground-water table in several locations and has contributed to land-surface collapse. Foose (1953) described how ground-water pumpage by mining companies dried up wells and springs and triggered ground collapse and subsidence depressions in the Hershey Valley, Pennsylvania. Similar conditions were described near marble quarries at Sylacauga, Alabama by Swindel (1956) and near a limestone quarry at Birmingham, Alabama by Newton and Hyde (1971). Quarry dewatering operations in Maryland were responsible for collapses on a nearby farm (Walker and Cox, 1976).

Sinkhole collapses in carbonate terranes have been triggered by ground-water pumpage from wells. Powell and LaMoreaux (1969) described land-surface collapses caused by excessive pumpage from two municipal wells in a highly-fractured karst aquifer at Columbiana, Alabama. Spigner (1974) described how excessive pumpage and the use of high pressures during well-development operations caused land-surface collapse and subsidence at the Eastwood Mall near Birmingham, Alabama. A hydrogeologic study of folded carbonate-rock aquifers near Irondale, Alabama revealed that subsidence and land-surface collapse were caused by excessive pumpage from wells drilled into fault or fracture zones (Spigner, 1975). Spigner and Graves (1976) described the problems experienced by water-well contractors in completing and developing wells in both confined and unconfined carbonate-rock aquifers in Alabama and provided suggestions on methods to avoid cratering and land-surface collapse.

In the Jamestown area, the following conditions have combined to make the area prone to the development of collapses and subsidence depressions: (1) the presence of the Santee aquifer, a cavernous, uncapped limestone aquifer at shallow depths below land surface; (2) a variable thickness of unconsolidated sands and clays overlying the Santee aquifer; (3) hydraulic connection of the surface to the aquifer through natural features such as vertical solution slots (cutters), sinkholes, and features constructed by man (e.g., drainage ditches); (4) withdrawal of large quantities of ground water by quarrying operations which has resulted in dramatic water-level fluctuations and a substantial lowering of the ground-water table (potentiometric surface); and (5) the movement of ground water from areas of recharge to areas of discharge.

Once an area has been made prone to the development of collapses by a lowered water table and weakened soils overlying bedrock, various "triggering" mechanisms can cause final collapse of the land surface. Collapses can be triggered naturally or by activities of man. A natural triggering mechanism is rainfall because rain falling on the ground surface adds a surcharge load which can trigger collapse by the simple addition of weight. Commonly, runoff in drainage ditches or furrows in a plowed field can trigger a collapse--especially where a weakened arch in the soil occurs near land surface. Triggering mechanisms caused by man's activities include (1) addition of load by vehicles moving over weakened soils, (2) blasting or setting off explosive charges in quarries or for construction projects, (3) construction of various drainage features, and (4) water-well construction--especially if high pressures or pumping is utilized in developing wells.

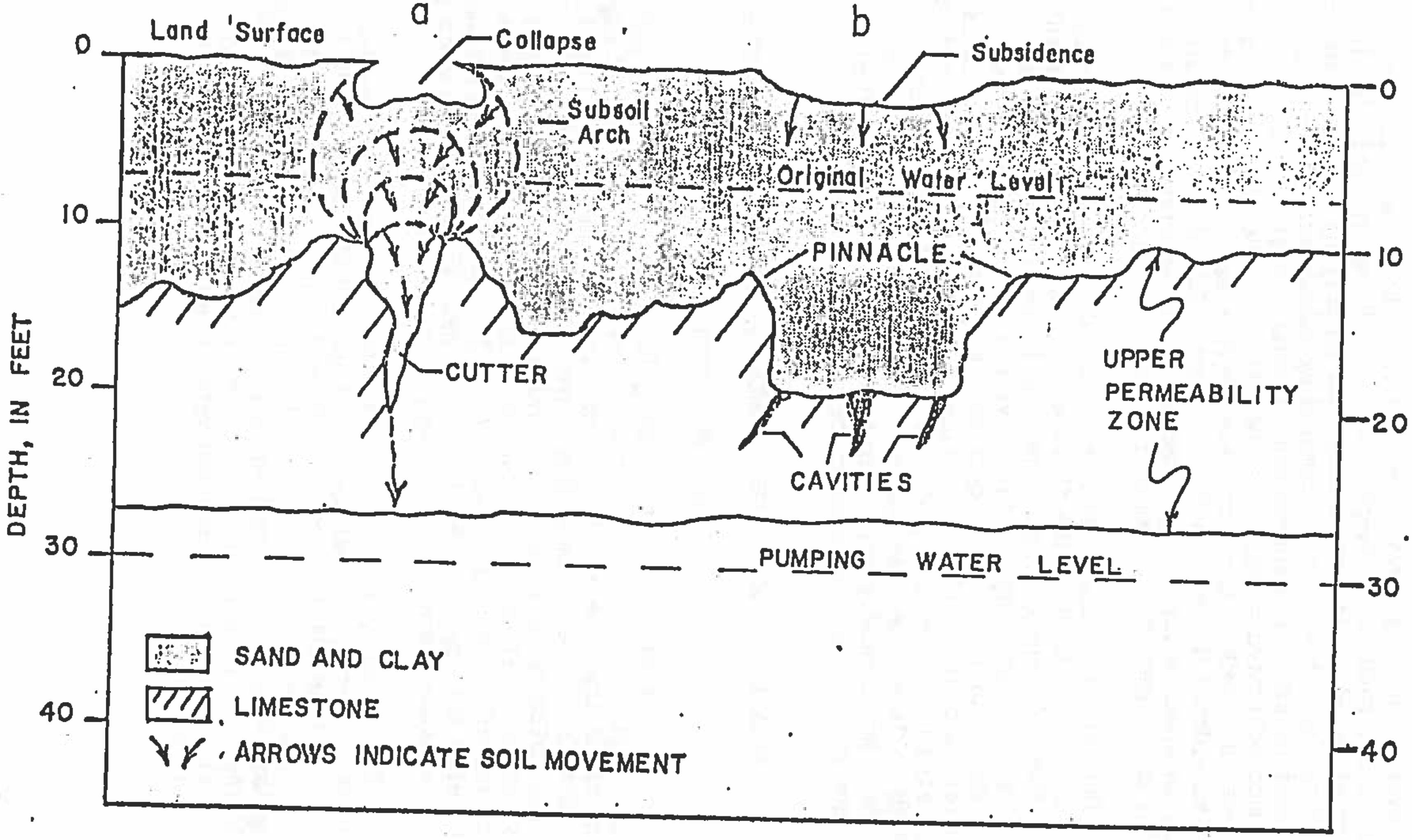
The underlying cause of collapses and subsidence depressions in the Jamestown area has been a substantial lowering of the ground-water table or potentiometric (artesian) head of the Santee aquifer. As shown previously (fig. 6), a large cone of depression exists around the limestone quarries and the water level in the Santee aquifer has been substantially lowered. Prior to the beginning of dewatering in 1975, the potentiometric head (water level) of the Santee aquifer was at an approximate elevation of +15 ft msl in the southwest end of the B.A.S.S. quarry. Conversation with quarry employees indicates that when drill holes (4-in diameter) were drilled for the first explosive charges in the B.A.S.S. quarry (March or April, 1975), the artesian pressure forced ground water from the blast holes approximately 5 ft above land surface. Wooden logs had to be driven into the blast holes to stop the flow of ground water in order to keep working levels dry (T. E. Casselman, oral communic., 1976). On April 7 and 8, 1977, the non-pumping water level in the B.A.S.S. quarry was at an elevation of -4 ft msl. Therefore, the total head decline at the B.A.S.S. quarry has been a minimum of 19 ft. Pumping water levels at the B.A.S.S. quarry were probably on the order of -10 ft msl in the past which indicates a total head decline of 25 ft. Total potentiometric head decline in the Ware quarry is estimated to have been a minimum of 35 ft.

The normal fluctuation in the ground-water level in the Santee aquifer for the period October, 1971 to the present, recorded by U. S. Geological Survey observation well Brk 53 at Jamestown, has not been more than about 10 ft (fig. 5).

Figure 8 is a schematic diagram which illustrates the formation of collapses and subsidence depressions in the Jamestown area. Collapses (a) occur when subsoil arches form in cohesive clays overlying the Santee Limestone. These arches form between pinnacles of limestone which provide the solid abutments or "hinge lines" of the arch. Vertical solution cavities (cutters) are filled with clays that are cohesive as long as the ground-water table is fairly stable. As the ground-water table declines, soil is removed by subsurface erosion (piping) and carried into underlying cavities in the limestone. The clays have sufficient strength to form a temporarily stable (metastable) arch in the clays below land surface. Eventually, the clays lose strength and the arch collapses, or a collapse is triggered by the addition of a load, such as a passing vehicle, on the land surface. The problem is compounded if surface runoff enters the subsurface over or in the immediate vicinity of a subsoil arch. Collapses often occur immediately following periods of heavy rainfall because the rainfall can trigger the collapse of subsoil arches. Evidence which supports this "arching" theory of collapse is the absence of any accumulation of sediments in the bottom of collapses, the frequently observed convex-outward (bell-shaped) shape of collapses, and the fact that clays (as opposed to sand) are generally exposed in the sides of these bell-shaped collapses.

Indirect evidence to support the arching theory is also provided by examination of the soil-limestone contact in the quarry walls. Cutters and pinnacles are exposed in the northwest wall of the B.A.S.S. quarry and in the southeast wall of the Ware quarry. Cutters are filled with cohesive clays and the soil-limestone contact is highly irregular. The irregular contact is responsible for differential subsidence because of uneven stress distribution of loads imposed on the ground surface or as the water table declines. This irregular contact provides the necessary conditions for arching; the limestone pinnacles provide the solid abutments and the cutters provide the conduits for subsurface erosion of soils.

FIGURE 8. FORMATION OF COLLAPSES IN JAMESTOWN AREA



Subsidence depressions (fig. 8 b) are more likely to form in areas where the pinnacles are more widely spaced so an arch cannot form. Such depressions are also more likely to form where the soils overlying limestone bedrock are sandy and non-cohesive. As the water table declines and unconsolidated sands are carried into underlying cavities, inward soil creep replaces the material removed by subsurface erosion. Subsidence depressions are often surrounded by radial tension cracks which form as the unconsolidated material is sheared along the circumference of the depression. Such cracks sometimes provide early warning of the formation of a subsidence depression or a collapse. Subsidence depressions can also occur in areas underlain by cohesive clays. As clays are drained, compaction of the clays results in compaction subsidence depressions.

The lateral diameter and depth of collapses and subsidence depressions are directly related to the thickness of unconsolidated sediments in which these features occur. The size is not necessarily related to the diameter of underlying solution cavities in the Santee Limestone nor the total amount of water-level decline. A solution cavity which is 6-in in diameter is capable of transporting large volumes of water and sediment. It is also not necessary that cavities in the limestone occur directly beneath collapses because sediment can be transported vertically a short distance, horizontally for several hundreds of feet, and then discharged into quarries or natural subsurface outlets.

RELATION OF WATER-TABLE LOWERING, LAND-SURFACE COLLAPSE AND WELL PROBLEMS

There is a direct relation among land-surface collapse, water-well problems and lowering of the water table. The potentiometric map (fig. 6) indicates that the +20 ft msl contour approximately delineates the outer limits of the collapse-prone area (fig. 7). As of this writing, only one collapse is known by the writer to have occurred outside the +20 ft msl water-level contour. The incidence of collapses increases toward the center of the cone of depression. The lowering of the ground-water table below the upper permeability zone near the quarries favors greater subsoil erosion--both from above and below land surface.

On September 1, 1977, pumpage at the Ware quarry was estimated by the writer to be approximately 15,000 gpm and the water level in the quarry was at an altitude of -15.2 ft msl. This rate of pumpage, according to local residents, had been maintained, although not continuously, during late August, 1977, and for several weeks in September, 1977. It was during this time interval (mid-August to mid-September, 1977) that additional collapses occurred and water levels lowered below the pumps of additional wells.

DAMAGE AND HAZARDS

The collapses and subsidence depressions in the Jamestown area have caused damage to private property, County Highway 45, and the foundation of a church and recreation building (table 3). The most potentially dangerous situations exist from unstable (metastable) subsoil arches which cannot be seen. Various "triggering" mechanisms, as previously described, have caused the sudden collapse of land surface. One local resident was reportedly injured when a collapse occurred in her back yard, and at least four other residents are reported to have escaped injury when subsoil arches were collapsed by a combine, farm tractor, or car.

Collapses and subsidence depressions have occurred on and near the apron of Highway 45, requiring filling and periodic maintenance by the S. C. Department of Highways and Public Transportation. A collapse (no. 26) has damaged the foundation of the Mt. Zion Church recreation building. Church members have, on several instances, added fill to the depression in order to prevent further damage.

Subsidence depressions occur more slowly and are less likely to result in personal injury. Nevertheless, such depressions have required costly filling and maintenance along Highway 45 and in several driveways; if surface water is allowed to collect in these depressions, they are susceptible to the formation of collapses.

DETECTION AND PREVENTION

The detection of collapses and subsidence depressions prior to their occurrence is a difficult, if not impossible, task. It is literally impossible to predict the exact locations of unstable soil arches before collapse occurs. The collapse-prone area outlined in figure 7 delineates the area where all collapses and subsidence depressions known to the writer have occurred. Some collapses or subsidence depressions may have occurred outside this collapse-prone area, but have not been discovered or reported to this writer. Figure 7 depicts the critical problem area based on hydrogeologic conditions existing in September, 1977. If pumpage is increased, then the collapse-prone area will most likely be enlarged.

Land-surface collapse is not likely to cease until ground-water levels are allowed to recover into the upper permeability zone of the Santee aquifer. This recovery of water levels will most probably require a cessation of large-scale ground-water withdrawals. Without a cessation of pumping, a grouting program is the only other solution to the problems if the limestone is to be mined as a "wet" operation. A grouting program would be expensive and available data are not sufficient to predict with any degree of accuracy whether grouting is technically or economically feasible.

SUMMARY AND CONCLUSIONS

The Jamestown area, located in northeastern Berkeley County, South Carolina is a covered karst underlain at shallow depth by the Santee Limestone. The Santee Limestone, quarried for agricultural lime and construction aggregate, is also the most important source of ground water for domestic and stock use, and limited public and industrial use in the Jamestown area. Less than 25,000 gpd of ground water is currently withdrawn from the Santee aquifer for these uses in the Jamestown area. Wells completed in the deeper Black Mingo aquifer system and the Cretaceous Black Creek aquifer system supply less than 50,000 gpd for public-supply and industrial uses in the study area.

Since the Summer of 1975, large quantities of ground water have been pumped from the Santee aquifer during dewatering operations. At one quarry pumpage has reportedly been in excess of 10,000 gpm (14.4 mgd), and more than 15,000 gpm (21.6 mgd) has been periodically withdrawn from another quarry since February, 1976. Combined pumpage at both quarries for certain periods of time during 1977 was likely more than 25,000 gpm (36 mgd).

These large ground-water withdrawals have caused a large cone of depression in the Santee aquifer and a potentiometric map, constructed in September, 1977, indicates that water levels have been lowered in wells located over 1.5 miles from the quarries. Water levels have been drawn below the bottoms of some wells, below the pump intakes of some wells, and below the practical pumping lifts of shallow-well jet pumps in other wells. In many wells the water pressure has been so low at times that wells have been unable to pump sufficient water for normal household uses. Several residents have had to make pump or well repairs, install new pumps, or drill a new well.

Blasting operations have caused "muddying" of wells as shock waves loosen clay particles from solution cavities and solutionally-enlarged bedding planes in the Santee aquifer. Muddied ground water is then withdrawn through wells.

The most serious problem in the Jamestown area has been land-surface collapse. Collapses of the land surface, ranging from less than 1 ft to over 24 ft in diameter, have occurred on private property, on the apron of County Highway 45, and in the Francis Marion National Forest. These collapses occur in unconsolidated sands and clays overlying the Santee aquifer, and are caused by dramatic fluctuations of the ground-water table. Total water-level decline since the Summer of 1975, caused by dewatering operations, has been as much as 35 ft at one quarry. The distribution of collapses, as presently mapped, has been within a northwest-trending collapse-prone area and the most dramatic collapses have occurred within about 5,000 ft from the points of largest groundwater withdrawals. Available data indicates that collapses will probably continue to occur as long as the ground-water table remains below a highly-weathered, cavernous upper permeability zone of the Santee aquifer. If pumpage were ceased, the ground-water table should be expected to rise into this upper permeability zone. If large ground-water withdrawals continue, then collapse of the ground surface will probably continue. If pumpage is increased and ground-water levels are lowered further, the collapse-prone area will likely become larger and problems will probably become more severe.

Currently, ground-water pumpage and water levels in the one operating quarry are not monitored and water levels are likely lowered below 10 ft below msl for certain periods of time. Water levels in a series of small-diameter (1¼-in casing) unused, abandoned domestic wells have been periodically measured, but not on a regular, systematic basis. It is of critical importance that ground-water pumpage, if allowed to continue, be monitored regularly by appropriate personnel, and water-level elevations at points of withdrawal should be determined.

The water-supply problems of the Jamestown area could likely be solved by deepening selected wells into the Santee aquifer, installing 2-in or 3-in diameter casing and deep-well packers. In some cases it would probably be more economical to drill a new well. Some residents may wish to tap onto a distribution line from the Jamestown municipal water system if the distrubution line is extended near their property; however, distribution lines could probably not economically be extended to all of the affected area. If extension of public water lines is contemplated, consideration should be given to the collapse-prone area delineated in this report. Without proper surface-drainage control and adequate compaction of soils, additional collapses can be triggered by construction operations. Some of the largest and deepest collapses have occurred along County Highway 45, a critical collapse-prone area.

Solutions to the problem of land-surface collapse are not so straightforward. The area has been made prone to the development of collapses by large ground-water withdrawals near Dutart Creek. Although a collapse-prone area has been delineated, scientific methods are not presently available to accurately predict the exact locations of collapse before they occur. The sudden collapse of "bell-shaped" subsoil arches is the most dangerous type of collapse because these cannot be seen and the overlying soils can be collapsed by even light loads, such as the weight of a person. Data from other areas in the world where similar collapse has occurred indicate that the occurrence of collapses is drastically reduced or stopped entirely once ground-water levels are allowed to recover.

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APPENDIX

EXPLANATION OF TABLE 2

Column

(1)-(4) Self explanatory

(5) Measured well depths reported to nearest tenth of a ft. Reported well depths reported to nearest ft.

(6) Most drilling dates are reported by well owners and are approximate. Designation "old" refers to wells older than 10 years.

(7) Self explanatory

(8) Use of well

- P - Public-supply well
- A - Well abandoned and destroyed, or cannot be used
- D - Domestic supply
- S - Stock use
- N - Well not used
- I - Industrial supply

(9) Aquifer

- Ts - Santee
- Tbm - Black Mingo
- Kbc - Black Creek

(10) Pump type

- P - Pitcher pump
- Js - Shallow-well jet pump
- Jd - Deep-well packer assembly
- N - None

Table 2. Summary of well data, Jamestown area, South Carolina.

(1) SCWRC Well No.	(2) Field No.	(3) USGS Well No.	(4) Owner/Location	(5) Well Depth (ft)	(6) Driller Date Drilled	(7) Well Diam. (in)	(8) Use of Well	(9) Aquifer	(10) Pump Type	(11) Comments
14X-m1			U.S. Forest Serv. Guillard Lake Rec. Area	unkn.	unkn.	2	P	Ts?	P	
14X-p1	37		Glenn Pipkin	24.6	Cales 1952	1¼	N obs. well	Ts	P	
14X-p2	23		Glenn Pipkin	40	unkn. 1950?	3	S	Ts	Jd	Reduced water pressure, new pump with deep-well packer installed in May, 197
14X-p3	30		James Pipkin	37.4	Mitchum 1940	2	N obs. well	Ts	P	
14X-p4	31		James Pipkin	75	Brazzell 1973	2	S	Ts	Js	Reduced water pressure, Summer, 1977.
14X-p5	32		James Pipkin	33.4	Cales 1940	1¼	N obs. well	Ts	N	Abandoned in 1973.
14X-p6	33		Louis Washington		1964	1¼	D	Ts	Js	No water. Has been hauling water since Jan., 1977, during low-rainfall periods.
14X-p7	36		Glenn Pipkin	11.7	dug old	36	S	Ts	N	Stock use only. Dry sometimes.
14X-p8	39		Ruby Martin	42.0	1930	1¼	N obs. well	Ts	P	
14X-x1	67		Rubin Simmons	30.1	Cales 1952	1¼	D	Ts	P	Problems since Thanksgiving, 1976. Sor times hauling water. Bought new pump Se 1977 but did not help.

Table 2. Summary of well data, Jamestown area, South Carolina. Cont'd

(1) SCWRC Well No.	(2) Field No.	(3) USGS Well No.	(4) Owner/Location	(5) Well Depth (ft)	(6) Driller Date Drilled	(7) Well Diam. (in)	(8) Use of Well	(9) Aquifer	(10) Pump Type	(11) Comments
14X-x2	6		Louis Casselman	85	Mitchum 1975	2	D	Ts	Js	Well deepened in June 1976. Water lines broken by blasting at quarr
14X-x3	11		W. H. Wiles	50	1957	1¼	S	Ts	Js	Only occasional stock use.
14X-x4	35		Leo Casselman	85	Mitchum 1975	2	D	Ts	Js	Well repaired in Nov.-Dec., 1976. Water muddy after blast at quarri
14X-x5	3		Javen Casselman	85	unkn. 1960's	1¼	D	Ts	Js	Water muddy after blast at quarri
14X-x6	7		Mrs. Pearl Casselman	60±	Cales old	1¼	D	Ts	Js	Well went dry on Aug. 31, 1977. Reduced water pressure.
14X-x7	61		Chesley McCormick	50.0	unkn. old	1¼	D	Ts	P	Only occasional use.
14X-x8	53		Mrs. Katherine Langley	15.1	unkn. old	1¼	D	Ts	P	No problems til July 4, 1977. Wel periodically dry since then. Sand problems.
14X-x9	54		Chance Brown	82	Cales old	1¼	D	Ts	Js	No problems reported. Some iron staining - filter on well.
14X-x10	12		E. S. Guerry	65	Mitchum 1930's	1¼	D	Ts	Js	Supplies only 1 person. Not much water used.
14X-x11	9		Harold Stewart	50±	1970	1¼	D	Ts	Js	Used only on weekends.
14X-x12	8		J. B. Ackerman	52±	unkn. 1950's	1¼	D	Ts	Js	No problems reported. Supplies onl person. Not much water used.
14X-x13	76		Albert Nolo				D	Ts	Js	Supplies 3 homes.

ble 2. Summary of well data, Jamestown area, South Carolina. Cont'd.

(1) WRC ID	(2) Field No.	(3) USGS Well No.	(4) Owner/Location	(5) Well Depth (ft)	(6) Driller Date Drilled	(7) Well Diam. (in)	(8) Use of Well	(9) Aquifer	(10) Pump Type	(11) Comments
X-x14	77		Henry Washington				D	Ts		No problems reported.
X-x15	78		Willie Ramsey	60±	1950's±	1¼	D	Ts	Js	Water "rusty"; no quantity problems.
X-x16	79		Emma Ricks		J. Cales 1950's±	1¼	D	Ts	Js	Water "rusty"; no quantity problems.
X-x17	80		George Myers		1970±		D	Ts	Js	
X-x18	81		William Rogers			1¼	D	Ts	Js	
X-x19	82		Ellen Washington	40±			D	Ts	P	
X-x20	83		Roslyn Simmons	30±	1974	2	D	Ts	N	Had shallow-well jet pump, now inoperable.
X-y1	45		Ware Bros. Cons. Co.	167	Ackerman 1976	6	I	Tbm	S	Used for drinking, bathrooms, washing quarry equipment.
X-y2	26		Glen Pipkin	45±	Cales 1948	1¼	D	Ts	Js	Low Pressure, water "rusty." Operate pump manually.

: 2. Summary of well data, Jamestown area, South Carolina. Cont'd.

:	(2) Field No.	(3) USGS Well No.	(4) Owner/Location	(5) Well Depth (ft)	(6) Driller Date Drilled	(7) Well Diam. (in)	(8) Use of Well	(9) Aquifer	(10) Pump Type	(11) Comments
3	25		George Pipkin	55±	Cales 1940's	1¼	D	Ts	Js	Low pressure. Never any problems til Summer, 1977.
4	24		Joe C. Smith	42	Cales 1955	1¼	D	Ts	Js	Well periodically dry. Low pressure.
5	21		Unknown	37.1	unkn. old	1¼	N obs. well	Ts	N	Abandoned well.
6	40		Mrs. Maggie Fordham	25±	Shore 1971	1¼	D	Ts	P	Pressure low in August, 1977. Not much water use.
7	41		Mrs. Barbara Rogers	22.4	Cales 1952	1¼	D	Ts	P	Never any problems til Summer, 1976. Well went dry in June, 1977 and had to haul drinking water.
8	22		Mrs. Quennie Brown	±25	unkn. 1965	1¼	D	Ts	P	Low pressure since Summer, 1975. Water sometimes muddy.
9	20		Nose Myers	16.4	unkn. old	1¼	D	Ts	Js	Well dry since Summer, 1977. Hauling drinking water.
10	21		Mt. Zion A.M.E. Church	36.2	Mitchum 1962	1¼	P	Ts	Js	Low pressure. Pump loses prime. Used only on Sunday.
11	10		St. James Cemetery	36.2	unkn. old	1	N obs. well	Ts	N	
12	44		B.A.S.S. Ltd.	55±	Mitchum 1975	2	N	Ts	Js	Went dry in Fall, 1977.

Table 2. Summary of well data, Jamestown area, South Carolina. Cont'd.

(1) SCWRC Well No.	(2) Field No.	(3) USGS Well No.	(4) Owner/Location	(5) Well Depth (ft)	(6) Driller Date Drilled	(7) Well Diam. (in)	(8) Use of Well	(9) Aquifer	(10) Pump Type	(11) Comments
14X-y13	14		T. E. Casselman	55	unkn. 1960's	1¼	N	Ts	Js	Pressure low. Could not wash clothes, etc. Had new well drilled in August, 1977.
14X-y14	14a		T. E. Casselman	110	Mitchum 1977	3	D	Ts	Jd	Water very hard. Have noticed reduced pressure.
14X-y15	13		David Cooper			2	D	Ts	Js	Water pressure low.
14X-y16	1		James Brunson	37.4	Cales 1960	1¼	D	Ts	Js	Low water pressure. On Sept. 10, 1977 well went dry.
14X-y17	42		Winston W. Ward	36.9	Cales 1970	2	D	Ts	Js	Started pumping air in Aug., 1977. Could not get pump primed.
14X-y18	5		Harold Sprague	45±	Cales 1960	1¼	D	Ts	Js	Pressure problems started about Aug., 1976. Still low pressure.
14X-y19	2		Thomas Mathis	55	D. Mitchum 1970	1¼	D	Ts	Js	Pressure problems, Summer, 1976. Staining reported.
14X-y20	52		Unknown				A	Ts	N	
14X-y21	10		H. W. Gaskins	65±	Mitchum 1970	1¼	D	Ts	Js	Supplies 2 trailers. Water hard - water softener on well.
14X-y22	59		Katherine Morrison	34.5	unkn. 1940's	1¼	N obs. well	Ts	P	
14X-y23	43		Katherine Morrison	70.3	unkn. 1950's	1¼	D	Ts	Js	In Sept., 1977 well went dry. Now hauling water.

le 2. Summary of well data, Jamestown area, South Carolina. Cont'd.

(1)	(2) Field No.	(3) USGS Well No.	(4) Owner/Location	(5) Well Depth (ft)	(6) Driller Date Drilled	(7) Well Diam. (in)	(8) Use of Well	(9) Aquifer	(10) Pump Type	(11) Comments
X-y24	15		Mr. Morrison	unkn		1	A	Ts	N	
X-y25	50		Johnny Redd Sr.	45	Cales 1966	2	D	Ts	Js	
X-y26	51		David Morrison	50.7	unkn. old	1¼	N obs. well	Ts	P	
X-y27	47		Willie N. Davis		1950's	1	D	Ts	Js	Reduced pressure, muddy and sandy water problems started Jan., 1977.
X-y28	46		William Hartley	70±	unkn. 1957		D	Ts	Js	Reduced pressure, sand in water.
X-y29	48		Mrs. Ollie E. Anderson	85		2	D	Ts	Js	Problems started July, 1977. Reduced pressure. Have had to operate pressure switch manually.
X-y30	49		Mrs. Ollie E. Anderson	41.8	unkn. old	1	N obs. well	Ts	N	
X-y31	38		Mr. Ackerman			1	N	Ts	Js	
X-y32	16		Curtiss Jones	93	Riley 1974	3	D	Ts	Jd	Water muddy after blast.
X-y33	17		Curtiss Jones	23.5	1950's	1¼	N obs. well	Ts	N	
X-y34	4		Van & Carrie Millwood	±45	Mitchum 1960	1	D	Ts	Js	Water pressure low. Burned out 1 pump on Nov. 20, 1976.

Table 2. Summary of well data, Jamestown area, South Carolina. Cont'd.

(1) [illegible]RC [illegible]ll [illegible].	(2) Field No.	(3) USGS Well No.	(4) Owner/Location	(5) Well Depth (ft)	(6) Driller Date Drilled	(7) Well Diam. (in)	(8) Use of Well	(9) Aquifer	(10) Pump Type	(11) Comments
3X-L1	71	Brk-39	City of Jamestown	894	Ackerman 1971	5 5/8	P	Kbc	S	
3X-L2	72	Brk-53	USGS Obs. Well	32	Ackerman 1970	6	N	Ts	N	
3X-L3	74	Brk-15	Berkeley Day-Care Cntr.	39	1954	2	N	Ts	N	Well not used.
3X-L4	75	Brk-22	U.S. Forest Serv.	43	unkn. 1951	1¼?	A	Ts	N	Well has been abandoned and covered up. Water quality data on this well from USGS files.
3X-L5	73	Brk-26	Santee Wool Combing Inc.		Layne 1955	6	I	Kbc	T?	
3X-t1	69		Lawton Shuler	unkn.	unkn. old	1¼	S,D	Ts	Js	Used mainly for stock. Went dry in Sept., 1977.
3X-t2	66		Lawton Shuler	15.2	unkn. old	1¼	N	Ts	N	Abandoned. Not used in years.
3X-t3	65		Herbert Shuler	42.6	unkn. old	1¼	N obs. well	Ts	P	Abandoned. Not used in years.
3X-t4	64		H. W. Wiles	50±	1953	1¼	S	Ts	Js	Well used for stock. Problems with mud after blasts.
3X-t5	68		Mr. Johnson		unkn. old	1¼	N	Ts	N	Abandoned well.
3X-t6	70		Lawton Shuler	9	unkn. old	1¼	N	Ts	N	Abandoned. Caved in at 9 ft below surface.

le 2. Summary of well data, Jamestown area, South Carolina. Cont'd.

[illegible]	(2) Field No.	(3) USGS Well No.	(4) Owner/Location	(5) Well Depth (ft)	(6) Driller Date Drilled	(7) Well Diam. (in)	(8) Use of Well	(9) Aquifer	(10) Pump Type	(11) Comments
-t7	58		Mr. Cokley	unkn	unkn. old	1¼	N	Ts	N	Not used. On city water.
-t8	29		Elmer Ramsey	50±	Mitchum 1976	1¼	D	Ts	Js	Reduced pressure. Operates pressure switch manually.
-t9	56		Jamestown United Metd.	48.4	unkn. old	1¼	N obs. well	Ts	Js	Well not used. Parsonage is on city water.
-t10	57		Lorenzo Phyall	45±	unkn. 1969	1¼	D	Ts	Js	No problems reported in Sept., 1977
-t11	34		Mrs. Rosifier	unkn.	unkn. 1920's	1¼	D	Ts	Js	Pressure problems. Have to operate pump manually in August, 1977.
-t12	28		Mrs. Juanita McCormick	20±	Cales 1920	1¼	D	Ts	P	Pressure low in May, 1977. Went dry in June, 1977. Stayed dry until Winter, 1977.
-t13	27		Mrs. Edwin Simmons	18.7	Cales 1940	1¼	D	Ts	P	Pressure low in May, 1977. Went dry in June, 1977. Stayed dry until Winter, 1977.
-d1	55		Daisy Miller	40	Mitchum 1976	2	D	Ts	Js	No problems in August, 1977. Reported staining.
-d2	62		E.S. Guerry, Jr.	50±		2	D	Ts	Js	No problems reported.
-d3	63		Manning Stone	50	Mitchum	1¼	D	Ts	Js	Pressure low. Problems with mud after blasts. Had to install new pressure valve.

Table 3. Summary of data on collapses and subsidence depressions.

(1)	(2) Property Owner Location	(3) Surface Dimensions (feet) Length	Width	Depth	(4) Date Occurred or Discovered	(5) Comments
1	St. James Cem.	4	4	several ft deep	Occurred Feb. 2, 1977	Collapsed under truck driven by Mr. Harris Hires.
2	- do -	6	4	+10	Occurred Feb. 3, 1977	Collapsed under car driven by Mrs. James Schuler.
3	- do -				Occurred near tractor driven by Glenn Pipkin, week before 8/10/77.	
7	T. E. Casselman	4.8	3.5	1.5	June 20-July 1, 1976	Discovered by Mr. Casselman in July, 1976.
8	- do -	0.5	0.1	1.0	- do -	- do -
9	- do -	2.8	2.1	0.9	- do -	- do -
10	- do -	5.0	5.0	1.0	- do -	- do -
11	- do -	20.0	13.4	3.1	- do -	- do -
12	- do -	6 ft diam. several ft deep			June 20-July 1, 1976	Two collapses, several ft deep Covered by Mr. Casselman.
13	- do -		Unknown		Discovered when corn was combined-Fall, 1976.	Covered by Mr. Casselman.
14	- do -	4	4	3.5	Mar. 25-28, 1977	Collapsed under tractor.
15	- do -	5	5	unkn.	Aug. 31, 1977	Collapsed under combine. Bell-shaped.

able 3. Summary of data on collapses and subsidence depressions. Cont'd.

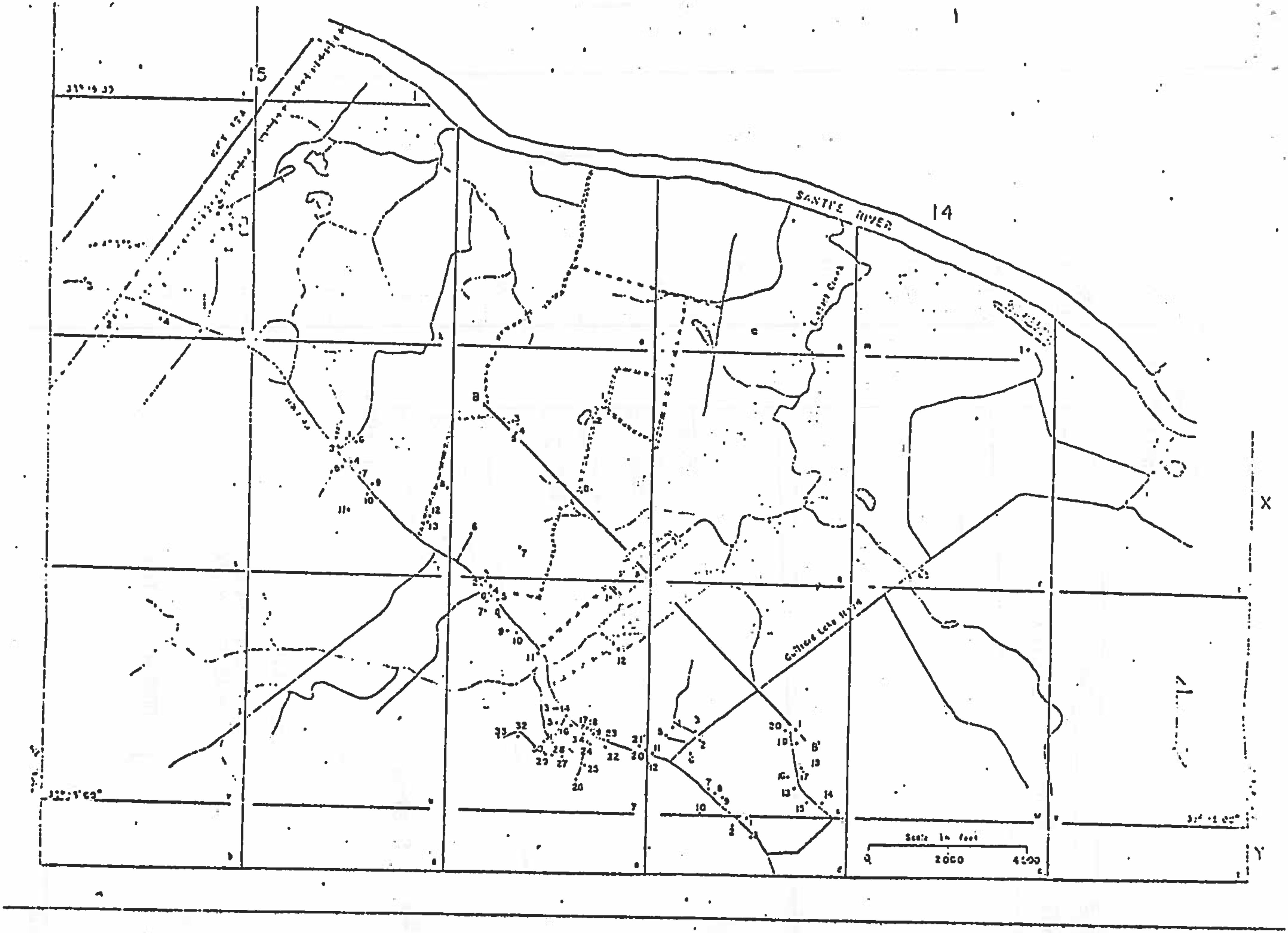
(2) Property Owner Location	(3) Surface Dimensions (feet) Length	Width	Depth	(4) Date Occurred or Discovered	(5) Comments
- do -	3	2	5	Occurred May 26, 1978	Collapsed during disking. Bell shapped. Lateral limits could not be observed.
- do -	3	2	unkn.	Occurred Sept. 3 or 4, 1977	Collapsed during harvesting.
U.S. Forest Serv.	3.5	2.1	3.3	Discovered by T. E. Casselman in July, 1976	
- do -	5.9	2.9	2.5	- do -	
- do -	4	3	8	Discovered Feb. 8, 1977	Area of many small collapses.
Curtiss Jones	24.9	14.4	1.5	Discovered Sept. 11, 1976	Filled in and covered by Mr. Jones.
- do -	21.3	19.2	3.0	Feb.-Mar., 1976	- do -
- do -	6	6	4	Sept., 1976	Filled in and covered by Mr. Jones.
Co. Hwy. 45 right of way	5	3	unkn.	Aug. or Sept., 1976	Reported to be several ft deep; filled and covered with asphalt by S.C. Hwy. Dept. Bell-shaped.
- do -	5	3	unkn.	- do -	- do -
- do -	8	6	+10	Occurred Fall-Winter, 1977	Required several truck loads of fill material. Bell-shaped.
- do -	6	6	+10	- do -	- do -

'able 3. Summary of data on collapses and subsidence depressions. Cont'd.

:)	(2) Property Owner Location	(3) Surface Dimensions (feet) Length	Width	Depth	(4) Date Occurred or Discovered	(5) Comments
:	Mr. Joe C. Smith	2	2	unkn.	Summer, Fall, 1976	Adjacent to porch on NW side house. Covered by Mr. Smith.
:	- do -	2	2	unkn.	Summer, Fall, 1976-present	Area of many small collapses.
	Mr. Glenn Pipkin	2	2	2	Fall 1977-Spring 1978	Discovered in swine lot in Spring, 1978.
	- do -	2	2	2	- do -	- do -
	Mr. Glenn Pipkin	2.7	2.7	5.1	Summer-Fall, 1976	Bell-shaped. Covered by Mr. Glenn Pipkin.
	Mr. James Pipkin	Several ft in diam.				Filled in and covered by Mr. J. Pipki Exact location uncertain.
	Mr. James Brunson	0.5	0.5	unkn.	1976	Area of small, circular collapses around house.
	Carrie M.llwood	1.0	1.0	unkn.	Some occurred 1976; More occurred in 1977.	Area of many small collapses 1 ft diam. and some several ft deep.
	Mr Harold Sprague	2	2	unkn.		Several small collapses in back yard.
	Mt. Zion Cem.	6	4	1.5	Discovered Fall, 1977	Area of many small circular collapses.

ıle 3. Summary of data on collapses and subsidence depressions. Cont'd.

(2) Property Owner Location	(3) Surface Dimensions (feet) Length	Width	Depth	(4) Date Occurred or Discovered	(5) Comments
Mt. Zion Church Recreation Bldg.	6	6	+8	Fall-Winter, 1976	SE side bldg.; caused damage to foundation.
Mr. Mose Myers	3	3	4	Winter, 1976	Collapsed under Mrs. Myers; filled in by Mr. Myers.
Mr. McCray	4	3	2	Prior to Sept. 21, 1976	Has not been filled or covered.
Barbara Rogers					Many small circular collapses less than 1 ft diam. (8 were counted, Aug. 1977).
B.A.S.S. quarry	unkn.	unkn.	unkn.		Collapse in Dutart Creek during late Summer, 1975.
In woods behind Zion Church				Discovered by Mr. Joe C. Smith in Winter, 1977	Mr. Smith reported that it is over 10 ft in diam. and several ft deep. Bell-shaped.
Willie Ramsey					Hole several ft in diam. under front porch. Partially filled with gravel.
Property owner unknown	8	8	6	Discovered by Mr. Joe C. Smith in Winter, 1977; was not there in Summer, 1977.	Bell-shaped.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15
SANTEE RIVER
14
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Y
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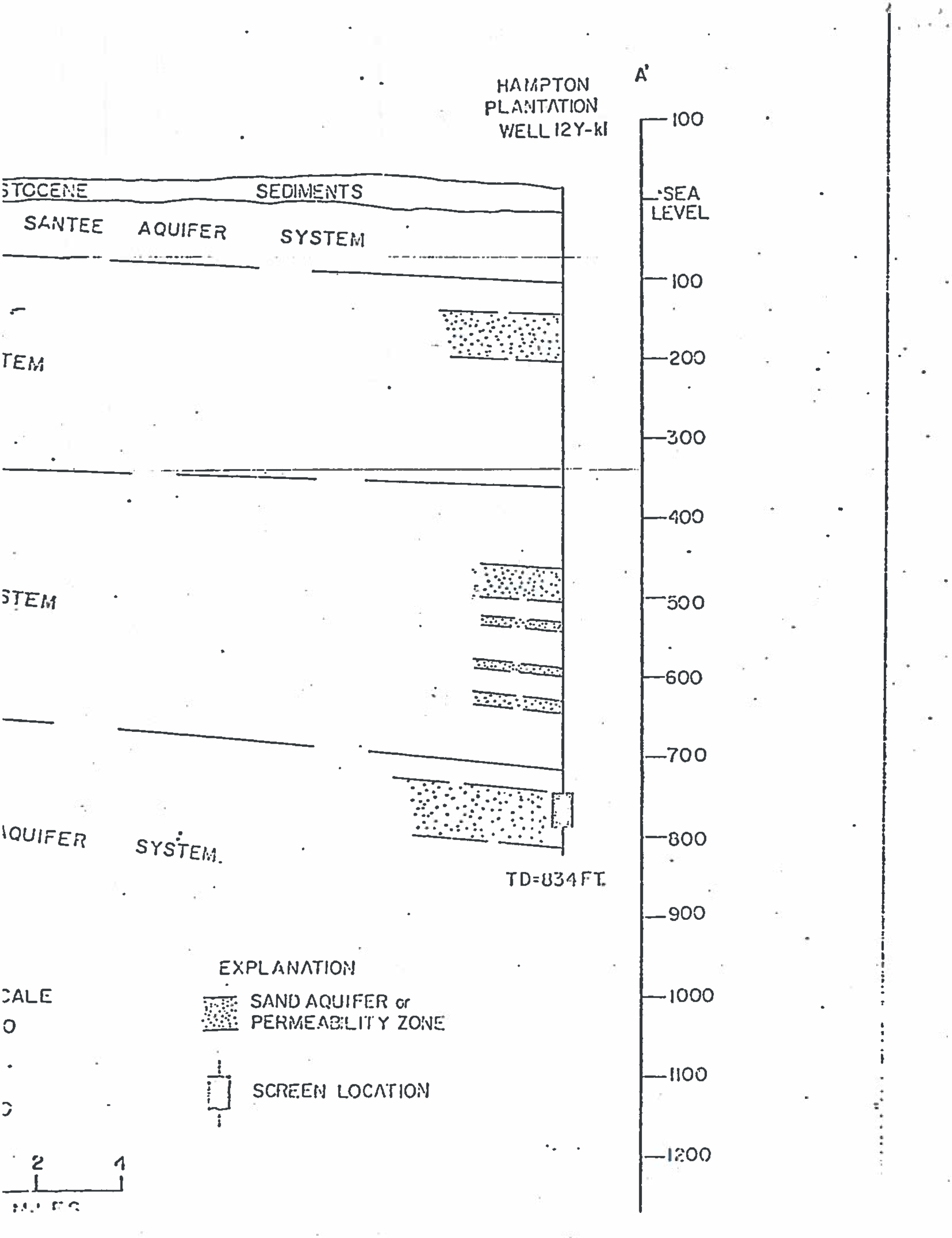
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AQUIFER
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800
TD=834 FT.
900
EXPLANATION
SAND AQUIFER or
PERMEABILITY ZONE
SCREEN LOCATION
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4

FIGURE 4. HYDROGEOLOGIC CROSS SECTION, DUTART CREEK AREA SHOWING CONE OF DEPRESSION, SEPTEMBER 7, 1977

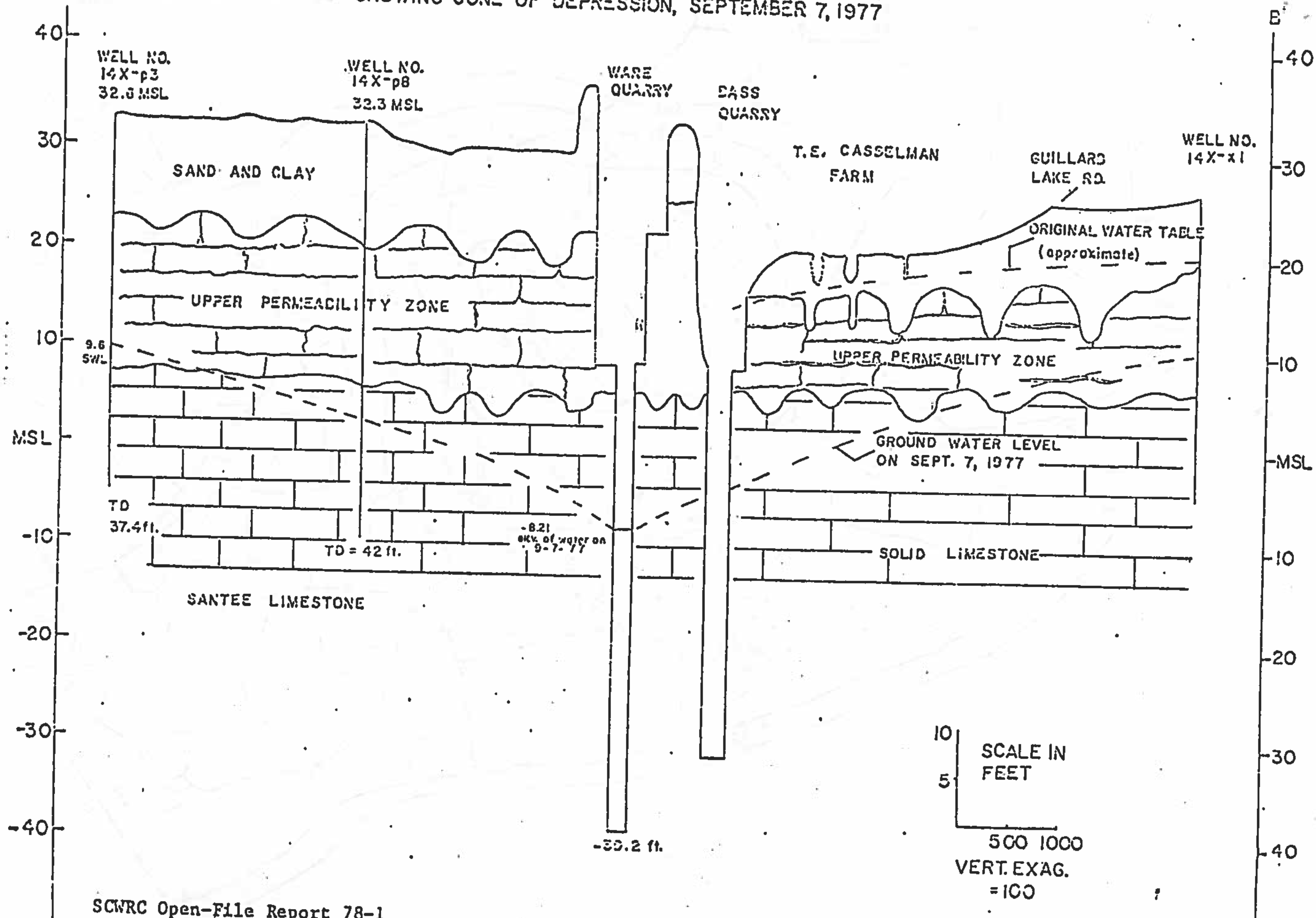

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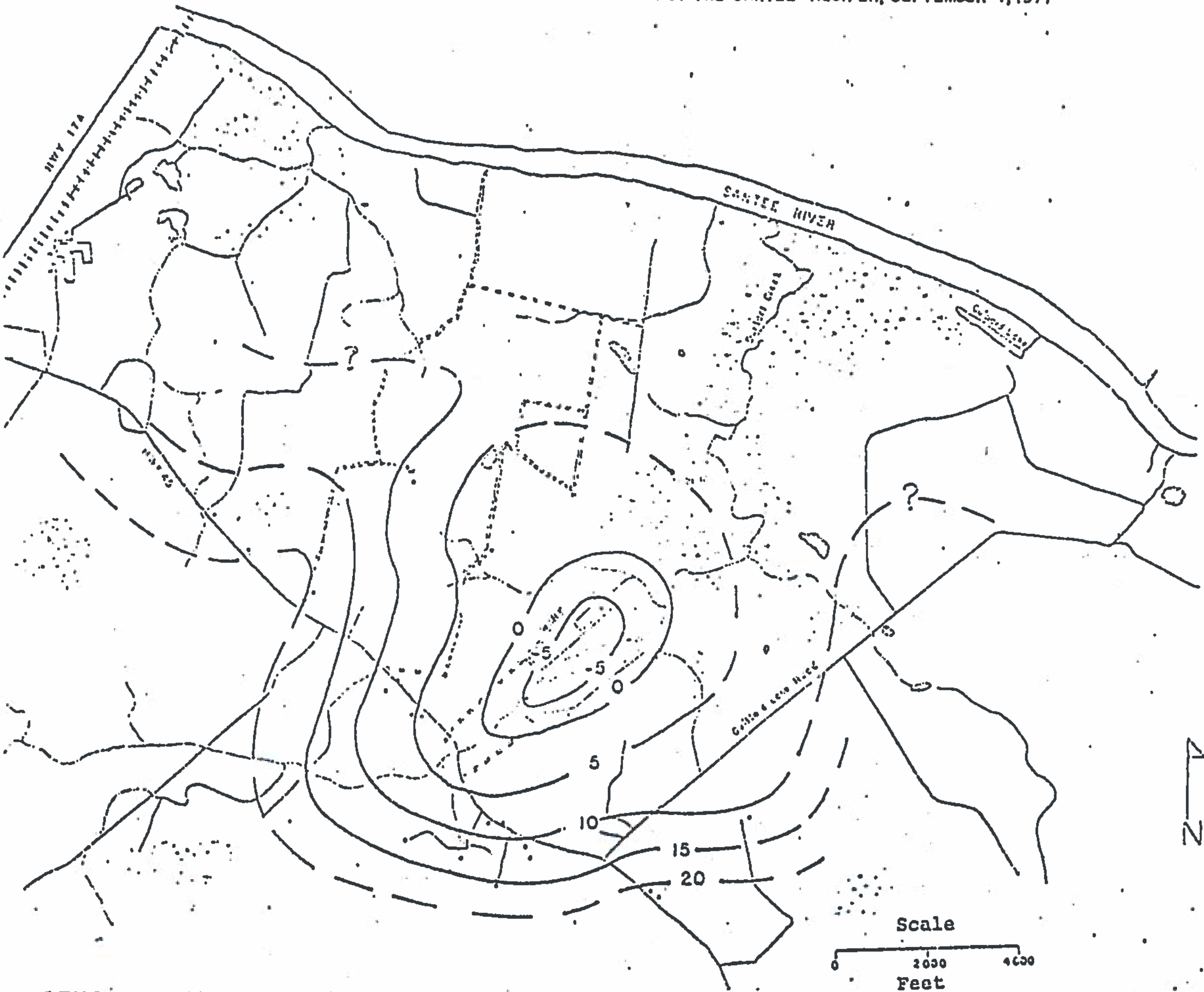
FIGURE 6. MAP SHOWING POTENTIOMETRIC SURFACE OF THE SANTEE AQUIFER, SEPTEMBER 7, 1977



EXPLANATIO

Well used as contro

— 5 — — —Potent
contour shows altitud
level in wells. Dashe
inferred. Contour int
feet. Datum is mean

SUBSIDENCE DEPRESSIONS, JAMESTOWN AREA.