Natural Sources of Salinity in the Brazos River, Texas

WITH PARTICULAR REFERENCE TO THE CROTON AND SALT CROTON CREEK BASINS

By R. C. BAKER, L. S. HUGHES, *and* I. D. YOST

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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NATURAL SOURCES OF SALINITY IN THE BRAZOS RIVER, TEXAS, WITH PARTICULAR REFERENCE TO THE CROTON AND SALT CROTON CREEK BASINS

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ABSTRACT

The average daily load of the Brazos River at Possum Kingdom Reservoir is about 2,800 tons of dissolved solids, of which 1,000 tons is chloride. More than 85 percent of the chloride load is contributed by the Salt Fork Brazos River, and more than 50 percent of the chloride load of the Brazos River originates from salt springs and seeps in Croton and Salt Croton Creeks, which are tributaries of Salt Fork Brazos River. The rest of the chloride is contributed from many small sources.

The average daily chloride load of Croton Creek is 70 tons, much of which is carried during periods of flood runoff. The average daily chloride load of Salt Croton Creek is about 480 tons. Of this total, 330 tons is contributed by the base flow, which ranges from 0.5 to 2 cubic feet per second.

The principal areas of salt springs and seeps in the Croton Creek basin are Hot Springs and Short Croton Salt Flats in northeastern Kent County. In the Salt Croton Creek basin, saline water is discharged in Dove Creek Salt Flat, Dove Creek near Dove Creek Salt Flat, and three small salt flats on Haystack Creek, all in southwestern King County and northwestern Stonewall County.

Salt springs and seeps discharge from the rocks of the Whitehorse Group undifferentiated in the Croton Creek basin, and from the upper part of the Dog Creek Shale of the Pease River Group in the Salt Croton Creek basin. Both groups are of Permian age. The water that is discharged by springs and seeps in the Croton Creek basin is derived from the infiltration of precipitation and seepage from streams in the Duck Creek basin. The source of the water that discharges in the Salt Croton basin is not known.

The salt load contributed to the Brazos River by the springs and seeps can be reduced, although the volume of salt water for disposal probably cannot be reduced or eliminated. Collecting and disposing of the base flow of Salt Croton Creek would reduce the salt load of the Brazos River by 30 percent; disposal of the total flow of Salt Croton Creek would reduce the salt load by 45 percent.

The salt water may be disposed of by impounding it in reservoirs for evaporation or by injecting it underground through oil wells, oil tests, or wells drilled for salt-water disposal. Sediments in which the salt water possibly could be injected underlie the Dove Creek Salt Flats at depths of less than 7,000 feet.

INTRODUCTION

PURPOSE AND SCOPE

The Brazos River is one of the major potential sources of water in the State. The water of the Brazos River impounded in Possum Kingdom Reservoir is undesirably high in sulfate and chloride, although it is used for irrigation and by some industries.

Streams tributary to the Brazos River above the reservoir contribute water that varies widely in chemical quality. During periods of low flow the water in the Brazos River is saline, and even during floodflow some tributaries contribute water too highly mineralized for most uses. A large part of the salt load of the Brazos River originates within a relatively small area, which includes parts of four countries (fig. 1).

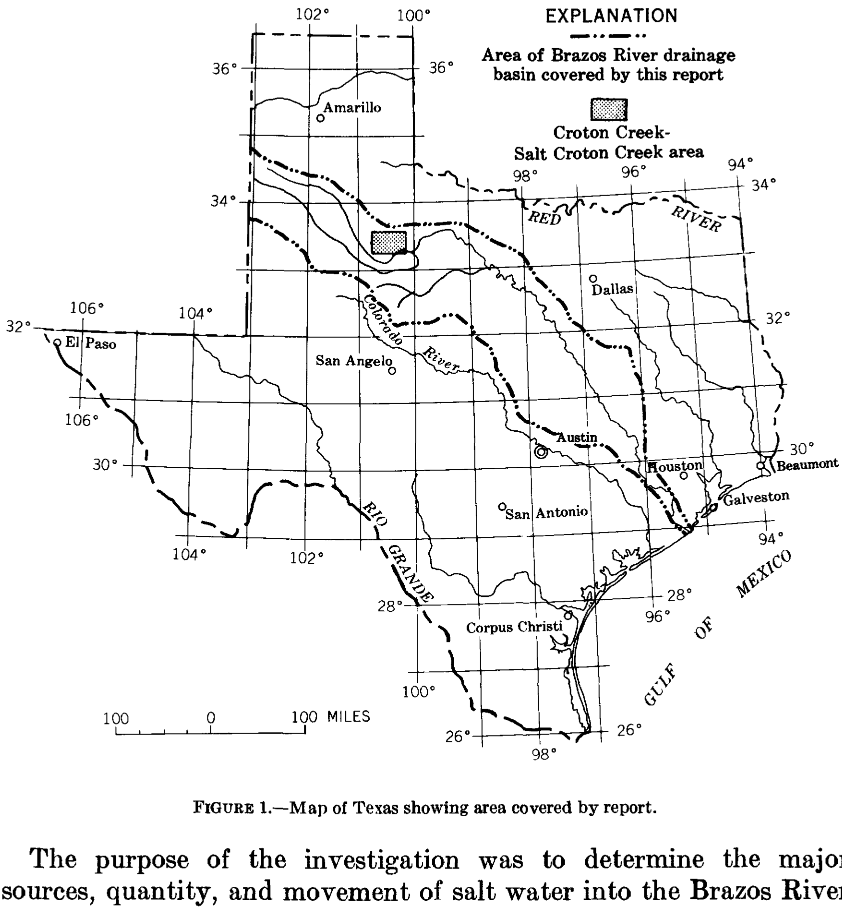

FIGURE 1.—Map of Texas showing area covered by report.

The purpose of the investigation was to determine the major sources, quantity, and movement of salt water into the Brazos River above Possum Kingdom Reservoir; to study the geology and ground-water hydrology in relation to the principal salt-producing areas; to determine the sources of salt and how the systems yielding salt water originated; and to provide data that might be used as a basis for reducing the salt load of the Brazos River.

The report contains records of 60 water wells, 1 oil well, and 3 springs (table 10); 11 stratigraphic sections (table 2); chemical analyses of water samples from 12 wells, 3 springs (table 9), and 19 stream-sampling sites in the upper Brazos River basin (table 5). Data were obtained for 230 other wells including exploration holes (1 to 209), oil tests (210 to 228), and shot holes (229 and 230). These data are not included in table 10, although they were used for control of such illustrations as structure maps and geologic sections. Streamflow measurements were made at 45 sites in the upper Brazos River basin. Included also are records of water levels and contents of four reservoirs (table 3). The location of the wells, springs, sampling sites, and streamflow measuring stations are shown in plate 1*A* and figure 2. The unpublished records may be consulted at the office of the U.S. Geological Survey in Austin, Tex.

The investigation was made possible through a cooperative agreement between the Brazos River Authority and the U.S. Geological Survey.

LOCATION AND EXTENT OF AREA

The area covered by the investigation includes that part of the Brazos River drainage area above Possum Kingdom Dam that is within the State of Texas (fig. 2). It is in the High Plains section of the Great Plains province, the Osage Plains section of the Central Lowland province, and the Central Texas section of the Great Plains province (Fenneman, 1931, pl. 1). Data pertaining to the quantity and chemical quality of the water in the Brazos River basin included in the report show that a substantial part of the salt load is contributed by Croton Creek and Salt Croton Creek. The report is concerned principally with an area that includes the drainage basin of Salt Croton Creek and parts of the drainage basins of Croton Creek and Duck Creek (fig. 2). This area is designated as the Croton Creek-Salt Croton Creek area for convenience of reference.

The Croton Creek-Salt Croton Creek area encompasses nearly 500 square miles and includes southeastern Dickens County, northeastern Kent County, southwestern King County, and northwestern Stonewall County (fig. 1). It lies in the Osage Plains section, the western edge of which is represented by an eastward-facing escarpment known as the "Break of the Plains," between lat 33°15′ and 33°30′ N and long 100°15′ and 100°45′ W. The area, which is 28.8 miles east-west and 17.3 miles north-south, is included on the following U.S. Geologi-

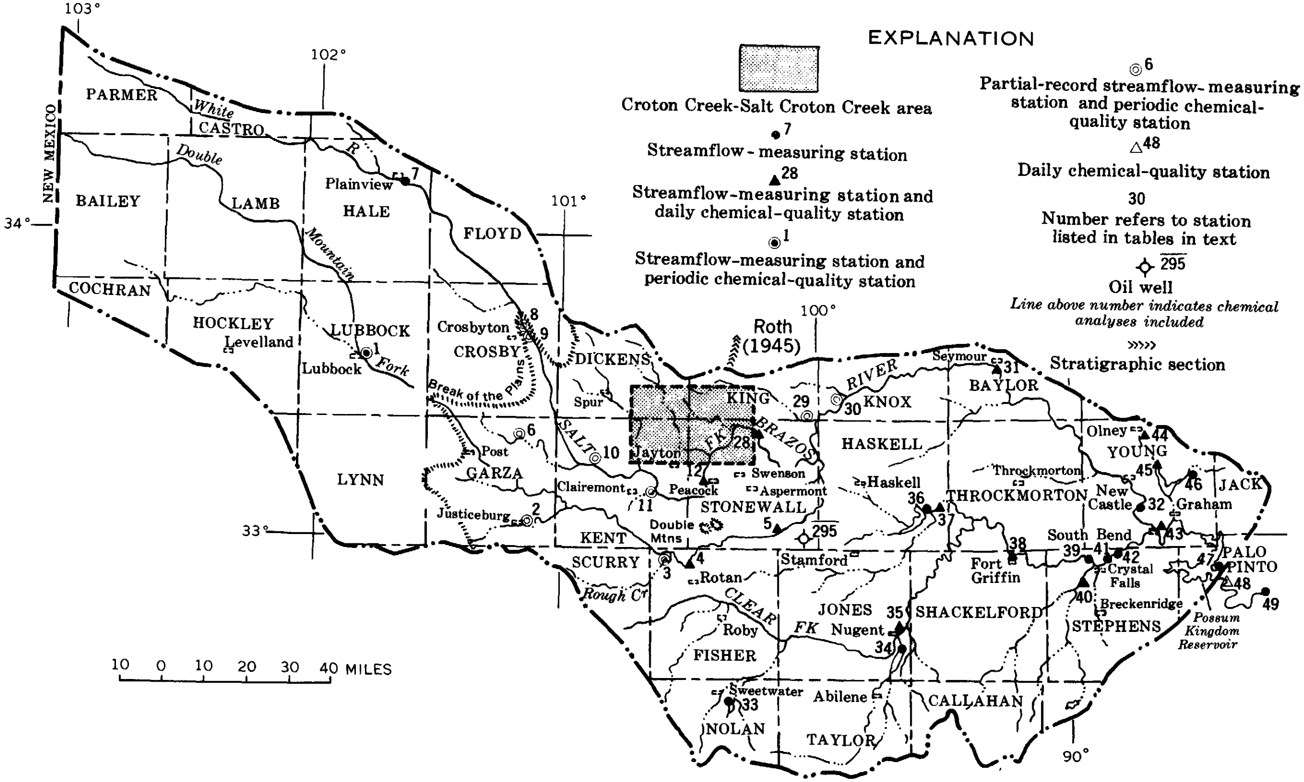

FIGURE 2.—Map of Texas part of the Brazos River basin above Possum Kingdom Dam showing location of Croton Creek-Salt Croton Creek area, streamflow measuring stations, sampling sites, and stratigraphic section outside basin area.

cal Survey topographic 7½-minute quadrangle maps: Gilpin, Girard, Pursley House, Jayton, Southerland Canyon, Seven Diamond L Canyon, Bobs Creek, and Lovers Resort.

ECONOMIC DEVELOPMENT

The Croton Creek-Salt Croton Creek area is sparsely populated. The principal towns and their population in 1960, according to the Bureau of the Census, are: Gilpin, 25; Girard, 350; and Jayton, 649. The combined population of Dickens, Kent, King, and Stonewall Counties in 1960 was 10,347.

The area is served by the Fort Worth and Denver (Burlington) Railway and a network of paved Federal and State highways, farm-to-market roads, and graded roads, except in the northern part of the area.

Much of the area is rangeland and is used for raising cattle and forage crops. Farming is confined largely to the western and southeastern parts of the area; the crops are grasses, small grains such as oats, grain sorghum, and wheat, and cotton and peanuts. The most important mineral resources in the area are the soil and water. Several small oil fields in the eastern and western parts of the area produce from the Ordovician, Pennsylvanian, and Permian rocks. Other mineral resources, such as gypsum, caliche, sand and gravel, volcanic ash, and dolomite are worked for domestic use or on a limited commercial basis; salt from the salt flats is reported to have been used in the past.

PREVIOUS INVESTIGATIONS

Since 1941, the Geological Survey, in cooperation with the Texas Board of Water Engineers (changed to Texas Water Commission in January 1962), the Brazos River Authority, the U.S. Bureau of Reclamation, the Corps of Engineers, and several local agencies, has studied the chemical quality of surface and ground waters in the Brazos River basin above Possum Kingdom Dam. The Geological Survey began collecting streamflow records as early as 1915. Part of the studies since 1941 were directed toward finding the principal sources of contamination of the Brazos River.

In 1955, Dr. H. R. Blank of the Agricultural and Mechanical College of Texas, prepared a report[1] for the Brazos River Authority titled, "The sources of salt water entering the upper Brazos River." The area studied by Dr. Blank included those parts of the Salt Fork and Double Mountain Fork of the Brazos River westward from Knox and Haskell Counties to the eastern edge of the High Plains. Dr. Blank reported "Three unique salt flats, anomalous flat lowlands surrounded

[1] Report on file in offices of the Brazos River Authority, 4400 Cobbs Drive, Waco, Tex.

by a deeply dissected plateau, were visited and studied. One is on a tributary of Dove Creek in northwestern Stonewall County, and the others on tributaries of Croton Creek in northeastern Kent County. In each of these places nearly saturated brine rises through seeps and springs under slight artesian pressure * * *" Dr. Blank concluded that the discharge from the salt flat in the Dove Creek (now Salt Croton Creek) basin accounts for a considerable part of the salt content of the Brazos River. Other sources of salt contamination or indications of salt contamination were the salt springs in Croton Creek and Salt Creek basins, and saline water in North Croton Creek, Rough Creek, Butte Creek, Red Mud Creek, McDonald Creek, and an unnamed creek east of Justiceburg. Suggestions for detention and disposal of the more concentrated water were given in the report.

Acting on the recommendations in Dr. Blank's report, the Brazos River Authority contracted with the Ambursen Engineering Corp. of New York to study the engineering problems of improving the water of the Brazos River. Part of their studies included drilling in the salt flat on Salt Croton Creek to determine foundation properties for a proposed dam to impound and evaporate salt water from springs that rise in the flat. Results of the core drilling indicated that water-saturated gypsiferous shale and clay underlie the salt flat and that the water was under a low artesian head. The report suggested that the salt water issuing in the salt flat of Croton Creek may flow through joint fissures in the underlying shale.

McMillion (1958) studied the geology of an area that encompassed the salt flats in the drainage basins of Salt Croton and Croton Creeks. He concluded that the salt-water seepage in the Salt Croton and Croton Creek drainage basins, on the salt flats, and on the floors of the main canyons was the result of ground-water recharge of both unconfined and confined ground-water reservoirs in the area. He believed the salt-water seepage from ground-water reservoirs was substantial and would fluctuate with changes in annual precipitation. McMillion's suggestions for further studies in the area were used as a guide for some of the studies described in this report.

ACKNOWLEDGMENTS

The cooperation and assistance of many geologists and engineers associated with the petroleum industry are gratefully acknowledged. Appreciation is expressed to the many farmers and ranchers who supplied well data. Fletcher Rich, Derwood Pickens, F. L. Rinker, C. C. York, E. M. Jones, E. E. York, W. A. Springer, Sr., W. A. Springer, Jr., Will Proctor, and T. H. Ward gave information about the occurrence of salt water in the area.

Miss Ada Swineford of the University of Kansas identified the volcanic ash, and Dr. J. C. Frye of the Illinois Geological Survey and Prof. A. B. Leonard of the University of Kansas spent part of a day in the field studying the alluvial deposits in the western part of the area.

Continental Oil Co., Skelly Oil Co., General Crude Oil Co., Union Oil Co. of California, Sun Oil Co., and Schlumberger Well Surveying Corp.. furnished considerable surface and subsurface data.

CLIMATE

The climate of the Croton Creek-Salt Croton Creek area is mild· In general, days are clear, humidity is low, and evaporation is high. Precipitation is fairly small but, fortunately, most of it falls during the growing season. The winters are mostly cool, but include some severe cold spells of short duration. In the spring, high winds and dust storms are common. The summers are hot but, owing to the low humidity and constant wind, are not oppressive.

According to records of the U.S. Weather Bureau, the normal annual temperature at Spur, which is about 6 miles west of the area, is 62.5° F. The normal annual precipitation at Spur is 20.24 inches, and at Aspermont, which is about 8 miles southeast of the area, it is 21.73 inches. The average annual evaporation from a free-water surface at Spur is 63.45 inches; the average growing season is about 215 days a year.

The normal monthly temperature, precipitation, and average evaporation at Spur, and the normal monthly precipitation at Aspermont are given in the following table. The normal, as used by the U.S. Weather Bureau, is an arithmetic mean based on the 30-year period, 1931–60.

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Normal temperature (° F)													
Spur	42.2	46.1	52.8	62.6	70.6	79.5	81.9	81.2	74.0	63.9	51.1	44.2	62.5
Normal precipitation (inches)													
Spur	0.69	0.85	0.71	1.52	3.03	2.60	2.22	2.12	2.53	2.22	0.84	0.91	20.23
Aspermont	.75	1.11	.83	2.06	3.72	2.26	2.02	2.19	2.24	2.46	1.10	.99	21.72
Evaporation from free-water surface (inches) [Average based on period 1941–48]													
Spur	2.20	2.80	4.71	6.48	7.57	8.47	7.99	8.02	6.01	3.88	3.31	2.01	63.45

SURFACE FEATURES

The Croton Creek-Salt Croton Creek area is in the Osage Plains. The principal surface is an upland plain, which descends from an altitude of about 2,300 feet in the northwestern part of the area to less than 1,800 feet in the eastern part. The surface of the plain is flat to gently rolling and is characterized by gentle sags, broad valleys, and low rounded hills. The surface slopes toward the larger streams, which have cut their valleys below the broad gentle sags in the upland plain. At several places the sags are asymmetrical, being steepest on the west or south sides of the major streams.

The valleys of the large streams and of many of the tributaries that have been cut below the level of the upland plain generally are steep walled, and in some places they form canyons. Most of the valleys contain alluvial terraces or terraces of differential erosion.

In the southwestern part of the area between Duck Creek and State Highway 70 and in the southeast corner of the area, eolian sand has accumulated to form dunes, some of which rise above the general level of the upland plain. Duck Creek, which flows southward across the southwest corner of the area, has cut its valley to below the level of the upland plain.

Croton Creek flows southward across the west half of the area and joins the Salt Fork Brazos River in the southeastern part of the area. North of Jayton, the broad upland sag in which the valley of Croton Creek has been entrenched is asymmetrical; its east side is gentle but its west side is steep owing to a resistant bed of gypsum. The tributaries on the west side of Croton Creek have cut narrow, steep-sided valleys as much as 200 feet deep. This area of thoroughly dissected rough terrain is known locally as the "Croton Breaks."

Salt Croton Creek, whose upper reach is called Dove Creek, rises in Dickens County, flows generally southeast, and empties into Salt Fork Brazos River near the center of the eastern part of the area. The downstream part of Salt Croton Creek and its major tributaries have cut their valleys deeply into the Permian rocks. The valleys are steep walled, and the more resistant gypsum layers form terraces.

In the northeastern part of the upland plain, a resistant layer of gypsum trends southwestward and forms a southeast-facing escarpment.

Salt Fork Brazos River flows in a northeasterly direction across the southeastern part of the area. The valley of Salt Fork Brazos River is bordered by steep bluffs. Above its confluence with the Salt Croton Creek, the valley of the Salt Fork Brazos River averages about a mile wide, and two alluvial terraces have been formed along some stretches of the valley. Below the mouth of Salt Croton Creek, the valley of Salt Fork Brazos River narrows perceptibly to about 0.1 mile wide.

Salt flats are small surface features in the area; however, they are important because they occur at places where salt water is discharged. The major ones (pl. 1*A*) are Hot Springs Salt Flat, about 7 miles north of Jayton in the valley of Hot Springs Creek, a tributary stream entering Croton Creek from the west; Short Croton Salt Flat, about 4.5 miles north of Jayton in the valley of Short Croton Creek, a tributary entering Croton Creek from the west; Dove Creek Salt Flat, about 12 miles northeast of Jayton in the valley of Salt Croton Creek; and three small salt flats 2 to 3 miles northeast of Dove Creek Salt Flat in the valley of Haystack Creek (Hayrick Creek), a tributary entering Salt Croton Creek from the north.

GEOLOGY

GEOLOGIC HISTORY

Rocks deposited in the Croton Creek-Salt Croton Creek area are of Paleozoic and Cenozoic age. The rocks of Paleozoic age, which were deposited during the Cambrian, Ordovician, Mississippian, Pennsylvanian, and Permian Periods, underlie the area to a depth of about 7,000 feet and rest on a basement complex of almost impermeable Precambrian rocks. The Paleozoic rocks may be used for the disposal of salt water (p. CC72).

During parts of the Cambrian and Ordovician Periods, the sea inundated the area. The sediments deposited during the Cambrian consisted predominantly of sandstone, but those deposited during the Ordovician consisted mainly of limestone and dolomite. Sediments of Silurian and Devonian age have not been recognized in the subsurface because the area probably was above sea level and did not receive sediments, or, if sediments were deposited, they were removed subsequently by erosion. During parts of the Mississippian, Pennsylvanian, and Permian Periods, the sea again advanced over the area and deposited limestone, shale, sandstone, and limestone reefs. After the desiccation of the Permian seas and the emergence of the continents, a red-bed facies consisting of clay, fine sand, anhydrite, gypsum, salt, and dolomite was deposited in Permian time. The Permian rocks are the source of the salt that is discharged in the area.

Deposits of Mesozoic age are not known in the area; however, deposits of Mesozoic age only a few miles outside the area indicate that at one time they probably covered the area, but subsequently were removed by erosion. Sediments of Triassic age, consisting of nonmarine conglomerate, sandstone, and shale, crop out in western Dickens County and southwestern Stonewall County. In Jurassic time, the area was subjected to extensive erosion that removed at least a part of the Triassic deposits. The area was inundated during Cretaceous time, as indicated by the marine limestone that crops out on Double Mountain in southwestern Stonewall County. At the close of the Cretaceous, the land was again emergent.

The Cenozoic Era, which includes the Tertiary and Quaternary Periods, was one of extensive erosion, alluviation, and stream incision. Sediments of early Tertiary age are not known in the area either because of nondeposition or removal by erosion. In the latter part of the Tertiary Period, the Ogallala Formation of Pliocene age, an extensive alluvial deposit of sand and some gravel, silt, and clay, was deposited in the area of the present High Plains, possibly deposition extended eastward and covered the report area. If the Ogallala Formation at one time covered the area, it was removed by erosion in late Tertiary or early Quaternary time. Erosion during this period removed any Triassic and Cretaceous sedimentary rocks not removed during an earlier period of erosion. In the early part of the Quaternary Period, an alluvial plain was formed on the eroded surface of the Permian sedimentary rocks. As many as three separate periods of valley cutting and alluviation occurred in the valley of Duck Creek. During this time, salt and possibly some gypsum was removed from the Permian rocks, and the overlying material subsided. In the latter part of the Quaternary Period, the area was subjected to erosion, although in several parts of the area sand dunes were formed. Salt water probably has been discharged in the vicinity of some of the present salt flats in the area during much of the Quaternary Period.

STRATIGRAPHY

Rocks cropping out in the Croton Creek-Salt Croton Creek area are of Permian and Quaternary age. Their principal characteristics are shown in table 1. The area is underlain to a depth of about 7,000 feet by rocks of Paleozoic age. The stratigraphy of the Paleozoic rocks underlying the area is discussed in the section "Potential abatement of contamination."

PERMIAN SYSTEM

The Permian rocks that crop out in the area are about 1,000 feet thick and dip westward at about 26 feet per mile. The oldest beds in the Permian are exposed in the eastern part of the area.

The stratigraphy of the Permian is given as a basis for showing the relative positions of the places of discharge of salt water and the relationship of the places of discharge to places where salt and gypsum may have been removed from the Permian by solution.

Correlations in the part of the Permian exposed in the area largely are based on beds of gypsum and dolomite, some of which can be correlated over wide areas. In this report, these marker beds are given letter designations (pl. 2). Names applied to the beds in other areas are not used because a single bed may have two or more designations, or the same designation may be applied to two or more beds. Moreover, the position of contacts and the names of groups differ among various authors. Formation and group names used by different authors are not discussed in this report except as they are pertinent to the contact of the Dog Creek Shale and the Whitehorse Group.

Thirteen marker beds generally dolomite or gypsum, were selected and correlated on the electric logs of 251 exploration holes drilled in the Croton Creek-Salt Croton Creek area by oil companies. The electric log measures some of the electrical properties of the materials and fluids penetrated by the well and consists of a spontaneous-potential (self potential) curve and a resistivity curve. The resistivity curve is influenced by the resistivity of the beds and the contained fluid as well as the drilling fluid that has invaded the material during the drilling of the hole. Beds of dolomite, gypsum, or anhydrite are highly resistive, and are represented by a sharp deflection of the resistivity curve.

Correlations based on the 13 marker beds, as shown on a composite log, were made with nine stratigraphic sections measured in the Croton Creek-Salt Croton Creek area, a stratigraphic section measured in central King County about 9 miles north of the east end of the area, and with four columnar sections (pl. 2). (Columnar sections represent graphically the sequence and relationship of the rock units in a region.) These sections are correlated with the composite log principally on marker bed Dc. The nine stratigraphic sections measured in the area are given in table 2 to show in detail the kinds of material in the Permian rocks.

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TABLE 1.—*Geologic units that crop out in the Croton Creek-Salt Croton Creek area*

System	Series	Unit	Thickness (feet)	Physical character	Location	Remarks
Quaternary	Recent	Alluvium	0–30(?)	Sand and some gravel	Flood plains of streams	Carries subsurface flow so that some streams at periods of low flow are interrupted streams.
		— Unconformity —				
	Recent and Pleistocene (undifferentiated).	Terrace deposits	0–60	Sand, silt, and gravel	In valleys of larger streams	Stream deposits. Generally not a source of water.
		— Unconformity —				
		Dune sand	0–50+	Meduim- and fine-grained sand and silt. Some associated deposits contain gypsum gravel.	South of Girard and east of Duck Creek, south and east of Salt Fork Brazos River. Upstream parts of basins of Hot Springs and Short Croton Creeks.	Eolian deposits overlying Wisconsin(?) deposits. Partly fills the valleys of Hot Springs and Short Croton Creeks and partly covers ancestral salt flats. Not a source of water.
		— Unconformity —				
	Pleistocene	Wisconsin(?) deposits.	0–50+	Sand and gravel in lower part. Sand, silt, clay, and calcareous nodules in upper part.	In valley of Duck Creek. South and east of Salt Fork Brazos River.	Alluvial deposits yield water to irrigation and public-supply wells in Duck Creek valley. May, in part, be source of water emerging at Hot Springs and Short Croton salt flats. Deposits largely covered by dune sand. Age uncertain, but younger than the Pearlette Ash Member of Sappa formation of Kansan age.
		— Unconformity —				
		Illinoian deposits	0–10(?)	Silt, fine sand, and clay	Interstream areas except south of Girard and east of Duck Creek, and south and east of Salt Fork Brazos River.	Eolian deposits cover most of the upland plain, but are not a source of water.
		— Unconformity —				
		Kansan deposits	0–100(?)	Gravel, conglomerate, sand, silt, clay, and volcanic ash. Some invertebrate fossils.	Near and below bed of Duck Creek and some tributaries. Deposits in bottom of bed of Short Croton and Hot Springs Creeks are probably of Kansan age.	Yield water to irrigation and public-supply wells in valley of Duck Creek. May, in part, be source of water emerging at Hot Springs and Salt Croton Salt Flats. Position of deposits near and below level of Duck Creek may indicate subsidence owing to solution of salt from the underlying Permian. Probable Kansan Deposits in beds of Short Croton and Hot Springs(?) Creeks indicate the streambeds were as low or lower in Kansan time than at present and that ancestral salt flats probably existed. Exposures of gypsum on upland plain beveled by chemical weathering during Kansan time. Volcanic ash identified as equivalent to Pearlette Ash Member of Sappa Formation. Invertebrate fossils are of Kansan age.
		— Unconformity —				

		Nebraskan deposits	0-11+	Gravel, sand, and algal limestone caliche.	Gravel capping some hills in valley of Duck Creek, the valley of Croton Creek near mouth of Short Croton Creek, and Salt Croton Creek near Dove Creek salt flat. At places in the drainage basin of Duck Creek, algal limestone caliche crops out at the level of the upland plain.	Where the Nebraskan deposits have not been eroded, the upland plain coincides with the top of the deposits. Generally not a source of water in the area.
		— Unconformity —				
Permian	Guadalupe	Whitehorse Group undifferentiated	0-700+	Fine sand and interbedded layers of gypsum.	Crops out in western part of area.	Hot Springs and Short Croton salt flats are about 300 feet above base of Whitehorse Group undifferentiated. Generally only a thin layer of fresh water overlying salt water.
		— Unconformity —				
		Dog Creek Shale of Pease River Group.	0-200+	Shale and interbedded gypsum and dolomite.	Crops out in eastern part of area. Underlies Whitehorse Group in western part of area.	Dove Creek salt flat is at top of Dog Creek Shale. Salt flats on Haystack Creek are about 50 feet below top of Dog Creek Shale. Generally not a source of fresh water in the area.

TABLE 2.—*Stratigraphic sections in the Croton Creek-Salt Croton Creek area*

Section 1

[Section of the Permian rocks 4 to 6 miles east-southeast of Dove Creek Salt Flat measured by Roth (1937, p. 463–464) from near the center of sec. 139, Blk. F., Houston and Texas Central R.R. Co. Survey to the top of the promontory in SW¼SE¼ sec. 159]

	Ft	In
"Triassic."		
Custer:		
Sandstone, orange, polished, eolian; interval not measured		
Childress dolomite horizon		
Gypsum and anhydrite, white, with pink laminations	1	0
Sandstone, orange, polished, eolian; silt and grits	20	8
Unconformity.		
Permian		
"Blaine of Texas:"		
Shale, reddish-brown, soft; ordinarily absent		2
Wagon Yard Gypsum or Royston Gypsum		
Gypsum, white and gray dolomitic gypsum; this is maximum thickness observed; bed is very prominent bench—former continuing many miles; locally removed due to unconformity above	15	0
Shale, reddish-brown, soft; locally there are a few beds of gypsum 1 to 3 inches in thickness; interval ordinarily forms very steep slope	60	10
Dolomite, light gray, blocky, and gypsum; very local		4
Shale, reddish-brown, soft, with some thin beds of gypsum about 2 feet below top	6	8
As below (material) with gypsum and selenite dikes	10	9
Interval consists of about 6 benches, each capped with gray dolomite and gray gypsum or shale, or both; benches separated by reddish-brown shale	31	0
Shale, reddish-brown	5	2
Shale, gray-green and reddish-brown, with 1 to 2 inches gypsum layers	5	2
Shale, reddish-brown with reddish-brown to salmon gypsum and selenite	5	2
Dolomite, gray to buff, silty; much greenish-gray shale conglomerate associated with this dolomite; bed forms minor bench and contains many pelecypods, *Pleurophorus* sp		10
Shale, reddish-brown; upper few feet of gray-green shale and selenite	13	6
Gypsum, gray-green, white, and salmon; bed very massive and blisters well developed on its surface	10	0
Shale, reddish-brown	2	6
Gypsum, white, massive, nodular	6	0
Dolomite, light gray, blocky, very thin-bedded		10
Shale, greenish-gray and ochre		10
Shale, reddish-brown and selenite	2	0
Gypsum, greenish, reddish-brown and white, with some reddish-brown shale shells; greenish gypsum locally very persistent and about 1½ feet thick; on average about 2 feet above the dolomite	3–4	0
Aspermont or Guthrie Dolomite		

TABLE 2.—*Stratigraphic sections in the Croton Creek-Salt Croton Creek area*—Con.

	Ft	In
"Blaine of Texas"—Continued		
Dolomite, gray, slabby; upper one-third is coquina; fossils forming this coquina occur in beds about 3 inches thick; main part of dolomite must have been deposited in rather shallow water; plentiful ripple marks and 2 to 3 inch beds of greenish shale conglomerates in dolomite matrix; great abundance of dephalopods and ammonites probably due to marine current moving fast enough to carry animals into environment alien to their existence, causing extinction; *Perronites hill* and *Eumedlicotta* sp. This bed has been mapped as Aspermont or Guthrie Dolomite. It is doubtful if this correlation can be established as it is extremely local in mode of occurrence	6	0
Dolomite, salmon to reddish, granular, blocky to slabby; some dolomite has greenish cast	1	0
Gypsum conglomerate in greenish matrix; some of this material has reddish cast	1–2	0
Shale, greenish-gray, blocky, gritty; brown and ocher colors near top	3	0
Mostly covered; some reddish-brown shales exposed	2	0

Section 2

[Section of Permian rocks on Salt Croton Creek about 2 miles northeast of Dove Creek Salt Flat measured by McMillion (1958, section 1, p. 29) "on bluff north side of Dove Creek at gaging stations in northeast corner, section 177, block F, H & T C RR Survey, Stonewall County."]

	Ft	In
Childress Gypsum, massive, white; fractured and weathered	9	0
Clay, green nodular		9
Clay, red; nodular and conchoidal fractures	26	6
Gypsum, gray, platy		2
Clay, red, nodular, silty	2	0
Gypsum, greenish-gray		1
Clay, red; nodular and conchoidal fractures	8	0
Gypsum, white; crumbles easily		3
Clay, red, nodular	8	0
Gypsum, green to gray, strongly laminated	5	0
Clay, red and green; exhibits nodular and conchoidal fractures	4	6
Clay, red, nodular; crumbly when dry	3	6
Clay, green to gray; nodules about ¼ to 1½ in. in diameter	1	6
Clay, red, nodular, shaly	3	6
Floor of Dove Creek.		
Total of section	72	9

Section 3

[Section of Permian rocks on south bank of Dove Creek about half a mile north of Dove Creek Salt Flat measured by McMillion (1958, section 5, p. 30) "on bluff, south side of Dove Creek, near center of section 197, block F, H & T C RR Survey, Stonewall County."]

	Ft	In
Lower Eskota Gypsum, massive, white; some residual dolomitic layers	10	0
Sand, red, very fine, unconsolidated	42	0
Dolomite, gray, dense		6
Sand, red, very fine, unconsolidated	60	6

TABLE 2.—*Stratigraphic sections in the Croton Creek-Salt Croton Creek area*—Con.

	Ft	In
Gypsum, white, anhydritic and dolomitic	4	0
Sand, red, fine, unconsolidated	20	0
Clay, red and green, gypsiferous, hard	3	6
Top of Childress Gypsum in creek bed.		
Total of section	140	6

Section 4

[Section of Permian rocks on west bank of Haystack Creek about 4.5 miles north of Dove Creek Salt Flat measured by McMillion (1958, section 6, p. 31) "at head of Hayrick Creek canyon in SE corner, section 193, block F, H & T C RR Survey, King County."]

	Ft	In
Gypsum, white, massive (top of Hayrick Mountain)	3	6
Sand, red, very fine, unconsolidated	22	0
Gypsum, gray, massive	0	4
Sand, red, very fine, loose	5	6
Gypsum, white, massive	3	0
Sand, red, fine loose	8	2
Gypsum, white to gray, platy	2	0
Sand, red, fine unconsolidated	55	0
Upper Eskota Gypsum, massive, white; near base is 1 ft of red silty dolomite	10	0
Sand, red, fine, silty	19	0
Dolomite, brownish-red, silty; breaks into thin sheets and flagstones when exposed at surface	1	2
Sand, red, fine, silty	13	2
Lower Eskota Gypsum, white, massive; many solution cavities	10	0
Total of section	152	10

Section 5

Section of Permian rocks on the west bank of Croton Creek about a mile upstream from the mouth of Short Croton Creek, measured by R. C. Baker]

	Ft	In
Gypsum, white- and brown-banded; caps hill	2	0
Sand, brown, fine grained, poorly cemented	5	6
Gypsum, white	0	5
Sand, brown, fine grained, poorly cemented	8	0
Gypsum, white	0	4
Sand, brown, fine grained, poorly cemented	7	4
Sand, brown, medium- to fine-grained; partly cemented with gypsum. Some thin pink gypsum layers	4	10
Sand, brown, medium- to fine-grained, poorly cemented	2	0
Gypsum, white, massive; forms bench. Is marker bed C of composite log (pl. 2)	2	4
Sand, brown; has some gray lenses; medium to fine grained. Upper and lower parts poorly cemented, middle part slightly indurated	32	0
Sand, brown or gray, medium- to coarse-grained. Some layers cemented with gypsum, alternating with layers of white gypsum as much as 3 in. thick. Some layers stand out on steep slopes	6	0
Sand, reddish-brown, fine-grained, poorly cemented; some gray layers	19	0
Total of section	89	9

TABLE 2.—*Stratigraphic sections in the Croton Creek-Salt Croton Creek area*—Con.

Section 6

[Section of Permian rocks at the west end of Short Croton Salt Flat measured by McMillion (1958, section 8, p. 32) "on steep bluff at west end of Short Croton Flat and directly south of fence (north line of James Castleberry Survey, Kent County)."]

	Ft	In
Sand, red, very fine, loose; surface covered with powdery gypsum crust	22	0
Sandstone, red with gray blotches; fine grained; highly gypsiferous	0	3
Sand, red, fine, unconsolidated, white	3	6
Gypsum, white, massive and granular	3	4
Sand, red, very fine grained, unconsolidated	108	6
Base of Short Croton flat.		
Total of section	137	7

Section 7

[Section of Permian and Quaternary rocks about half a mile south of the west end of Short Croton Salt Flat measured by McMillion (1958, section 9, p. 32) "on east side of steep canyon, which is tributary to Short Croton flat from the south in James Castleberry Survey, Kent County."]

	Ft	In
Silt, red; scattered rounded chert cobbles	33	0
Gypsum, white, pure, massive	12	0
Sand, red, very fine grained to silty, unconsolidated	36	6
Gypsum, white, massive; forms small ledge	1	2
Sand, red, very fine-grained, silty, loose; has high angle of repose	121	0
Gypsum, white, massive (is same bed as 3 ft 4 in. gypsum of Section 8) (Section 6, above)	3	4
Total of section	207	0

Section 8

[Section of Permian rocks on west bank of Duck Creek about 6 miles southwest of Girard, measured by R. C. Baker]

	Ft	In
Gypsum, white to pink, banded. Marker bed Ab of composite log (pl. 2)	3	0
Sand, reddish-brown, fine-grained, some gray layers	32	0
Gypsum, gray, massive to platy. Marker bed Ac of composite log (pl. 2)	8	0
Sand, reddish-brown, fine-grained; largely covered or slumped	45	0
Gypsum, gray; some pink bands; massive. Marker bed Ad of composite log (pl. 2)	9	0
Sand, reddish-brown and some gray, fine-grained	6	0
Gypsum, gray, lenticular	1	0
Sand, reddish-brown, fine-grained, largely slumped; to level of Duck Creek	43	0
Total of section	147	0

Section 9

[Section of Permian rocks on the south bank of a tributary entering Duck Creek from the west about 3 miles southwest of Girard, measured by R. C. Baker]

	Ft	In
Gypsum, white, massive. Marker bed Aa of composite log (pl. 2)	5	0
Sand, reddish-brown and gray, fine-grained; some layers of sand as much as 1 ft thick cemented with gypsum and some thin layers of gypsum	40	0

TABLE 2.—*Stratigraphic sections in the Croton Creek-Salt Croton Creek area*—Con.

	Ft	In
Gypsum, gray; in contorted layers as much as 1 ft thick; some layers consist of small euhedral crystals of gypsum with some calcareous material; some irregular-shaped clay pellets or molds from clay pellets; some thin layers of gray sand. Probably marker bed Ab of composite log (pl. 2)	5	0
Sand, mottled red and gray; fine grained	2	0
Total of section	52	0

Section 10

[Section of Quaternary rocks on west bank of Duck Creek about 4 miles southwest of Girard, measured by R. C. Baker]

	Ft	In
Terrace deposits:		
Sand, pale brown, fine-grained, unconsolidated; contains invertebrate fossils	2	0
Sand, mottled brown and gray; fine-grained, slightly consolidated; grades into underlying unit	2	0
Sand and gravel, gray, unconsolidated	4	0
Kansan deposits:		
Sand, moderate reddish-brown, slightly consolidated; contains ¼-in. euhedral crystals of gypsum	4	0
Volcanic ash, yellowish-gray (Pearlette Ash Member of Sappa Formation equivalent)	2	0
Sand and silt, moderate reddish-brown; some disseminated gravel	7	0
Conglomerate, brown; pebbles of siliceous material, rounded; very few water-worn Cretaceous fossils; to level of Duck Creek	7	0
Total of section	28	0

Section 11

[Section of Quaternary rocks on east bank of Duck Creek about 3½ miles southwest of Girard, measured by R. C. Baker. Section is generalized to show important features cropping out at different places on the exposure, which is about half a mile long]

	Ft	In
Dune sand:		
Sand, grayish-brown, fine-grained, and silt; poorly consolidated; contact with Wisconsin(?) deposits undulating but distinct	3	0
Wisconsin(?) deposits:		
Sand, silt and clay, reddish-brown, slightly consolidated; has vertical prismatic structure	2	0
Sand, reddish-brown, fine-grained; contains silt and some disseminated gravel; contains nodular calcareous material in upper part; grades downward into gray to tan or brown, generally unconsolidated sand and gravel; most beds of sand and gravel are cross-bedded; some lenses of greenish-gray or nearly white even-bedded fine sand; cobble to boulder-sized armored mud balls of white to brown soft impalpable clay are common in lower part; unconformable with deposits below	45	0

TABLE 2.—*Stratigraphic sections in the Croton Creek-Salt Croton Creek area*—Con.

	Ft	In
Kansan deposits:		
Sand, brown to reddish-brown, fine-grained, slightly consolidated; very sparse disseminated pea gravel; to level of Duck Creek	15	0
Total of section	65	0

DOG CREEK SHALE

The lower approximately 300 feet of the Permian rocks that crop out in the area are in the Dog Creek Shale of the Pease River Group. In general, the upper 200 feet of these beds consists of red to brown shale and contains numerous layers of gray gypsum and some beds of gray dolomite. Although some of the gypsum beds are as much as 15 feet thick, most are only a few inches thick; most of the dolomite beds are less than 6 feet thick.

Marker bed Df, the lowermost bed of the composite log (pl. 2), generally is readily distinguishable. However, the exact correlation is difficult in some places because of highly resistive beds above and below. Projection of marker bed Df to the surface indicates that it probably crops out at Salt Croton Falls, about 1 mile upstream from the mouth of Salt Croton Creek. Bed Df of the composite log probably correlates with bed Df of Storm (1929, geologic map).

Roth (1937, p. 464) says of the 6-foot bed of dolomite at Salt Croton Falls, which may be equivalent to marker bed Df, "This bed has been mapped as Aspermont or Guthrie. It is doubtful if this correlation can be established as it is extremely local in mode of occurrence."

Marker bed Dd of the composite log is not easily recognized in logs of many exploration holes. In its outcrop (pl. 1*B*), bed Dd consists of a layer of gypsum about 5 feet thick and forms a prominent rock terrace in the valley of Salt Croton Creek in southwestern King County and northwestern Stonewall County. Bed Dd becomes increasingly shaly southward until, in the valley of Salt Fork Brazos River, it is not recognizable. It is correlative with bed Dd (Wagon Yard Gypsum of Storm, 1929) and bed Dd (Childress Dolomite of Hubbard and Fischer, 1930).

Marker bed Dc is readily identified in the logs of exploration holes except in northwestern Kent County, where locally it is indistinguishable from an overlying, highly resistant bed. Dc, which is a layer of gypsum ranging in thickness from 10 feet to nearly 15 feet, crops out in the vicinity of Dove Creek Salt Flat, in the valley of Dove Creek near the salt flat, and in the valley of Haystack Creek. East of the mouth of Haystack Creek it caps the bluffs on both sides of Salt Croton Creek. It also caps the bluff on the west side of Salt Fork

Brazos River between the valleys of Salt Croton Creek and Croton Creek and crops out on the east bank of the Salt Fork Brazos River less than a mile south of the mouth of Croton Creek.

Bed Dc of this report probably is equivalent to bed Dd mapped by Storm (1929) in Stonewall County and to the Swenson Gypsum Member of Patton (1930, pl. 1); it probably is also equivalent to the Childress Dolomite Member of the Dog Creek Shale of Lloyd and Thompson (1929a, p. 952; 1929b).

In southwestern King County, Hubbard and Fischer (1930) mapped beds Db_3 and Dc, which probably are equivalent to beds Dc and Dd, respectively, of this report. Bed Dc of Hubbard and Fischer may be equivalent also to the Wagon Yard Gypsum of Storm (1929), and bed Db_3 of Hubbard and Fischer was referred to as the Ward, but descriptions or type localities were not given. However, the name Ward is preoccupied and cannot be used (Sellards and others, 1932, p. 167). Hubbard and Fischer (1930) referred to bed Dc (of this report) as the Royston in their stratigraphic section, but Royston was designated by Cheney (1929, p. 26) as a formation that included as a member the bed Dc referred to as Royston by Hubbard and Fischer in their stratigraphic section (1930). Therefore, the use of the name Royston for bed Dc is not correct. Patton (1930, p. 46) assigned the name Swenson Gypsum Member to a bed in Stonewall County that probably is the same as bed Dd of the geologic map of Stonewall County (Storm, 1929) and Dc of the composite log and stratigraphic sections (pl. 2). If Dc is the same as Dd on the geologic map of Stonewall County (Storm, 1929) and if the correlation of this bed with the Childress Dolomite Member of Lloyd and Thompson (1929, p. 952) is correct, it follows that the name Childress probably should be used because of more common usage.

The contact between the Dog Creek Shale and the overlying Whitehorse Group is at the top of the Childress Dolomite Member of Lloyd & Thompson (1929). The position of the contact on the composite electric log is not definitely known because of uncertainties in correlation with other sections. In this report the contact is considered to be at the top of marker bed Dc of the composite log (pl. 2).

WHITEHORSE GROUP UNDIFFERENTIATED

The upper 700 feet of the Permian rocks cropping out in the Croton Creek-Salt Croton Creek area are in the Whitehorse Group undifferentiated. The rocks consist largely of fine-grained red sand interbedded with layers of gypsum, some of which are nearly 15 feet thick.

Marker bed Db on the composite log, which consists of a layer of gypsum about 10 feet thick, caps the bluffs on both sides of Croton Creek near its mouth. It also crops out in the upper reaches of Salt

Croton Creek, in the lower part of Dove Creek, and Panther and Haystack Canyons (pl. 1*C*). Bed Db is correlative with the Croton Gypsum of Storm (1929), Hubbard and Fischer (1930), and the Oriana Gypsum of Patton (1930, p. 47), but it probably is not correlative with the Eskota Gypsum on the columnar section by Lloyd and Thompson (1929a).

Marker bed Da of the composite log (pl. 2) consists of a layer of gypsum about 10 feet thick and crops out in Croton Creek and in the upper part of Haystack Canyon. The outcrop of marker bed Da is shown on plate 1*c*; over a larger part of the area it is mantled by eolian sand and silt. Bed Da is correlated with bed Da_2 of Storm (1929) and with bed Da of Hubbard and Fischer (1930).

Marker beds C, Bd, Ba, Ad, Ac, Ab, and Aa were designated either because they could be correlated on most of the logs or they could be correlated with the exposures of gypsum layers, some of which are as much as 15 feet thick. The logs of some wells fail to show the marked deflection of the resistivity curve characteristic of bed Dd, and on some logs one or more of the sharp deflections of the resistivity curve characteristic of the beds above or below bed C may be absent. Marker beds C, Ba, and Ad crop out in the vicinity of Short Croton Creek or Hot Springs Canyon (pl. 1*D*).

QUATERNARY SYSTEM

Sediments of the Quaternary System are present in most of the larger stream valleys and cover much of the upland plain in the Croton Creek-Salt Croton Creek area. The Quaternary deposits were studied because the position of some of the deposits indicate that salt was removed by solution from the Permian rocks and salt water was discharged in the vicinity of Hot Springs and Short Croton Salt Flats during Quaternary time.

The deposits of the Quaternary System are divided into the Pleistocene and Recent Series.

PLEISTOCENE SERIES

NEBRASKAN DEPOSITS

Sediments, probably of Nebraskan age, are exposed in the valleys of Duck Creek, Croton Creek, and Salt Croton Creek, and probably underlie a considerable area in the valley of Duck Creek. They also cap terraces and low hills in the valley of Croton Creek near its confluence with Short Croton Creek and in the lower end of the valley of Duck Creek near Dove Creek Salt Flat. Erosion of the Nebraskan deposits that cap the terraces and low hills produces a general hummocky or knobby appearance.

In general, the Nebraskan deposits consist of sand and gravel. The gravel consists largely of quartz pebbles and some calcareous pebbles, silicified wood, and water-worn Cretaceous fossils. The largest pebbles are about 6 inches long. Locally, the gravel, particularly in the basal part of the formation, is cemented with soft calcareous material that probably is weathered caliche. Pinkish-gray to pale-reddish indurated rock is exposed about 3½ miles west-southwest of Girard. This rock is believed to be caliche at the top of Nebraskan deposits because of its resemblance to the caprock of the Ogallala Formation on the High Plains.

The Nebraskan deposits are at least 11 feet thick in the valley of Duck Creek; however, the maximum thickness is not known because a part of the deposit has been removed by erosion.

The surface of the upland plain coincides with the top of the Nebraskan deposits at several places in and near the Croton Creek-Salt Croton Creek area and indicates that the plain was fairly well developed by the end of Nebraskan time.

KANSAN DEPOSITS

Deposits of Kansan age are exposed in the bluffs and in the beds of Duck Creek and some of its tributaries and of Short Croton Creek above the salt flat. In general, the exposures are small and isolated, and crop out only a few feet above the stream beds. The extent of the Kansan deposits is not known because they are largely covered by younger deposits.

The Kansan deposits consist of reddish brown, slightly consolidated sand and silt, brown conglomerate, gray to yellowish-gray volcanic ash, olive-green to dark-gray carbonaceous silt containing some fossils, and black carbonaceous clay, which is not known definitely to be of Kansan age. Stratigraphic section 10 (table 2) shows the character of the Kansan deposits about 4 miles southwest of Girard.

Data from several irrigation wells in the valley of Duck Creek southwest and west of Girard indicate that the Kansan deposits are as much as 100 feet thick.

The volcanic ash that crops out at several places in the valley of Duck Creek was identified as the Pearlette Ash Member of Sappa Formation equivalent by Ada Swineford (written communication, 1961). The Pearlette Ash Member was deposited in lakes and ponds (Leonard, 1950, p. 5) during late Kansan time (Frye and Leonard, 1957a, p. 6). Fossils from the ash confirm a Kansan age (A. B. Leonard, oral communication, 1961). The deposits of Kansan age may be correlative with the Tule Formation, which crops out on and near the High Plains, and also with the Seymour Formation, which crops out in Haskell and Knox Counties (fig. 2). However, the Seymour Formation may include some deposits other than Kansan.

According to J. C. Frye and A. B. Leonard (oral communication, 1961), the position of the Kansan deposits in the general vicinity of the Croton Creek-Salt Croton Creek area is normally on terraces above the general level of the stream beds. The position of the Kansan deposits near the level of and below the present bed of Duck Creek is unusual. The removal of salt and gypsum by solution from the Permian may have caused local subsidence of the overlying material. In addition, the volcanic ash may have accumulated in ponds formed by the subsidence.

Fossiliferous olive-green silty clay crops out in the bottom of a gully in the valley of Short Croton Creek upsteam from the salt flat. At the time of deposition of the clay, the valley floor was as low or lower than the present bottom of the gully. The age of the clay has not been determined definitely, but it probably is Kansan.

The Kansan deposits yield water to irrigation and public-supply wells in the valley of Duck Creek. In localized areas, where the Kansan and Wisconsin(?) deposits are in contact, water may be obtained from both deposits.

ILLINOIAN DEPOSITS

Illinoian deposits, consisting principally of eolian silt and fine sand, thinly mantle the upland areas, except in the stream valleys where the deposits have been removed by post-Illinoian erosion. The deposits typically consist of dark reddish-brown to brown silt, fine sand, and clay, and a few scattered siliceous pebbles in the lower part. Locally, they contain calcareous material either as small nodules or as disseminated fine-grained particles. The thickness of the deposits is not known exactly, but it probably is about 10 feet.

The eolian sand and silt mantling the upland areas probably are correlative, in part, with the "cover sands" of Frye and Leonard (1957b, p. 28–29) on the High Plains that they considered to be largely of Yarmouth and Illinoian age.

WISCONSIN(?) DEPOSITS

Alluvial deposits, younger than the Kansan deposits that contain the Pearlette Ash Member of the Sappa Formation equivalent, are designated as Wisconsin(?) and are exposed in the valley of Duck Creek and in the southeast banks of the Salt Fork Brazos River in the southeastern part of the area. Similar deposits are exposed in the east side of White River in western Kent County and on the south side of Salt Fork Brazos River in eastern Stonewall County.

Stratigraphic section 11 (table 2) shows the character of the Wisconsin(?) deposits where they are exposed in the east bank of Duck

Creek about 3½ miles southwest of Girard. The lower part of the Wisconsin(?) deposits, which rests on deposits of Kansan age, consists largely of unconsolidated gray to brown sand, in places cross-bedded, and gravel. It also contains lenses of greenish-gray or white, evenly bedded sand and some armored mud balls of brown to white, soft impalpable clay that range in size from a few inches to several feet in diameter. The Wisconsin(?) deposits grade upward into reddish-brown fine sand, silt and some scattered gravel and calcareous nodules. The upper 2 feet of the Wisconsin(?) deposits consist of reddish-brown, slightly consolidated sand, silt, and clay, with vertical prismatic structure that is part of a fairly well-developed soil profile. Overlying the Wisconsin(?) deposits in stratigraphic section 11 is 3 feet of grayish-brown, poorly consolidated fine sand that is probably of Recent age. The maximum thickness of the Wisconsin(?) deposits in the area is about 50 feet.

The Wisconsin(?) deposits probably yield water to irrigation and public-supply wells in the valley of Duck Creek. It is possible that in some wells water is obtained also from the underlying Kansan deposits.

PLEISTOCENE AND RECENT SERIES UNDIFFERENTIATED

DUNE SAND

Windblown sand of Pleistocene and Recent age overlies Wisconsin(?) deposits in the valley of Duck Creek south of Girard, and south and east of Salt Fork Brazos River in the southeastern part of the area. The sand generally forms a surficial covering except in localized areas where the sand has developed a dune topography. The marginal parts of the windblown sand are cultivated. The dune areas are covered with shrubs and small trees and are known locally as "shinnery sand." Parts of the dune areas stand above the general level of the upland plain.

Although the thickness of the windblown sand is not known, the height of some of the dunes suggests that the deposits locally are at least 50 feet thick.

The valleys of Hot Springs and Short Croton Creeks, and some of the tributaries at and above the salt flats, have a general U-shaped cross section that indicates partial filling of ancestral valleys that incised the Permian rocks. The fill consists largely of reddish-brown fine sand and silt and some lenses of gravel composed of gypsum pebbles, generally in the lower part. At some places a zone ranging from 3 to 5 feet in width and from 2 to 3 feet below the top of the fill is darker reddish-brown and contains vertical tubes of white calcareous material.

Gullys have cut the material that partly fills the valleys. The fill is older than the fossiliferous silty clay (believed to be of Kansan age) which is exposed in the bottom of the gully of Short Croton Creek and is younger than the salt flats. The gypsiferous gravel is of local origin and indicates transportation by water; however, much of the material probably was carried into the area at the time dune sand accumulated in the valley of Duck Creek; a Pleistocene and Recent age of the fill is thus indicated.

TERRACE DEPOSITS

Alluvial terraces and terraces of differential erosion have been formed in many of the stream valleys. Croton Creek, near its mouth, and Salt Fork Brazos River, about 1 mile south of the confluence of Croton Creek, have two alluvial terraces.

The terrace deposits generally consist of fine sand and silt, although well 291 was reported to contain sand and gravel. The well is in the lower part of the upper terrace along the Salt Fork Brazos River near the mouth of Croton Creek. The thickness of the terrace deposits is not known, except that is it nearly 60 feet in well 291.

RECENT SERIES

ALLUVIUM

The Salt Fork Brazos River, Croton Creek, and Salt Croton Creek are aggradational streams. The filling of the channels of these streams has resulted in stream braiding during periods of low water.

The Recent alluvium consists largely of sand and some gravel. The thickness of the alluvium in the stream beds is not known. However, Dr. H. R. Blank (see footnote, p. CC5) reported to the Brazos River Authority, that at the crossing of U.S. Highway 83 over the Salt Fork Brazos River, about 14 miles north of Aspermont, a well point reached a depth of 21 feet. It is not known if the well point was still in alluvium.

STRUCTURE

The Permian rocks dip west or southwest into the Midland basin, the eastern edge of which is only a few miles west of the area. The configuration of the top of the marker beds in the exposed Permian rocks is shown on plate *1B–D*. The beds near the surface dip generally west-southwest at a uniform rate of about 26 feet per mile; locally, the regional dip is interrupted by minor gentle warps.

The fold indicated by bed Dc (pl. 1*B*) in the northeastern part of the area probably is due to differential compaction between bed Dc and the limestone reef 4,700 feet below the surface. North of Girard the folding indicated in marker bed Ba (pl. 1*D*) is due largely to an eastward thinning of the sediments between beds Ba and Da. The thinning may have been the result of the removal of salt by solution and is discussed in the section "Theories of sources of salt water."

Some of the minor folds shown by the contours may be due to errors in picking deflections of the curves on some electric logs.

Although no joint systems were recognized, the linearity of some of the valleys, as seen on aerial photographs, suggests that joints may exist in the Permian rocks.

CHEMICAL QUALITY OF THE WATER

Surface water of the upper Brazos River basin is subject to extreme variations in chemical quality. Brine flows containing dissolved solids of more than 260,000 ppm (parts per million) and storm runoff having less than 100 ppm occur in Brazos River tributaries.

Storage of water in Possum Kingdom Reservoir and Whitney Reservoir, which is 245 river miles below Possum Kingdom Dam, mixes the flows from the upper basin and results in a water supply relatively uniform in quality. The water of the two reservoirs, however, still has undesirably high concentrations of dissolved solids, particularly sulfate and chloride.

RELATIONSHIP OF QUALITY OF WATER TO USE

Quality-of-water studies usually are concerned with the suitability of the water for a proposed use. The chemical quality is often a limiting factor in the effective use of the water of the Brazos River basin.

The U.S. Public Health Service (1962) has approved standards for drinking water. These standards, which are mandatory for carriers engaged in interstate commerce, are recommended for public water supplies. Some of these standards are reproduced in the following table.

Allowable limits for potable water

Constituent	*Limiting concentration (parts per million)*
Iron	0. 3
Chloride	250
Sulfate	250
Dissolved solids	500

Concentrations of dissolved solids, chloride, and sulfate in water from Possum Kingdom Reservoir generally exceed the Public Health Service limits.

The chemical-quality requirements for industrial water supplies have a wide range, and the standards are different for almost every industrial application. Water of the Brazos River is used by a few industries in the lower basin, but extensive use has been prevented because the water has been too saline for many industries.

Fixing definite limits for mineral content of irrigation water is difficult. For the purpose of this report, water containing more than

1,000 ppm dissolved solids is regarded as saline and is classified further as slightly saline, moderately saline, very saline, or brine, according to the following tabulation.

Description	*Dissolved solids (parts per million)*
Slightly saline	1,000–3,000
Moderately saline	3,000–10,000
Very saline	10,000–35,000
Brine	More than 35,000

Slightly saline water is used by many irrigators with good results, especially for salt-tolerant crops and on permeable soils. Even moderately saline water has been used successfully for supplemental irrigation in areas where the clay content of the soils is low and there is a moderate amount of precipitation. Water in the lower Brazos River generally is satisfactory for irrigation during low-flow periods, but at times it has been so saline as to be harmful to rice, one of the principal crops irrigated.

FACTORS AFFECTING WATER QUALITY

The kinds and quantities of minerals dissolved in surface water depend on many environmental factors, including geology, patterns and characteristics of streamflow, and cultural influences.

GEOLOGY

The amount of soluble products of weathering or dissolved solids carried by streams depends principally on the physical and chemical properties of the rocks and soils in the drainage basin. The physical and chemical properties of the rocks and soils depend not only on the environment in which the rocks are formed but also on the post-depositional environment. In some areas of high precipitation, rocks that originally contained large amounts of easily soluble minerals have been leached by circulating water until the residual soil and mantle rock contain relatively small amounts of readily soluble minerals. Conversely, the soils and rocks in arid or semiarid regions may be incompletely leached and may therefore contain large amounts of soluble material.

Many rocks, such as siltstone and shale, expose large areas to the solvent action of water, and water from areas underlain by these fine-grained rocks may contain large amounts of dissolved material. The cementing material of many rocks is calcium carbonate, which is easily dissolved in water that contains carbon dioxide. Some rocks, such as limestone, are almost completely calcium carbonate.

The drainage basin of the Brazos River above Possum Kingdom Dam is underlain by shale, siltstone, sandstone, limestone, and beds of

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evaporites, such as gypsum and halite (sodium chloride, or table salt). These rocks range in age from Mississippian to Recent.

The Salt Fork Brazos River and Double Mountain Fork Brazos River rise in the High Plains section in New Mexico and Texas northwest of Lubbock. The High Plains section is underlain principally by the Ogallala Formation of Tertiary (Pliocene) age. Analyses of many samples of ground water from the Ogallala indicate that the infrequent surface runoff from the High Plains is low in dissolved solids (probably less than 500 ppm) and is calcium bicarbonate type.

Immediately to the east of the "Break of the Plains," which marks the eastern boundary of the High Plains section, rocks of Triassic age crop out in the drainage basins of the Salt Fork Brazos River and Double Mountain Fork Brazos River. Clear Fork Brazos River also drains rocks of Triassic age. Records of the quality of the water of streams rising in the area underlain by Triassic rocks are insufficient to show the effect of these rocks on the quality of the water. However, indications that the runoff water from the Triassic rocks in the Brazos River basin would be of good quality are given by chemical analyses of water from Lake J. B. Thomas, which is in the southwest corner of Scurry County and which impounds water of the Colorado River from an area underlain by similar rocks (Burdge Irelan and H. B. Mendieta, written communication, 1961). The sodium bicarbonate water in Lake J. B. Thomas is moderately hard (61–120 ppm), and the dissolved-solids concentration has never exceeded 400 ppm.

Rocks of Permian age that underlie large areas of the drainage basins of the three forks of the Brazos River contribute large amounts of dissolved solids, mostly sodium, calcium, chloride, and sulfate, to the Brazos River system. These rocks consist of shale, fine-grained sandstone, gypsum, and dolomite. Beds of salt and anhydrite or gypsum underlie the surface, and gypsum crops out in many places. Ground water, which circulates through the rocks, comes in contact with the soluble minerals, and surface water, which travels over the exposed beds of gypsum or beds containing soluble minerals disseminated in the rocks, dissolve large quantities of these minerals. Records of the dissolved-solids discharge at different sites indicate that a large percentage of the dissolved solids entering Possum Kingdom Reservoir comes from areas underlain by Permian rocks, and a large part of the salt load can be isolated as coming from certain small areas within the zone of outcrop of the Permian rocks. The sodium and the chloride concentrations of the springs and seeps of these same small areas are high, ranging up to 100,000 ppm sodium and 160,000 ppm chloride.

Rocks of Pennsylvanian and Cretaceous age underlie large areas of the drainage basin above Possum Kingdom Reservoir. These rocks are mostly limestone, shale, and sandstone. Analyses of water from lakes and streams draining areas underlain by these rocks indicate that the water is a calcium bicarbonate type having a dissolved-solids concentration ranging from 150 to 500 ppm.

STREAMFLOW

The patterns and characteristics of streamflow affect the chemical characteristics of the water in streams, particularly the dissolved-solids concentration of water and the concentration of individual constituents. Water discharge of any stream varies from day to day and from hour to hour. The variation may be large, such as for streams that flow mostly in response to storms, or small, such as for streams whose flow is mostly from ground water. Likewise, the concentration of dissolved solids carried by a stream varies from day to day, usually in inverse relation to the water discharge. The base flow, or low sustained flow, of a stream usually is composed predominantly of water that has entered the stream from the ground-water reservoir. The water has been in contact with rock and soil particles for a sufficient time to leach part of the soluble minerals. Thus, the low flow of the streams is more mineralized than the surface runoff, which usually has a lower dissolved-solids content than the ground water. At high rates of discharge, the more mineralized ground water entering the stream is diluted by surface runoff; the dilution is proportional to the dissolved-solids concentration of the water from the two sources and the amount of water from each source.

Figure 3 shows the dissolved-solids concentration and discharge and water discharge of the Salt Fork Brazos River near Aspermont, Tex., for the 1950 water year. Although the concentration is highest during periods of low flow, most of the salt load of the stream is transported during periods of high flow. During periods of high flow, the salt load carried by the stream is increased by the addition of dissolved minerals picked up by the overland flow from on or near the surface and from encrustation of salt that was precipitated along the stream channels during low flow.

The relation of the chemical quality of the water of Salt Croton and Croton Creeks to water discharge is similar to the streamflow-quality pattern of the Salt Fork, but differs both in the magnitude of the dissolved-solids concentration and water discharge. Mineralization of the water of all streams is at a maximum at low-water discharge and at a minimum at high-water discharge.

The streamflow-quality relation of the streams was used to estimate and to extend the chemical-quality records at key stations. The techniques of extension are summarized briefly on page CC35.

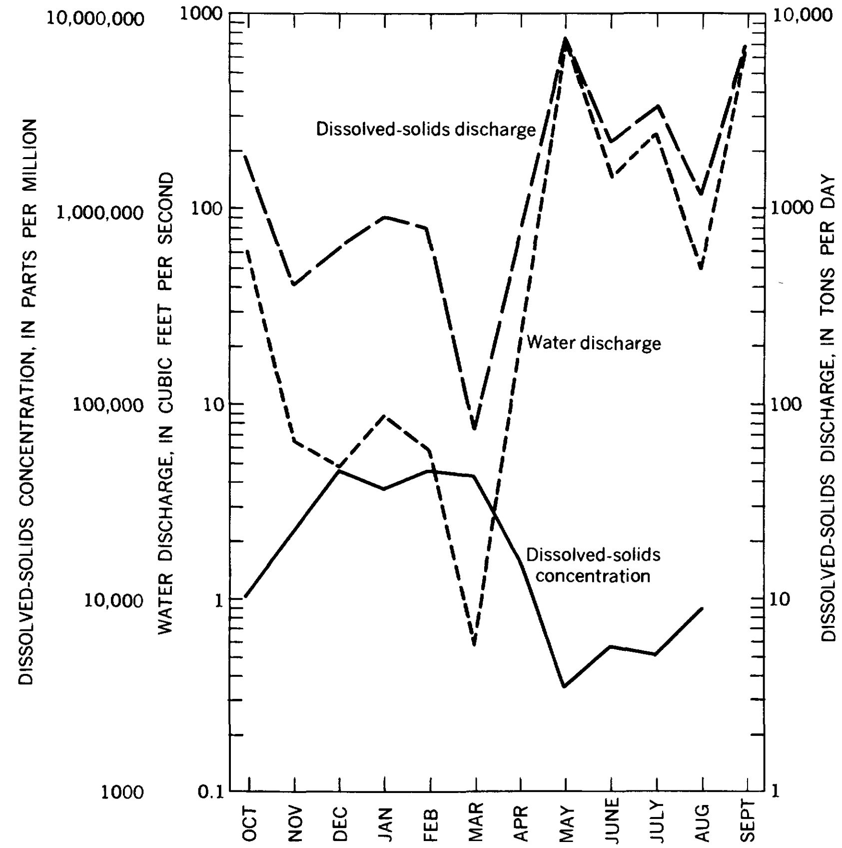


FIGURE 3.—Dissolved-solids concentration and discharge, and water discharge of Salt Fork Brazos River near Aspermont, Tex., 1950 water year.

Figure 4 shows the differences in the mineral content and chemical composition of the Salt Fork near Aspermont for three different rates of discharge. The effect of ground-water inflow and overland runoff on the chemical quality of water is clearly evident. At all flows the water of the Salt Fork Brazos River is a sodium chloride type, but the range of dissolved-solids concentration between high and low flows is great. The concentration of each constituent, except bicarbonate, increases significantly as the water discharge decreases, but at the low flows, sodium and chloride ions make up about 90 percent of the dissolved solids; at high flows about two-thirds of the dissolved solids is sodium and chloride.

CULTURAL INFLUENCES

The activities of man may have significant effects on the chemical quality of surface water. The disposition of oil-field brine and

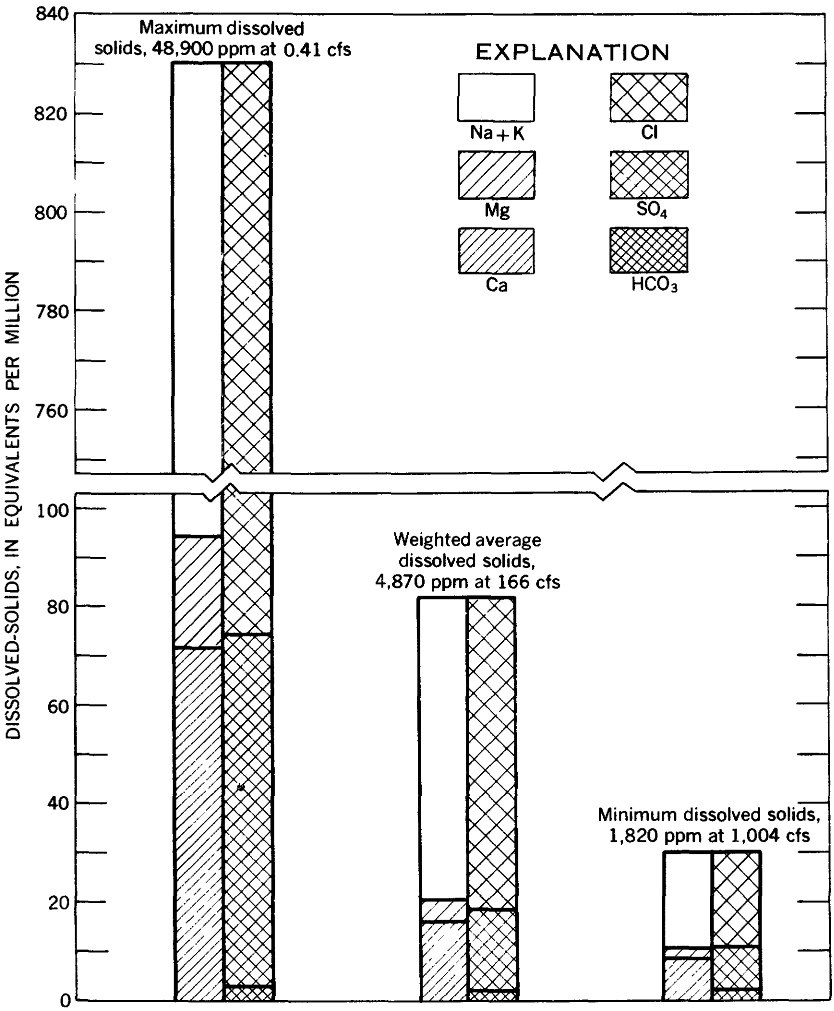


FIGURE 4.—Relation of the chemical composition and concentration of dissolved solids to water discharge, Salt Fork Brazos River near Aspermont, Tex., 1950 water year.

municipal waste and the depletion of streamflow by diversion for irrigation and municipal use produce changes in water quality.

Oil-field brine contributes to the dissolved minerals in surface water in many parts of the upper Brazos River basin. Brine is produced in nearly all oil fields and, if improperly handled, eventually reaches the streams. The composition of oil-field brine varies, but the principal chemical constituents, in order of their concentration, are usually chloride, sodium, calcium, and sulfate. The extent of stream pollution by oil-field brine in the Brazos River basin has not been determined, but in some areas the usability of the water is being seriously affected.

Use of surface water for irrigation affects the chemical quality of the remaining water in the basin, because water removed from streams for irrigation is no longer available for dilution of more saline flows. In addition, drainage water carries mineral salts dissolved from the irrigated land back to the streams. Although, in general, use of surface water for irrigation increases the concentration of dissolved solids in the water downstream, it probably is not yet a significant factor in the quality of water in the upper Brazos River basin.

Irrigation with ground water also affects the quality of water in streams where salts derived from the irrigation water are drained from the land. Principal use of ground water for irrigation in the upper Brazos basin is in the High Plains, from which very little drainage occurs.

Municipal use of water tends to increase the concentration of dissolved solids in a stream system. Municipal waste introduced into a stream may have a considerable affect on water quality, and the depletion of the flow of a stream by diversion of water of good quality for municipal purposes results in higher average concentrations of dissolved solids in the remaining water. Reservoirs, which impound water of good quality, have been constructed on many of the smaller tributaries in the upper Brazos basin. Much of the dissolved mineral matter in the water eventually returns to the river system in a volume of water greatly reduced by evaporation and municipal use. Decreased flow as a result of diversions probably has a greater effect on the quality of the water of the Brazos River than does the introduction of municipal waste to the streams.

CHEMICAL-QUALITY RECORDS

Data on the chemical quality of surface water have been collected at continuous sampling stations in the upper Brazos River basin since 1941, and one or more samples have been collected at many other sites in the area. These data collections are summarized in table 3. The location of the sampling sites are shown on figure 2. Most of the analyses and stream-flow data are included in the series of annual reports on quality of surface waters published by the Texas Board of Water Engineers and in the following U.S. Geological Survey publications:

Report year	Water-Supply Paper No. Streamflow records	Water-Supply Paper No. Chemical-quality records	Report year	Water-Supply Paper No. Streamflow records	Water-Supply Paper No. Chemical-quality records	Report year	Water-Supply Paper No. Streamflow records	Water-Supply Paper No. Chemical-quality records
1916	438	----------	1932	733	----------	1947	1088	1102
1917	458	----------	1933	748	----------	1948	1118	1133
1918	478	----------	1934	763	----------	1949	1148	1163
1919-20	508	----------	1935	788	----------	1950	1178	1188
1921	528	----------	1936	808	----------	1951	1212	1199
1922	548	----------	1937	828	----------	1952	1242	1252
1923	568	----------	1938	858	----------	1953	1282	1292
1924	588	----------	1939	878	----------	1954	1342	1352
1925	608	----------	1940	898	----------	1955	1392	1402
1926	628	----------	1941	928	942	1956	1442	1452
1927	648	----------	1942	958	950	1957	1512	1522
1928	668	----------	1943	978	970	1958	1562	1573
1929	688	----------	1944	1008	1022	1959	1632	----------
1930	703	----------	1945	1038	1030	1960	1712	----------
1931	718	----------	1946	1058	1050			

TABLE 3.—*Index of streamflow and chemical-quality records in the Brazos River basin above gaging station near Palo Pinto, Tex.*

[Many sites for which one or two analysis are available are omitted from this list. Type of station: PR, partial record, low flow, periodic; R, reservoir levels and contents; S, streamflow, continuous record]

Station (fig. 2)	Stream and location	Permanent station number	Drainage area (square miles)	Streamflow and reservoir contents: Period of record	Streamflow and reservoir contents: Type of station	Chemical analyses: Period of record	Chemical analyses: Frequency of sampling
1	Double Mountain Fork Brazos River at Lubbock.	795	----------	1939-49	S	----------	
2	Tributary to Double Mountain Fork Brazos River near Justiceburg.	797	----------	1959-61	PR	1959-	Periodic.
3	Rough Creek at mouth near Rotan.	799	----------	1959-61	PR	1959-	Do.
4	Double Mountain Fork Brazos River near Rotan.	800	[1] 7,739	1949-51	S	1949-51	Daily.
5	Double Mountain Fork Brazos River near Aspermont.	805	[1] 7,980	1923-34, 1939-	S	1948-51, 1956-	Do.
6	McDonald Creek at mouth near Post.	805.5	----------	1959-61	PR	1959-	Intermittent.
7	White River at Plainview	807	----------	1939-49, 1961-	S	----------	
8	White River near Crosbyton	808	----------	1951-	PR	1950-	Intermittent.
9	White River below Crosbyton	809	----------	1951-	PR	1950-	Do.
10	Red Mud Creek at mouth near Clairemont.	809.2	----------	1959-61	PR	1959-	Periodic.
11	Butte Creek at mouth near Jayton.	809.6	----------	1959-61	PR	1959-	Do.
12	Salt Fork Brazos River near Peacock.	810	[2] 4,260	1949-51	S	1949-51	Daily.
13	Hot Springs Creek one-fourth mile above confluence with Croton Creek near Jayton.	----------	----------	----------	----------	1960	Intermittent.
14	Short Croton Creek at mouth near Jayton.	810.5	----------	1959-	PR	1959-	Periodic.
15	Croton Creek below Short Croton Creek near Jayton.	811	----------	1959-	PR	1959-	Do.
16	Croton Creek near Jayton	812	310	1959-	S	1959-	Do.
17	Dove Creek at weir A near Aspermont.	812.9	----------	1956-58	PR	1956-57	Do.
18	Dove Creek 1,000 ft downstream from weir A near Aspermont.	----------	----------	----------	----------	1961	Intermittent.

See footnote at end of table.

TABLE 3.—*Index of streamflow and chemical-quality records in the Brazos River basin above gaging station near Palo Pinto, Tex.*—Continued

[Many sites for which one or two analysis are available are omitted from this list. Type of station: PR, partial record, low flow, periodic; R, reservoir levels and contents; S, streamflow, continuous record]

Station (fig. 2)	Stream and location	Permanent station number	Drainage area (square miles)	Streamflow and reservoir contents: Period of record	Streamflow and reservoir contents: Type of station	Chemical analyses: Period of record	Chemical analyses: Frequency of sampling
19	Dove Creek about 0.65 mile upstream from Salt Flat Creek near Aspermont.	--------	------------	----------	------	1961	Do.
20	Dove Creek 200 ft above Salt Flat Creek near Aspermont.	--------	------------	----------	------	1957, 1961	Do.
21	Salt Flat Creek at weir B near Aspermont.	813	------------	1956–59	PR	1956–59	Periodic.
22	Salt Croton Creek at weir C near Aspermont.	813.5	------------	1956–59	PR	1956–59	Do.
23	Salt Croton Creek at weir D near Aspermont.	814	------------	1956–	PR	1956–	Do.
24	Haystack Creek at weir E near Aspermont.	814.5	------------	1956–	PR	1956–	Do.
25	Salt Croton Creek near Aspermont.	815	69	1956–	S	1956–	Do.
26	Salt Croton Creek at falls near Aspermont.	815.5	------------	1959–61	PR	1959–	Do.
27	Salt Croton Creek at mouth near Aspermont.	816	------------	1957–59	PR	1957–58	Do.
28	Salt Fork Brazos River near Aspermont.	820	[2] 4,830	1923–25, 1939–	S	1948–51, 1956–	Daily.
29	North Croton Creek at mouth near Knox City.	822	------------	1959–61	PR	1959–	Periodic.
30	Mustang Creek at mouth near Knox City.	824	------------	1959–61	PR	1959–	Do.
31	Brazos River at Seymour	825	[3] 14,490	1924–	S	1959–	Daily.
32	Brazos River near Graham	830	[3] 15,730	1915–20	S	----------	
33	Lake Sweetwater near Sweetwater.	832	104	1936–	R	----------	
34	Fort Phantom Hill Reservoir near Nugent.	835	478	1940–	R	----------	
35	Clear Fork Brazos River at Nugent.	840	2,220	1924–	S	1948–53	Do.
36	Lake Stamford near Haskell	845	360	1953–	R	----------	
37	Paint Creek near Haskell	850	879	1949–50	S	1949–51	Do.
38	Clear Fork Brazos River at Fort Griffin.	855	3,974	1923–	S	1949–51	Do.
39	Clear Fork Brazos River at Crystal Falls.	860	4,323	1921–29	S	----------	
40	Hubbard Creek near Breckenridge.	865	1,087	1955–	S	1955–	Do.
41	Clear Fork Brazos River near Crystal Falls.	870	5,658	1928–51	S	----------	
42	Clear Fork Brazos River near Eliasville.	875	5,740	1915–20, 1923–25	S	1961–	Do.
43	Brazos River near South Bend	880	[3] 21,600	1938–	S	1942–48	Do.
44	Salt Creek at Olney	881	9.6	1958–	S	1958–60	Do.
45	Salt Creek near Newcastle	882	57.9	1958–60	S	1958–60	Do.
46	Oak Creek near Graham	883	19.7	1958–	S	1958–60	Intermittent.
47	Possum Kingdom Reservoir near Graford.	885	[3] 22,550	1941–	R	----------	
48	Brazos River at Possum Kingdom Dam near Graford.	886	[3] 22,550	----------	------	1942–	Daily.
49	Brazos River near Palo Pinto	890	[3] 22,760	1924–	S	----------	

[1] of which 6,470 square miles is probably noncontributing.
[2] of which 2,770 square miles is probably noncontributing.
[3] of which 9,240 square miles is probably noncontributing.

EXTENSION OF RECORDS

Long-term daily records of analyses are desirable for defining the chemical-quality characteristics of a stream, particularly for the computation of loads of dissolved solids transported by the stream. In the upper Brazos River basin, only the records for the station below Possum Kingdom Dam are considered adequate. For other stations, estimates of long-term average chemical-quality traits are based on available data.

Estimates of chemical-quality data for the periods October 1939 to September 1948 and October 1951 to September 1956 were computed for the Salt Fork Brazos River near Aspermont from chemical-quality data collected during the water years 1949–51 and 1957–60 and from streamflow records.

Yearly weighted-average concentration of dissolved solids was plotted against the yearly mean water discharge (fig. 5). The construction of the curve, particularly in the upper concentration range, was based partially on the dissolved solids-water discharge relationships observed in daily station operations. From the curve and the yearly mean water discharge, yearly weighted-average concentrations were estimated, and the yearly dissolved-solids discharge for the periods of no chemical-quality record was computed. Curves similar to that in figure 5 were constructed for chloride and sulfate, and the yearly discharge of each of these constituents was computed for missing periods. Those curves are not included in this report.

Estimates of the yearly salt discharge of the Double Mountain Fork Brazos River near Aspermont for years of missing record in the water years 1940–60 were made from the relation of dissolved-solids concentration to water discharge.

Daily discharges of chloride and sulfate for Salt Croton Creek near Aspermont and Croton Creek near Jayton were determined from measured concentrations of these constituents and their relation to water discharge. Monthly and yearly values were computed from these determinations of daily loads.

The salt discharges of each of the above streams and other streams are discussed in more detail in the sections on salt discharge, pages CC38 to CC52.

SOURCES OF SALT IN POSSUM KINGDOM RESERVOIR

One of the principal purposes of this investigation was to define the major sources of the dissolved minerals, especially chloride and sulfate, in the water reaching Possum Kingdom Reservoir, and to determine the part of the total salt load contributed by the tributary areas.

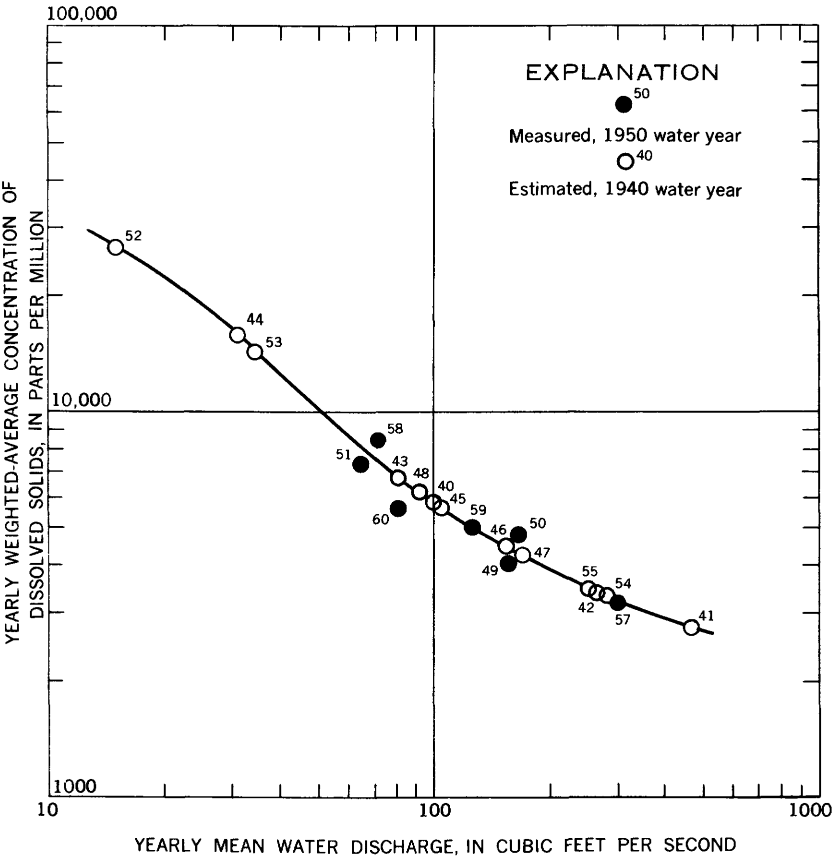


FIGURE 5.—Relation of dissolved-solids concentration to water discharge, Salt Fork Brazos River near Aspermont, Tex.

Chemical-quality records of releases and spills from Possum Kingdom Reservoir are available beginning in January 1942. In figure 6, monthly average concentrations of dissolved solids, sulfate, and chloride are plotted for the period January 1942 to September 1960. Dissolved-solids concentrations ranged from 331 to 2,640 ppm, sulfate from 63 to 663 ppm, and chloride from 91 to 980 ppm. The dissolved-solids concentration of water released from the reservoir exceeded 1,000 ppm more than 90 percent of the time.

The weighted-average dissolved-solids concentration of water passing Possum Kingdom Reservoir from January 1942 to September 1960 is given in table 4. From this average and the average water discharge of 958 cfs (cubic feet per second), the average daily load of dissolved solids leaving the reservoir was a calculated 2,800 tons.

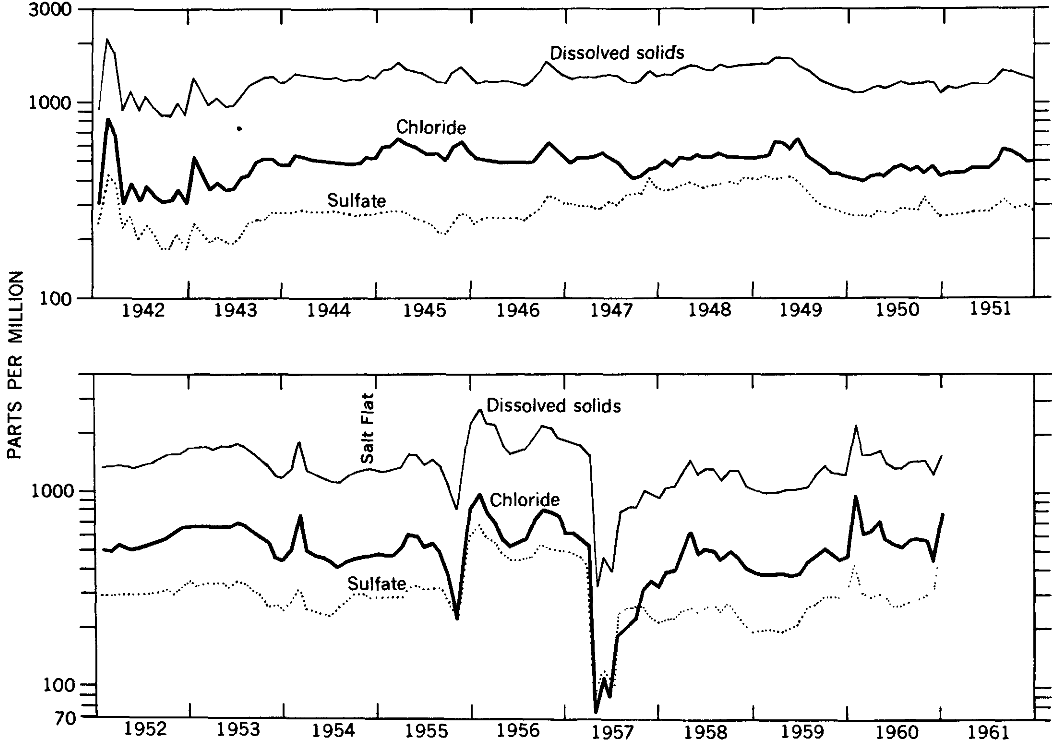


FIGURE 6.—Monthly average concentrations of dissolved solids, sulfate, and chloride of Brazos River at Possum Kingdom Dam, Tex., January 1942 to September 1960.

The average load of chloride and sulfate was 1,000 and 625 tons per day, respectively.

TABLE 4.—*Weighted average of analyses of water of Brazos River at Possum Kingdom Dam, Tex., January 1942 to September 1960*

[All data in parts per million, except as noted]

Silica (SiO_2)	10	Hardness as $CaCO_3$:	
Calcium (Ca)	116	Calcium, magnesium	368
Magnesium (Mg)	19	Noncarbonate	275
Sodium (Na)	242	Percent sodium	59
Potassium (K)		Sodium-adsorption-ratio	5.5
Bicarbonate (HCO_3)	113	Specific conductance micromhos at 25°C	1,840
Sulfate (SO_4)	242	Sulfate tons per day	625
Chloride (Cl)	386	Chloride do	1,000
Nitrate (NO_3)	1.5	Dissolved solids do	2,800
Dissolved solids (calculated)	1,080	Mean discharge cubic feet per second	958

The total drainage area of the Brazos River above Possum Kingdom Dam is 22,500 square miles, of which 9,240 square miles in the High Plains is probably noncontributing. The three principal tributaries draining the area are the Double Mountain Fork and the Salt Fork, which join in eastern Stonewall County to form the Brazos River, and Clear Fork, which enters the Brazos River in southern Young County about 100 miles downstream from the junction of the Double Mountain Fork and the Salt Fork.

DOUBLE MOUNTAIN FORK BRAZOS RIVER

The streamflow station, Double Mountain Fork Brazos River, near Aspermont, measures runoff from approximately 1,500 square miles of contributing area. Records are available from December 1923 to September 1934 and from June 1939 to September 1960. The average water discharge for 31 years was 178 cfs. Chemical analyses are available from October 1948 to September 1951 and from October 1956 to September 1960.

The principal dissolved constituents of the water in the Double Mountain Fork are calcium and sulfate, although sodium and chloride may predominate in the more concentrated, low-flow water. The maximum dissolved-solids concentration of record was 6,350 ppm, of which 2,400 ppm was chloride and 1,660 ppm was sulfate.

As described earlier in the section "Extension of Records," estimates were made of yearly salt discharge of the Double Mountain Fork Brazos River near Aspermont for years of missing record during the water years 1940–60. These estimates were based on the relation of dissolved-solids concentration to water discharge. During the 1940–60 period, the average discharge was 177 cfs. The following weighted-average concentrations and loads for water years 1940–60 were estimated: dissolved solids, 1,010 ppm and 485 tons per day;

chloride, 160 ppm and 75 tons per day; and sulfate, 448 ppm and 210 tons per day.

A streamflow and chemical-quality station was operated during the period December 1949 to September 1951 at a site near Rotan, about 30 miles upstream from Aspermont. Comparison of the short-term chemical-quality records for the Double Mountain Fork Brazos River near Rotan with the records from near Aspermont indicates that the water is similar in character at both sites and that the increase in salt load between the two stations is proportional to the increase in streamflow. No important source of salt occurs in the intervening drainage.

Low-flow partial-record stations, with periodic measurements of flow and sampling for chemical analysis, were established in August 1959 on an unnamed tributary of the Double Mountain Fork Brazos River near Justiceburg and on Rough Creek at its mouth near Rotan. Dr. Blank (see p. CC5) suggested further investigation of these streams as possible sources of salt. The streams flow intermittently, and analyses of water samples collected at low flow and from pools indicate that neither stream is a source of significant amounts of salt. Representative analyses are given in table 5.

SALT FORK BRAZOS RIVER

Studies of the chemical quality of the surface water of the Brazos River basin since 1941 show that the Salt Fork Brazos River contributes more to the salinity of the Brazos River than does any other tributary.

SALT FORK BRAZOS RIVER NEAR ASPERMONT

The most comprehensive streamflow and chemical-quality records on the Salt Fork are for the gaging station near Aspermont. Streamflow records were collected from December 1923 to August 1925 and since June 1939. The average water discharge for water years 1940–60 was 150 cfs. Chemical-quality records are available for October 1948 to September 1951 and since October 1956.

The minimum concentration of dissolved solids at the Aspermont station was 1,240 ppm, which is greater than the maximum dissolved solids permitted by the drinking-water standards of the U.S. Public Health Service (1962). The maximum concentration observed was 99,200 ppm. Chloride concentrations ranged from 412 to 57,400 ppm.

Yearly weighted-average concentrations of dissolved solids, chloride, and sulfate have been estimated for the years of missing records. Table 6 lists the mean discharges for the water years 1940–60 and the determined and estimated concentrations and loads of dissolved solids, chloride, and sulfate. The loads estimated for the 21-year period

TABLE 5.—*Selected analyses of streams in the upper Brazos River basin, Texas*

[Chemical analyses in parts per million]

Station No. (fig 2; table 3)	Date of collection	Discharge (cfs)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (calculated)		Hardness as $CaCO_3$		Percent sodium	Sodium-adsorption-ratio	Specific conductance (micromhos at 25° C)	pH	Density at 20° C
											Parts per million	Tons per acre-foot	Calcium, magnesium	Noncarbonate					
2	Dec. 17, 1959	3.96				66	1.6	156	15	9			24	0	85		306	7.8	
	June 22, 1961	0								505							2,000		
3	Jan. 20, 1960	0.08							1,140	56							2,020		
	May 12	0								1,440							7,690		
6	Dec. 17, 1959	12.7				1,160		172	238	1,730			320	179	89		5,850	7.9	
	Jan. 20, 1960	.22							1,670	13,200							33,800		1.015
10	July 26, 1960	[1] 0.01				4,680			2,010	7,920			3,320		75		22,100		1.010
	Nov. 16	.04				99	6.9	142	1,400	158			1,540	1,420	12		2,670	7.3	
11	Dec. 17, 1959	0.60				30	4.8	112	1,260	22			1,320	1,230	5		2,090	7.9	
	Nov. 16, 1960	0								7,780							23,600		1.009
13	Oct. 6, 1960					41,700			7,030	63,300			6,930		93				1.082
14	Sept. 21, 1960	0.01				9,090			3,410	14,500			4,220		82		37,000		1.019
15	Sept. 21, 1960	0.05				5,910			2,710	9,400			3,110		81		26,100		1.011
16	Apr. 28, 1960	0.91				11,500			3,540	18,100			4,740		84		46,700		1.023
17	Oct. 20, 1956	0.10	9.0	293	46	780		56	1,190	940	3,290	4.47	920	874	65	11	4,750	7.2	
18	May 24, 1961	0				39,900			5,460	62,000			7,960		92				1.081
19	May 24, 1961	0.02				82.200			3,540	129,000			6,960		96				1.163
20	May 24, 1961					98,200			3,150	153,000			7,600		97				1.198
21	Mar. 26, 1959	0.30	24	1,810	1,280	92,400		38	3,010	147,000	246,000	397	9,780	9,750	95	406		7.5	1.187
	May 24, 1961					90,000			3,050	143,000			9,810		95				1.183
23	Mar. 26, 1959	0.40	22	1,700	1,280	99,800		41	2,370	159,000	264,000	432	9,500	9,470	96	445		7.5	1.203
24	Mar. 26, 1959	0.18	53	1,840	573	44,300		77	4,800	68,900	121,000	179	6,950	6,880	93	231		7.9	1.089
25	May 12, 1958	450				1,840		100	979	2,900			1,220	1,140	77		10,000	7.3	
	Mar. 26, 1959	.73	28	1,780	1,180	88,100		54	3,300	140,000	234,000	376	9,290	9,250	95	397		7.5	1.181
29	Feb. 16, 1960	0.78				4,230			2,190	6,940			2,980		76		20,700		1.008
	Aug. 16	2.67				372	5.5	43	433	600			500	465	61		2,760	6.5	
30	Mar. 14, 1960	[1] 0.10						138	2,330	760			2,110	2,000			5,620	7.8	
	Aug. 16	29.8				25	5.2	91	358	30			415	340	11		901	7.3	

[1] Field estimate.

closely approximate those calculated for the 7 years during which chemical-quality records were obtained. The estimates of 1,860, 870, and 280 tons per day of dissolved solids, chloride, and sulfate, respectively, probably are representative of long-time yields of the Salt Fork Brazos River. Thus, more than 60 percent of the dissolved solids, 80 percent of the chloride, and 40 percent of the sulfate reaching Possum Kingdom Reservoir originates in the area drained by the Salt Fork Brazos River above the Aspermont station.

TABLE 6.—*Annual summaries of water discharge and dissolved solids, chloride, and sulfate loads, Salt Fork Brazos River near Aspermont, Tex.*

[Roman figures are estimated from relationships of dissolved constituents to water discharge; italicized figures are from station records]

Water year	Water discharge (cfs)	Dissolved solids		Chloride		Sulfate	
		Weighted-average concentration (ppm)	Load (tons per day)	Weighted-average concentration (ppm)	Load (tons per day)	Weighted-average concentration (ppm)	Load (tons per day)
1940	*100*	5,900	1,590	3,000	810	790	210
1941	*463*	2,800	3,500	1,300	1,630	600	750
1942	*265*	3,400	2,430	1,500	1,070	625	450
1943	*81.5*	6,800	1,500	3,500	770	850	190
1944	*30.7*	15,900	1,320	7,200	600	1,250	100
1945	*104*	5,700	1,600	2,900	810	780	220
1946	*153*	4,500	1,860	2,200	910	690	290
1947	*170*	4,300	1,970	2,000	920	675	310
1948	*91.5*	6,200	1,530	3,200	790	815	160
1949	*157*	*4,080*	*1,730*	*1,820*	*770*	*709*	*300*
1950	*166*	*4,870*	*2,180*	*2,230*	*1,000*	*786*	*350*
1951	*64.5*	*7,380*	*1,290*	*3,560*	*620*	*1,020*	*180*
1952	*14.8*	27,000	1,080	12,300	490	1,620	65
1953	*34.3*	14,400	1,330	6,600	610	1,190	110
1954	*281*	3,400	2,580	1,500	1,140	620	470
1955	*252*	3,500	2,380	1,600	1,090	630	430
1956	*155*	4,500	1,880	2,100	880	690	290
1957	*299*	*3,220*	*2,600*	*1,360*	*1,100*	*625*	*500*
1958	*71.4*	*8,500*	*1,640*	*4,410*	*850*	*826*	*160*
1959	*126*	*5,020*	*1,710*	*2,420*	*820*	*666*	*230*
1960	*80.2*	*5,660*	*1,230*	*2,820*	*610*	*653*	*140*
Average, 1949–51, 1957–60	*138*	*4,750*	*1,770*	*2,220*	*820*	*715*	*270*
Average, 1940–60	*150*	4,570	1,860	2,150	870	697	280

SALT FORK BRAZOS RIVER NEAR PEACOCK

Streamflow and chemical-quality records are available for Salt Fork Brazos River at station 12 near Peacock for the period December 1949 to September 1951. The discontinued station near Peacock is about 25 miles upstream from the station near Aspermont; Salt Croton and Croton Creeks drain a large part of the 570 square miles of the intervening basin area. Dissolved-solids concentrations at the Peacock station were much lower than at the station near Aspermont. Figure 7 shows the weighted average chemical composition and concentrations of dissolved solids for the two stations for the 1951 water year.

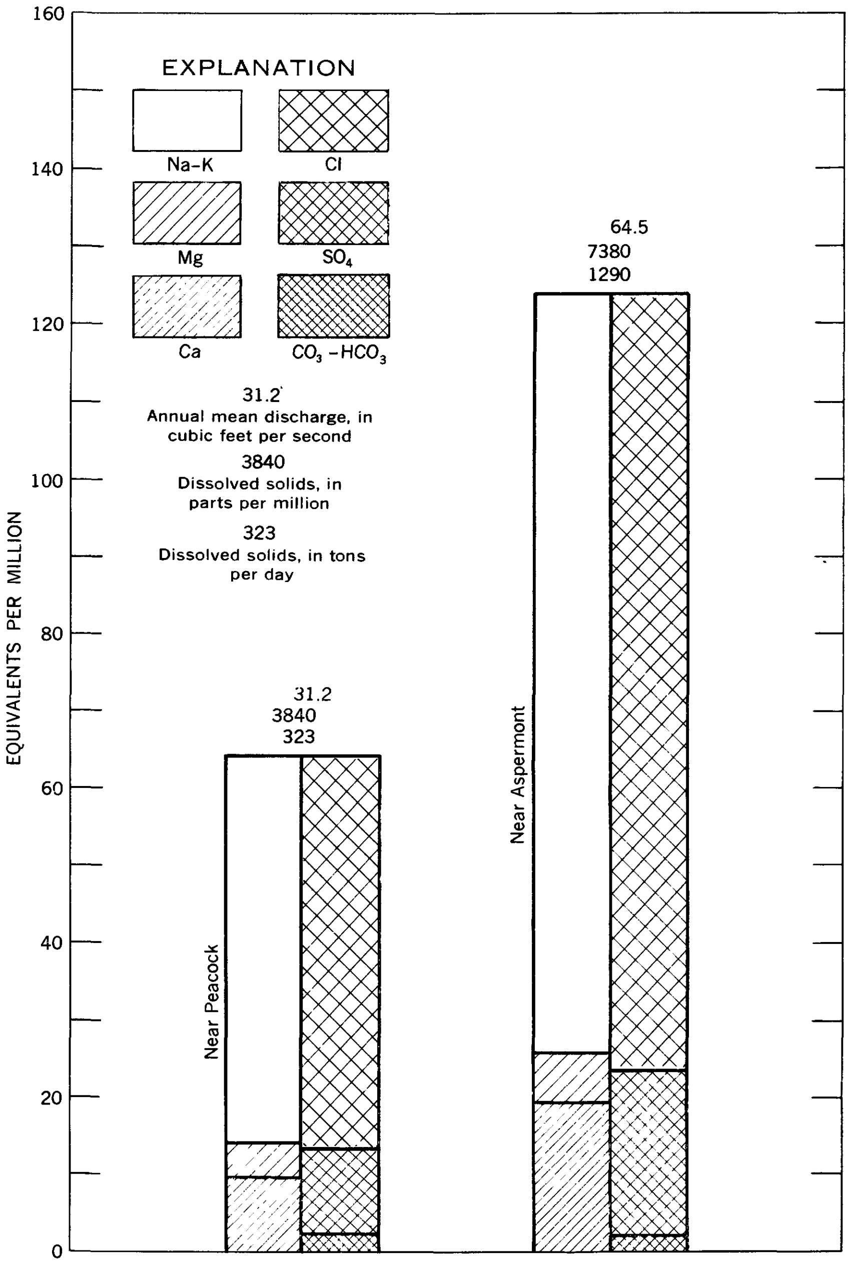


FIGURE 7.—Weighted average chemical composition and concentration of dissolved solids, Salt Fork Brazos River near Peacock and near Aspermont, Tex., 1951 water year.

By means of correlation, the average runoff at the station near Peacock for 1940–60 was estimated as 80 cfs and the daily loads as 810 tons of dissolved solids, 280 tons of chloride, and 95 tons of sulfate. The estimated loads indicate that about 25 percent of the chloride load reaching Possum Kingdom Reservoir originates in the 1,490 square miles drainage area above the Peacock site.

SALT CROTON CREEK

According to Dr. Blank (see footnote, p. CC5), Salt Croton (Dove) Creek contributed a considerable part of the salt load of the Brazos River. A description of the salt flats and springs in this area are given in the section "Description of Salt Producing Areas" on page CC52.

In October 1956, the Geological Survey began an intensive investigation that included the collection of data on the quantity and quality of the water of the Dove Creek-Salt Croton Creek area. A streamflow station was established on Salt Croton Creek, 2.5 miles downstream from Salt Flat, 0.1 mile downstream from Haystack Creek, and about 8 miles upstream from the point where Salt Croton Creek enters Salt Fork Brazos River. Five low-flow, partial-record stations were established upstream from the streamflow station. These stations were identified as follows: Dove Creek at weir A, Salt Flat Creek at weir B, Salt Croton Creek at weir C, Salt Croton Creek at weir D, and Haystack Creek at weir E. The location of the stations is shown in plate 1*A*.

Water samples were collected and current-meter measurements were made at about 2-week intervals at all the stations. More frequent sampling was not practicable because of the isolation of the area. An automatic single-stage sampler was installed at the streamflow station on Salt Croton Creek, and samples of rising stages were collected during several periods of flood runoff. The results of the analyses and streamflow data have been published by the Geological Survey in a series of water-supply papers (see p. CC33).

DOVE CREEK

Results of sampling Dove Creek at weir A during the first year the stations were operated showed the water to be only moderately saline (having 3,000 to 10,000 ppm dissolved solids) and indicated that the salt load being contributed by base flow at that point was inconsequential. The station, therefore, was discontinued. However, investigations have shown that saline water enters Dove Creek below the station, and a significant part of the salt load of the Dove Creek-Salt Croton Creek area probably originates in Dove Creek below weir A and above the confluence with Salt Flat Creek. Analyses of samples collected at weir A and at sampling points 18, 19, and 20, farther downstream on Dove Creek, are given in table 5.

SALT FLAT CREEK

The outflow from Dove Creek Salt Flat was measured and sampled periodically at weir B during the period October 1956 to March 1959. The data indicate an average base flow of about 0.4 cfs of an almost saturated brine having a density of 1.18 and a chloride concentration of 145,000 ppm. The average load contributed by the base flow from the salt flat is about 190 tons of chloride and 4 tons of sulfate per day. A representative analysis of the brine is given in table 5 (No. 21).

Base flow carried only a part of the salt load that the flat ultimately contributes to the Brazos River. Other brine evaporates and salts are deposited over the entire surface of the flat to be redissolved and carried away during periods of flood runoff.

SALT CROTON CREEK AT WEIRS C AND D

During 2½ years of sampling and measuring at weir C, about half a mile below the confluence of Dove and Salt Flat Creeks, average streamflow and salt loads were not significantly different from those at weir D, about 2 miles downstream. In the summer months, evaporation was high and salts were deposited between the two sites, but during the winter or during flood-runoff periods, the salts were redissolved. The average of about 100 lowflow measurements at weir D during the period October 1956 to September 1960 was 0.89 cfs; the range was from 0.17 cfs to 3.90 cfs. The averages of the loads for these series of measurements were 300 tons of chloride and 8 tons of sulfate per day.

HAYSTACK CREEK

Haystack (Hayrick) Creek enters Salt Croton Creek just above the gaging station at Salt Croton Creek near Aspermont, 500 feet below weir D and about 2 miles downstream from Salt Flat Creek. Measurements at the partial-record station at weir E indicate that about 25 percent of the base flow passing the stream-gaging station comes from Haystack Creek. The base flow of Haystack Creek averages about 0.2 cfs.

Brine in Haystack Creek is less concentrated than in Salt Croton Creek. The maximum chloride concentration was 90,800 ppm; generally, it ranged from 35,000 to 70,000 ppm. Sulfate concentrations in Haystack Creek are higher than in the Salt Croton Creek brine, averaging more than 4,000 ppm. A typical analysis is given in table 5 (No. 24). The base flow of Haystack Creek contributes about 30 tons of chloride and 3 tons of sulfate per day.

SALT CROTON CREEK AT GAGING STATION

The gaging station on Salt Croton Creek near Aspermont is 0.1 mile downstream from Haystack Creek and about 8 miles upstream from Salt Fork Brazos River. The total outflow from the known salt-producing areas in the Salt Croton Creek basin is measured at the station. Since October 1956, a continuous record of discharge has been obtained and water samples have been collected at approximately 2-week intervals.

Although the flow at the station has been as low as 0.1 cfs, sustained base flow has ranged from 0.5 to more than 2 cfs and has averaged slightly more than 1 cfs. According to the chemical-quality and the streamflow data, the salt load contributed by the base flow of Salt Croton Creek was about 330 tons of chloride and 12 tons of sulfate per day.

In addition to the periodic samples collected on regular visits to the gaging station, floodflows were sampled by means of an automatic single-stage sampler. This device contained bottles mounted so they filled during rising stream stages. For example, in April 1957 samples were obtained at stages representing 50, 760, 2,800, and 5,500 cfs.

Determination of concentrations of dissolved constituents over the full range of streamflow has demonstrated the existence of a relationship between these concentrations and the water discharge. From this relationship, daily concentrations and loads of chloride and sulfate have been estimated for those days for which samples were not available. The monthly and annual discharge-weighted averages, computed by using these estimated values, are given in table 7.

The average total load contributed by both base flow and flood runoff from the Dove Creek-Salt Croton Creek area during the 4-year period October 1956 to September 1960 was 485 tons of chloride and 30 tons of sulfate per day.

SALT CROTON CREEK BELOW GAGING STATION

About 25 discharge measurements were made and samples were collected at the falls near Aspermont on Salt Croton Creek, about 7 miles downstream from the gaging station and 1 mile upstream from the Salt Fork Brazos River. The results of the sampling indicate that there is probably no significant salt inflow to Salt Croton Creek below the station, that deposition by evaporation and resolution by rainfall occurs, and that the loads determined at the gaging station probably approximate the salt yield of Salt Croton Creek basin.

The average flow of Salt Croton Creek may have been somewhat greater during the 4-year period of the investigation than the long-time average. According to the records at Spur and Aspermont, rainfall was above normal during 3 of the 4 years. However, the average discharge of the Salt Fork Brazos River near Aspermont was 152 cfs, which was close to the 1939–60 average of 150 cfs. The loads

TABLE 7.—*Monthly and annual summary of water discharge and chloride and sulfate loads, Salt Croton Creek near Aspermont, Tex.*

Year and month	Water discharge (cfs)	Chloride: Weighted-average concentration (ppm)	Chloride: Load (tons per day)	Sulfate: Weighted-average concentration (ppm)	Sulfate: Load (tons per day)
1956					
October	1.56	92,100	405	3,140	13.8
November	1.07	128,000	430	3,550	11.9
December	1.53	107,000	502	3,320	15.6
1957					
January	1.05	131,000	433	3,570	11.8
February	1.74	98,900	523	3,180	16.8
March	1.56	99,400	471	3,240	15.4
April	38.2	9,480	989	1,530	160
May	42.2	10,200	1,180	1,600	184
June	38.3	10,900	1,140	1,590	167
July	1.35	65,200	257	2,900	11.4
August	.68	146,000	318	3,750	8.17
September	1.10	122,000	419	3,490	12.0
Water year 1957 (average)	10.8	18,600	554	1,730	51.5
October	9.85	23,100	632	1,860	50.9
November	6.12	38,200	660	2,150	37.2
December	1.69	115,000	601	3,370	17.6
1958					
January	1.65	109,000	552	3,330	16.9
February	1.78	108,000	590	3,320	18.1
March	3.26	64,500	613	2,710	25.8
April	2.39	72,100	507	2,890	20.3
May	7.07	26,900	530	1,930	38.0
June	1.55	99,700	470	3,240	15.3
July	1.85	65,900	356	2,730	14.8
August	.97	99,500	293	3,190	9.40
September	9.06	22,300	560	1,870	47.0
Water year 1958	3.95	45,900	517	2,290	25.8
October	0.80	134,000	339	3,620	9.16
November	1.49	92,800	417	3,090	13.9
December	.79	141,000	355	3,700	9.31
1959					
January	.80	141,000	359	3,690	9.41
February	.94	134,000	398	3,610	10.7
March	1.17	125,000	458	3,500	12.8
April	1.03	128,000	414	3,520	11.4
May	3.45	52,900	525	2,550	25.3
June	11.9	17,700	581	1,790	58.7
July	4.89	27,500	375	2,080	28.4
August	14.2	10,100	392	1,470	57.0
September	.95	111,000	325	3,340	9.77
Water year 1959	3.55	38,700	387	2,090	21.0
October	10.9	19,000	572	1,770	53.3
November	1.82	103,000	572	3,250	18.0
December	5.45	39,700	612	2,260	34.9
1960					
January	2.18	88,400	578	3,100	20.3
February	2.18	97,100	641	3,190	21.1
March	1.56	116,000	560	3,400	16.4
April	1.05	131,000	433	3,580	11.8
May	1.22	110,000	413	3,350	12.6
June	2.09	71,000	436	2,790	17.1
July	13.6	13,300	496	1,650	61.6
August	5.00	30,000	420	2,040	28.5
September	.83	138,000	363	3,650	9.61
Water year 1960	4.02	42,700	486	2,200	25.0
Water years 1957–60 (average)	5.58	31,000	485	1,970	30.8

contributed by Salt Croton during the water years 1957–60 probably approximate closely the average long-time contribution. Salt Croton Creek thus contributes about 45 percent of the chloride entering Possum Kingdom Reservoir. The base flow of Salt Croton Creek is probably the source of about 30 percent of the chloride entering Possum Kingdom Reservoir.

CROTON CREEK

Short Croton and Hot Springs (upper Croton) Salt Flats on tributaries to Croton Creek were mentioned by Dr. Blank (see footnote p. CC5) as possible sources of significant salt inflow to the Brazos River. The two flats are described in pages CC55 to CC56.

A streamflow station was established on Croton Creek near Jayton in August 1959, 1.5 miles upstream from its confluence with the Salt Fork Brazos River, to measure the salt load from the drainage basin of Croton Creek. Because the area is isolated, an engineer was stationed at a field camp from April to September each year to measure floodflows and to collect water samples of base and floodflows. Chemical analyses were thus obtained for the measured range of streamflow.

Croton Creek had a sustained low flow for long periods during winter months, but was dry in summer except during periods of storm runoff. During the water year for which complete records are available, runoff in the area, as indicated at the station on Salt Fork Brazos River near Aspermont, was a little more than 50 percent of the long-time average. During 9 months of the 1961 water year, runoff was about 180 percent of the average. From August 1959 to June 1961, the mean discharge of Croton Creek near Jayton was 21.4 cfs, which may be near normal.

The water of Croton Creek is less saline than the nearly saturated brine of Salt Croton Creek to the north. The chloride concentration of flowing water ranged from 18,100 to 182 ppm, although water in pools concentrated by evaporation contained as much as 34,300 ppm. The chloride concentration varies widely with changes in water discharge. The sulfate is less variable, usually ranging from 3,300 to 1,600 ppm, and the sulfate load carried by the stream exceeds the chloride load.

Daily concentrations and loads of chloride and sulfate were estimated for those days for which samples were not available. These estimates were based on the relationship between the concentrations of dissolved constituents and the water discharge. A base-flow load for the area could not be determined because the stream is intermittent. From August 1959 to June 1961, Croton Creek contributed an estimated 70 tons of chloride and 100 tons of sulfate per day to the Brazos River.

To supply additional information on the sources of flow, two low-flow, partial-record stations were established upstream from the stream-flow station on Short Croton Creek where it enters Croton Creek and on Croton Creek below the mouth of Short Croton Creek. Measurements were made at about 2-week intervals and water samples were collected for chemical analysis.

During much of the time there was no flow in Short Croton Creek, which drains the Short Croton Salt Flat; measured flows ranged from 0.01 to 0.1 cfs. Floodflows, which could flush out deposits of salt, were not measured or sampled. Chloride concentration in the low flows ranged from 11,100 to 23,100 ppm and sulfate from 2,980 to 3,810 ppm. A typical analysis is given in table 5 (No. 14).

The combined base flow from Hot Springs and Short Croton Creeks was measured at the partial-record station on Croton Creek below Short Croton Creek. Croton Creek at this station was dry much of the time. Chloride concentrations ranged from 23,500 ppm at a flow of 0.02 cfs to 478 ppm at a flow of 12 cfs. A typical analysis is given in table 5 (No. 15).

Available information is not sufficient to estimate the salt yield of Hot Springs and Short Croton Salt Flats. According to the record from the gaging station on Croton Creek near Jayton, the combined yield of the Croton Creek basin is about 7 percent of the chloride load that reaches Possum Kingdom Reservoir.

OTHER TRIBUTARIES

Dr Blank (see footnote, p. CC5) mentioned several other tributaries of the Salt Fork Brazos River which he believed should be investigated further as possible sources of significant quantities of salt. Beginning in August 1959, partial-record stations were operated near the mouths of three tributaries—McDonald, Red Mud, and Butte Creeks. Discharge measurements were made and water samples were collected at approximately monthly intervals. The locations are shown on figure 2 and representative analyses are given in table 5.

The three creeks have been dry during most of the time since August 1959. A sample collected from McDonald Creek near Post when the water discharge was 0.22 cfs had a chloride concentration of 13,200 ppm; the lowest chloride observed at a flow of 12.7 cfs was 1,730 ppm. Sulfate concentrations were much lower than chloride in all samples from McDonald Creek. In Red Mud Creek near Clairemont, chloride concentrations ranged from 158 to 7,920 ppm; all samples were collected at low flows. In the samples of lower concentrations calcium and sulfate were the predominant constituents. Samples of water from pools in Butte Creek near Jayton were high in chloride content, whereas samples taken during periods of streamflow were low in chloride content.

The investigations of the upper tributaries of the Salt Fork Brazos River suggest that the salt load at Peacock is the result of comparatively small increments from many sources.

CLEAR FORK BRAZOS RIVER

The Clear Fork Brazos River drains about 40 percent of the contributing area above Possum Kingdom Dam and contributes about 40 percent of the water that enters the reservoir. Principal tributaries of Clear Fork Brazos River are Elm Creek, Paint Creek, and Hubbard Creek.

Surface water of the Clear Fork basin is mostly fresh, although pollution by oil-field brine is occurring in some areas. Unpolluted water in the basin usually has less than 500 ppm of dissolved solids. Calcium and bicarbonate are the principal dissolved constituents, and chloride ranges from 20 to 70 ppm.

Chemical-quality records are available for 2 or more years for Paint Creek near Haskell, Clear Fork Brazos River at Nugent, Clear Fork Brazos River at Fort Griffin, and Hubbard Creek near Breckenridge (table 3). Estimates of salt loads for the Clear Fork basin are based principally on the records for the stations at Fort Griffin and near Breckenridge.

The average water discharge at station Clear Fork Brazos River at Fort Griffin for the 36 water years from 1923 to 1960 was 249 cfs. During the period 1940–60, on which the dissolved-solids-load studies in this report are based, the discharge was 215 cfs. The lower mean discharge for the 1940–60 period was due partially to evaporation losses from reservoirs constructed just before or during the early part of the period and partially to the increased use of surface water in the basin.

Chemical-quality records were collected at Fort Griffin only from November 1949 to September 1951 and provide no means of evaluating the changes that may have occurred in recent years as the result of oil-field activities and increased water use. The average daily load carried by the Clear Fork Brazos River at Fort Griffin is about 200 tons of dissolved solids, 40 tons of chloride, and 40 tons of sulfate.

Hubbard Creek, which drains more than 1,000 square miles, is the principal tributary to the lower Clear Fork. Chemical-quality and streamflow records are available for Hubbard Creek near Breckenridge since April 1955. Average flow for the 5 complete water years, 1956–60, was 198 cfs. The average chloride load was 39 tons per day and the sulfate load 10 tons per day. A comparison of Hubbard Creek streamflow records with the longer records of the Clear Fork Brazos River at Fort Griffin and near Crystal Falls suggests that the runoff of Hubbard Creek during the 1956–60 period was above average and that the long-time average flow would be about 120 cfs. The chloride load of Hubbard Creek, therefore, is about 25 tons per day and the sulfate load is about 8 tons per day. The chemical-quality records indicate that the salt load of Hubbard Creek has been increasing during the last few years, probably as a result of increased oil activities in the basin.

The drainage area of the Clear Fork Brazos River below the Fort Griffin and Hubbard Creek stations is about 600 square miles. If the dissolved-minerals discharge of this area is proportional to the yield of Hubbard Creek, which seems reasonable, the total daily yield for Clear Fork Brazos River is about 320 tons of dissolved solids, 75 tons of chloride, and 50 tons of sulfate.

OTHER TRIBUTARIES

Dr. Blank (see p. CC5) mentioned North Croton and Mustang Creeks as probable sources of contamination of the Brazos River. The streams enter the Brazos River downstream from the confluence of the Double Mountain and Salt Forks, North Croton Creek in northeastern Stonewall County, and Mustang Creek in southwestern Knox County. Partial-record streamflow and chemical-quality stations have been operated near the mouths of the two streams since August 1959. Representative analyses are given in table 5 (Nos. 29 and 30). Both streams frequently were dry.

North Croton Creek (station 29), which had chloride concentrations ranging from 600 to about 7,000 ppm, may contribute significant quantities of salt to the Brazos River. A program of more frequent sampling and a continuous streamflow record would be required to determine the salt contribution of North Croton Creek.

Calcium and sulfate are the principal dissolved constituents in the water of Mustang Creek. The water is of good quality (having less than 500 ppm of dissolved solids) at moderate flows; Mustang Creek does not appear to be a source of contamination of the Brazos River.

A chemical-quality station has been operated since August 1959 on the Brazos River near Seymour. The drainage area above this station and below the gaging stations Double Mountain Fork Brazos River and Salt Fork Brazos River near Aspermont is 1,680 square miles. The chemical-quality record at Seymour indicates that there are no large sources of salt in the area below the Aspermont stations.

Tributaries entering the Brazos River between Seymour and Possum Kingdom Dam include Millers Creek and Salt Creek. A few samples from Millers Creek have shown that the water is fresh. Although the Salt Creek drainage basin at one time was badly polluted by oil-field waste, corrective measures have reduced this source of pollution, and the natural water of Salt Creek now is of excellent quality.

SUMMARY OF SALT DISCHARGE

The Brazos River transports into Possum Kingdom Reservoir an average of 2,800 tons of dissolved solids per day, including 1,000 tons of chloride and 625 tons of sulfate. Other principal dissolved constituents are sodium and calcium. A summary of the salt yield of the various tributaries is given in table 8.

TABLE 8.—*Summary of salt yields of the upper Brazos River basin*

Stream and location	Drainage area (square miles)			Streamflow			Loads (tons per day)		
	Total	Noncontributing	Contributing	Period of record: Years	Period of record: Mean discharge (cfs)	Mean discharge 1940–60	Dissolved solids	Chloride	Sulfate
Double Mountain Fork Brazos River:									
Double Mountain Fork Brazos River near Aspermont	7,980	6,470	1,510	31	178	177	485	75	210
Salt Fork Brazos River:									
Salt Fork Brazos River near Peacock	4,260	2,770	1,490	2	--------	80 [1]	810	280	95
Croton Creek near Jayton	310	--------	310	1.8	22	22 [1]	240	70	100
Salt Croton Creek near Aspermont	69	--------	69	4	5.6	5.6 [1]	750	485	30
Salt Fork Brazos River near Aspermont	4,830	2,770	2,060	21	150	150	1,860	870	280
Clear Fork Brozos River:									
Clear Fork Brazos River at Fort Griffin	3,974	--------	3,974	36	249	215	200	40	40
Hubbard Creek near Breckenridge	1,087	--------	1.087	5	198	120 [1]	75	25	8
Clear Fork Brazos River below Crystal Falls	5,740	--------	5,740	26	425	425 [1]	320	75	50
Brazos River below Possum Kingdom Dam	22,500	9,240	13,260	35	1,180	1,050 [2]	2,800	1,000	625

[1] Estimated.
[2] Allowance has been made for flow required for initial filling of Possum Kingdom Reservoir.

The Salt Fork Brazos River is the source of about 870 tons of chloride per day or about 85 percent of the chloride load carried by the Brazos River into Possum Kingdom Reservoir. The Double Mountain Fork and the Clear Fork each contributes less than 10 percent of the chloride load.

About 280 tons per day of the Salt Fork chloride load is derived from the basin above the site of the former gaging station near Peacock, apparently in small increments from many sources. More than half of the chloride carried by the Salt Fork, 485 tons per day or 45 percent of the load entering Possum Kingdom Reservoir, originates in the drainage basin of Salt Croton Creek. The base flow of Salt Croton Creek at the gaging station near Aspermont is from salt springs on Dove Creek in the Dove Creek Salt Flat and on Haystack Creek. The base flow ranges from 0.5 to 2 cfs and carries about

330 tons of chloride per day, or more than 30 percent of the load reaching Possum Kingdom Reservoir.

Croton Creek is of secondary importance as a source of salt. The records indicate that the average flow, which is about 20 cfs, transports into the Salt Fork an average of 70 tons of chloride per day, or about 7 percent of the load entering Possum Kingdom Reservoir.

Sulfate is one of the principal dissolved constituents in most of the surface water of the upper Brazos River basin. Much of the sulfate load that reaches Possum Kingdom Reservoir is derived by the leaching of calcium sulfate from the gypsiferous rocks and soils of the basin by surface runoff. Because calcium sulfate is only slightly soluble in water, sulfate concentrations rarely exceed 7,000 ppm. Thus, the quantity of sulfate contributed by the brine-spring areas is only a fraction of the chloride contribution, and there is no concentrated source of sulfate comparable to the chloride brine.

The Salt Fork Brazos River near Aspermont carried an average of about 280 tons of sulfate per day. Of this load, about 95 tons originates above the Peacock station, 100 tons is contributed by Croton Creek, and only about 30 tons by Salt Croton Creek.

Sulfate constitutes more than 40 percent of the mineral content of the Double Mountain Fork Brazos River. At the gaging station near Aspermont, the daily sulfate load is about 210 tons, which probably is contributed rather uniformly by all parts of the drainage basin.

The Clear Fork Brazos River contributes only about 50 tons of sulfate per day.

DESCRIPTION OF SALT-PRODUCING AREAS

GENERAL OCCURRENCE OF SALT WATER IN THE PERMIAN ROCKS

Most of the saline ground water in the area occurs in the Permian rocks at depths generally less than 100 feet but possibly as much as 250 feet below land surface. Throughout most of the area, the saline water is under water-table conditions and is overlain by a thin layer of fresh water. In most of the area, saline water is not discharged, probably because the salt has been flushed out of the Permian within the zone of circulation of meteoric water. In several widely scattered, relatively small areas, however, the saline water is under pressure and either emerges at the surface as seeps or springs, or flows to the surface when tapped by wells.

The areas from which saline water emerges are Short Croton Salt Flat, about 4½ miles north of Jayton and Hot Springs Salt Flat, about 7 miles north of Jayton, both of which are tributary to Croton Creek; Dove Creek Salt Flat, about 12 miles northeast of Jayton; Dove Creek, less than 1 mile north of Dove Creek Salt Flat; and three small salt flats on Haystack Creek near the mouth of Haystack Creek, which are tributary to Salt Croton Creek (pl. 1*A*).

A detailed study was made of the surface geology of Short Croton and Hot Springs Salt Flats, and samples of water were collected at Dove Creek Salt Flat and Dove Creek. The small salt flats on Haystack Creek were not studied; however, data concerning the salt flats on Haystack Creek, obtained by Dr. Blank for the Brazos River Authority, are included in this report.

SALT FLATS

GENERAL FEATURES

The salt flats are parts of the flood plains of small streams; in general, they are irregular in outline, are somewhat digitate, and parts extend into the valleys of tributary streams. As their name implies, they are relatively flat, except for small islands of Permian rocks that extend above the general level of the salt flat. The surfaces are nearly devoid of vegetation except for scattered clumps of grass in the south side of Short Croton Salt Flat near and downstream from the mouth of the tributary stream that heads just east of State Highway 70, about 2.7 miles north of Jayton. Generally, the salt flats are encrusted with a thin layer of white salt, except after heavy rains when the salt is removed.

The flow of Short Croton and Hot Springs Creeks and tributaries usually is comprised of the flow from numerous salt springs and seeps. Although the flow from any one spring or seep may be too small to be measured, the aggregate flow from a group of springs or seeps at times results in surface flow. Except during periods of surface runoff, the flow of the streams is interrupted. Along some stretches of the streams, water occurs in small disconnected pools; between these pools the water moves as underflow. The water usually is clear and devoid of vegetation, and in some pools may support considerable fish life. For example, in the Hot Springs Salt Flat, a sample of water from a pool having abundant minnows contained 63,300 ppm of chloride.

Fairly steep bluffs border the salt flats. The bluffs bordering Short Croton and Hot Springs Salt Flats consist mainly of Permian rocks, which are principally fine sand containing some silt and clay and layers of gypsum as much as 1 foot thick. Near the mouth of streams tributary to the salt flats and at the upstream end of the salt flats, the bluffs are composed of alluvial silt and fine sand with some lenses of gypsiferous gravel. Typical of the surface of the bluffs that border the salt flats is a thin crust of salt that extends a variable distance above the floor of the salt flats. In the lower part of the bluff, the salt layer is fairly continuous, becoming somewhat irregular upward. The salt is derived probably from the evaporation of the saline water that either migrates upward from the Permian or laterally from the contiguous alluvium. As a result of the accumulation of salt, the materials forming the bluffs are fractured due to a volumetric expansion, and the bluff is eroded. This process, which is similar to stoping, in addition to erosion from surface runoff, may be the primary cause of enlargement of the salt flats.

Several distinctive differences are readily discernable between the salt-flat areas and comparable areas where salt flats have not been formed.

The salt flats are many times wider than the flood plains of the other comparable streams in the area; the gradient of the salt flats is estimated to be about 5 feet per mile, whereas the gradients of the comparable reaches of the other streams is estimated to be about 10 feet per mile; and the absence of vegetation is characteristic of the salt flats. These differences are caused mostly by the large volume of saline water that seeps into the stream beds and forms the salt flats.

The valleys of Hot Springs and Short Croton Creeks and tributaries upstream from the salt flats are U-shaped and the slopes are concave, but the valleys of the comparable tributaries entering Croton Creek from the west are V-shaped and the slopes are convex. The prominent gypsum bed, designated Ad in plate 1*D*, forms vertical cliffs in the basins of Hot Springs and Short Croton Creeks, but in the basins of other comparable streams in the area, bed Ad generally is beveled and rounded, and conforms to the convex slopes of the valleys; at many places in these valleys, it is covered with eolian silt. The occurrence of deposits believed to be of Kansan age in the gully upstream from Short Croton Salt Flat and probably in Hot Springs Creek upstream from the salt flat indicates that, possibly in Kansan time, the valleys in the basin of Hot Springs and Short Croton Creeks were cut as low or lower than they are at present. The deposits also indicate that erosion was more vigorous in these valleys than in the valleys of the other comparable streams. It is possible that the downcutting of the valleys is associated with the solution of salt accompanied by subsidence in the valley of Duck Creek, which is discussed on pages CC64 to CC67.

Saline water probably was discharged into the valleys of Hot Springs and Short Croton Creeks in early Quaternary time and probably formed salt flats. The Pleistocene and Recent deposits that partly fill the valleys covered the ancestral salt flats. Possibly this material represents the alluvium of ancestral salt flats, which were at a higher level and extended farther back into the valleys than the present salt flats.

HOT SPRINGS SALT FLAT

Hot Springs Salt Flat, which is in northeastern Kent County about 7 miles north of Jayton (pl. 1*A*), is elongated in shape, the long axis extending in an easterly direction. It is 1.3 miles long and 0.2 mile wide. The altitude ranges from about 1,795 to 1,800 feet.

Hot Springs Salt Flat spans an estimated stratigraphic interval of about 40 feet of the Permian rocks between marker beds Da and Bd of the composite log (pl. 2). The eastern end of the salt flat is about 65 feet stratigraphically above marker bed Da and the western end is about 105 feet above Da. This relation is shown in plate 3 in which the Hot Springs Salt Flat has been projected into the line of section. Marker bed C crops out in the bluffs that border the salt flat and its stratigrahic position is approximately at the surface near the western end of the salt flat.

No springs were observed on Hot Springs Salt Flat. The flow of the streams in the upper part of the salt flat was interrupted, but downstream from a point about a mile above the confluence of Hot Springs and Croton Creek, the flow was continuous. Information is not available on the ground water in the vicinity of the salt flat.

SHORT CROTON SALT FLAT

Short Croton Salt Flat is in northeastern Kent County about 4.5 miles north of Jayton. In general, the salt flat is elongated, the long axis extending in an easterly direction. The length is estimated to be about 2 miles and the width about 0.6 mile in the western part, but narrower in the eastern part. The altitude ranges from about 1,780 to 1,790 feet.

Short Croton Salt Flat spans an estimated stratigraphic interval of about 55 feet of the Permian rocks between marker beds Bd and Da. The eastern end of the salt flat is about 50 feet stratigraphically above bed Da in the western end about 105 feet above bed Da (pl. 3). Marker bed C crops out in the bluffs bordering the salt flat, but was not observed at the west end of the salt flat.

Although no springs were visible on Short Croton Salt Flat in October 1960 or January 1961, Dr. Blank (see p. CC5) reported "* * * at one place in the Short Croton flat—concentrated brine rises through holes and joints in the floor * * *" The disconnected pools of salt water on the salt flats are maintained by seeps that issue at the contact of the alluvium and the Permian rocks.

Plate 3 shows that the body of saline water tapped in well 267 is not in hydraulic connection with the regional water table. It shows, however, that the saline water may be connected hydraulically with the salt flat and that water in the deeper part of the Permian rocks moves upward and into the salt flats in response to a difference in pressure. Actually, the saline water may be moving through the fractured and distorted beds in the Permian from which salt has been removed and which crop out in the vicinity of the salt flats.

DOVE CREEK SALT FLAT

Dove Creek Salt Flat is in northwest Stonewell County, about 12 miles northeast of Jayton. The salt flat extends southward about a mile and eastward about three-fourths of a mile. The salt flat is irregular in outline and extends into the valleys of tributary streams. The altitude is slightly less than 1,700 feet on the east side and nearly 1,710 feet on the west side.

The bluffs that surround Dove Creek Salt Flat consist almost entirely of Permian rocks. Marker bed Dc, a layer of gypsum about 10 feet thick, crops out at the surface of the western part of the salt flat and in the surrounding bluffs, except in the western part of the salt flat where the top of bed Dc is at the level of the salt flat. This relation is shown in plate 3, in which the Dove Creek Salt Flat has been projected into the line of section. The Permian deposits, which crop out in the eastern half of the salt flat, consist of partly indurated green clay and silt; the surficial material consists of a thin discontinuous mantle of salt-encrusted gravel and sand, particularly near the seeps and springs.

Salt water flows on the surface of Dove Creek Salt Flat from numerous small springs and seeps and from one relatively large spring (294). Actually, the spring issues from an open hole, which was drilled by Mason-Johnson & Associates in about 1955 and designated as boring C–4. In the consulting report given by Mason-Johnson & Associates to the Brazos River Authority, two distinct strata of salt-water flow were reported by the driller: (1) a top stratum between the estimated altitudes of 1,674 to 1,665 feet in which the water flowed about 3 to 5 feet above the land surface (altitude about 1,700 feet) and (2) a lower stratum between estimated altitudes of 1,662 to 1,648 feet in which the water flowed about 6 feet above the land surface. After the casing was removed, salt water flowed about 15 to 20 gpm (gallons per minute).

In May 1961, the spring flowed about 0.2 cfs, or 90 gpm. The water contained 133,000 ppm of chloride and natural gas. A sample of the gas collected in May 1961 and analyzed by the U.S. Dept. of Interior Bureau of Mines showed the following: methane, 2.1 percent; ethane, trace; propane, trace; nitrogen 95.9 percent; oxygen, trace: argon, 1.2 percent; and carbon dioxide, 0.1 percent. In May 1961, a sample of water from Salt Flat Creek, taken at a point about 200 feet above the confluence with Dove Creek and near weir B, contained 143,000 ppm of chloride.

DOVE CREEK NEAR DOVE CREEK SALT FLAT

Dove Creek flows in a southeasterly direction to about weir A (pl. 1*A*), 0.6 mile west-northwest of Dove Creek Salt Flat, thence it flows northeastward and circles the salt flat. Less than half a mile east of the salt flat, Dove Creek joins Salt Flat Creek and forms Salt Croton Creek.

In the area northeast, north, and northwest of the part of Dove Creek below weir A, the surface of the upland plain is only 40 to 60 feet above the bed of Dove Creek. Low hills bordering Dove Creek at or below the level of the plain are capped with gravel, probably of Nebraskan age.

Marker bed Dc crops out in the stream bed and in the bluffs bordering Dove Creek northeast and north of the salt flat. Bed Dc contains numerous solution channels as much as a foot in diameter, which produce a honeycomb appearance. About 0.8 mile north of the salt flat on the west bank of a tributary entering Dove Creek from the northwest and about 700 feet from Dove Creek, bed Dc contains a cave estimated to be about 8 feet high and 12 feet wide, the mouth of which has collapsed. Saline water that seeped from the mouth of the cave contained 22,100 ppm of chloride in May 1961 (table 9). Solution and collapse in bed Dc has formed a sinkhole in the upland surface about 500 feet west of the mouth of the cave.

Dove Creek between weir A (pl. 1*A*) and Salt Flat Creek is an interrupted stream, the flow of which is maintained by springs and seeps. This part of Dove Creek is similar to the salt flats in that the salt-encrusted flood plain is about 0.1 mile wide, is nearly devoid of vegetation, and some of the pools of water contain salt crystals. A sample of water from a pool about 1,000 feet downstream from weir A in May 1961 contained 62,000 ppm of chloride.

About 0.65 mile northwest of Dove Creek Salt Flat and below weir A, a spring (292) on the south bank of a small tributary stream entering Dove Creek from the northwest flowed about 0.1 cfs, or 45 gpm. A sample of water from spring (292) in May 1961 contained 32,100 ppm of chloride (table 9). The spring also produced gas, which was not analyzed. On the same date, a sample of water in Dove Creek, about 200 feet upstream from the mouth of Salt Flat Creek, contained 153,000 ppm of chloride.

About a mile northwest of Dove Creek Salt Flat, exploration hole 174 (pl. 3) tapped saline water at a depth of about 70 feet (altitude 1,655 feet). Local residents reported that the saline water, which is from a zone a few feet below marker bed Dc, flowed to a height of more than 43 feet above the land surface for a period ranging from 36 to 48 hours. The altitude to which the water flowed, 1,770 feet, is about 70 feet above the salt flat and about 60 feet above the

TABLE 9.—*Analyses of water from selected wells and springs in the Croton Creek-Salt Croton Creek area*

[Chemical constituents, dissolved solids, and hardness of water are in parts per million]

Well or spring (pl. 1 A)	Owner	Depth of well (feet)	Date of collection	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (calculated)	Hardness (as $CaCO_3$)	Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos at 25° C)	pH	Density (at 20°C)
240	C. C. Kimbell.	102	June 21, 1960.	45	358	60	44		194	898	88	0.8	19	1,610	1,140	78	0.6	1,920	7.0	------
242	W. W. Hodges.	100	Apr. 20, 1961.	44	240	61	84		201	480	229	.7	54	1,290	850	18	1.3	1,860	6.8	------
243	do	100	Apr. 20, 1961.	41	535	104	13	2.7	147	1,540	30	------	4.0	2,340	1,760	2	.1	2,500	6.6	------
256	L. C. Johnson.	98	June 21, 1960.	47	301	53	132		344	590	225	.7	51	1,570	970	23	1.8	2,150	7.0	------
257	Fletcher Rich.	136	June 22, 1960.	------	------	------	------	------	------	344	88	------	40	------	------	------	------	1,510	------	------
258	do	126	June 21, 1960.	52	288	44	121		308	610	168	.5	47	1,480	900	23	1.8	1,970	7.0	------
261	do	110	June 21, 1960.	24	203	45	85		236	514	88	.7	26	1,100	692	21	1.4	1,500	7.2	------
280	City of Jayton.	52	June 21, 1960.	25	252	42	85		249	578	112	.6	25	1,240	800	19	1.3	1,680	7.0	------
281	do	52	June 21, 1960.	20	104	12	21		229	113	20	.5	25	428	309	13	.5	649	7.5	------
282	do	62	June 21, 1960.	21	96	8.9	3.0	5.9	214	86	5.2	.5	24	356	276	2	.1	550	7.3	------
291	Homer Hodges.	59	May 22, 1961.	17	695	176	605		84	2,020	1,130	.5	7.5	4,690	2,460	35	5.3	5,930	6.8	------
292	W. A. Springer, Jr.	Spring	May 24, 1961.	------	------	------	20,700	------	------	4,270	32,100	------	------	------	5,230	90	------	69,800	------	1.043
293	do	Spring	May 24, 1961.	------	------	------	14,500	------	------	3,980	22,100	------	------	------	4,270	88	------	52,600	------	1.030
294	do	Spring	May 11, 1961.	------	1,880	1,400	82,200	370	16	3,060	133,000	------	------	222,000	10,400	94	350	------	6.1	1.169
295[1]	------	3,400	------	------	7,710	1,762	39,800	------	22	860	78,850	------	------	------	------	------	------	------	5.2	1.101

[1] Oil field brine, Swenson field, about 20 miles southeast of area. Analysis from Beeler and others (1953).

piezometric surface of the saline water in the bore hole at the salt flat. The rate of flow is not known, but the period of flow and the artesian head indicates that the water-bearing material is very permeable and extends over a large area.

Whether salt water flowed from the other exploration holes in the vicinity of Dove Creek Salt Flat is not known definitely. In most of the holes, the land surface approximately coincided with the altitude to which the saline water rose in exploration hole 174.

Well 286 (table 10), about 2.2 miles north-northwest of the northeastern part of Dove Creek Salt Flat, is bottomed at an altitude of about 1,727 feet, which is about 27 feet above the top of marker bed Dc. The altitude of the water level was 1,736 feet in 1957.

Well 287 (table 10), about 1.9 miles north-northeast of Dove Creek Salt Flat, was completed at an altitude of about 1,719 feet, which is about 16 feet below the top of marker bed Dc. The altitude of the water level was 1,735 feet in 1957.

The bottom of water well 288, about 0.6 mile southwest of the salt flat, is at an altitude of about 1,726 feet, which is about 50 feet above the top of marker bed Dc. The altitude of the water level was 1,737 feet in 1957.

The data obtained from wells 286, 287, and 288 indicate that the saline water in exploration hole 174 is not in hydraulic connection with the local water table. In these three wells, the altitude of the water table ranged between 1,735 and 1,737 feet, about 35 feet below the piezometric surface in the exploration hole.

HAYSTACK CREEK

The following description of the salt flats on Haystack Creek is given by Dr. Blank (see footnote, p. CC5):

* * * An examination was also made on October 10th of some of the "Suspicious Areas" along Hayrick Creek which are noted on Mr. C. E. Mark's blueprint of the Dove Creek salt flat vicinity. These areas are salt flats of the same general type as the main Dove Creek flat, although smaller. They may be designated as the Upper, Middle, and Lower Hayrick Creek salt flats, and are located approximately 1½ miles, 1¼ miles, and ⅝ mile, respectively, upstream from the mouth of that creek and on its west side. Only the Lower and Middle flats were visited. The Lower flat is the largest of the three, being perhaps 2,000 feet or more long and about 500 feet wide.

The flats are floored by hard green clay, or soft shale, thinly covered over much of their area by reddish silt and clay washed in from the surrounding bluffs. The bluffs, like all those in this region, consist of red clayey silt, with one or more thick beds of hard, massive gypsum.

Salt water is rising through the floor of the flats as seeps and springs and depositing a thin salt crust as it evaporates.

The Lower flat heads in two narrow, steep-walled gullies, each of which contains a salt spring, which at the time of our visit was flowing feebly. The contrast in taste between the spring-fed pools and the pools containing runoff water immediately upstream from them was readily apparent.

TABLE 10.—*Records of selected wells and springs in the Croton Creek-Salt Croton Creek area*

All wells are drilled unless otherwise noted in Remarks column.
Water level: Reported water levels given in feet; measured water levels given in feet and tenths.

Method of lift and type of power: C, cylinder; E, electric; G, gasoline, butane or Diesel engine; N, none; T, turbine; W, windmill; Number indicates horsepower.
Use of water: D, domestic; Irr, irrigation; N, none; P, public supply; S, stock.

Well (pl. 1A)	Owner	Driller	Date completed	Depth of well (feet)	Diameter of well (inches)	Altitude above sea level (feet)	Water level: Below land-surface datum (feet)	Water level: Date of measurement	Method of lift	Use of water	Remarks
231	W. A. Stephens	Myles Drilling Co.	1956	90	14	2,104	37.2	Mar. 28, 1957	T,E, 7½	Irr	Reported drawdown 14 ft after pumping 3 hours at 130 to 140 gpm. Red beds at 90 ft.
232	Ben Loe	Garner Bros	1956	165	16	2,114	26.3 25.8	Feb. 10, 1960 Feb. 27, 1961	T,G	Irr	Estimated discharge 135 gpm. Reported drawdown 56 feet after pumping 90 gpm. Reported sand from 40 ft to bottom; rock at bottom. Flow of creek ceases when well is pumped.
233	T. D. Wilson	do	1956	82	14	2,070	28.5 28.4 28.1	Feb. 8, 1958 Feb. 10, 1960 Feb. 27, 1961	T,G	Irr	Reported drawdown 29 ft after pumping 30 hours at 130 gpm.
234	W. P. Peak				5	2,105	50.9 48.2	Mar. 26, 1957 Mar. 18, 1960	C,W	N	Old well.
235	Gewel Cooper			150		2,181	133.6 133.6	Apr. 3, 1957 Mar. 18, 1960	C,W	S	Do.
236	Floyd Willis	Lester Gardner	1957	104		2,055	16.6 14.6	Feb. 10, 1960 Feb. 27, 1961	T,G	Irr	Reported drawdown 37 ft after pumping 37 hours at 100 gpm. Pump set at 98 ft.
237	R. L. Bingham	Myles Drilling Co.	1957	65	16	2,055	34.8 34.4	Feb. 10, 1960 Feb. 27, 1961	T,G	D, Irr	Reported drawdown 7 ft after pumping 62 hours at 90 gpm.
238	T. A. Bailey	Garner Bros	1956	83	14	2,075	33.6 32.4	Feb. 10, 1960 Feb. 27, 1961	T,G	Irr	Reported drawdown 33 ft after pumping 40 gpm.
239	C. C. Kimbell	do	1956	90	16	2,063	27.3 26.2	Feb. 10, 1960 Feb. 27, 1961	T,G	Irr	Reported discharge 120 gpm. Red beds at 87 ft.
240 [1]	do	do	1956	102	16	2,065			T,G	Irr	Reported discharge 585 gpm. Pump set at 90 ft. Temp. 69° F.
241	W. B. Francis			80	8	2,107	41.0 48.2	Mar. 26, 1957 Mar. 18, 1960	N	N	
242 [1]	W. W. Hodges		1927	100		2,075			C,W	D	Estimated discharge 1 gpm.
243 [1]	do			100		2,073	30	1961	C,W	S	Do.
244	J. R. Carr		1947	82	8	2,116	58.2 56.5	Apr. 3, 1957 Mar. 18, 1960	C,W	D,S	Supplied water to irrigate garden.
245	Girard Garage			90		2,120	62.1 63.4	Mar. 26, 1957 Mar. 18, 1960	C,W	S	
246	Charles Dunlap		1917	120		2,161	105.2 102.8	Mar. 26, 1957 Mar. 18, 1960	C,W	D,S	
247	Lum Davidson		1925	120		2,153	107.9 106.8	Mar. 26, 1957 Mar. 18, 1960	C,W	S	
248	Red Cooper		1925	90		2,131	71.0 69.7	Mar. 26, 1957 Mar. 18, 1960	C,W	N	

249	Hamlin Standlind			75	6	2,143	53.8 48.8	Apr. 3, 1957 Mar. 18, 1960	C,W	S	
250	J. G. Page			175		2,150	98.6 96.1	Apr. 3, 1957 Mar. 17, 1960	C,W	S	Old well.
251	Occie Barrows		1951	120	6	2,145	51.3 49.9	Mar. 26, 1957 Mar. 17, 1960	C,W	S	
252	Hastings Estate			220	6	2,173	148.5 146.0	Apr. 7, 1957 Mar. 18, 1960	C,W	S	
253	Raymond Hooper	Myles Drilling Co.	1956	70	12	1,994	20.9 19.9	Feb. 10, 1960 Feb. 27, 1961	T,E	Irr	Reported discharge 17 gpm.
254	D. D. Thompson	Garner Bros	1956	64	14	2,005	27.5 21.5 20.4	Apr. 27, 1957 Feb. 10, 1960 Feb. 27, 1961	T,E, 5	Irr	Reported drawdown 20 feet after pumping 2 hours at 200 gpm.
255	do	do	1956	62	14	2,002	27.0 22.5 21.4	Apr. 27, 1957 Feb. 10, 1960 Feb. 27, 1961	T,E, 7½	Irr	Reported drawdown 14 feet after pumping 2 hours at 200 gpm.
256 [1]	L. C. Johnson	do	1957	98	16	2,051	45.2 43.8 43.8 43.1	Apr. 27, 1957 Jan. 11, 1960 Feb. 10, 1960 Feb. 27, 1961	T,G	Irr	Reported drawdown 18 ft after pumping 2 days at 275 gpm. Temp. 69° F.
257 [1]	Fletcher Rich	do	1959	136	16	2,069	57.3 57.4	Feb. 10, 1960 Feb. 27, 1961	T,E, 20	Irr	Reported clay at bottom. Temp. 68° F.
258 [1]	do	do	1959	126	16	2,059	55.6 55.6	Feb. 10, 1960 Feb. 27, 1961	T,E, 20	Irr	Do.
259	Mrs. Hagan	Myles Drilling Co.	1960	130	14	2,045	73.1 73.1	Feb. 10, 1960 Feb. 27, 1961	T,E, 10	Irr	Reported drawdown 14 ft after pumping 40 gpm.
260	Fletcher Rich	Garner Bros	1956	132	16	2,037	66.0 62.7 61.1	Apr. 27, 1957 Feb. 10, 1960 Feb. 27, 1961	T,G	Irr	Reported drawdown 80 ft after pumping 2 hours at 135 gpm.
261 [1]	do	do	1960	110	12	2,032	65.5	Feb. 27, 1961	T,E, 7½	Irr	Reported discharge 145 gpm.
262	Mrs. B. F. Spradling.	B. F. Spradling	1909	53	48	2,117	33.3 30.8	Apr. 4, 1957 Mar. 17, 1960	C,W	S	Dug well.
263	E. W. Clark			140	6	2,115	86.7 87.0	Apr. 2, 1957 Mar. 17, 1960	C,W	S	
264	C. C. York			42	48	2,071	28.0 17.1	Apr. 11, 1957 Mar. 17, 1960	N	N	Dug well.
265	W. L. Buckelew			45	36	2,047	30.2 28.2	Apr. 2, 1957 Mar. 17, 1960	C,W	S	Do.
266	E. M. Jones	Black and Jay	1941	36	48	2,054	30	Apr. 1957	T,E	S	Dug 48-in. hole curbed with 2×4 wood, put in 6 in. pipe and filled hole with gravel.
267	do	do	1940	202		2,066			T,E	S	Drilled to 256 ft, plugged back to 202 ft. Salt water at 253 ft, water rose 30 to 40 ft in hole.
268	do	Merle Jay	1943	14	48	1,815	8.2 7.0	Mar. 25, 1956 Mar. 17, 1960	C,W	S	Dug well.
269	do	Shorty Leach		250	7	2,072	236.5 227.4	Mar. 25, 1957 Mar. 17, 1960	C,G	S	
270	do	Webb		110		1,902	94.0 87.5	Mar. 25, 1957 Mar. 17, 1960	C,W	D	
271	John Montgomery	Garner Bros	1956	160	14	1,982	53.1 52.7	Mar. 17, 1960 Feb. 27, 1961	C,W	S	Reported drilled for irrigation, but pumps too much sand. Did not reach red beds. Test hole 200 ft west reached red beds at 70 ft.

See footnote at end of table.

TABLE 10.—*Records of selected wells and springs in the Croton Creek-Salt Croton Creek area*—Continued

Well (pl. 1*A*)	Owner	Driller	Date completed	Depth of well (feet)	Diameter of well (inches)	Altitude above sea level (feet)	Water level: Below land-surface datum (feet)	Water level: Date of measurement	Method of lift	Use of water	Remarks
272	Marvin Fuller	Floyd Wilhoit	1947	170	5	2,028	146.5 146.1	Apr. 5, 1957 Mar. 17, 1960	C, W	S	
273	W. D. Hall	do	1942		5	2,024	162.0 147.3	Apr. 5, 1957 Mar. 17, 1960	C, W	D, S	Can be used for drinking, well pumped 3 days prior to water level measurement in 1957.
274	E. E. York				6	2,038	171.9 168.8	Apr. 5, 1957 Mar. 17, 1960	C, W	S	
275	C. D. McCurry			120	6	1,978	48.7 86.7	Apr. 4, 1957 Mar. 17, 1960	C, W	S	
276	E. M. Jones	Shorty Leach	1950	290	7	2,100	272.0 268.8	Mar. 25, 1957 Mar. 17, 1960	C, W	S	
277	E. E. York			265	6	2,070	228.3 226.5	Apr. 5, 1957 Mar. 17, 1960	C, W	S	
278	O. C. Lowrance	Webb		180	5	2,011	135.1 134.5	Apr. 4, 1957 Mar. 17, 1960	C, W	S	
279	City of Jayton	J. T. Leach	1945	45		1,950	28.5 27.5 27.7	Feb. 11, 1960 Mar. 20, 1960 Oct. 31, 1960	T, E, 7½	P	Reported drawdown 1.4 ft after pumping 5 hours at 150 gpm.
280[1]	do	do	1949	52	10	1,950	27.5	Feb. 16, 1960	T, E, 10	P	Reported discharge 150 gpm. Pumping level 28.7 ft below land surface while pumping 150 gpm, Mar. 30, 1960.
281[1]	do	do	1953	52	10	1,950			T, E, 10	P	Reported discharge 150 gpm.
282[1]	do	C. H. Wyley	1959	62	10	1,950	29.8	Oct. 31, 1960	T, E, 10	P	Reported pumping level 34 ft below land surface while pumping 150 gpm. Temp. 68°F.
283	W. A. Springer, Sr.			55	6	1,946	51.7	Jan. 14, 1957	C, W	S	
284	do			105	7	1,984			C, W	S	
285	W. A. Springer, Jr	Obie Wright	1953	75	7	1,961	59.1	Jan. 14, 1957	C, W	S	
286	G. W. Springer			113	12	1,840	104.3	Feb. 13, 1957	C, W	S	Old well.
287	W. A. Springer, Jr.	Russel	1939	135	7	1,854	118.6	Jan. 14, 1957	C, W	S	
288	G. W. Springer	Obie Wright	1949	150	6	1,876	138.6	Feb. 13, 1957	C, W	S	
289	Ben Roach	Ben Roach	1936	100		1,888	70.2	Jan. 10, 1957	C, W	S	
290	G. W. Springer			30	5	1,734	26.4	Feb. 15, 1947	C, W	S	
291[1]	Homer Hodges		1961	59		1,755			C, E	D, S	Reported discharge 5 gpm.
292	W. A. Springer, Jr.			Spring			(+)		Flows		Estimated discharge 45 gpm.
293	do			Spring			(+)		Flows		Estimated discharge 1 gpm.
294	do			Spring			(+)		Flows		Estimated discharge 90 gpm.
295				3,400							Oil well. Swenson field. Located 20 miles southeast of area.

[1] See table 9 for analyses of water from wells and springs in the Croton Creek-Salt Croton Creek area.

The strongest spring in this Lower flat occurs not at its head but at its extreme southeast corner, close to the bank of Hayrick Creek. Here clear, strong brine (Sample 28–1; dissolved solids about 200,000 ppm) issues from a joint in the green clay. Partial evaporation of the water has built up small "natural levees" of salt along its outlet stream.

Stratigraphically the salt flats on Haystack Creek are just below marker bed Dd of the composite log (pl. 2).

OTHER OCCURRENCES

Saline water occurs in several other areas north and northeast of Dove Creek Salt Flat. About 7 miles north of Dove Creek Salt Flat, exploration hole 135 (pl. 1*A*) drilled to a depth of 400 feet, penetrated marker beds Da, Db, and Dc at altitudes of 1,925, 1,880, and 1,731 feet, respectively. Local residents reported that saline water rose to an altitude of 2,000 feet, or about 45 feet above the land surface. The source of the saline water is reported by McMillion (1958, p. 34) to be a zone in the "lower or upper Eskota," which are correlated with beds Db and Da of the composite log (pl. 2). However, exploration holes 127, 129, 130, 136, and 138 (pl. 1*A*), west, southwest, southeast, and east of 135, penetrated beds Da, Db, and Dc, but it is not known if water flowed from the holes.

In spite of the high artesian head in exploration hole 135, saline water is not known to seep at the surface; this fact indicates a lack of hydraulic connection with the surface or with the local water table.

Water well 283, about 0.2 mile southwest of exploration hole 135, was completed at an altitude of about 1,891 feet and obtained fresh water from the sediments between beds Da and Db. In 1957, the altitude of the water level in this well was about 1,894 feet. Wells 284 and 285, about 1 and 1.6 miles southwest of exploration hole 135, obtained fresh water possibly from bed Dc. In 1957, the altitude of the water level in well 285 was about 1,902 feet.

The altitude of the bed of North Croton Creek, about a mile north of exploration hole 135, is about 1,850 feet, which is below the level of marker bed Db. Salt water is not reported to be seeping into North Croton Creek in this area.

Local residents reported that salt water flowed from shot holes 229 and 230, about 6½ and 7 miles northeast of Dove Creek Salt Flat (pl. 1*A*). Information is not available as to the source of the saline water from these two holes or the rate of flow. No salt water is known to be discharged at the land surface in the vicinity of the two shot holes, nor was any reported in any of the exploration holes in the vicinity of shot holes 229 and 230.

THEORIES OF SOURCES OF SALT WATER

GENERAL CONDITIONS

In the areas where saline water emerges at the land surface or is known to be under hydrostatic pressure at depths less than about 400 feet, the water is not in hydraulic connection with the local water table. The strong flows of salt water from exploration holes 139 and 174 indicate that the salt water is probably in solution channels in gypsum which were formed by circulating water. However, at present, the movement of salt water to the land surface is impeded in the vicinity of Dove Creek Salt Flat and is prevented at exploration hole 139 and shot holes 229 and 230.

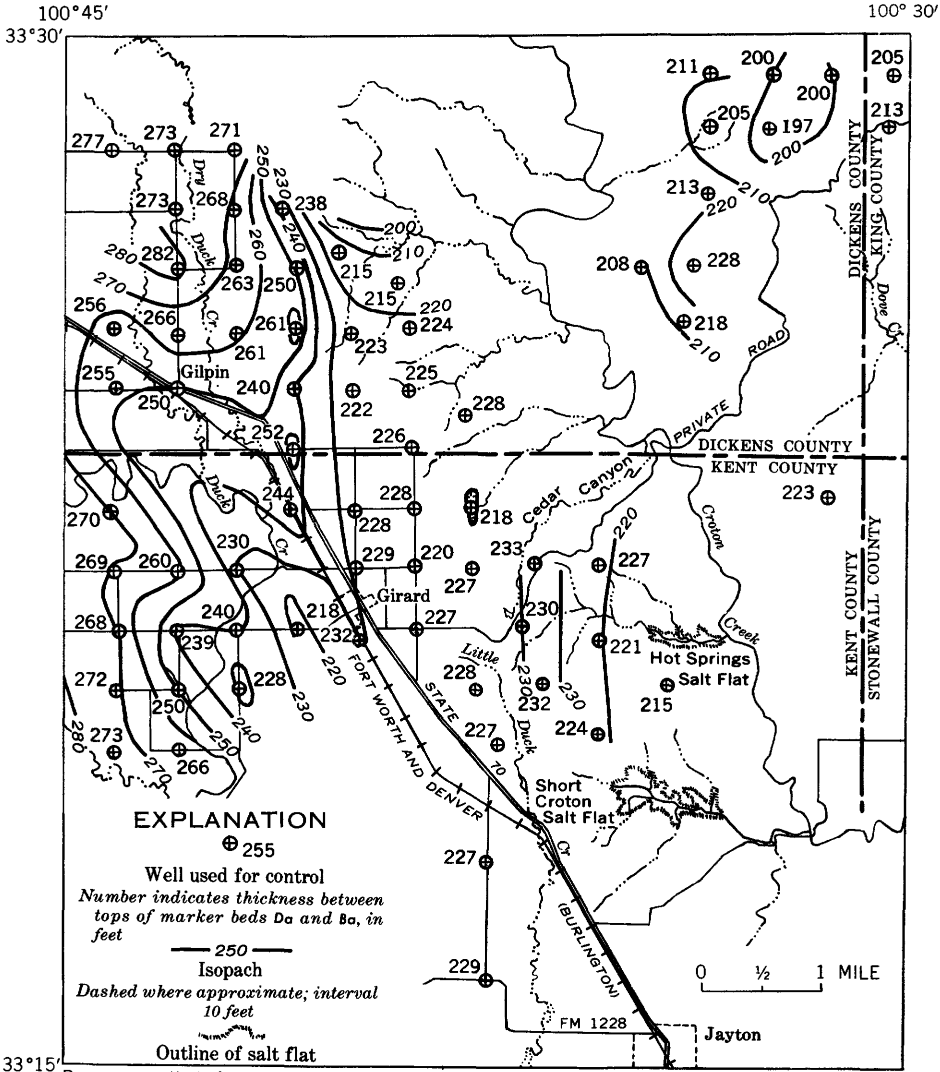
Mr. P. E. Ward, U.S. Geological Survey, Norman, Okla., in his studies of the areas where salt water is discharging from the Permian in the basins of the Red and Arkansas Rivers in northern Texas, Oklahoma and southern Kansas, reports (oral communication, 1960) that the head on the salt water is comparable to the local water table and that the flow is gravity flow.

The present investigation originally included the drilling of test wells in and near Dove Creek Salt Flat to determine the source and movement of the water that issues as seeps and springs in the salt flat. However, the test drilling was not performed because access to the Dove Creek Salt Flat area could not be obtained. Consequently, the sources of the salt water in Croton Creek-Salt Croton Creek area is a matter of considerable speculation at least until more detailed information is obtained. This report discusses briefly several possibilities: circulation of meteoric water through the Permian rocks in artesian systems; localized zones in the Permian that contain salt and are surrounded by clay, in which the clay acts as a semipermeable membrane producing osmotic pressure; and brine moving upward from the deep subsurface.

CIRCULATION OF METEORIC WATER

The saline water in the salt flats may be derived from precipitation (meteoric water) that has circulated through the Permian rocks and has taken minerals into solution. Little Duck Creek, a few miles north-northwest of Jayton, is reported to have numerous sinkholes in its bed. About 4½ miles north of Gilpin, a stream having a drainage basin of several square miles drains into sinkholes, and only the flows from large floods escape downstream to Dry Duck Creek.

The interval between the tops of marker beds Da and Ba is thinner toward the east in an area northeast of Gilpin and in the valley of Duck Creek northwest and west of Girard, as shown on figure 8. The thinning also is shown on the geologic section along line *A–A′*



Base compiled from topographic maps of the U. S. Geological Survey, aerial photographs, and county maps of the Texas Highway Department

FIGURE 8.—Isopachous map of western part of Croton Creek-Salt Croton Creek area drawn on the interval between the tops of marker beds Da and Ba.

(pl. 3) between exploration holes 36 and 41 and on the geologic section along line *B–B'* (pl. 3) between exploration holes 52 and 53. Northeast of Gilpin the interval thins as much as 40 feet between exploration holes 11 and 12, and 14 and 16 (fig. 9). This thinning may be attrib-

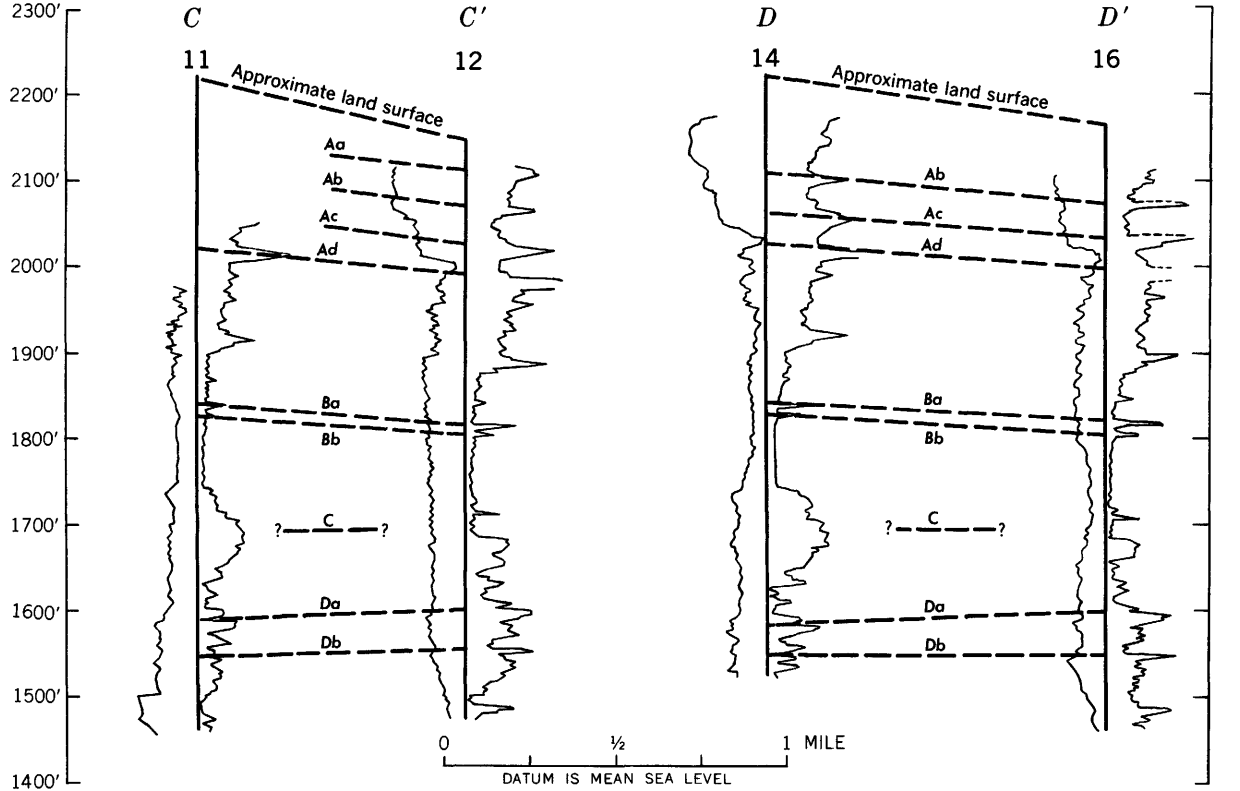


FIGURE 9.—Electric-log correlations along lines C–C′ and D–D′ northeast of Gilpin.

uted, at least in part, to the removal of salt by solution from the part of the interval at or near marker bed C, which crops out in the bluff at Hot Springs and Short Croton Salt Flats.

The position of the Kansan deposits in the valley of Duck Creek relative to the stream bed and the ponded conditions suggested by the Pearlette Ash Member of the Sappa Formation equivalent indicate that subsidence due to the solution and removal of salt from the Permian rocks probably began in early Quaternary time. Similar subsidences have been described by Frye and Schoff (1942, p. 35–39) in Meade and Clarke Counties, Kan., and Beaver County, Okla.

The saline water issuing at Hot Springs and Short Croton Salt Flats probably is derived from precipitation in the Duck Creek drainage basin; however, the area of effective recharge was not determined definitely. The total flow of saline water from the salt flats on Croton Creek probably is less than 2 cfs. Tracing the underground path of such a small flow in an area the size of the Duck Creek drainage basin was beyond the scope of the present investigation.

Aerial photographs did not show any indications of sinkholes in the vicinity of Dove Creek Salt Flat or in the vicinity of the occurrence of salt water to the north and northeast, where water may be entering the Permian at sufficient elevations to give the hydrostatic heads as reported. McMillion (1958, p. 22–24) reported that the unconfined body of ground water extending west of Dove Creek Salt Flat to the vicinity of Girard is the source of salt water that emerges in the salt flat. Salt water from this unconfined water body enters marker bed Dc, thence moves updip through solution cavities in the anhydrite of marker bed Dc. The alteration of anhydrite to gypsum results in an increase in volume and, as a consequence, the permeability of marker bed Dc is reduced markedly. Because of this decrease in permeability, the water moves into the underlying jointed clay and shale of the Dog Creek Shale and comes to the surface under low hydrostatic head.

Subsurface information in the vicinity of Dove Creek Salt Flat does not indicate the source or movement of the water or the salt. The log of exploration hole 182, about a mile south of the salt flat, indicates that the interval between marker beds Df and Dc is about 10 feet less than on the logs of other wells in the area; however, the interpretation of the log of well 182 is uncertain, and marker bed Dc is above the tops of the logs of several exploration holes, particularly to the north and northwest of the salt flat. Marker bed Dd could not be identified on the logs of several holes near the salt flat.

If the hydrostatic pressure at Dove Creek Salt Flat, at exploration hole 135, and at shot holes 229 and 230 is artesian, differences in geographic location and artesian head would indicate at least three artesian systems: one in the vicinity of Dove Creek Salt Flat, one in the vicinity of exploration hole 135, and a third in the vicinity of shot holes 229 and 230.

THEORY OF OSMOTIC PRESSURE

The salt water in the vicinity of Dove Creek Salt Flat at exploration hole 135 and shot holes 229 and 230 (pl. 1*A*) may be in lenses of material in the Permian that contain salt and that are surrounded by shale or clay. For example, during deposition of the Dog Creek Shale, lenses of salt or sand containing salt possibly were surrounded by clay, or circulating meteoric water may have carried colloidal clay downward. When the water came into contact with salt or salt water, flocculation of the clay resulted and, at some places, isolated parts of the Permian that contained salt.

If the clay is permeable to water but prevents the passage of salt, it behaves as a semipermeable membrane. Relatively fresh water may move through the clay membrane to the salt-bearing deposits of the Permian where it takes salt into solution. Where the Permian deposits are enclosed by the clay membrane, this circulation of water builds up the concentration of salt solution, and thereby increases the osmotic pressure and the permeability of the material.

According to F. A. F. Berry, Petroleum Research Corporation (written communication, 1960), the membrane properties of shale have been demonstrated and measured in the laboratory. R. R. McLeod, Gulf Oil Corp. (written communication, 1960) indicated that according to the theory formulated from laboratory work on synthetic membranes, the osmotic-pressure difference across a shale membrane would be about 12 to 15 psi (pounds per square inch) per 1,000 ppm difference of dissolved solids for most subsurface brines. Because concentrations of sodium chloride in excess of 300,000 ppm are theoretically possible, osmotic pressure could approach 4,500 psi. The water emerging from the spring on Dove Creek Salt Flat contained about 222,000 ppm dissolved solids. With a theoretical membrane producing 12 psi per 1,000 ppm difference in dissolved solids and pure water, the resulting osmotic pressure would be 2,664 psi. This pressure would support a column of salt water (of specific gravity 1.18) of about 5,200 feet. The differential hydrostatic head observed in the water near Dove Creek Salt Flat is about 70 feet. If it is assumed that this hydrostatic pressure is due to osmotic pressure and if the above theoretical membrane is also assumed, the 70 feet of pressure head would be produced by a difference of 3,000 ppm of dissolved solids in the water.

The theory of osmotic pressure caused by shale membrane has not been widely used or accepted. Its applicability to the conditions that exist in the report area cannot be demonstrated; however, it is offered as a possible explanation of these conditions.

BRINE MOVING UPWARD FROM DEEP SUBSURFACE

Brine is associated with petroleum in the deep subsurface in the area. It is possible that the saline water that emerges at the salt flats may be brine which has percolated upward from the subsurface. The chemical analyses of a sample of water from the spring (294) on Dove Creek Salt Flat and the analysis of a sample of brine from a depth of 3,400 feet in an oil well (295) in the Swenson oil field (Beeler and others, 1953, p. 8) are shown in table 9. The Swenson oil field is in southeastern Stonewall County, about 20 miles south-southeast of the eastern edge of the area. The spring water is high in sodium and chloride ions, and the percentage of sodium, chloride, and sulfate is larger than in the brine, which has a larger percentage of calcium. The gas associated with the spring water is nearly 96 percent nitrogen, whereas the gas that generally is associated with oil-field brine is principally hydrocarbon. These data indicate that the water in spring 294 is not brine that percolated upward from the deep subsurface.

POTENTIAL ABATEMENT OF CONTAMINATION

Contamination of the Brazos River by salt water from the Croton Creek-Salt Croton Creek area can be reduced either (1) by controlling the circulation of water in the salt-producing systems and reducing or eliminating the amount of salt water produced or (2) by disposing of the salt water after it has been produced.

REDUCING OR ELIMINATING THE PRODUCTION OF SALT WATER

The area west of Croton Creek and between Girard and Jayton was discussed by Dr. Blank (see footnote, p. CC5) and by McMillion (1958, p. 19–20, 24) as a possible source of the saline water that discharges at the salt flats. McMillion (1958, p. 24) also stated, "Large withdrawals from the usable part of the ground-water reservoir * * * probably would cause a decline in the water table and by so lowering the head of the reservoir cause a decrease in the surface seepage in the low areas of the Croton Creek drainage system."

The water that is discharged at Hot Springs and Short Croton Salt Flats probably is derived from the infiltration of precipitation in the drainage basin of Duck Creek. The intake area could not be determined definitely, but it may be the alluvium near Duck Creek, the sand dunes between Girard and Jayton, or the sinkholes in the Permian about 4½ miles north of Gilpin.

If the alluvium near Duck Creek is the intake area for the springs, then pumping water from the alluvium to reduce the flow of the springs in the salt flats probably would not be feasible. The alluvium supplies water to 17 irrigation wells. Data on these wells (table 10) show that during the period 1957–58 to 1960–61 the water levels rose in most of the wells. Additional large withdrawals would lower the water level; however, the water level in the alluvium probably cannot be lowered more than about 50 feet. The water level in the alluvium is about 200 feet above the level of the salt flats; lowering the water level in the alluvium by 50 feet would therefore result in a small decrease in the hydraulic gradient and, hence, only a small decrease in the flow at the salt flats.

Analysis of the avilable data does not indicate a feasible means by which the circulation of water in the reservoirs can be controlled and the production of salt water reduced or eliminated.

DISPOSAL OF SALT WATER

GENERAL CONDITIONS

The mixing of salt water with surface water may be prevented by pumping salt water from shallow wells in and near the salt flats. Lowering the hydrostatic head in the salt-water aquifers would eliminate the discharge from springs and seeps; however, this lowering would not reduce the amount of salt water produced, and provisions would still have to be made for disposal of the salt water pumped out of the ground.

The average daily quality of water at Possum Kingdom Dam provides the best available basis for evaluating the effects of eliminating all or part of the flows of Croton Creek and Salt Croton Creek. However, the records include measurements of floodflows of relatively low mineralization that spilled over the dam and were not available for use in the upper Brazos River basin. The average concentration of dissolved solids in the water in Possum Kingdom Reservoir is considerably larger than the average concentration for the total flow. Therefore, elimination of all or part of the flows of Croton Creek and Salt Croton Creek would have a proportionally greater effect on the quality of the water stored in Possum Kingdom Reservoir than on the total flow.

Croton Creek contributes an average of 70 tons of chloride per day, or about 7 percent of the average daily load of 1,000 tons entering Possum Kingdom Reservoir. Croton Creek does not have a sustained base flow, particularly in the summer, because much of the salt water discharged at Hot Springs and Short Croton Salt Flats is evaporated and the salt is left. Much of the salt load of Croton Creek is picked up and carried downstream during periods of surface runoff. For the period August 1959 to June 1961, for which streamflow records are available, the monthly runoff ranged from 5.2 acre-feet in September 1959 to 13,240 acre-feet in October 1960, and the average monthly runoff for the 22-month period was 1,310 acre-feet.

Salt Croton Creek carries an average of about 485 tons of chloride daily, which is about 45 percent of the chloride entering Possum Kingdom Reservoir. Data for the period 1942–60 show that elimination of the total flow of Salt Croton Creek would reduce the average chloride concentration at Possum Kingdom Dam from about 386 ppm to about 210 ppm and the average dissolved solids by about 25 percent. Sulfate is a minor constituent of the Salt Croton Creek water, and the sulfate concentration in Possum Kingdom Reservoir would not be affected significantly.

The flow of Salt Croton Creek varies widely owing to the erratic occurrence of runoff-producing storms in the area. On the basis of streamflow records collected since October 1956, the sustained base flow has averaged less than 900 acre-feet per year and generally has ranged from 0.5 to 2.0 cfs, whereas total runoff from the basin has ranged from 2,570 acre-feet in the 1959 water year to 7,850 acre-feet in the 1957 water year. The base flow is largely from saline seeps and springs on Dove Creek Salt Flat, Dove Creek near Dove Creek Salt Flat, and Haystack Creek. The water issuing from these springs and seeps contains an average of about 330 tons of chloride per day. If the salt load carried by the base flow of Salt Croton Creek were eliminated, the average salt load entering Possum Kingdom Reservoir would be reduced by about 30 percent.

Salt Croton Creek is the largest single natural source of salinity to the Brazos River, and if the base flow of this stream could be detained and returned to the subsurface, evaporated, or otherwise disposed of, there would be a substantial improvement in the chemical quality of the water entering Possum Kingdom Reservoir. If the base flow of Salt Croton Creek is collected for disposal, it should be taken from properly designed, low-head detention ponds located as near as possible to the places where the salt water emerges from the ground. From these ponds the salt water could then be diverted to the disposal area.

EVAPORATION BASINS

Dove Creek Salt Flat is not suitable as a site for an evaporation basin because marker bed Dc, a layer of gypsum generally about 10 feet thick, crops out on the banks and in the bed of Dove Creek north of the flat, in the bluffs bordering the flat, and at the surface of the western end of the flat. In this area, marker bed Dc is cavernous and contains numerous solution channels. Landowners report that stock ponds bottomed in marker bed Dc or only a few tens of feet above the top of the bed generally will hold water only for a few years. Any reservoir in which marker bed Dc crop out along the wetted perimeter or in which the top of the bed is less than several tens of feet below the bottom of the impoundment probably would not hold water for an appreciable length of time unless special provision is made by paving the reservoir area with impermeable material. The reservoir should not be in the immediate vicinity of Dove Creek Salt Flat but preferably should be downstream and below the exposure of marker bed Dc.

Should economic studies of the problem indicate that evaporation basins are the most practical way to reduce salt-water pollution, then detailed engineering studies of streamflow and associated hydrology should be made at the proposed dam sites to determine whether or not the evaporation basin should retain only the highly mineralized base flow in an off-channel reservoir, or whether the reservoir should detain both the base and flood runoff (total flow) of the stream.

DISPOSAL UNDER GROUND

The saline water that emerges in the salt flats may be disposed of by injecting it through wells into subsurface formations, provided the formations are permeable and the saline water is compatible with the water in the formation. Disposal might be accomplished by injecting the saline water into unused oil wells, as a means of repressuring nearby oil fields, or into the numerous oil tests in the area.

The salt flats are underlain by at least 7,000 feet of sediments that range in age from Cambrian to Permian. The hydraulic and geologic properties of these sediments are inferred from electric logs of oil tests in the vicinity of Dove Creek Salt Flat. Whether these properties are applicable over a larger area cannot be determined because of the scarcity of data. Geologic sections along lines *E–E′* and *F–F′* (pl. 4) show the general stratigraphy of the Paleozoic rocks underlying the Dove Creek Salt Flat. Sediments of Cambrian age rest on a basement complex of relatively impermeable Precambrian rocks. The Cambrian rocks, which consist of sandstone and conglomerate, are about 150 feet thick in the area of the Dove Creek Salt Flat and occur at a depth of about 6,700 feet, or an altitude of about 5,000 feet below sea level. Overlying these sediments is a relatively porous sequence of limestone and dolomite of Ordovician age. This sequence is about 150 feet thick and underlies the salt flats at a depth of 6,560 feet, or at an altitude of 4,860 feet below sea level. Limestone and shale of Mississippian age overlie the Ordovician rocks, but the low porosity of these sediments precludes the possibility that they may be used for the disposal of saline water. Deposits of Pennsylvanian age overlie the Mississippian rocks and consist, in part, of limestone reefs into which saline water possibly could be injected.

The Pennsylvanian reefs have been classified for the purposes of this report as reefs of Strawn and Canyon age and of Cisco age. Dove Creek Salt Flat is about a mile west of the axis of the Strawn-Canyon reef, which trends in a northeasterly direction (fig. 10). The thickness of the reef varies considerably from place to place. Although oil tests in the immediate vicinity of the salt flat did not penetrate the complete thickness of the reef, it is at least 500 feet thick under the salt flat. The top of the reef of Strawn and Canyon age is about 4,600 feet below the surface in the southeastern part of the salt flat and 4,800 feet in the northwestern part, or 2,900 and 3,100 feet below sea level, respectively. During a test in well 219, the bottom-hole pressure at 5,000 feet, which was the top of the reef, was reported to be 1,925 psi. The pressure of a column of salt water of specific gravity 1.18 and equivalent to the depth of the well would be 2,555 psi. Salt water might be injected into the reef by gravity flow owing to the difference in pressure, which amounts to 630 psi, or 1,230 feet of salt-water load.

About 5 miles southeast and east of Dove Creek Salt Flat, electric logs of oil tests show that the reef of Cisco age has a thickness of about 400 feet and that the altitude of the top of the reef is less than 1,900 feet below sea level. The reef pinches out westward and the western limit of the reef is about 3 miles east of the salt flat (fig. 10). Because of the high permeability of limestone reefs in other areas, salt water might be injected into the reefs that underlie the salt flats.

Electric logs of oil tests in the vicinity of Dove Creek Salt Flat indicate that the sediments less than 200 feet below bed A may possess porosity. Whether these beds are permeable, however, cannot be determined from the available data. According to the geologic sections along lines *E–E′* and *F–F′* (pl. 4), bed A is about 3,700 feet below Dove Creek Salt Flat. The contact between Pennsylvanian and Permian deposits in the geologic sections along lines *E–E′* and *F–F′* cannot be determined definitely, but it may be closely approximated by bed A.

The lower part of the Permian sedimentary rocks that underlie the area consists of limestone, shale, and sandstone that interfinger upward into fine sand, anhydrite or gypsum, salt, and dolomite. The base of the Coleman Junction Limestone Member of the Putnam Formation of the Wichita Group is shown in plate 4. Electric logs show that the deposits about 100 feet above and 200 feet below the base of the Coleman Junction Member probably possess some porosity, but whether the deposits are satisfactory for the disposal of salt water depends upon their permeability. Configuration of the base of the Coleman Junction Member in the vicinity of Dove Creek

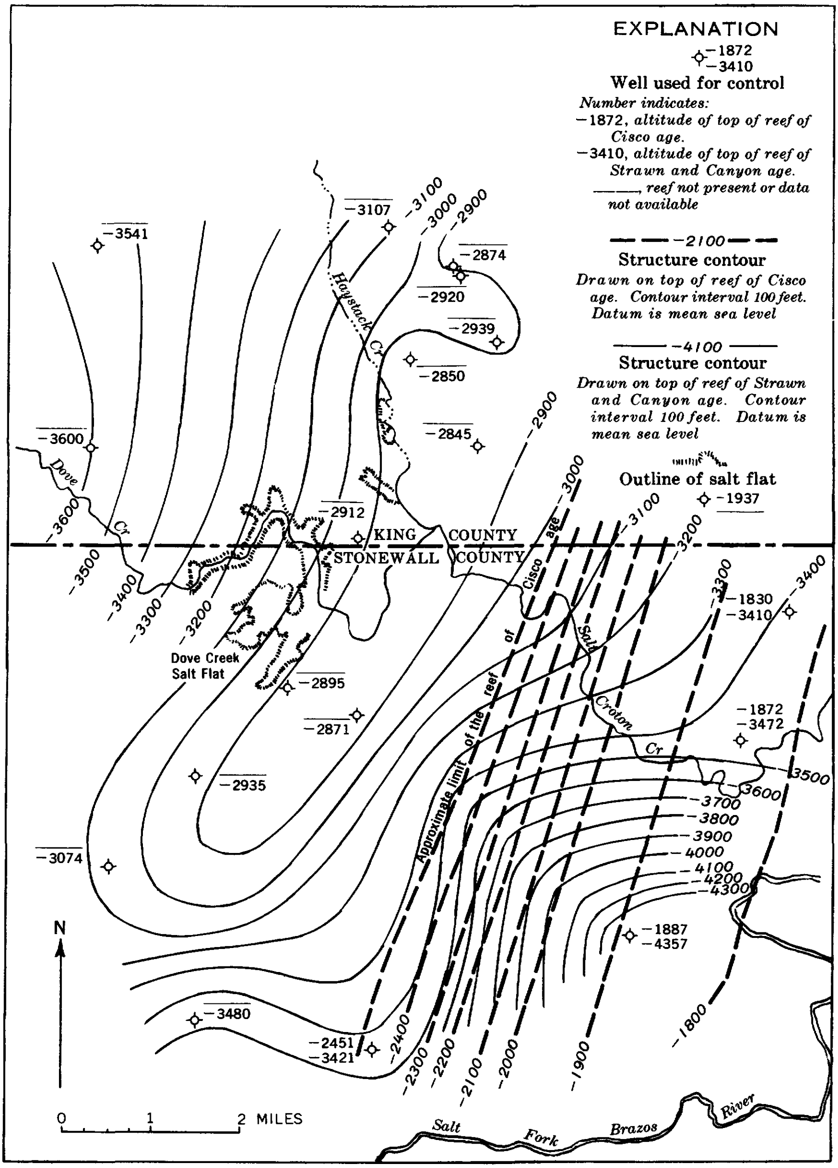


FIGURE 10.—Structure-contour map drawn on the tops of the reef of Strawn and Canyon age and the reef of Cisco age in the vicinity of Dove Creek Salt Flat.

Salt Flat is shown in figure 11. The nearest outcrop of the Coleman Junction Member is about 70 miles east-southeast of Dove Creek Salt Flat at an altitude of about 1,200 feet.

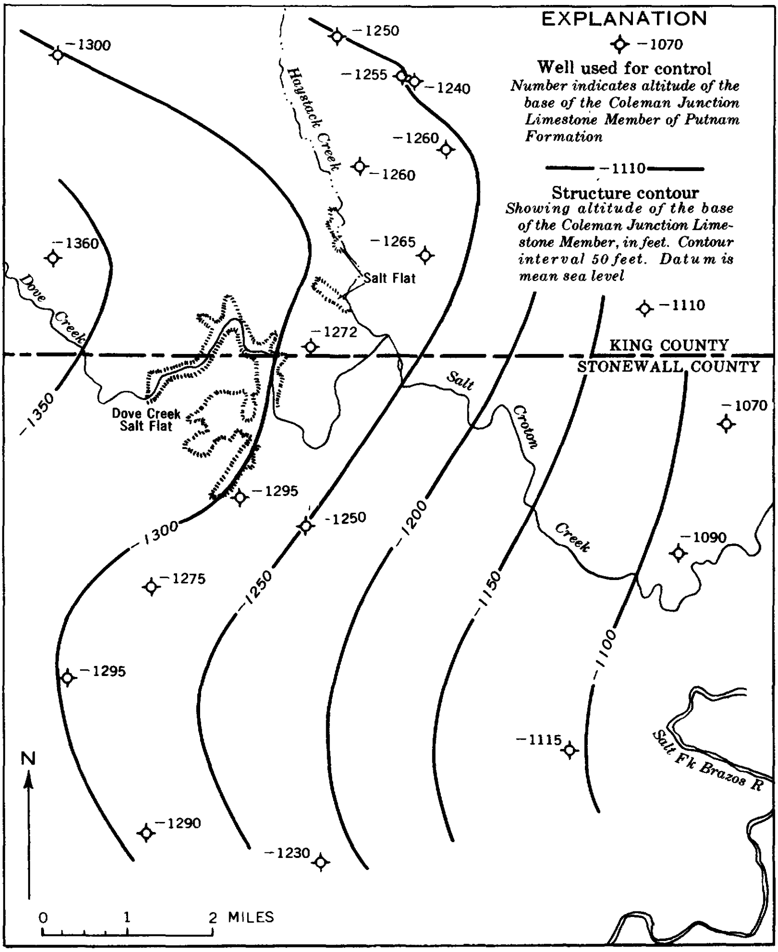


FIGURE 11.—Structure-contour map of the Coleman Junction Limestone Member of the Putnam Formation in the vicinity of Dove Creek Salt Flat.

Data are not available for evaluation of these formations as reservoirs for the disposal of salt water. The evaluation can be done only when the physical and hydraulic properties of these formations have been determined. In addition, other factors that relate to the ability of a formation to serve as a disposal reservoir require consideration; among these factors is the compatability of the formation water and the injected water.

CONTROL OF EROSION

The salt water in the vicinity of Dove Creek Salt Flat at exploration hole 135 and at shot holes 229 and 230 (pl. 1*A*) is under pressure and occurs at shallow depths. Salt water is discharged in the vicinity of Dove Creek Salt Flat probably because the material that tends to confine the salt water has been partly breached by erosion. Salt water flowed from the exploration hole and the shot holes when they were penetrated by wells.

Salt water may occur under pressure and near the land surface at other places in the area. An important step in the prevention of additional contamination in the area is the reduction of erosion which might result in a breaching of the material confining salt water.

RECOMMENDATIONS FOR FUTURE STUDIES

As of October 1961, the Geological Survey was collecting continuous streamflow records at 17 gaging stations in the Brazos River basin above Possum Kingdom Dam. At seven of the stations, data that pertained to the chemical quality of the water were being collected. In the Croton and Salt Croton Creek basins, quantity and quality data were being collected at two stream-gaging stations and at four low-flow partial-record stations. The location of the stations operated in the Brazos River basin above Possum Kingdom Dam is given in figure 2 and plate 1*A*. The present program of collecting streamflow and quality-of-water records that are essential to the design of reservoirs should be continued so as to obtain additional basic data through varied periods of drought, ordinary flows, and floodflows.

In addition to the current program, a streamflow station and data on the quality of water are needed on the Salt Fork Brazos River near Peacock, so that the salt yield of the area upstream can be determined more precisely. Also, a streamflow station and data on the quality of water are needed on North Croton Creek for information about the salt discharge of that stream.

The program outlined above will provide a general basis for the design of salt-control projects and also allow the evaluation of the effects of any control measures that may be taken; however, additional data may be required to meet the specific needs of some salt-control projects.

In addition, test drilling should be done to serve one or more of several purposes. Shallow drilling definitely should be done in connection with any specific disposal project, particularly in the vicinity of evaporation basins or impoundments, to determine conditions that might have a bearing on feasibility and proper design of such projects.

Test drilling should be done to determine if the salt water can be disposed of without mixing with surface water. For example, the salt water may be drained directly into deep disposal wells or it may be pumped from wells, thus lowering the hydrostatic head in the body of salt water and eliminating the flow from seeps and springs.

Test drilling also should be done to determine the nature of occurrence of the salt water. For example, if the body of salt water is part of an artesian system, the area of recharge and the path of the ground water may be determined.

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[Major references are in italic]