PROJECTED EFFECTS OF PROPOSED SALINITY-CONTROL PROJECTS ON SHALLOW GROUND WATER--PRELIMINARY RESULTS FOR THE UPPER BRAZOS RIVER BASIN, TEXAS

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METRIC CONVERSIONS

Most units of measurement used in this report are inch-pound units. For those readers interested in using the metric system, the inch-pound units may be converted to metric units by the following factors:

From	Multiply by	To obtain
acre-foot	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.189	meter per kilometer
foot per year	0.3048	meter per year
inch	25.4	millimeter
mile	1.609	kilometer
square mile	2.590	square kilometer
ton	0.9072	megagram

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "mean sea level."

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SUMMARY

As part of the plan to control the natural salt pollution in the upper Brazos River basin of Texas, the U.S. Army Corps of Engineers recommended construction of three impoundment and retention reservoirs. In connection with the proposed reservoirs, the U.S. Geological Survey was requested to define the existing ground-water conditions in the shallow ground-water system of the area and to project the post-construction effects of the reservoirs on the shallow aquifer, especially in relation to aquifer-head changes but also with respect to possible changes in the chemical quality of the ground water.

The Corps of Engineers' plan includes a total impoundment reservoir (Kiowa Peak Lake on North Croton Creek) with more than 170,000 acre-feet of storage at the 100-year average pool altitude of 1,550 feet. Croton Lake (23,000 acre-feet of storage at the 100-year average pool altitude of 1,760 feet) on Croton Creek and Dove Lake (no permanent storage) on Salt Croton Creek are projected to hold salt water for transfer to the large Kiowa Peak Lake.

The aquifer in the project area is a shallow water-table system with relatively fresh water (calcium sulfate type), in comparison to the saline streamflow, and contains 2,000 to 5,000 milligrams per liter of dissolved solids. The aquifer consists of Permian rocks with very small permeability and is separated from an even less permeable and deeper brine system (sodium chloride type of up to 200,000 milligrams per liter of dissolved solids) by a thin transition zone. Small quantities of infiltration from precipitation in the drainage area constitute the recharge to the aquifer. Discharge from the aquifer consists of the base flow along creeks; well discharge is negligible.

Two-dimensional digital-computer models were developed for aquifer simulation of steady and transient conditions in which the density effects of salt water are considered. The models were used to project the effects of the 100-year impoundment of salt water in Kiowa Peak Lake and Croton Lake on the fresh-water system. Rises in aquifer head of 10 to 50 feet are projected only for areas near each dam and along each lake shoreline. The maximum migration of salt water downstream from each dam is projected to be about 1 mile. The modeling efforts in this study did not include the effects of hydrodynamic dispersion nor consideration of possible changes in the hydraulic conductivity of the aquifer due to physical and chemical interactions in the salt-water and fresh-water environments.

INTRODUCTION

The Brazos River is a major source of water in Texas; however, during base-flow conditions, the water of the upper Brazos River basin contains excessive concentrations of chloride and sulfate. A large part of this upper-basin water is impounded in Possum Kingdom Reservoir (fig. 1), which is used to supply water for irrigation and industrial needs. An average daily load of 3,440 tons of dissolved solids, which includes 1,250 tons of chloride and 760 tons of sulfate, was transported into the reservoir by the Brazos River during water years 1957-66 (Rawson, Flugrath, and Hughes, 1968).

The sources of the salts are the natural brine springs and seeps issuing from Permian formations into streams tributary to the upper Brazos River, principally the Salt Fork Brazos River (fig. 1). The springs and seeps in Croton and Salt Croton Creeks, tributaries of the Salt Fork Brazos River, contribute most of the salt load. The discharge-weighted average chloride concentration of water in Croton Creek on a long-term basis is more than 3,000 mg/L (milligrams per liter), and that for water in Salt Croton Creek is more than 33,000 mg/L. Another tributary, the North Croton Creek, contributes some salt but is of considerable importance mainly because its drainage area has been included in a project recommended by the U.S. Army Corps of Engineers to control the natural salt pollution. The discharge-weighted average chloride concentration of water in North Croton Creek on a long-term basis is nearly 800 mg/L.

Three total impoundment and retention reservoirs, which have no provisions for controlled releases, are recommended in the Corps of Engineers plan for controlling the natural salt pollution in the area. The controlling method is disposal or retention of the brines through storage and evaporation. The three proposed reservoirs (Kiowa Peak Lake, Dove Lake, and Croton Lake) are interconnected by pipeline and are shown in figure 1. The recommended plan is the result of feasibility studies that included consideration of various alternative solutions to the problem (U.S. Army Corps of Engineers, 1973). In connection with the plan, the Corps of Engineers requested the U.S. Geological Survey to study the effects of the proposed reservoirs on the shallow aquifer in the vicinity of each reservoir. Specific recommendations included the use of digital-computer models as part of the study.

Purpose and Scope

The purpose of this report is to present preliminary results of the study on: (1) The existing ground-water conditions in the shallow aquifer systems in the project area and (2) the projection of the post-construction effects of the proposed reservoirs on the shallow aquifers, especially in relation to changes in aquifer head but also with respect to possible changes in the chemical quality of the ground water.

The data used to determine the existing ground-water conditions were obtained from various sources. The Geological Survey drilled 34 test wells in the project area in connection with a study by Stevens and Hardt (1965). Geophysical logs from these test wells and from more than 100 oil-company stratigraphic test holes were interpreted by Keys and McCary (1973). The Corps of Engineers provided test-hole data in connection with the foundation drilling

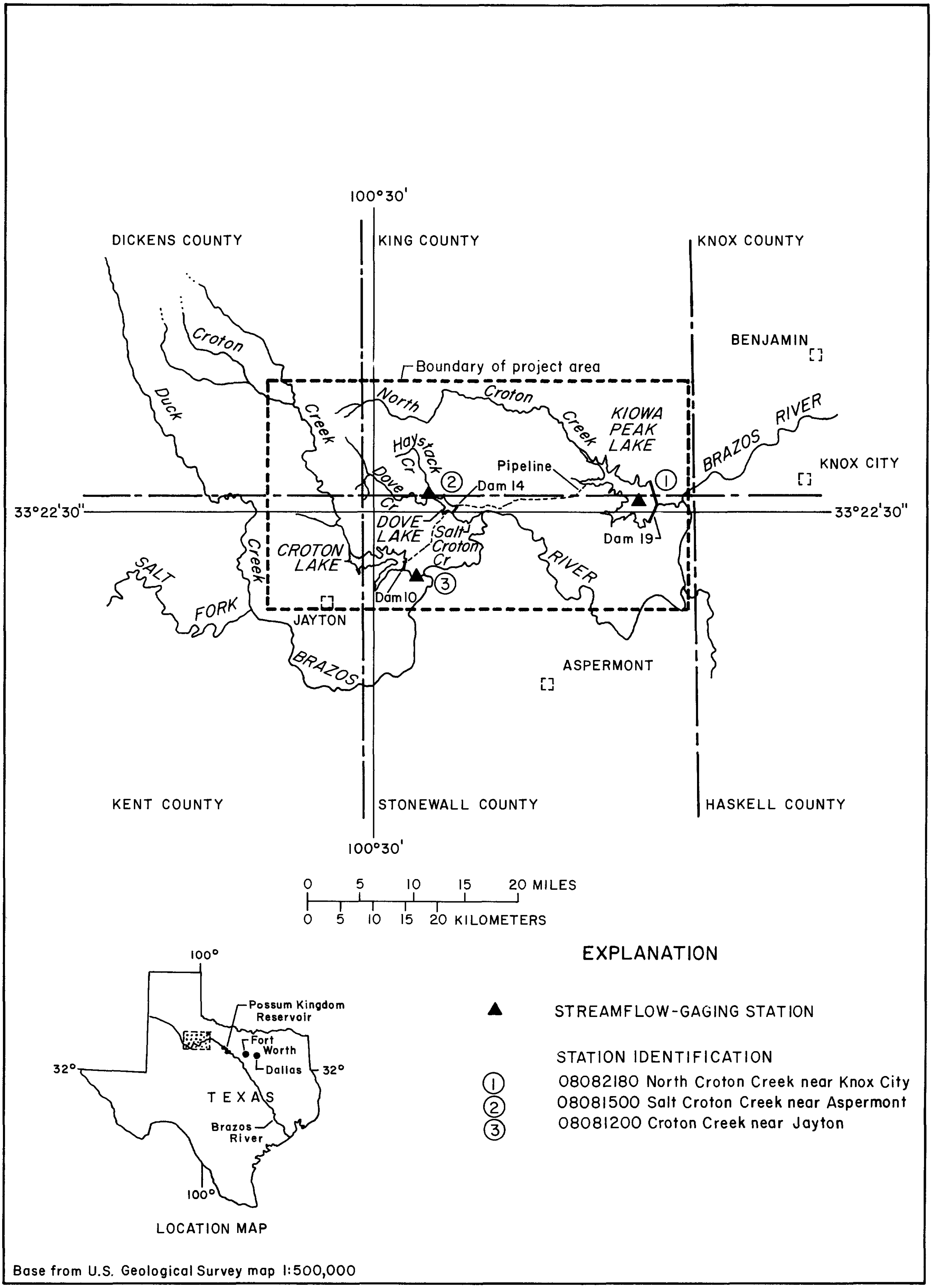

Figure 1.–Location of project area and proposed reservoirs

program at dam sites 10, 14, and 19 (fig. 1). Geophysical logs were obtained from 43 test wells drilled by the Corps of Engineers in the North Croton Creek area; the test wells also were used for measuring water levels and for sampling water for chemical analysis. Approximately 100 domestic and stock wells in the project area also were used for water-level measurement and sampling of water for chemical analysis. Useful information on the geology and hydrology of the area was derived from Blank (1955), Mason and Johnson and Associates (1955), McMillion (1958), Baker, Hughes, and Yost (1964), and Rawson, Flugrath, and Hughes (1968).

The modeling procedure used to simulate the flow of fresh ground water is the two-dimensional finite-difference method developed by the Geological Survey (Trescott, Pinder, and Larson, 1976). The effects of a salt-water reservoir on ground water were approximated through the use of a finite-difference modeling procedure for simulating areal flow of salt water and fresh water separated by a sharp interface (Mercer, Larson, and Faust, 1980a). The density effect of salt water is incorporated in the modeling procedure, but the effects of hydrodynamic dispersion are neglected with the assumption of a sharp interface. Therefore, predictions related to changes in the chemical quality of water are limited to generalizations.

The projections of the post-construction effects on the shallow ground water have been limited to Kiowa Peak Lake and Croton Lake because only these lakes will have permanent-storage facilities. The projections also are limited to simulations of long-term (100-year) average stresses of reservoir storage and salt-water density and viscosity. Physical and chemical changes in the reservoir and aquifer environments may affect the hydraulic conductivity of the aquifer; results of the projections do not reflect these possible effects.

Plan To Control Natural Salt Pollution

The plan proposed by the Corps of Engineers to control the natural salt pollution in the upper Brazos River basin includes three total retention dams and connecting pipelines. Dam 19 (Kiowa Peak Lake, fig. 1) will be located on North Croton Creek 5.4 river miles upstream from its junction with the Brazos River. The earthen embankment stucture is designed to impound all runoff originating upstream from the dam plus 29 ft^3/s of brine transferred from Dams 10 and 14 (fig. 1). Reservoir storage at the projected top of the brine pool (altitude of 1,583 feet above NGVD of 1929) is more than 400,000 acre-feet. The average pool altitude estimated for the first 100 years of impoundment is 1,550 feet, a level designed to store more than 170,000 acre-feet. A cut-off trench along the axis of the dam has been designed to prevent seepage under the dam.

Dam 10 (Croton Lake) will be located on Croton Creek 3.3 river miles upstream from its junction with the Salt Fork of the Brazos River (fig. 1). It is an earthen embankment designed to impound temporarily all runoff originating in the drainage area upstream from the dam, and a flow of 11 ft^3/s will be pumped from the impoundment through a subsurface pipeline to Kiowa Peak Lake whenever there is water in storage. The reservoir level is expected to fluctuate greatly, but the long-term (100-year) average pool altitude is estimated to be 1,760 feet, at which level the reservoir storage is about 23,000 acre-feet.

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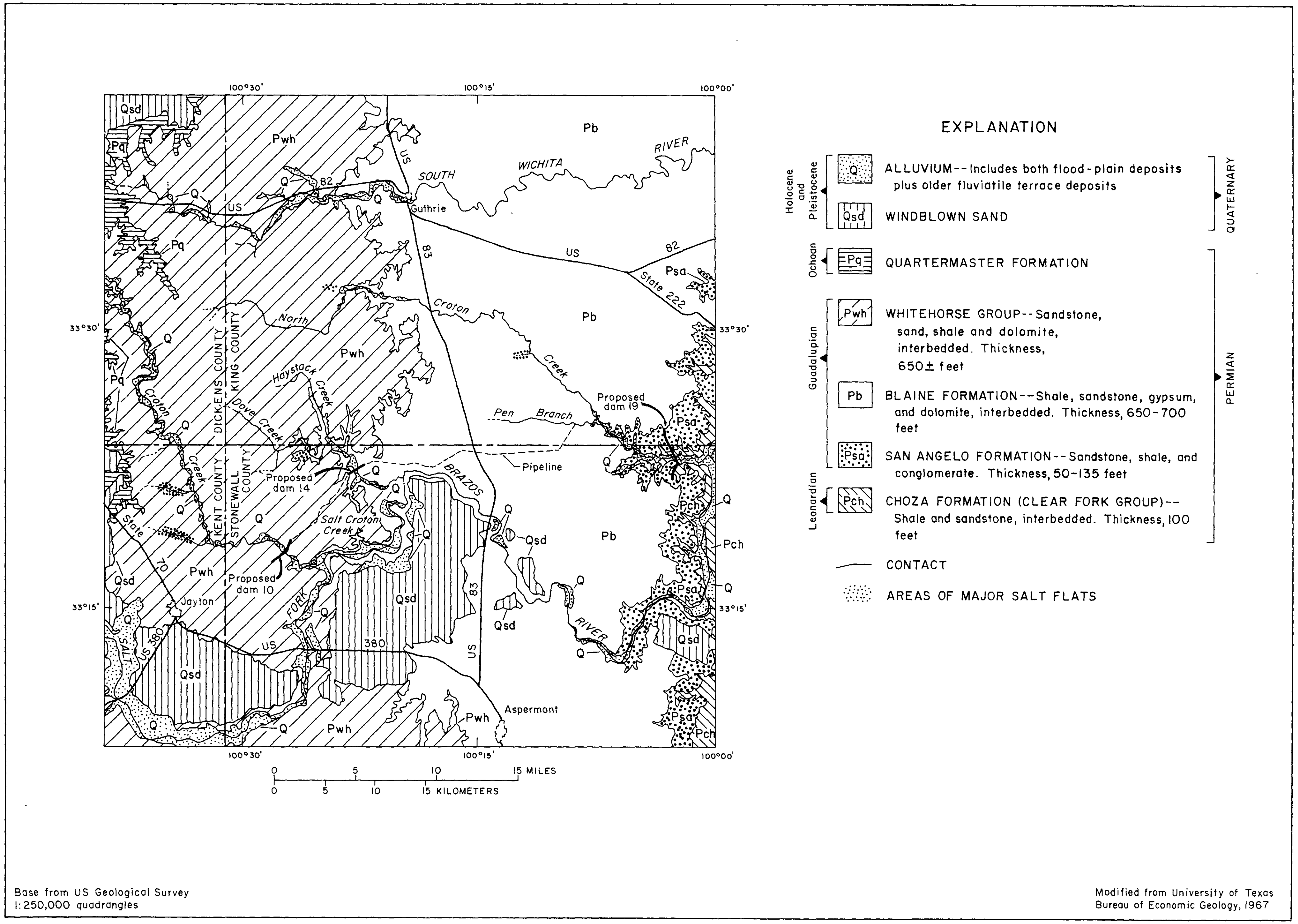


Figure 2.-Geology of the project area

Dam 14 (Dove Lake) will be located on Salt Croton Creek 5.6 river miles upstream from its junction with the Salt Fork of the Brazos River. The earthen structure is designed to impound all runoff temporarily, until it can be transported by pipeline for storage in Kiowa Peak Lake. The U.S. Army Corps of Engineers (1973) has estimated a long-term average transfer of 18 ft^3/s to Kiowa Peak Lake. Dove Lake will have no permanent storage.

All three proposed reservoirs will be located downstream from natural brine springs, the major sources of salinity in the basin. Dam 19 (Kiowa Peak Lake) purposely will be located in an area underlain by fine-grained sandstone and shale (Early Permian age) that contain very little permeability. The two other small reservoirs will be located in areas where the underlying fine-grained sandstone and shale are interbedded with dolomite and gypsum formations that contain extensive openings related to zones of solution, particularly in the gypsum beds. Dam 14 (Dove Lake) in particular has been excluded from permanent storage because of expected inundation of a salt flat (discharge point of brine) upstream from the dam site. Therefore, Croton Lake and Dove Lake have been designed mainly to hold the brine for transfer to the large Kiowa Peak Lake; Croton Lake will have some long-term storage capability. In effect, the Kiowa Peak Lake will become the central area in the basin for the disposal of the natural brines through the process of storage and evaporation. The Corps of Engineers has estimated the duration of the project to be 100 years and has found it to be the most acceptable plan of the many alternatives that were considered (U.S. Army Corps of Engineers, 1973).

Projecting the effects of the proposed Kiowa Peak Lake on the shallow aquifer is of paramount importance because of the impoundment of significant quantities of brine in the reservoir and the need to determine the effectiveness of the reservoir for controlling brine contributions to the aquifer and eventually to the runoff downstream from the reservoir. Projections were made for the proposed Croton Lake; none were made for Dove Lake because no permanent impoundment is planned.

EXISTING FRESH GROUND WATER

The only relatively fresh ground water in the project area is found in the shallow water-table system and contains 2,000 to 5,000 mg/L of dissolved solids. The ground water is termed "fresh" in relation to the widespread sodium chloride brine confined in deeper Permian rocks (up to 200,000 mg/l of dissolved solids), the source of the salt springs and seeps in the area. Very small quantities of the fresh water in the project area are withdrawn from small-capacity wells and used for domestic and stock purposes.

The fresh-water aquifer consists of rocks of Permian age. The only younger materials in the area are thin floodplain and fluviatile-terrace deposits, and windblown sand, which generally are not hydrologically significant in the project area. The area's surficial geology, derived from a geologic atlas developed by the University of Texas, Bureau of Economic Geology (1967) is shown in figure 2. Except for the Ochoan Quartermaster Formation, the Permian strata in figure 2 are very significant to the project's ground-water study. For purposes of this report, the Whitehorse Sandstone and Cloud Chief Gypsum of the Guadalupian Series, as used in the geologic atlas (University of Texas, 82-908

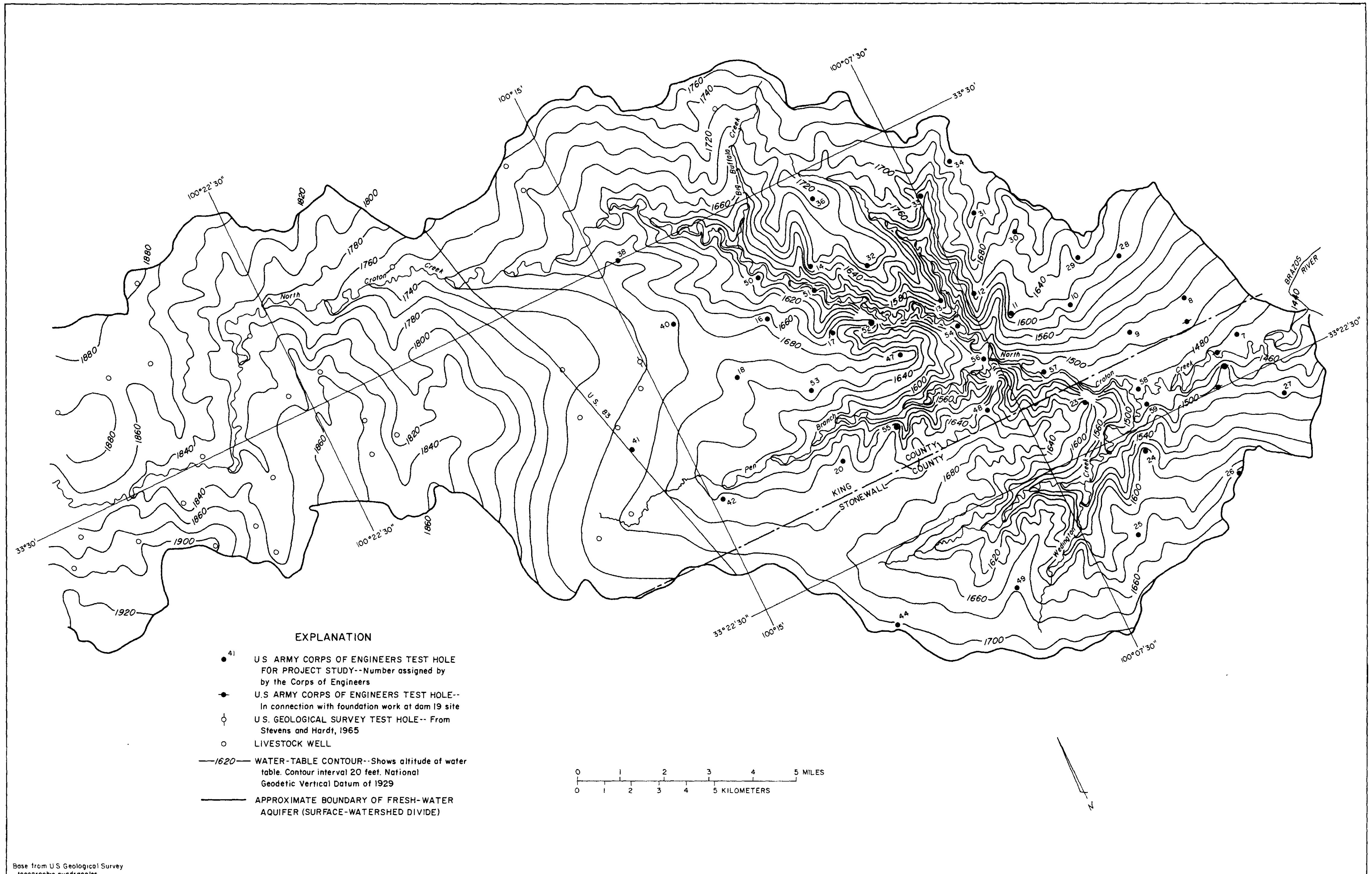


Figure 3.-Average altitude of the water table in the fresh-water aquifer, North Croton Creek area

Bureau of Economic Geology, 1967), will be referred to as the Whitehorse Group, a designation also used by McMillion (1958) and Baker, Hughes, and Yost (1964). McMillion (1958) refers to the Blaine Formation and the San Angelo Formation as the El Reno Group. Baker, Hughes, and Yost (1964) make reference to the same strata as the Pease River Group (north Texas designation). The Choza Formation is the upper part of the Clear Fork Group.

The Permian formations dip westward at about 26 ft/mi according to Baker, Hughes, and Yost (1964). Streams generally flow east or southeast; the resulting topography consists of rolling hills, canyons, and gullies--all products of the differential erosion within the Permian strata. A unique topographic feature in the project area is the salt flat, the discharge area of the brine. (See fig. 2 for major salt flats.) Additional information related to ground-water geology of the project area may be found in McMillion (1958) and in Baker, Hughes, and Yost (1964).

North Croton Creek Area

North Croton Creek flows across the oldest Permian formations in the project area (fig. 2). The drainage area upstream from streamflow station 1 (fig. 1) is 250 square miles, and the average discharge for water years 1966-77 was about 15 ft^3/s (U.S. Geological Survey, 1969a, 1972a, 1973a, 1974a, 1975a,b, 1976-78). The discharge-weighted average chloride concentration of North Croton Creek water at the streamflow station for this period was more than 785 mg/L (U.S. Geological Survey, 1965-68, 1969b, 1970-71, 1972b, 1973b, 1974b, 1975c, 1976-78). This stream contributes about 4 percent of the chloride load reaching Possum Kingdom Reservoir (fig.1). The proposed site for Dam 19 is located in strata of the Choza Formation and San Angelo Formation. The part of the Choza containing fresh water is a shale that is interbedded with sandstone. The Choza Formation has no known system of extensive fractures. The San Angelo Formation is a massive sandstone that is interbedded with shale and conglomerate. The San Angelo Formation also has no extensive fracture system. The Blaine Formation crops out at higher altitudes generally west of the dam; the fresh-water aquifer in the Blaine consists of shale and sandstone, interbedded with gypsum. Farther to the west, some gypsum beds may become massive, and dolomite also may be present. The Whitehorse Group (fig. 2) in the western part of the North Croton Creek area consists of interbedded sandstone, sand, shale, gypsum, and dolomite. Some of the gypsum beds have extensive systems of solution openings.

The water-table contours of the fresh-water aquifer and the location of test holes and wells in the North Croton Creek area are shown in figure 3. Delineation of water-table contours is based on: (1) Average water levels in wells used for control, mainly test holes drilled by the Corps of Engineers for this project (table 1), (2) stage estimates of North Croton Creek, (3) altitude of small springs and seeps along creeks tributary to North Croton Creek, and (4) topographic maps (7-1/2-minute) published by the Geological Survey.

The slope of the water table generally is from west to east; in detail it is from the high ridges and hills to the low areas along the creeks. The steep slopes near North Croton Creek and its tributaries are due to the large amount of topographic relief in these areas plus the minimal transmissive character of the aquifer material. The contours indicate a range in altitude from about 1,920 feet above NGVD of 1929 in the extreme northwestern part of figure 3 to about 1,440 feet near the junction of North Croton Creek and the Brazos River. The water table appears to be a modified image of the land surface, and the shallow ground water is inferred to move from topographically high areas to the lower creek valleys.

Recharge to the fresh-water aquifer is the quantity of water percolating to the water table from precipitation throughout the watershed. The total discharge from the aquifer is the springflow and seeps along the major creeks and tributaries, plus an unknown quantity of evapotranspiration, plus the quantity withdrawn through wells. The discharge from wells in the project area is assumed to be negligible. The fresh-water springflow and seeps in the North Croton Creek and its tributaries mix with the brine-system discharge along the creek beds. The average rate of this fresh-water base flow to the creeks is assumed to be the average accretion to the aquifer. Accretion is the net rate at which water is gained or lost vertically through the aquifer surface in response to external forces (Stallman, 1956). Records from the streamflow station North Croton Creek near Knox City (station 1, fig. 1) were used to derive an average rate of base flow of 2 ft^3/s (U.S. Geological Survey, 1969a, 1972a, 1973a, 1974a, 1975a,b, 1976-78). More than 90 percent of this base flow is estimated to be contributed by the fresh-water aquifer; the assumed average accretion is slightly more than 1.8 ft^3/s, or less than 0.1 inch per year over the watershed (250 square miles). Average precipitation at Aspermont is slightly more than 22 inches per year (U.S. Department of Commerce, 1978); this general scarcity of rainfall, high evapotranspiration rates, and the small permeability of the Permian strata are the main reasons for the small accretion.

The base of the fresh-water aquifer is a thin zone of transition, which can be approximated by a surface, between the fresh water and the deeper brine. This zone, which Stevens and Hardt (1965, p. 7-8) called the "brine-freshwater interface", has been found by test drilling and through interpretation of borehole geophysical logs (Keys and McCary, 1973). The water in the fresh-water aquifer is a calcium sulfate type that has a dissolved-solids concentration ranging between 2,000 and 5,000 mg/L. Stevens and Hardt (1965) attribute this general chemical composition to solution of gypsiferous material at shallow depths. The deeper brine-saturated rocks contain halite, and water from these rocks is a sodium chloride type, with dissolved solids of more than 200,000 mg/L (Baker, Hughes, and Yost, 1964, p. 58). (See table 2 for the chemical analyses of water samples from selected test holes in the North Croton Creek area.) An important factor indicative of the hydraulic separation of the two systems is the presence of halite in the brine rocks in an environment described by Stevens and Hardt (1965) as conducive to very small permeability and small halite-solution rates. Halite occurs in the unweathered and unflushed brine-rock system, which also is much less permeable than the flushed fresh-water system. Additional information regarding the "interface" may be found in Stevens and Hardt (1965), Keys and McCary (1973), and Zohdy and Jackson (1973). The base of the fresh-water aquifer is assumed in this report to be represented by this "interface", which constitutes a hydraulic boundary separating the fresh water from the brine system.

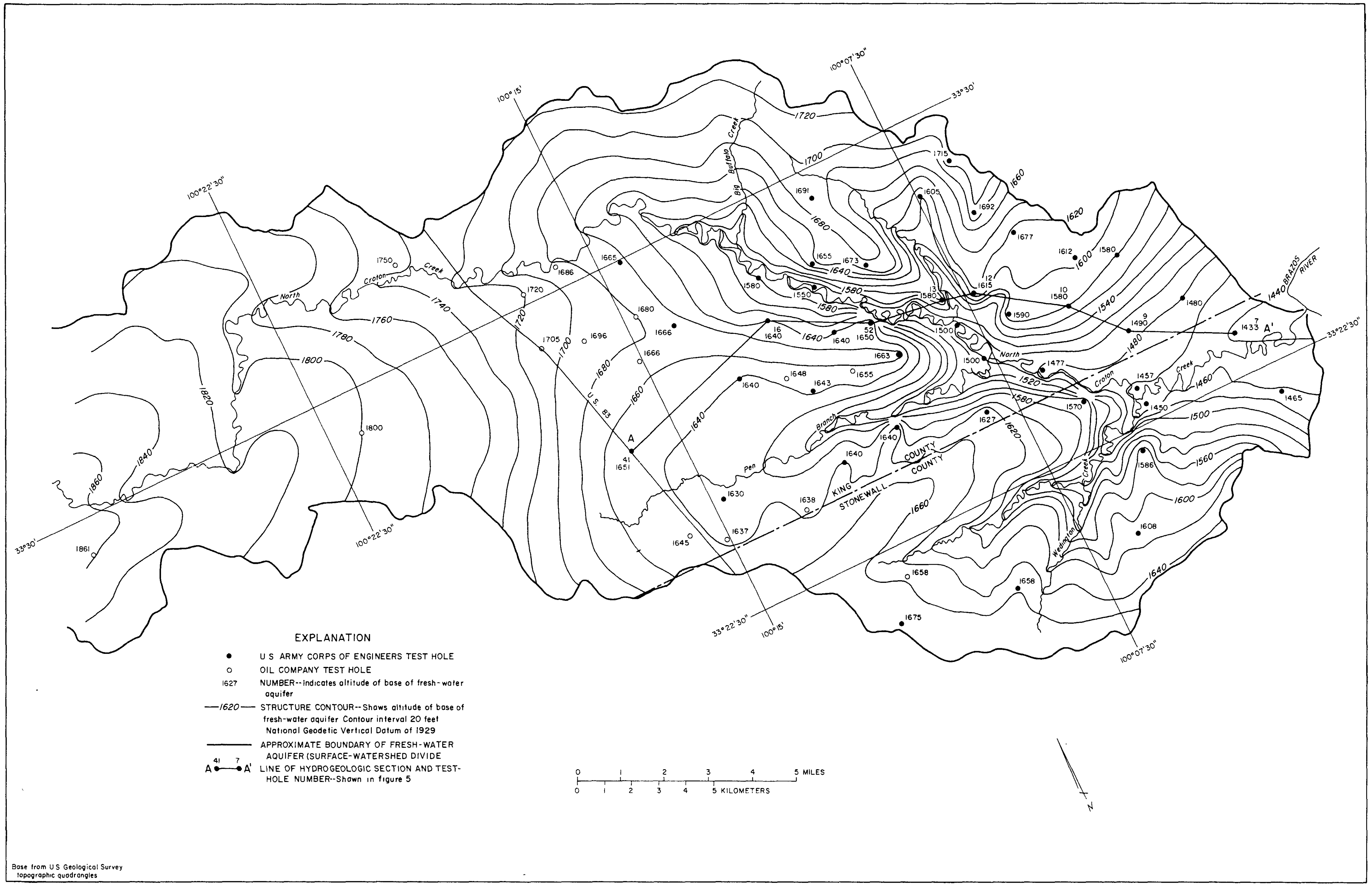


Figure 4.-Altitude of the base of the fresh-water aquifer, North Croton Creek area

The altitude of the base of the fresh-water aquifer in the North Croton Creek area is shown in figure 4. The delineation is based on the interpretation of test-hole data from the Corps of Engineers and commercial oil companies (table 1). Specific-conductance measurements of the drilling fluid were made by the Corps of Engineers in most of the test holes. These data provided a good measure of the "interface" position as it was penetrated during drilling. East-west section A-A', which indicates the approximate thickness of the fresh-water aquifer, is shown in figure 5. The specific-conductance traces are used to indicate the relatively sharp breaks in relation to the large differences in the chemical quality of the water in the fresh and brine systems. The absolute values of specific conductance reflect a mixture of the original drilling fluid and the ground water. The results for areas near North Croton Creek indicate thinning of the fresh-water system toward the areas of discharge.

The Corps of Engineers cored shallow test holes near observation wells 8 and 13 (table 1). Core samples representative of the San Angelo Formation and the Blaine Formation were analyzed in the laboratory for permeability. Permeability, the transmissive property of a rock or soil, was converted to hydraulic conductivity, a term used to reflect not only the permeability of the rock but also the fluid properties of the ground water at temperatures normally found in this environment. Values of hydraulic conductivity determined in the laboratory from cores of the sandstone in the San Angelo ranged from 0.002 to 0.009 ft/d and averaged about 0.005 ft/d; those for the shale in the Blaine averaged about 10^{-8} ft/d (U.S. Army Corps of Engineers, written commun., 1979). Results of several aquifer tests using Geological Survey test wells in the vicinity of Jayton indiçated an average value of about 0.5 ft/d for hydraulic conductivity in the fresh-water aquifer of the Whitehorse Group (P. R. Stevens, U.S. Geological Survey, written commun., 1980). Results of laboratory analysis of core samples representative of the brine rocks in the same area indicated average hydraulic-conductivity values that are about 100 times smaller. Hogan and Sipes (1966, table 1) reported laboratory values for horizontal hydraulic conductivity (converted from reported permeability) in the Permian basin of Texas and New Mexico, as follows: 0.002 to 0.07 ft/d for cores from the Artesia Group (equivalent to the Whitehorse Group); 0.0005 to 1.2 ft/d for cores from the San Andres Limestone (equivalent to the Blaine Formation, San Angelo Formation, and Clear Fork Group); 0.0005 to 0.306 ft/d for cores from the Glorietta Sandstone (equivalent to the San Angelo Formation), and 0.0002 to 0.06 ft/d for cores from the Clear Fork Group. These determinations indicate that values of hydraulic conductivity in the Permian rocks of the area generally are very small, from very small fractions of a foot per day to perhaps 1 or 2 ft/d. The values for the shales are extremely small, probably 10^{-6} to 10^{-8} ft/d.

Croton Creek Area

Croton Creek drains the western part of the project area and cuts across the entire outcrop of the Whitehorse Group (fig. 2). The proposed site for Dam 10 is located downstream from the two major salt flats on tributaries of Croton Creek (fig. 2). The drainage area upstream from streamflow station 3 (fig. 1) is 290 square miles, and the average discharge for water years 1960-78 was almost 15 ft^3/s; the average base flow was about 1.4 ft^3/s, 90 percent of which is estimated to have been contributed by the fresh-water aquifer (U.S.

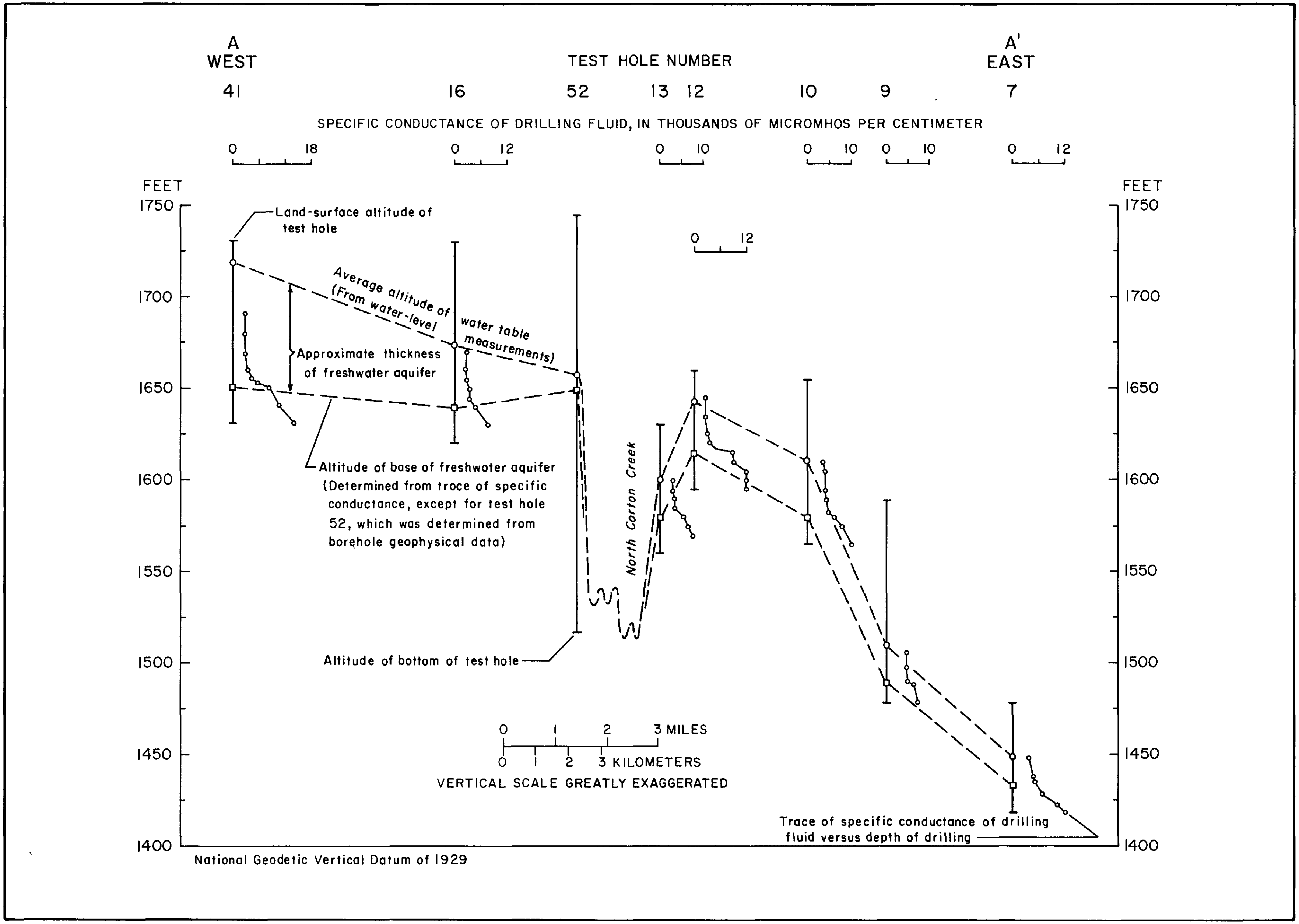


Figure 5 East-west section A-A' through North Croton Creek area showing approximate thickness of fresh-water aquifer

Geological Survey, 1960, 1969a, 1972a, 1973a, 1974a, 1975a,b, 1976-78). The discharge-weighted average chloride concentration of Croton Creek water at the station for water years 1966-78 was about 3,400 mg/L (U.S. Geological Survey, 1965-68, 1969b, 1970-71, 1972b, 1973b, 1974b, 1975c, 1976-78). Croton Creek contributes about 6 percent of the chloride load reaching Possum Kingdom Reservoir.

The Whitehorse Group consists of silty sandstone, interbedded with gypsum, dolomite, and some shale. According to McMillion (1958), who summarizes the correlation of the different formations and marker beds in the Whitehorse Group, the circulation of ground water is controlled by the geologic structure and the stratigraphy. Local inconsistencies within the regional structural pattern indicate slumpage due to solution of gypsum. Systems of solution channels are extensive in some gypsum beds.

The configuration of the water table of the fresh-water aquifer in the Croton Creek area is shown in figure 6. The contours are based on: (1) Water levels in wells (private domestic and stock wells and Geological Survey and Corps of Engineers test holes); (2) stage estimates of Croton Creek; (3) altitude of small springs and seeps tributary to Croton Creek; and (4) topographic maps (7-1/2-minute) published by the Geological Survey. The water-table contours range in altitude from about 2,000 feet above NGVD of 1929 in the northwestern area of figure 6 to about 1,700 feet near the junction of Croton Creek with the Salt Fork Brazos River. Recharge to the aquifer is from precipitation throughout the watershed, and discharge is along the major creeks and tributaries. The fresh-water discharge mixes with the brine-system discharge along Croton Creek and its major tributaries. The shallow ground water is inferred to move perpendicular to the contours from topographic highs to the lower creek areas. The average annual accretion, determined from records of streamflow for station 3 (fig. 1) and estimates of fresh-water discharge, is less than 0.1 inch.

The altitude of the base of the fresh-water aquifer in the Croton Creek area is shown in figure 7. Data for this illustration were derived from interpretation of oil-company and Geological Survey test-hole information (Stevens and Hardt, 1965). Comparison of figure 6 with figure 7 indicates a general thinning of the fresh-water body toward the major discharge points, which are Croton Creek, Short Croton Creek, and Hot Springs Canyon. The fresh-water aquifer is practically nonexistent at the discharge points of the deeper brines, namely the salt-flat areas at Short Croton Creek and Hot Springs Canyon. The thickness of the aquifer in some of the topographically high areas in the western part of the Croton Creek area is about 200 feet; the thickness in most of the Croton Creek area, however, ranges from about zero at the salt flats to about 150 feet. East-west section B-B' (modified from Stevens and Hardt, 1965, p. 11), indicates the water table, the base of the fresh-water aquifer ("interface" line), and some of the subsurface geology (fig. 8). Location of section B-B' is shown in figure 7.

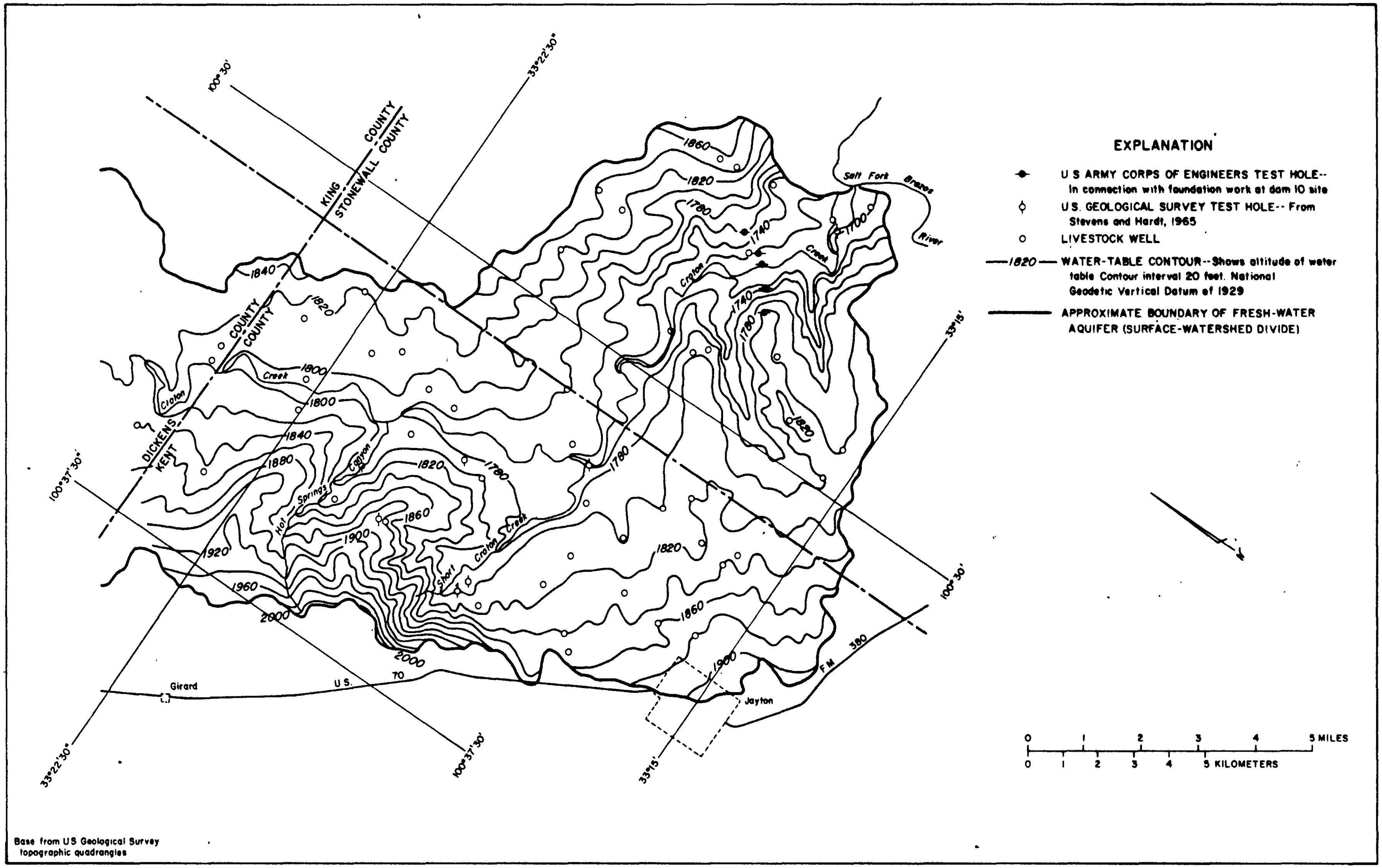


Figure 6.-Average altitude of the water table in the fresh-water aquifer, Croton Creek area

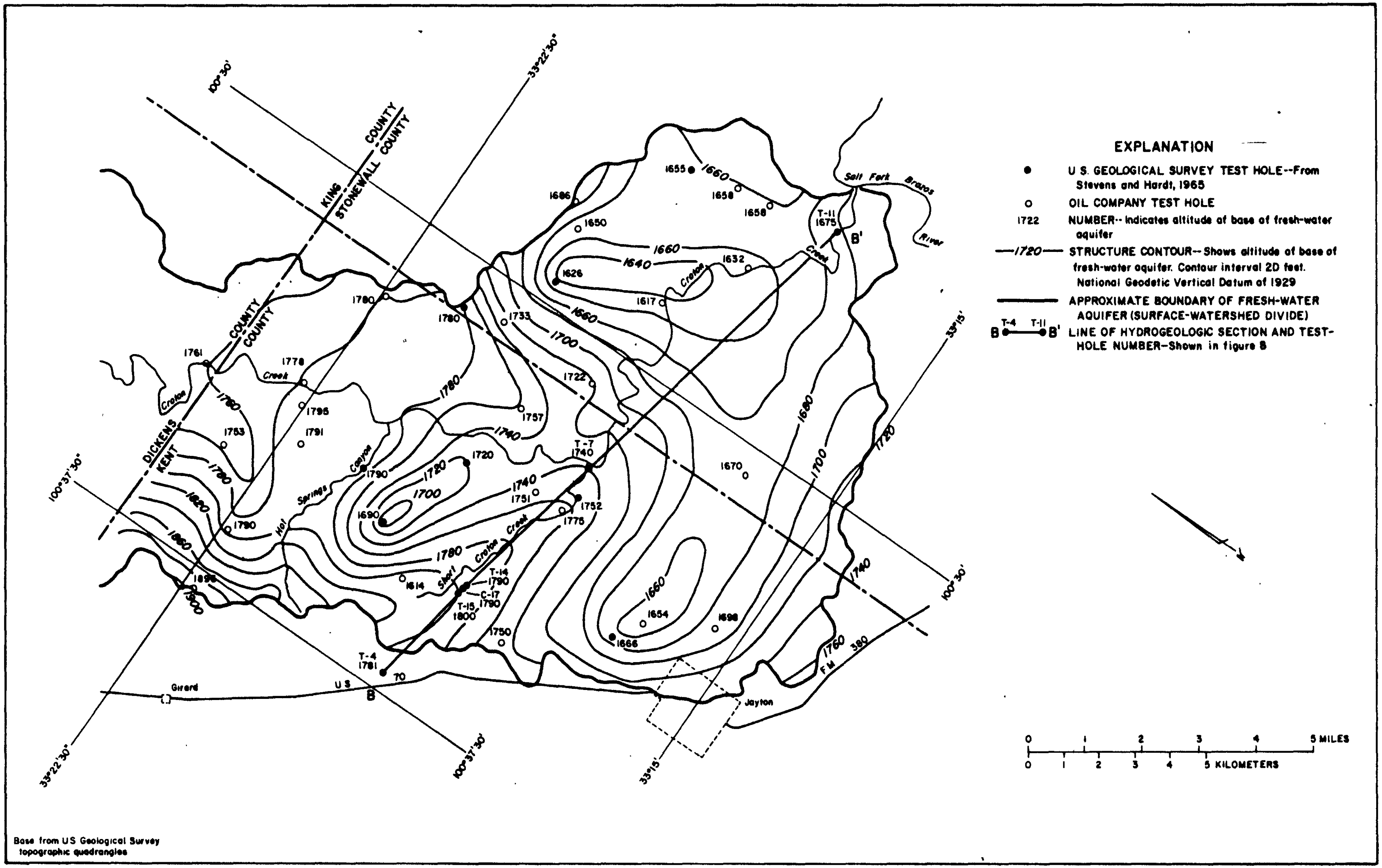
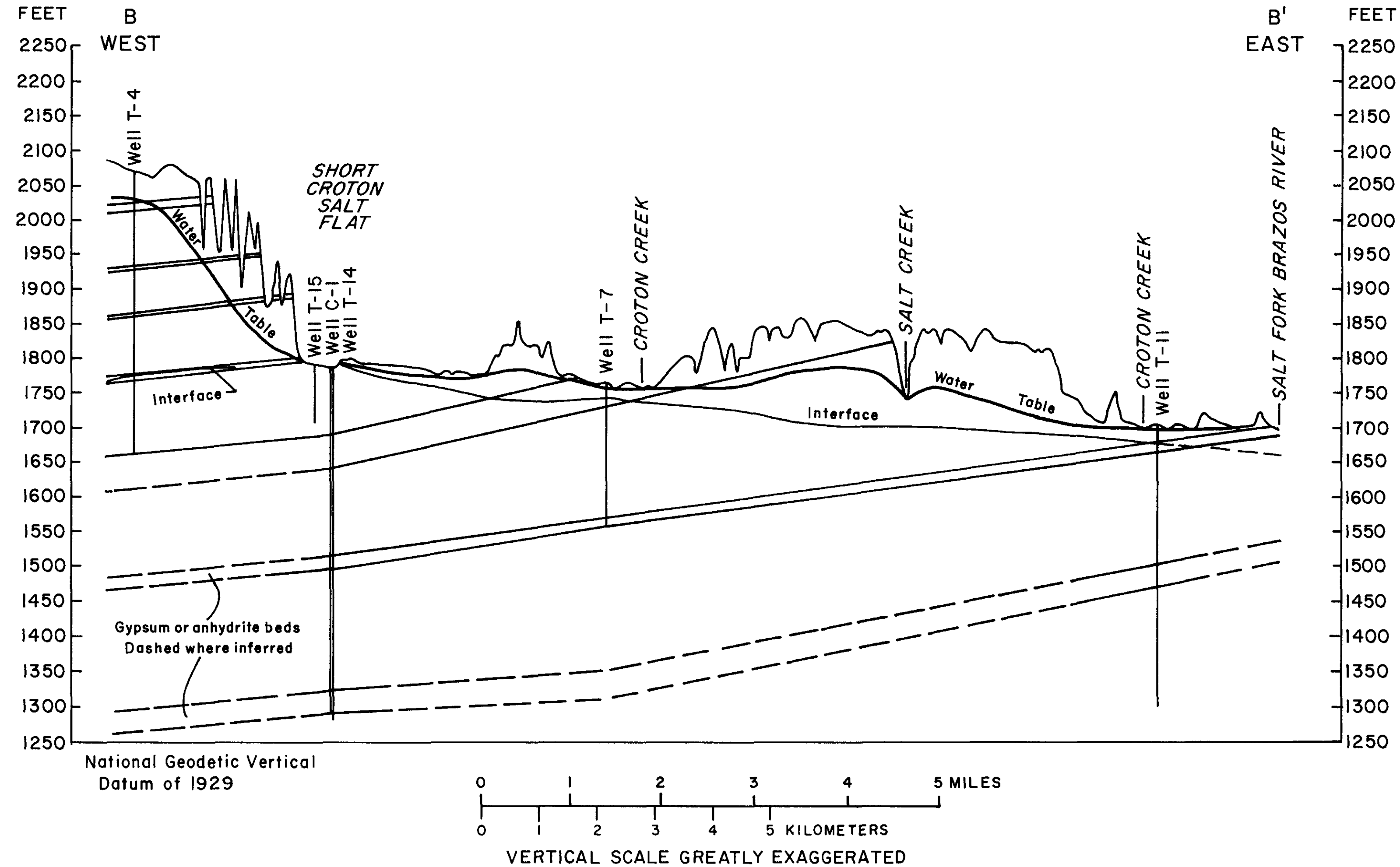


Figure 7.-Altitude of base of the fresh-water aquifer, Croton Creek area



Modified from Stevens and Hardt (1965)

Figure 8.-East-west section B-B' through Croton Creek area showing geologic and hydrologic relations

Salt Croton Creek Area

The Salt Croton Creek area is the small drainage area in the vicinity of proposed Dam 14 (Dove Lake), located on Salt Croton Creek downstream from the confluence of its tributaries, Dove Creek and Haystack Creek (fig. 2). A large salt flat is located along Dove Creek, and smaller ones are found along Haystack Creek. The drainage area upstream from streamflow station 2 (fig. 1) is 64 square miles. The average discharge at the station for water years 1957-76 was almost 6 ft^3/s (U.S. Geological Survey, 1960, 1969a, 1972a, 1973a, 1974a, 1975a,b, 1976-78); the base flow was almost 1 ft^3/s, of which less than 50 percent was fresh water. This area contributes about 42 percent of the chloride load at Possum Kingdom Reservoir (U.S. Corps of Engineers, 1973, p. III-22). The discharge-weighted average chloride concentration of Salt Croton Creek water at the station for water years 1969-77 was about 33,200 mg/L (U.S. Geological Survey, 1965-68, 1969b, 1970-71, 1972b, 1973b, 1974b, 1975c, 1976-78).

Dam 14 (Dove Lake) is an important part of the plan to control the natural brine pollution because of the relatively large quantities of brine contributed from the Salt Croton Creek area. A permanent impoundment is not planned for Dove Lake, and the effects of the proposed structure on the fresh-water aquifer are expected to be minimal. Therefore, no projections of these effects were made, and the description of the existing ground-water conditions in the area is limited to generalizations.

The Salt Croton Creek area encompasses the outcrops of the Blaine Formation and the Whitehorse Group (fig. 2). The lithologic character of these units are described by McMillion (1958), Baker, Hughes, and Yost (1964), and elsewhere in this report. Solution openings appear extensive and widespread in the gypsum beds.

A water-table map of the fresh-water aquifer in an area described as the Croton Creek-Salt Croton Creek area is presented by Stevens and Hardt (1965, p. 5). The altitude of the water table in the included Salt Croton Creek area ranges from about 1,640 feet above NGVD of 1929 at the mouth of Salt Croton Creek to about 1,900 feet in the northwestern part of the drainage area. The thickness of the fresh-water aquifer ranges from about zero at the salt flats to about 150 feet in the topographically high area between proposed Dam sites 10 and 14 (Stevens and Hardt, 1965, p. 13), but probably averages less than 50 feet. Recharge to the fresh-water aquifer is from precipitation throughout the watershed; discharge occurs in the topographically low areas along the creeks. The average annual accretion, assumed equivalent to the average base-flow discharge, is less than 0.1 inch.

MODELING PROCEDURES

The Corps of Engineers requested the Geological Survey to develop digital-computer models for projecting the effects of proposed brine reservoirs on existing fresh ground water. The modeling procedures that were used for this purpose include the simulation of ground-water flow in a fresh-water aquifer as well as in a system containing both brine and fresh water.

The modeling procedure used to simulate the flow of fresh ground water is the two-dimensional finite-difference approach developed by the Geological Survey (Trescott, Pinder, and Larson, 1976). This procedure is the basis for the development and calibration of each model that is representative of the fresh-water aquifer in the vicinity of each proposed brine reservoir. The primary purpose of each calibrated model was to determine the distribution of hydraulic conductivity of the aquifer. The main steps include construction of a model that is representative of the fresh-water aquifer through development of parameters derived from the hydrologic data and calibration of the model through a steady-state analysis by adjusting mainly the hydraulic conductivity until the model-computed water table is matched approximately with the water table (from historical data). The principal products of this modeling phase are the adjusted parameters, mainly hydraulic conductivity, that are used to develop the modeling effort to project the effects of the brine reservoirs.

The effects of a brine reservoir on fresh ground water were approximated through the use of a finite-difference modeling procedure for simulating two-dimensional areal flow of salt water and fresh water separated by a sharp interface (Mercer, Larson, and Faust, 1980a). The procedure was adopted for this study mainly because it incorporates the density effect of salt water, which is considerable in the project area. The modeling procedure was used to develop interface models to project the effects of Kiowa Peak and Croton Lakes on the fresh-water aquifer. Items related to the construction of each interface model include: (1) Information from each of the calibrated fresh-water models, (2) additional aquifer parameters essential in the transient analyses, including fluid properties and the initial interface conditions, and (3) the various stresses imposed by the brine reservoirs on the fresh-water aquifer.

The principal stress in each interface model is simulated by using a constant salt-water head that is representative of the hydraulic head throughout the brine-reservoir area. The initial model conditions consist of the distribution of parameters derived from steady-state conditions of the fresh-water system plus the distribution and altitude of the initial interface. The model's simulation period is 100 years, which is the projected duration of the proposed reservoirs. The final products of the projections include the increases of hydraulic head in the fresh-water system and the areal migration of the brine-fresh-water interface throughout the aquifer.

SIMULATION OF FLOW IN FRESH-WATER AQUIFER

Description of Modeling Procedure

Ground-water flow in the modeling procedure used in this study can be simulated in an artesian aquifer, a water-table aquifer, or a combined artesian and water-table aquifer. It is possible to simulate aquifers that are heterogeneous and anisotropic or that have irregular boundaries. Well discharge, constant recharge, leakage, and other features may be incorporated in the basic flow equation. The derivation of the finite-difference approximation to the partial differential equation describing ground-water flow is presented in the report by Trescott, Pinder, and Larson (1976). Also presented is the documentation of the computer programs with three numerical techniques to solve the approximation to the equation, as well as results of numerical experiments and instructions for input operations.

The assumptions and boundary conditions imposed on the aquifer system in the development of the two-dimensional fresh-water models used in the study were as follows:

(1) The movement of water occurs in a single layer comprising the fresh-water aquifer;

(2) The modeled areas were divided into discrete units or cells by a rectangular grid (cell blocks), and the hydrologic properties are constant throughout the area of each cell block;

(3) The aquifer head is simulated at the center (node) of each cell;

(4) The average water levels in wells and the average stream stages represent steady-state conditions in the aquifer-stream system. (The average water level of a well represents the average of the historical measurements in which the seasonal fluctuations are accounted for.);

(5) A model is assumed to be calibrated when the water-table surface, computed through steady-state analysis from an assumed position, matches the water-table surface derived from the average of observed water levels in wells. The principal parameter modeled as a function of aquifer head is the distribution of hydraulic conductivity; and

(6) The types of boundaries used in the simulations are constant head and no flow (zero constant flux or impermeable). For calibration purposes, constant-head boundaries were imposed on North Croton Creek and Croton Creek and parts of their principal tributaries. A no-flow boundary was imposed along the drainage divides within each of the watersheds. A no-flow boundary also was imposed at the base of the fresh-water aquifer; any vertical leakage, upward or downward, is assumed to be negligible. The borders of the models, including the western border located in an area distant from the principal area of interest, have no-flow boundaries for reasons inherent in the computational scheme of the models (Trescott, Pinder, and Larson, 1976, p. 30).

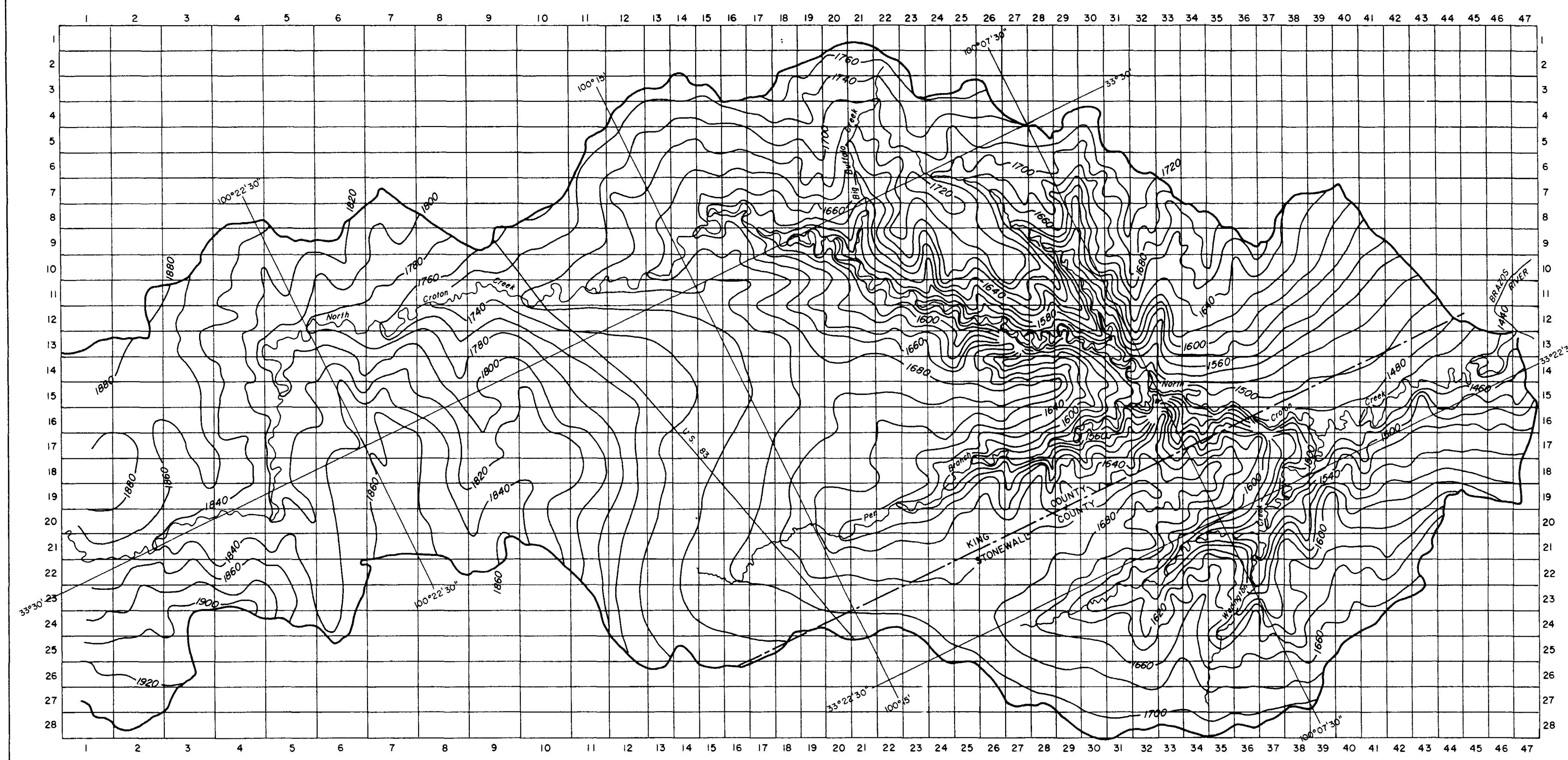
Construction and Calibration of Fresh-Water Models

The construction of the models for the North Croton Creek and Croton Creek areas includes the design of the rectangular-grid systems and the development and input of the aquifer parameters from the basic data. The grid network for the model of the North Croton Creek area consists of a matrix of 28 rows and 47 columns; the Croton Creek area model has a matrix of 22 rows and 27 columns. The nodal spacing for both models is 0.5 mile. The aquifer parameters used in the preparation of the models for the calibration procedure are as follows:

(1) The average altitude of the water table of the fresh-water aquifer in the North Croton Creek area (fig. 3) and in the Croton Creek area (fig. 6);

(2) A constant accretion rate, or a flux throughout each entire watershed; the value used for the North Croton Creek model was 0.08 inch per year, and that for the Croton Creek model was 0.06 inch per year;

(3) Distribution of hydraulic conductivity; the initial range of values assigned to each geologic unit (fig. 2) are: Whitehorse Group - 0.1 to 0.8 ft/d; Blaine Formation - 0.1 to 0.5 ft/d; San Angelo Formation - 0.2 to 1.0 ft/d; and Choza Formation - 1 X 10^{-6} to 5 X 10^{-8} ft/d; and



EXPLANATION

—1620— WATER-TABLE CONTOUR--Shows simulated altitude of water table. Contour interval 20 feet National Geodetic Vertical Datum of 1929

APPROXIMATE BOUNDARY OF FRESH-WATER AQUIFER (SURFACE WATERSHED DIVIDE)

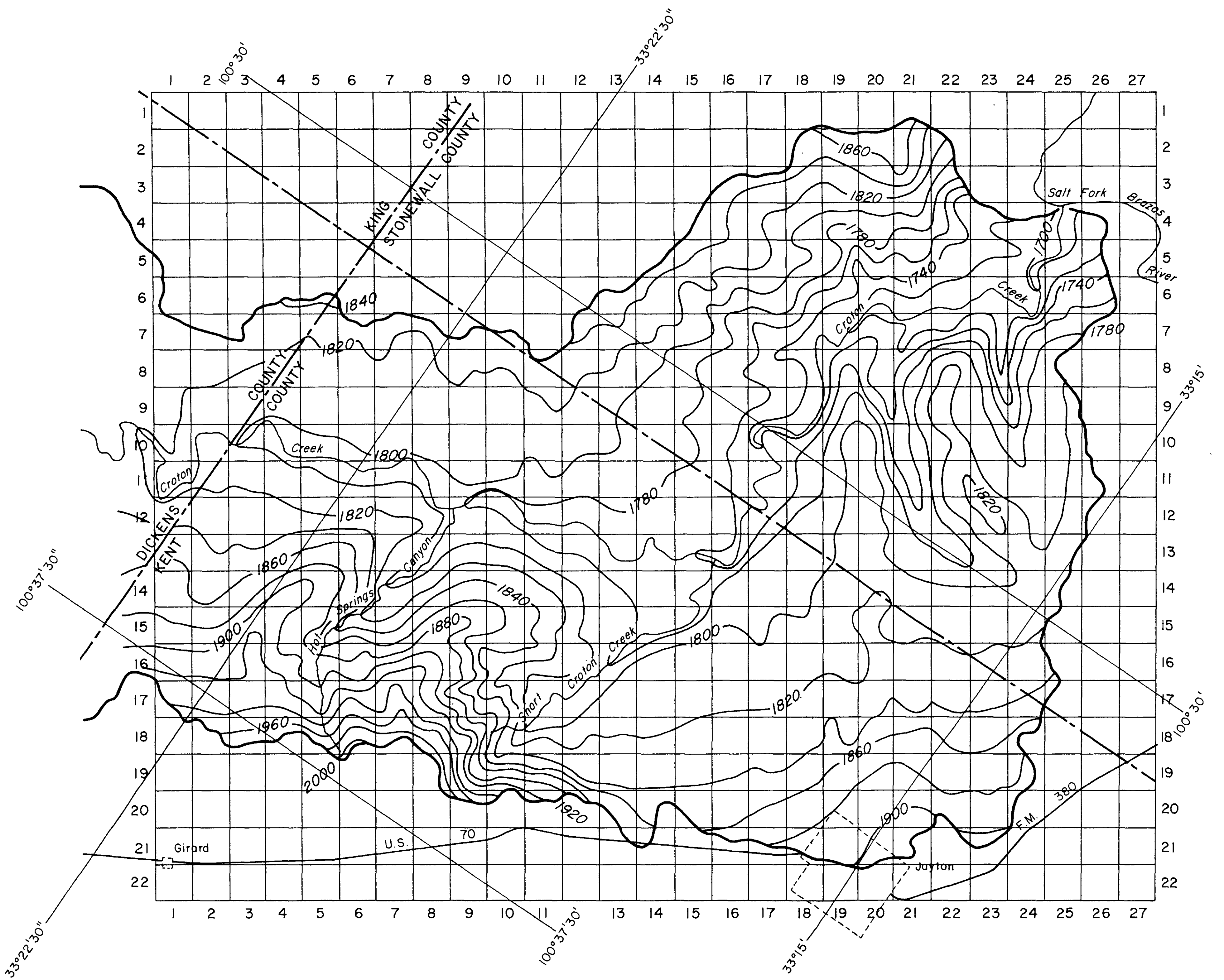
GRID SYSTEM OF DIGITAL MODEL

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

Base from U.S. Geological Survey topographic quadrangles

Figure 9.-Altitude of the water table in the fresh-water aquifer of the North Croton Creek area, as derived from model calibration



EXPLANATION

—1820— WATER-TABLE CONTOUR--Shows simulated altitude of water table. Contour interval 20 feet. National Geodetic Vertical Datum of 1929

APPROXIMATE BOUNDARY OF FRESH-WATER AQUIFER (SURFACE-WATERSHED DIVIDE)

GRID SYSTEM OF DIGITAL MODEL

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

Base from US Geological Survey topographic quadrangles

Figure 10.-Altitude of the water table in the fresh-water aquifer of the Croton Creek area, as derived from model calibration

(4) The altitude of the base of the fresh-water aquifer in the North Croton Creek area (fig. 4) and in the Croton Creek area (fig. 7).

The calibration procedure involved matching a model-computed water-table surface with the observed steady-state, water-table surface. The hydraulic conductivity, within the range assigned to each geologic formation in the fresh-water zone, was the major parameter that was varied during calibration. Accretion values were changed only slightly, about 20 percent for each model. Values of hydraulic conductivity that are representative of the fine-grained Permian formations in the area are difficult to obtain. In spite of the many values of reported hydraulic conductivity that are available for the Permian aquifer systems of the area, the reliability of these values as the basis for an areal distribution of hydraulic conductivity remains questionable. Therefore, determination of a representative distribution of hydraulic conductivity was accomplished through calibration. The other parameters derived from the basic data are assumed to be representative and were not changed during calibration, other than the small changes in accretion.

The altitude of the steady-state, water-table surface as computed during the calibration of the North Croton Creek area model is shown in figure 9. Comparison of figure 9 with figure 3, which is the map showing the observed altitude of the water table, indicates the good similarity accomplished in the calibratation procedure. Actually, the comparison between the "computed" and "observed" heads was made at each cell node of the model grid system, and figure 9 is used only to show the general agreement with figure 3. The difference between the computed and observed heads for about 84 percent of the model cell nodes was less than 3 feet; it was between 3 and 4 feet for about 13 percent of the nodes; and the remainder of the nodes (3 percent) had differences ranging from 4 to 6 feet. The significant factor is that the essential parameter variations were made for only one parameter (hydraulic conductivity), and only within the ranges of values originally assigned. The North Croton Creek model is assumed to be calibrated and to be a reasonable representation of the physical system.

During calibration of the North Croton Creek ground-water flow model, the errors in the mass balance were less than 0.1 percent. The calibrated model was subjected to sensitivity analysis by changing hydraulic conductivity and accretion. A change in hydraulic conductivity of 50 percent produces up to 6 feet of head change. A change in accretion of 50 percent produces only 1 to 2 feet of head change.

The altitude of the steady-state, water-table surface, as computed during calibration of the Croton Creek model, is shown in figure 10. Comparison of figure 6 (altitude of the water table) with figure 10 shows good similarity achieved during calibration. The difference between the computed and observed head values for about 80 percent of the nodes was less than 3 feet; it was between 3 and 4 feet for about 18 percent of the nodes, and the remainder of the nodes (2 percent) had differences ranging between 4 and 6 feet.

In contrast to the North Croton Creek model, calibration was accomplished with changes in hydraulic conductivity that were 10 to 30 times greater (as much as 8 ft/d) than the values originally assigned in some places. The range of the original values was 0.1 to 0.8 ft/d. Consideration was given to changing other parameters, such as accretion and the basic interpretation of figures 6 and 7, in lieu of the large increases in hydraulic conductivity; however, calibration could not be achieved with changes consistent with the information derived from the basic data. Therefore, the model reflecting hydraulic-conductivity values that are larger than originally anticipated in some places of the Croton Creek area appears reasonable and was assumed to be calibrated. The larger values probably are due to the solution zones that exist in the gypsum beds of the Whitehorse Group. Assuming this to be true, the applicability of the modeling procedure to such aquifer systems may be questioned. In essence, the representation of any calibrated model to the actual system generally is a matter of degree, which largely reflects the confidence placed in the applicability of the modeling approach and the identification and accuracy of the important model parameters. The modeling technique used in this study is not exactly applicable to systems of large and extensive solution openings. However, hydraulic-conductivity values of as much as 8 ft/d are actually small when compared to those found in most systems of this type of porosity; the values are large only in relation to the very small hydraulic conductivities commonly found in the area. Although the Croton Creek model is assumed to be calibrated, the results of the projections made with the model in this study are considered to be approximations.

The important product derived from the calibration procedures is the distribution of hydraulic conductivity for each of the models. The range of values determined for each geologic unit (fig. 2) of the North Croton Creek area model are: Whitehorse Group - 0.2 to 0.5 ft/d; Blaine Formation - 0.1 to 0.5 ft/d; San Angelo Formation - 0.1 to 0.8 ft/d; and the Choza Formation - 0.4×10^{-7} to 0.4×10^{-6} ft/d. Most of the values that resulted from calibration of the Croton Creek area model are between slightly less than 0.1 and 0.7 ft/d, but values between about 1 and 8 ft/d were used in several places.

SIMULATION OF FLOW IN BRINE- FRESH-WATER SYSTEM

Description of Modeling Procedure

The modeling procedure used in this study to project the effects of salt-water impoundments on the fresh-water aquifer is the finite-difference approach used to simulate the areal flow of salt water and fresh water separated by an interface (Mercer, Larson, and Faust, 1980a). This procedure mainly was developed to simulate the flow systems of coastal aquifers, where the salt-water front is assumed to be approximated by a sharp interface. The relationship between the salt water and fresh water in the coastal systems is similar, in principle, to the relationship between the salt-water impoundments proposed for the upper Brazos River basin and the existing fresh-water aquifers. The interface modeling procedure was used in this study principally because it incorporates the density effect of salt water, which is significant in the project area. A sharp-interface assumption is used in this modeling approach in order to neglect the effects of hydrodynamic dispersion. Use of the modeling procedure to project the distribution of hydraulic head in the fresh-water system appears valid. However, the projected location of the sharp salt-water front (interface) in this study is considered only an approximation. This interface is wholly within the fresh-water system and is not related to the "interface" defined by Stevens and Hardt (1965, p. 7-8) as the boundary that separates the fresh-water aquifer and the deeper brine system.

The interface modeling approach used by Mercer, Larson, and Faust (1980a) is based on the one-dimensional analysis of Shamir and Dagan (1971) and the two-dimensional extension of Bonnet and Sauty (1975). The two-dimensional partial-differential equation of ground-water flow is integrated throughout the thickness of fresh water and also throughout the thickness of salt water. The resulting two equations (one for the fresh water and the other for the salt water) are interrelated with terms defining the movement of the water table and the interface, along with the included densities and viscosities for the two water systems. The results are two vertically-integrated, two-dimensional equations that are formulated in terms of fresh-water and salt-water heads (equations 33 and 34, p. 17, Mercer, Larson, and Faust, 1980a). Finite-difference approximations of these equations then are solved through a block form of an iterative numerical technique called line-successive over-relaxation, which was found to be the most efficient and accurate of the several matrix-solution schemes that were attempted (Mercer, Larson, and Faust, 1980b). The interface modeling procedure is designed to simulate time-dependent problems and can be used to simulate water-table conditions or confined conditions that may include the steady-state leakage of fresh water. The computer program, documentation for construction of models, and data-input procedures are included in Mercer, Larson, and Faust (1980a).

Most of the assumptions that were made for the modeling of the fresh-water aquifer in the calibration procedure also are applicable to the interface-modeling procedure. In addition to the sharp-interface assumption, Mercer, Larson, and Faust (1980b) include two others: (1) The Dupuit approximation (hydraulic heads in both salt water and fresh water do not vary vertically); and (2) hydraulic conductivity and specific storage do not vary with depth. The ratio of the coefficient of storage to aquifer thickness is the specific storage, which is essential in the transient analyses used in the projections.

Development of Interface Models

Interface models were developed for the North Croton Creek and Croton Creek areas. The interface models represent the same areas as the fresh-water models developed for the calibration procedures, but are used to project the brine and fresh-water conditions in the fresh-water aquifer as a result of the stresses imposed by the brine reservoirs.

The construction of the interface models involved the assimilation of the information described under the data-input procedures in Mercer, Larson, and Faust (1980a, p. 34-40). Other than items related to model size and model control parameters, the information may be separated into three general categories: (1) Aquifer parameters from the calibrated fresh-water models; (2) information essential for the transient analyses, including additional aquifer parameters, fluid properties, and the initial interface; and (3) stresses imposed on the fresh-water system by the brine impoundments.

The aquifer parameters used in or determined from the calibrated fresh-water models include: (1) The average altitude of the water table (figs. 9 and 10), (2) the altitude of the base of the fresh-water aquifers (figs. 4 and 7), (3) the average accretion (less than 0.1 inch per year), and (4) the distribution of hydraulic conductivity, which was the principal purpose of the calibration procedures.

The additional aquifer parameters used in the transient analyses with the interface models include the effective porosity and specific storage of the fresh-water aquifer. Values of porosity determined from sandstone cores that are representative of the principal part of the fresh-water aquifer range from about 10 to more than 33 percent (Hogan and Sipes, 1966; P. R. Stevens, written commun., 1980). An average value of 20 percent was used to represent effective porosity, which is the interconnected pore space. Values of 0.15 to 0.20 were used to represent the coefficient of storage (specific yield), which was used to compute specific storage. The specific yield of the fresh-water system probably is somewhat less than the effective porosity. The difference in projected hydraulic head using values of specific yield with a difference of 0.02 is less than 1 foot.

The fluid properties needed for the interface models are the densities and viscosities of the aquifer's fresh water and the impounded brine. The density of fresh water is slightly more than 1.0 g/mL (gram per milliliter) and is assumed to be 1; the absolute viscosity of fresh water at 20°C (Celsius) is about 1 centipoise. The density and viscosity of brines that will be impounded in Kiowa Peak Lake were determined from the chloride-concentration curve projected for the 100-year brine impoundment (fig. 11), and the relationship between density and the chloride concentration of brines from Permian formations in the upper Brazos River basin (fig. 12). Also shown in figure 11 is the projected pool altitude for the 100-year impoundment; the relation between chloride concentration in a pure sodium chloride solution and density is included in figure 12. Water stored in Kiowa Peak Lake at the end of the 100-year period is projected to have a chloride concentration of about 120,000 mg/L and a density of 1.14 g/mL. For the purpose of simulating the 100-year brine impoundment, a chloride concentration of 60,000 mg/L and a density of 1.07 g/mL (100-year average values) were used for Kiowa Peak Lake. The absolute viscosity of a pure sodium chloride solution with a density of 1.07 g/mL is 1.18 centipoise at 20°C (Weast and Astle, 1978, p. D300), which is assumed to be the same for the impounded brine.

A similar analysis was made to determine the density and viscosity for the small impoundment in Croton Lake. For the purpose of simulating the 100-year brine impoundment, a density of 1.035 g/mL and a viscosity of 1.08 centipoise (100-year average) were used for Croton Lake.

The basis for the projected chloride concentration and pool altitude for Kiowa Peak Lake (fig. 11) is: (1) Information from the U.S. Army Corps of Engineers (1973) in relation to hypothetical lake-regulation routings using streamflow records for 1940-66 and (2) streamflow and water-quality records from the U.S. Geological Survey (1965-68, 1969b, 1970-71, 1972a,b, 1973a,b, 1974a,b, 1975a,b,c, 1976-78). Density and chloride-concentration information in figure 12 for the brine and pure sodium chloride solution were obtained from P. R. Stevens (written commun., 1981) and from Weast and Astle (1978, p. D299-300), respectively.

Part of the input data required for each interface model is the distribution of the initial interface between the brine and the fresh water. The initial interface consists of the altitude of the top of the brine pool throughout the areal extent of the proposed brine lake and the altitude of the base of the fresh-water aquifer throughout the remainder of the modeled area. The inter-

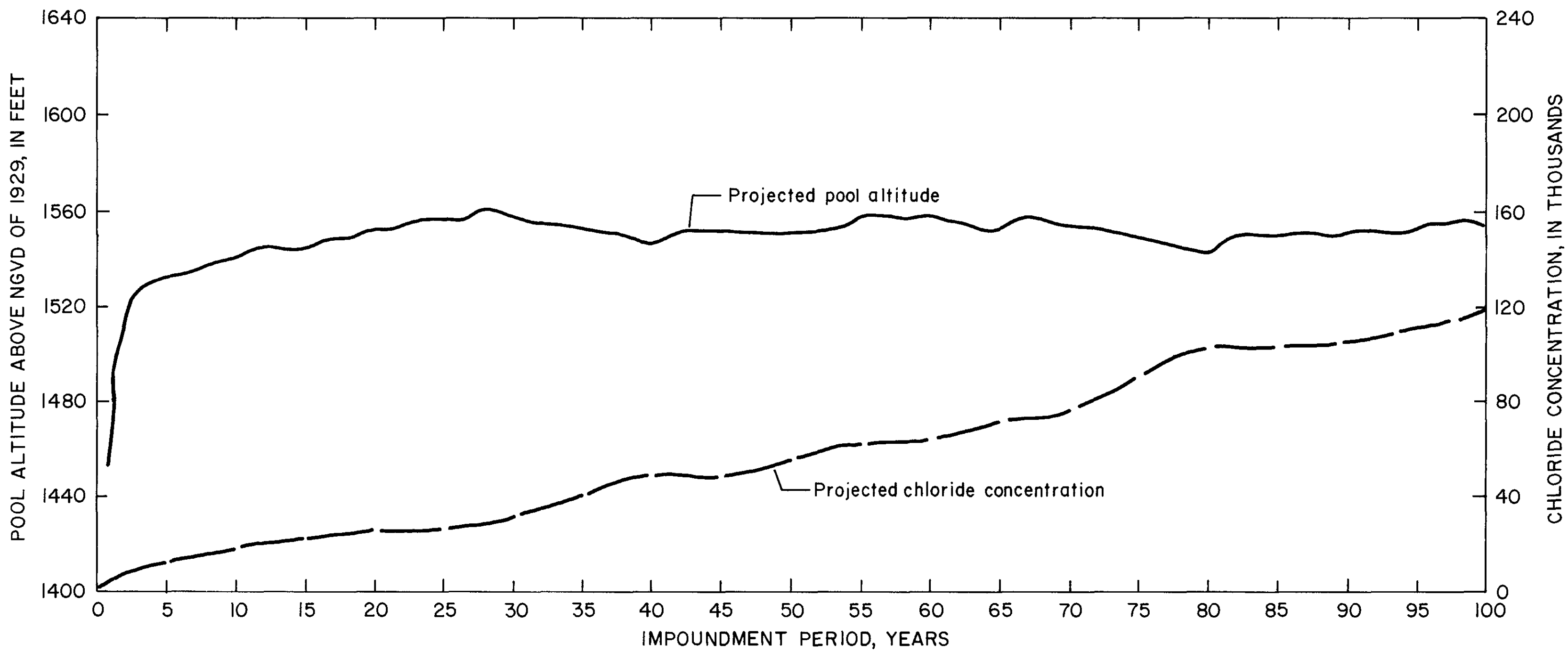


Figure 11.-Projected pool altitude and chloride concentration for 100-year brine impoundment in the proposed Kiowa Peak Lake, North Croton Creek

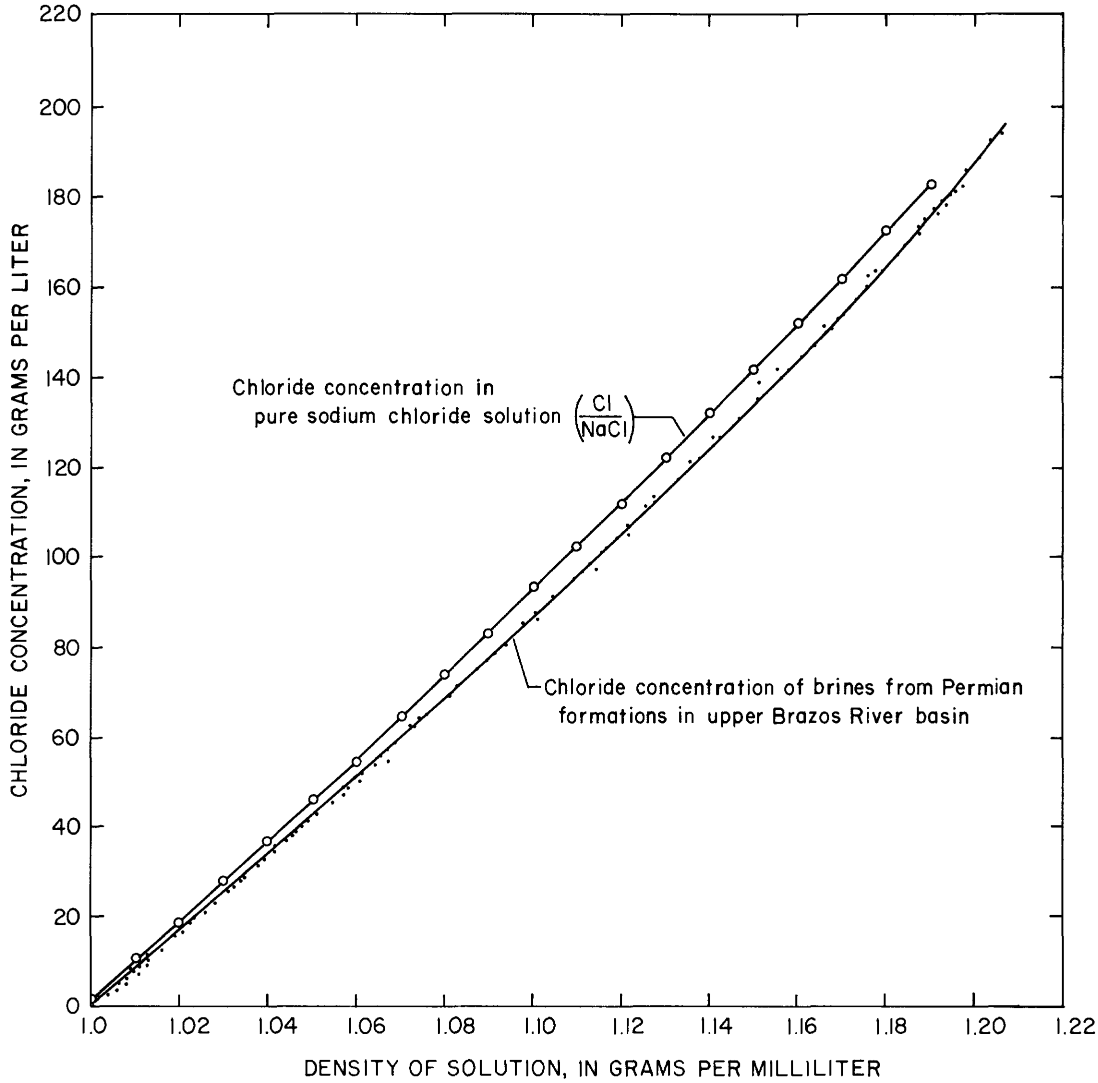


Figure 12.-Density versus chloride concentration of sodium solution and brine from Permian formations in the upper Brazos River basin.

face between model nodes representing the brine-pool surface at the proposed lake boundary and the nodes representing the base of the fresh-water aquifer is vertical and not the classical sloping interface presented by Mercer, Larson, and Faust (1980a). In order to test the model computations associated with the vertical interface, computations with several sloping (pseudo) interfaces were made. The tests indicated that the computations with the vertical interface are reasonable.

The main stresses imposed on the fresh-water aquifer are the hydraulic heads (constant salt-water heads) in the area of each brine impoundment. The 100-year average pool altitude estimated for the proposed Kiowa Peak Lake (1,550 feet above NGVD of 1929) is the principal stress simulated in the North Croton Creek interface model. The principal stress simulated in the Croton Creek interface model is the 100-year average pool altitude estimated for the proposed Croton Lake (1,760 feet above NGVD of 1929).

Projections with Interface Models

The simulation of the 100-year average brine-pool altitude in each of the interface models was effected by imposing a constant salt-water head throughout the areal extent of each proposed brine reservoir. The initial conditions in each interface model consisted of the steady-state aquifer head and accretion in the fresh-water system plus the distribution and altitude of the initial interface. The simulation period was 100 years, the expected duration of each proposed reservoir and the only simulation period requested by the Corps of Engineers for this preliminary study. The use of time steps of 4 to 12 months in the initial projections produced no significant head differences after 100 years. A time step of 1 year was used in the remainder of the projections. The principal results of the simulation are the fresh-water heads in the aquifer (or projected head increases) and the altitude and location of the resultant interface or salt-water front.

North Croton Creek Area

The projected head increases in the fresh-water aquifer after 100 years of brine impoundment in the proposed Kiowa Peak Lake in the North Croton Creek area are shown in figure 13. The interface model for the area consists of a grid system with a matrix of 21 columns and 22 rows (square cell of 0.5 mile to the side), an area large enough so that the projections are not affected by the no-flow boundaries imposed as borders of the model. Significant head increases (10 to 50 feet) are projected only for the areas in very close proximity to the lake shoreline and Dam 19. The line of zero head increase generally will not be far from the shoreline and will spread out somewhat in the vicinity of the dam and downstream from it. The precision derived from the grid system, which is suitable for the general purpose of this study, is inadequate to attain more detailed projections in the area immediately downstream from the dam. Therefore, the distribution of the head increases shown in figure 13 for this area is only approximate. The hydraulic-head effects of the proposed lake on the freshwater aquifer will not be extensive. This may be attributed to: (1) The large altitude difference between the lake and that part of the aquifer upstream from it, (2) the small accretion, and (3) the minimal transmissive property of the fine-grained aquifer system.

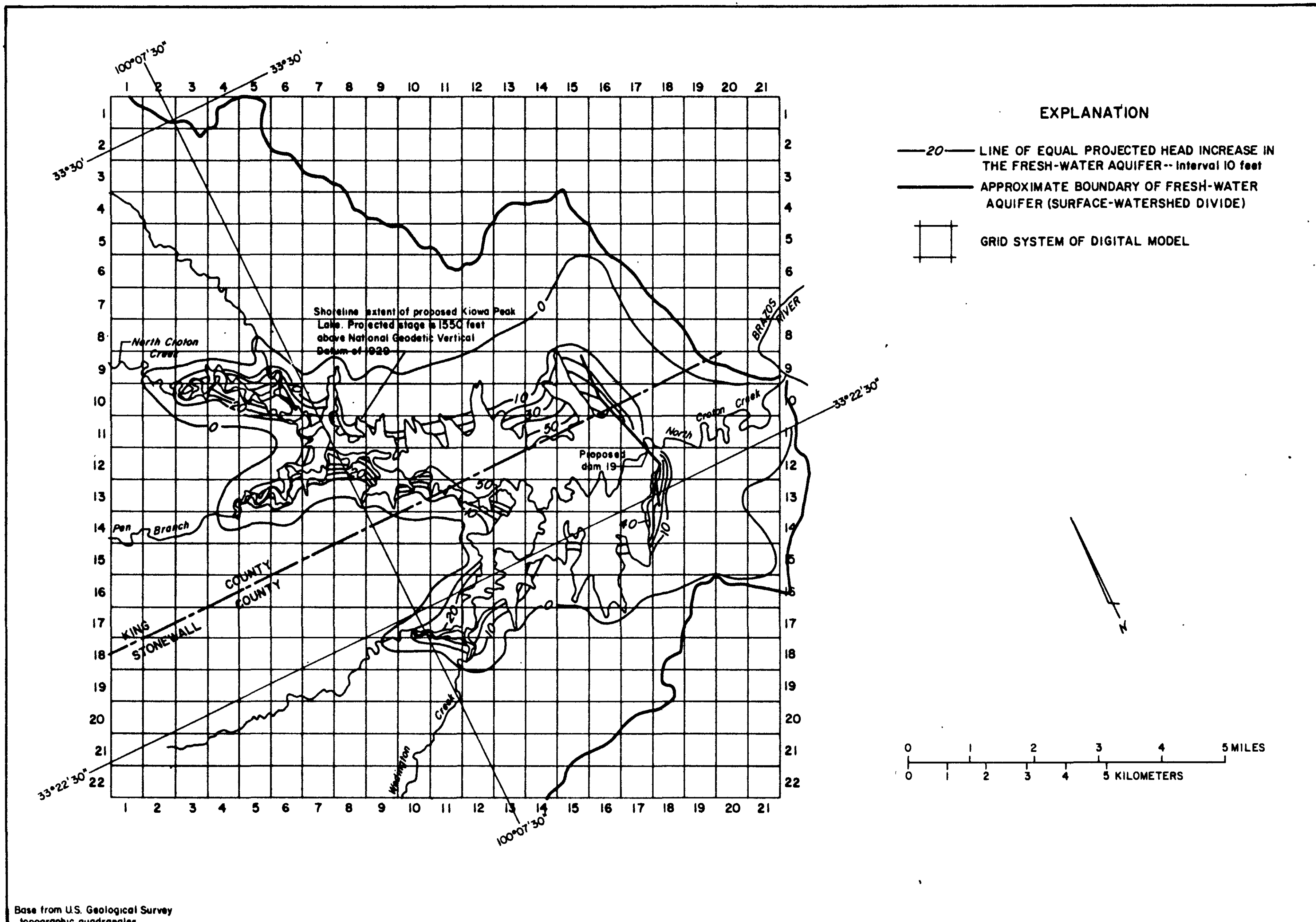


Figure 13.-Projected head increases in the fresh-water aquifer after 100 years of brine impoundment in the proposed Kiowa Peak Lake, North Croton Creek

No provisions were made in the interface model to simulate changes in evapotranspiration (ET) with changes in depth to water as a result of the projections. The effects of the average ET rate is reflected in the average steady-state accretion, and ET is not modeled in the calibration of the fresh-water aquifer. Changes in hydraulic head brought about by the proposed brine structures may change ET and with it the accretion. Under these conditions, the degree of the accretion changes will depend on the factors affecting the ET changes (applied stresses, depth to water, lithology of unsaturated zone), plus the volume by which the accretion itself can potentially change. The steady-state accretion in the project area is very small (less than 0.1 inch per year or about 2 X 10^{-5} ft/d). Changes in the ET rate per foot of water-level change in the area are estimated to be 10^{-4} to 10^{-5} ft/d. Therefore, the small accretion can be nullified by 1 to 2 feet of water-level rises; however, rises in water level due to the proposed impoundment will be limited to only a few areas in the vicinity of the dam and the lake shoreline. In order to test the effects of decreased accretion in these areas, the model used in the calibration procedure was stressed by eliminating the accretion in the areas of expected rise in water level. The effects were small, generally less than 1 foot of projected head change and only 1 to 2 feet in two small areas. The effects of negative accretion (aquifer storage losses to ET) on heads in the vicinity of the lake shoreline are considered to be minor, mainly because of the presence of the lake itself. These losses will be limited by the area's potential ET and are included in the inflow-outflow analyses that result in the estimate of the long-term average pool altitude, which is treated as a constant-head stress in the model. In summary, the effects of the changes in ET on the head projections are assumed to be negligible, primarily because the major head increases will occur in only a few areas along the lake shoreline and near the dam.

Simulations with the interface model are different than those with the calibrated fresh-water model; therefore, additional sensitivity analyses were made with changes in accretion and hydraulic conductivity. A regional change of 50 percent in accretion produced head changes of 0 to 2 feet. A regional change of 50 percent in hydraulic conductivity produced head changes of 0 to 5 feet.

The projected altitude of the brine- fresh-water interface (salt-water front) in the fresh-water aquifer after 100 years of brine impoundment in the proposed Kiowa Peak Lake is shown in figure 14. The approximate location of the salt-water toe, which is the extension of the salt-water front at the base of the aquifer, also is shown; its longest extension is slightly more than 1 mile downstream from the dam.

Movement of the salt water in the vicinity of the dam is expected to be in the form of interstitial bedrock flow, which will take place mostly in the San Angelo Formation, particularly around the abutments of the dam. Minor underflow is expected in the older part of the Choza Formation, a shale with very small hydraulic conductivity. Assuming a flow with no dispersion (piston-type), estimates of the interstitial velocities in areas downstream from the dam were made using hydraulic-head gradients derived from the simulation after 100 years of impoundment. Gradients of 40 to 80 ft/mi and an effective porosity of 20 percent were used to compute velocities in the San Angelo Formation

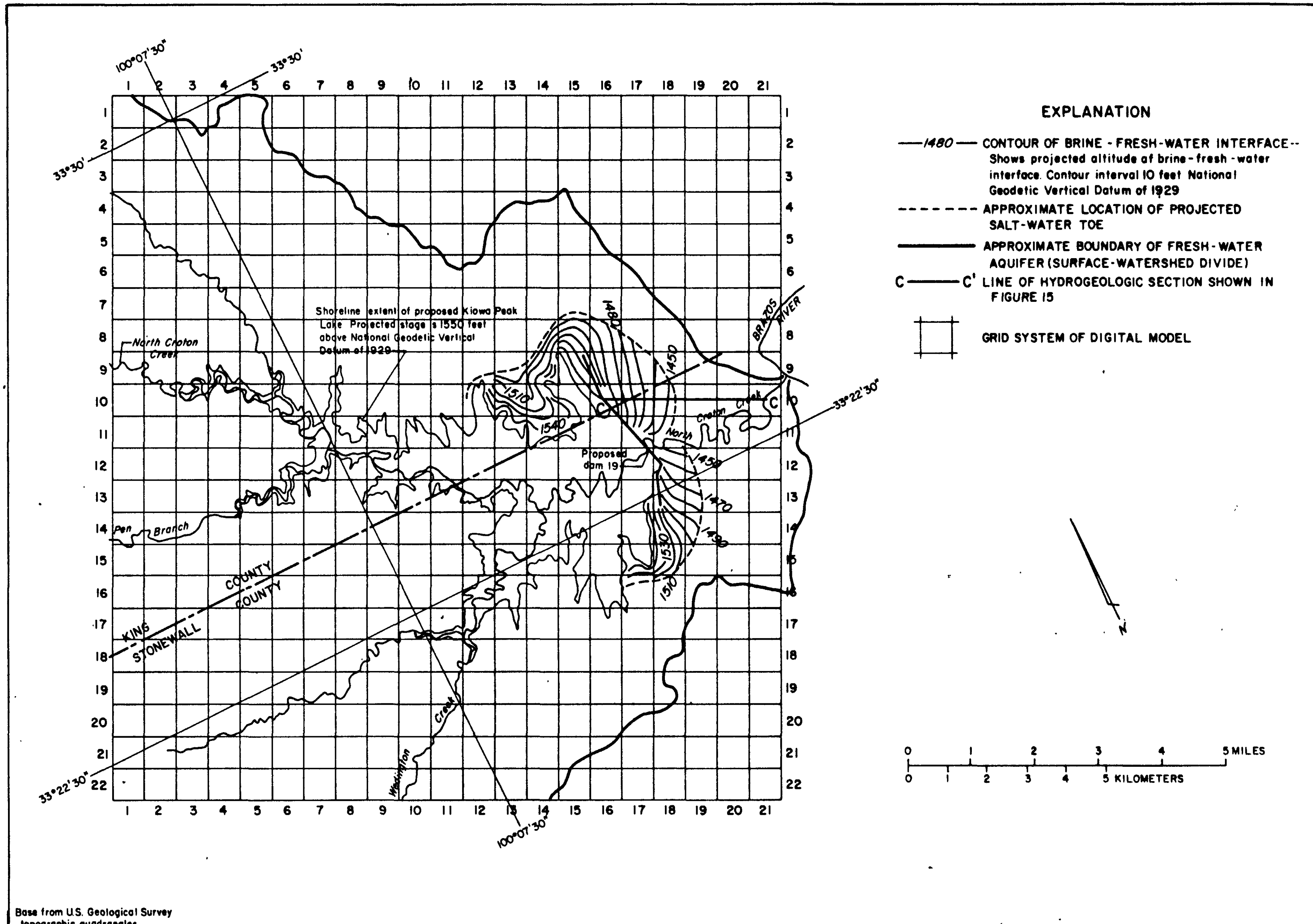


Figure 14.-Projected altitude of brine - fresh-water interface in the fresh-water aquifer after 100 years of brine impoundment in the proposed Kiowa Peak Lake, North Croton Creek

of a few feet to more than 20 feet per year. Velocities in the Choza Formation are limited to very small fractions of a foot per year under similar considerations of gradients and porosity; for practical purposes, the Choza may be considered impervious. Flow through fractures and solution openings, which are probably minor and not very extensive, was not considered in the velocity computations. The gradients in the vicinity of the dam at the start of the 100-year simulation period, as well as the average gradients during the entire period, are larger than at the end. It appears that the movement of salt water after 100 years will not have reached equilibrium (steady-state) under the stated conditions and assumptions.

East-west section C-C', located in figure 14 and shown in figure 15, is used to indicate the projected water table and the approximate location of the interface in the vertical dimension. Included in figure 15 are the location of the salt-water toe and the approximate contact between the San Angelo Formation and Choza Formation. The interface and water-table surface immediately downstream from the dam can only be estimated because of the model's coarse grid system. The vertical extension of the dam section, which will include a cut-off trench and a grout curtain, also is estimated. The Corps of Engineers will incorporate plans on these items with the embankment design to decrease the leakage through the abutments of the dam.

Additional simulations with the interface model were made for the purpose of projecting model results with changes in hydraulic conductivity. Increasing the hydraulic conductivity of the Choza Formation by a factor of 10^3 in the 100-year simulation produced only small changes in both the head and in the location of the salt-water front. However, increases by a factor of 10^6 (hydraulic conductivity similar to the San Angelo Formation) produced additional aquifer-head rises of as much as 8 feet in places near and downstream from the dam and decreases of 1 to 3 feet in other places; the salt-water front was extended an additional 0.5 mile downstream from the position shown in figure 14.

The location of the salt-water front in figure 14 is considered only an approximation, mainly because the simulation was completed under the modeling-technique assumption that the salt water is separated from the fresh water by a sharp surface or interface. In some cases, this interface can be a significant transition zone caused by the effects of hydrodynamic dispersion.

Croton Creek Area

The projected head increases in the fresh-water aquifer after 100 years of brine impoundment in the proposed Croton Lake in the Croton Creek area is shown in figure 16. The interface model for the Croton Creek area consists of a grid system with a matrix of 27 columns and 22 rows (square cell of 0.5 mile to the side). The fictitious no-flow boundaries at the model's borders do not affect the projections. The projected head increases (10 to 40 feet) appear significant only in areas near the lake shoreline and in the vicinity of Dam 10. The distribution of the head increases immediately downstream from the dam are approximate. In general, the hydraulic-head effects of the proposed structure on the freshwater aquifer will not be extensive. One explanation is

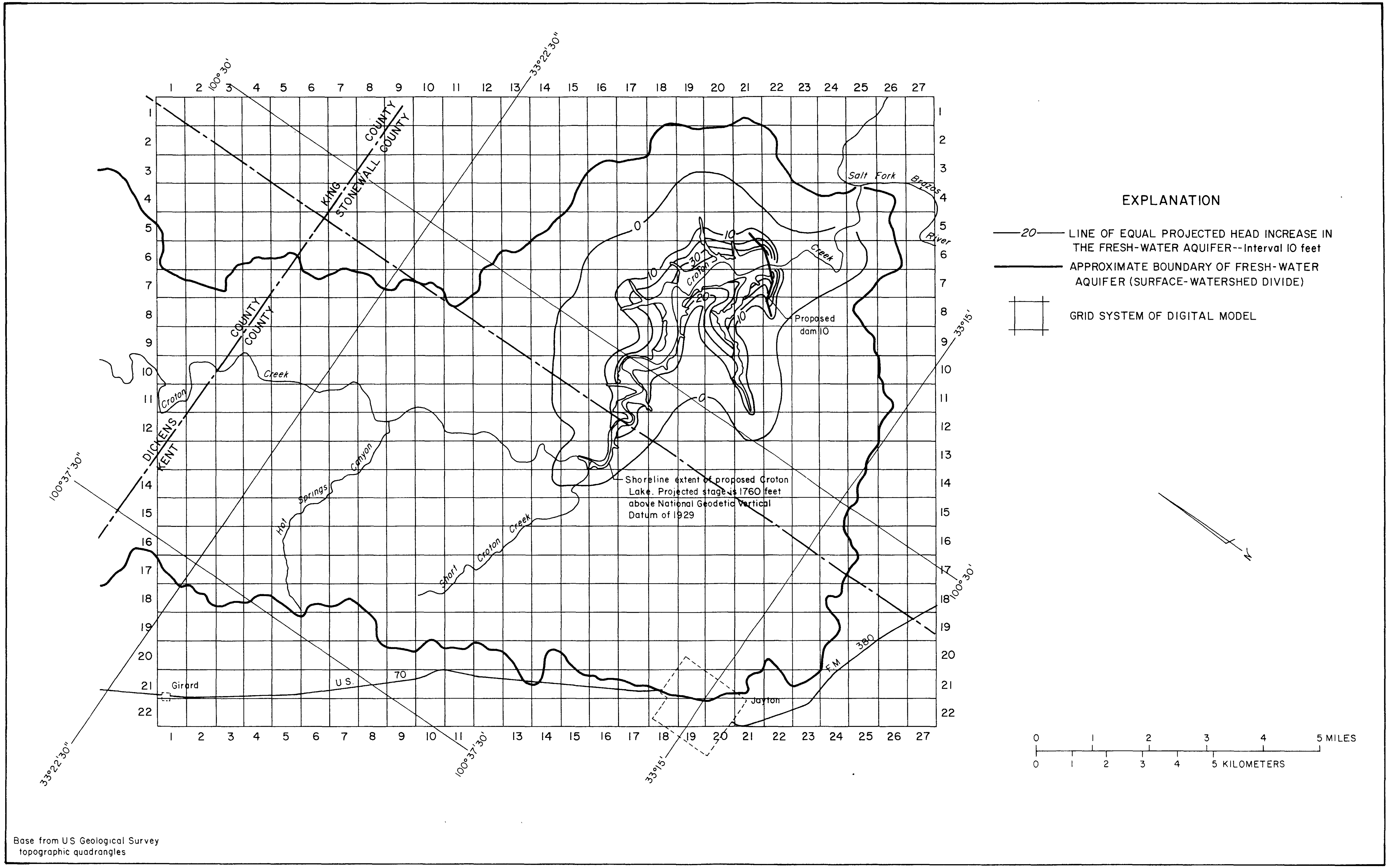


Figure 16.-Projected head increases in the fresh-water aquifer after 100 years of brine impoundment in the proposed Croton Lake, Croton Lake

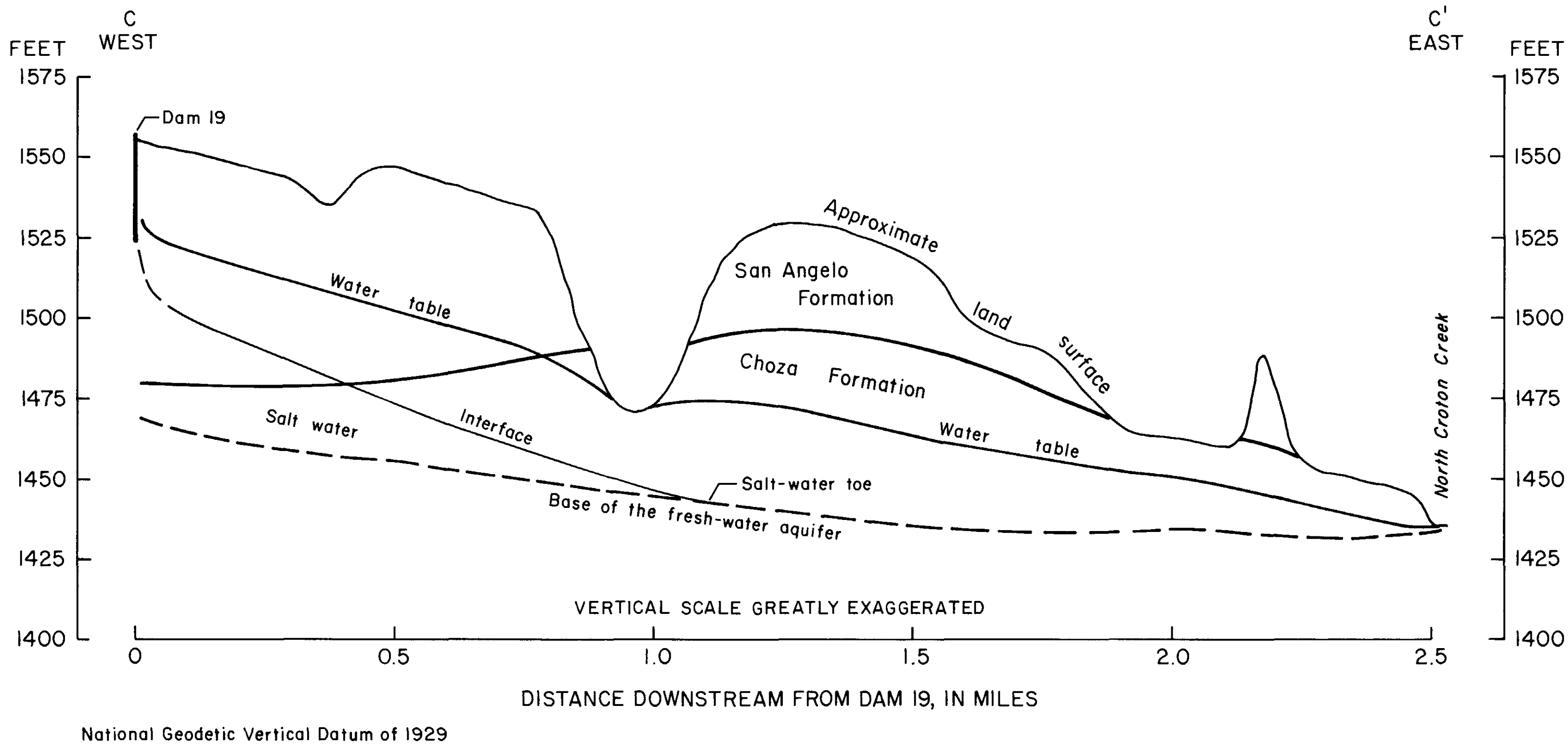


Figure 15.–East-west section C–C′ showing projected water table and interface, North Croton Creek area

that a large part of the fresh-water aquifer lies upstream from the proposed lake at significantly higher altitudes than the projected lake surface. Others are the small accretion in the area and the small hydraulic conductivities representative of the fresh-water aquifer.

The projected altitude of the brine and fresh-water interface (salt-water front) in the fresh-water aquifer after 100 years of brine impoundment in the proposed Croton Lake is shown in figure 17. Also included is the approximate location of the salt-water toe, which is shown only for areas where its extension is most significant. The greatest distance of migration of the toe is about 1 mile downstream from the dam. The salt-water migration probably did not reach steady-state equilibrium during the simulation. The salt-water toe would be very close to the lake shoreline, and the contours that represent the steep interface near the shoreline and immediately downstream from the dam are not included in figure 17. The primary purpose of the illustration is to show the approximate extent of the salt-water migration after the 100 years of impoundment at Croton Lake. The projections are based on the same stated assumptions under which the simulations for the North Croton Creek model were made. The U.S. Army Corps of Engineers (1973, p. IV-26-27) will provide for a cut-off trench in the alluvial section of Dam 10 and a grout curtain into fractured bedrock along the axis of the dam; if necessary, an additional impervious barrier will be used to cover the reservoir's valley floor in areas where leakage through gypsum beds (solution openings) might occur.

Hydraulic-head gradients (after the 100-year simulation period) were used to estimate interstitial-flow velocities in areas downstream from the dam. Velocity estimates of a few feet to more than 17 feet per year were computed for a gradient range of 40 to 100 ft/mi and an effective porosity of 20 percent for the fresh-water aquifer in the Whitehorse Group. Again, piston-type flow was assumed, and flow through systems of fractures and solution openings was not considered.

The most probable source of error in the projections made for the Croton Creek area appears to be the inability to model the type of flow through fractures and solution zones that may be extensive in parts of the fresh-water aquifer. Recognizing the leaky aspects of such a system, the Corps of Engineers has limited the proposed Croton Lake to a small storage reservoir (23,000 acre-feet at average pool altitude of 1,760 feet), from which a large part of the watershed's salt water will be transferred by pipeline to Kiowa Peak Lake.

Significance of Results of Projections

The results of the projections made in this study may be evaluated in part through a review of the modeling procedure used plus consideration of possible effects of certain physical and chemical aspects not included in the modeling effort. The interface model of Mercer, Larson, and Faust (1980a) has distinct advantages and disadvantages that are reflected in the results of the projections. The primary consideration in the use of this modeling approach has been the incorporation of the density effects of salt water in the projections. It is believed that head changes, as a result of stresses imposed by proposed impoundments of salt water, have been adequately projected. The

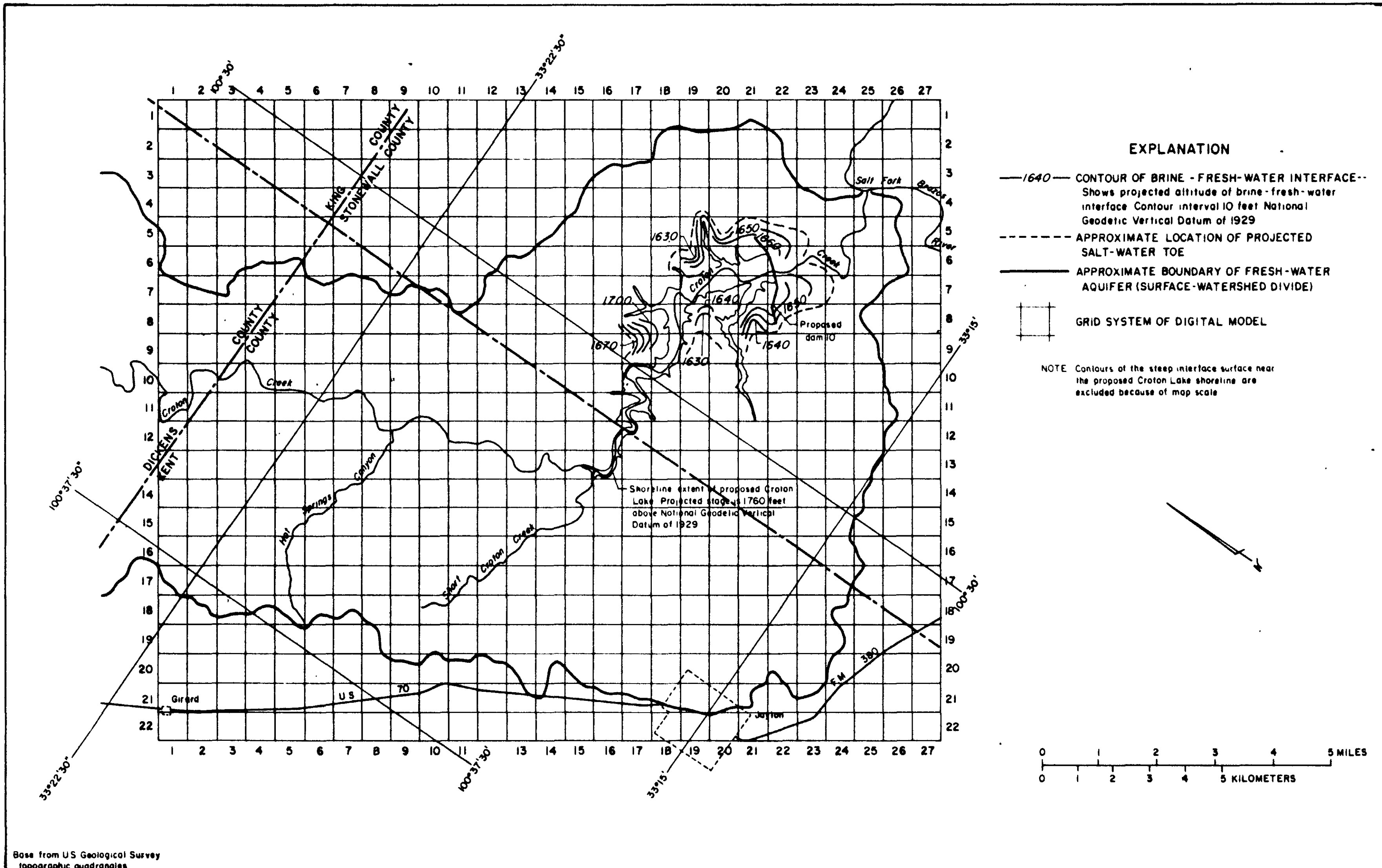


Figure 17.-Projected altitude of brine - fresh-water interface in the fresh-water aquifer after 100 years of brine impoundment in the proposed Croton Lake, Croton Creek

projected location of the sharp salt-water front or interface is believed to be an approximation mainly because the sharp-interface assumption may not be particularly applicable to the generally fine-grained aquifers in the area.

Use of the interface models in this study has produced some errors in the salt-water mass balance. Mercer, Larson, and Faust (1980b) attribute this to problems related to locating the salt-water toe. It seems that the equations describing the flow system at cell blocks along the salt-water toe may contain non-zero terms for both fresh and salt water but may indicate an interface position below the aquifer bottom. The changes in the interface position necessary to balance mass-flow residuals for the block may produce an artificial increase or decrease of mass within the block. One solution is the regeneration of a grid system for each time step so that the toe coincides with the edge of a grid block; for two-dimensional computations, this is prohibitive. Mercer, Larson, and Faust (1980b, p. 378) conclude that mass-balance errors in many cases will have to be tolerated. In this study, the fresh-water mass-balance errors in most of the simulations were less than 10 percent; however, the salt-water mass-balance error for the Kiowa Peak Lake projections varied between about 2 percent to more than 40 percent, and that for the Croton Lake projections varied between less than 1 percent to more than 100 percent. The location of the salt-water front will be considered as an approximation, pending additional efforts with perhaps new modeling approaches to verify these results.

Changes in the hydraulic conductivity of the fresh-water aquifer that may be brought about specifically by the physical and chemical changes in the salt-water and fresh-water areas were not considered in the simulations in this study. These physical and chemical changes may occur within the impounded salt water, between the salt water and the fresh water in the aquifer, and between the salt water and the aquifer material. The impoundment of salt water will result in an accumulation of sediment that may clog parts of the aquifer system. The reactions involving aqueous solutions (salt water, salt water and fresh water) include mineral precipitation by thermodynamic supersaturation with respect to a particular mineral; this action also may cause clogging of parts of the aquifer. The redox potential for the salt water may be determined in order to assess redox reactions, which are not likely to cause clogging but could result in decreased pH and mobilization of trace metals, if present in the aquifer material. The reactions between the chemically varying salt water and the type of material in the fresh-water aquifer can be complex and may increase or decrease the hydraulic conductivity of the aquifer. Generally, studies to determine the effects of these interactions on hydraulic conductivity will require: (1) Projections of the physical and chemical nature of the impounded salt water throughout the duration of the reservoir, (2) analyses of the mineral composition of the aquifer material, particularly those areas of the aquifer that may contain clay, and (3) additional analyses of the chemical quality of the fresh water.

CONCLUSIONS

The fresh-water aquifer in the North Croton Creek and Croton Creek areas is a shallow water-table system with relatively fresh water (calcium sulfate type) containing 2,000 to 5,000 mg/L of dissolved solids. The aquifer consists of Permian rocks with very small hydraulic conductivity; it is separated from an even less-permeable and deeper brine system (sodium chloride type) by a relatively thin transition zone. The average annual accretion, assumed equivalent to the average base-flow discharge, is about 0.1 inch per year.

The principal effects of the 100-year salt-water impoundments on the fresh-water aquifer in the project area are as follows:

(1) The hydraulic-head effects of the proposed Kiowa Peak Lake (North Croton Creek area) will not be extensive, and head increases of 10 to 50 feet will be limited to the areas near proposed Dam 19 and along the lake shoreline;

(2) The salt-water migration downstream from Dam 19 will be confined to approximately 1 mile and apparently will not have reached steady-state equilibrium;

(3) The hydraulic-head effects of the proposed Croton Lake (Croton Creek area) also will not be extensive, and head increases of 10 to 40 feet will be limited to areas near proposed Dam 10 and along the lake shoreline; and

(4) The salt-water migration downstream from Dam 10 will be confined to approximately 1 mile and apparently will not have reached steady-state equilibrium.

The principal intent of this study has been to provide the Corps of Engineers with preliminary results on the effects of the 100-year brine impoundments on the fresh-water aquifer in the project area. The results of the projections do not reflect possible effects associated with: (1) Hydrodynamic dispersion; (2) ground-water flow through systems of extensive fractures and solution openings; and (3) the physical and chemical changes interacting in the salt-water and fresh-water environments, the results of which may effect changes in the hydraulic conductivity of the aquifer. Extension of the projections beyond 100 years might be undertaken when additonal information and new approaches are available.

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Water year	USGS Water-Supply Paper No.	TDWR Report No.	Water year	USGS Water-Supply Paper No.	TDWR Report No.
1940-45	--	*1938-45	1952	1252	*1952
1941	942	--	1953	1292	*1953
1942	950	--	1954	1352	*1954
1943	970	--	1955	1402	*1955
1944	1022	--	1956	1452	Bull. 5905
1945	1030	--	1957	1522	Bull. 5915
1946	1050	*1946	1958	1573	Bull. 6104
1947	1102	*1947	1959	1644	Bull. 6205
1948	1133	*1948	1960	1744	Bull. 6215
1949	1163	*1949	1961	1884	Bull. 6304
1950	1188	*1950	1962	1944	Bull. 6501
1951	1199	*1951	1963	1950	Rept. 7

* "Chemical Composition of Texas Surface Waters" was designated only by water year from 1938 through 1955.

SUPPLEMENTAL INFORMATION

Table 1.--Records of test holes in the North Croton Creek area

(Location of test holes shown in fig. 3; depth measurements are from land-surface datum; PVC = polyvinyl chloride)

Test-hole number	Date completed	Depth (feet)	Hole-construction data: Hole record: Diameter (nearest inch)	Hole record: Depth (feet)	Casing record: Casing diameter (inches)	Casing record: Interval (feet)	Casing record: Type of casing	Depth of perforated intervals (feet)	Altitude (feet)	Depth to bottom of freshwater aquifer (feet)	Water level: Depth below land surface (feet)	Water level: Date	Aquifer geologic units	Remarks
Obs. 7	5-11-78	60	4	60	2	0-40	PVC	20-40	1,478	45	28.0	11- 2-78	Choza	
Obs. 8	5-17-78	110	4	110	2	0-80	PVC	50-80	1,565	85	48.6	10-18-78	San Angelo	Nearby hole cored 31-35 feet.
Obs. 9	5-16-78	110	4	110	2	0-95	PVC	55-95	1,588	98	78.8	11- 2-78	San Angelo	
Obs. 10	5-18-78	90	4	90	2	0-60	PVC	40-60	1,655	75	42.5	11-27-79	Blaine	
Obs. 11	5-23-78	95	4	95	4 2	0-26 0-55	PVC PVC	-- 35-55	1,647	57	24.3	6-11-79	Blaine	Lost circulation 20-80 feet.
Obs. 12	5-24-78	70	4	70	2	0-40	PVC	20-40	1,665	50	21.3	10-19-78	Blaine	
Obs. 13	6- 9-78	70	4	70	2	0-50	PVC	30-50	1,630	50	31.2	9- 5-79	Blaine	Nearby hole cored 43-52 feet.
Obs. 14	7-12-78	127	4	127	2	0-100	PVC	60-100	1,737	82	59.6	5-17-79	Blaine	Lost circulation 40-127 feet.
Obs. 16	7- 7-78	110	4	110	2	0-85	PVC	45-85	1,730	90	57.3	5- 8-79	Blaine	
Obs. 17	4-26-78	120	4	120	2	0-100	PVC	60-100	1,725	85	65.9	5- 8-79	Blaine	Lost circulation 10-120 feet.
Obs. 18	4-19-78	125	4	125	2	0-100	PVC	60-100	1,730	90	63.0	5- 8-79	Blaine	
Obs. 20	6-29-78	121	4	121	2	0-80	PVC	40-80	1,720	80	49.3	10-12-78	Blaine	
Obs. 23	6-27-78	90	4	90	2	0-65	PVC	45-65	1,644	74	19.1	10-17-78	Blaine	
Obs. 24	5- 8-78	90	4	90	2	0-60	PVC	40-60	1,664	78	53.0	10-17-78	Blaine	
Obs. 25	5- 8-78	70	4	70	2	0-45	PVC	25-45	1,670	62	39.7	10-16-78	Blaine	
Obs. 26	5- 9-78	80	4	80	2	0-50	PVC	10-50	1,710	80	57.0	5- 9-78	Blaine	
Obs. 27	5-10-78	140	4	140	2	0-100	PVC	60-100	1,560	95	44.3	5-10-79	San Angelo, Choza	

Table 1.--Records of test holes in the North Croton Creek area--Continued

Test-hole number	Date completed	Depth (feet)	Hole-construction data: Hole record: Diameter (nearest inch)	Hole record: Depth (feet)	Casing record: Casing diameter (inches)	Casing record: Interval (feet)	Type of casing	Depth of perforated intervals (feet)	Altitude (feet)	Depth to bottom of freshwater aquifer (feet)	Water level: Depth below land surface (feet)	Water level: Date	Aquifer geologic units	Remarks
Obs. 28	5-15-78	130	4	130	2	0-60	PVC	40-60	1,670	88	54.2	5-11-78	Blaine, San Angelo	
Obs. 29	5-18-78	60	4	60	2	0-45	PVC	25-45	1,665	53	15.9	5-15-79	Blaine	
Obs. 30	5-31-78	150	4	150	2	0-120	PVC	40-120	1,685	68	20.7	10-19-78	Blaine	
Obs. 31	5-26-78	130	4	130	2	0-90	PVC	50-90	1,790	98	68.2	9- 5-79	Blaine	Lost circulation.
Obs. 32	6-19-78	110	4	110	2	0-80	PVC	40-80	1,765	92	45.5	5-17-79	Blaine	
Obs. 33	6- 7-78	70	4	70	2	0-40	PVC	20-40	1,650	45	22.7	3-18-80	Blaine	
Obs. 34	6- 5-78	80	4	80	2	0-60	PVC	40-60	1,795	80	61.2	5-16-79	Blaine	
Obs. 36	6-14-78	105	4	105	2	0-75	PVC	35-75	1,785	94	58.7	5-17-79	Blaine	
Obs. 38	6-21-78	130	4	130	2	0-75	PVC	35-75	1,770	105	78.7	6-13-79	Blaine	Lost circulation.
Obs. 40	4-28-78	130	4	130	2	0-75	PVC	40-75	1,764	98	57.6	5- 8-79	Blaine	
Obs. 41	5- 1-78	100	4	100	2	0-70	PVC	30-70	1,731	80	17.6	8-21-79	Blaine	
Obs. 42	7- 5-78	80	4	80	2	0-50	PVC	30-50	1,700	70	36.7	10-12-78	Blaine	
Obs. 44	7-13-78	110	4	110	2	0-80	PVC	40-80	1,772	97	70.4	10-12-78	Blaine	
Obs. 47	6-28-78	100	4	100	2	0-80	PVC	40-80	1,756	93	62.5	5- 9-79	Blaine	
Obs. 48	6-23-78	70	4	70	2	0-50	PVC	30-50	1,685	58	28.7	5- 7-79	Blaine	
Obs. 49	5- 4-78	82	4	82	2	0-70	PVC	40-70	1,735	77	57.7	9- 4-79	Blaine	Lost circulation
Obs. 50	12-16-79	170	4	170	2	0-170	PVC	50-170	1,710	130	120.9	3- 6-80	Blaine	
Obs. 51	12-18-79	70	4	70	2	0-67	PVC	0-67	1,580	30	25.0	3- 5-80	Blaine	Lost circulation
Obs. 52	11-10-79	228	4	228	2	0-228	PVC	68-228	1,745	95	84.5	5-13-80	Blaine	
Obs. 53	11-27-79	131	4	131	2	0-131	PVC	0-131	1,735	92	67.3	3-11-80	Blaine	
Obs. 54	12-20-79	70	4	70	2	0-70	PVC	0-70	1,535	35	25.9	5-14-80	Blaine	
Obs. 55	12- 3-79	150	4	150	2	0-129	PVC	18-129	1,760	120	107.2	5-12-80	Blaine	
Obs. 56	1- 7-80	60	4	60	2	0-60	PVC	10-60	1,535	35	27.3	9-18-80	Blaine	
Obs. 57	1- 8-80	70	4	70	2	0-70	PVC	0-70	1,512	35	26.0	9-18-80	San Angelo	
Obs. 58	11-15-79	80	4	80	2	0-80	PVC	20-80	1,491	40	26.1	5-14-80	San Angelo, Choza	
Obs. 59	11-14-79	111	4	111	2	0-111	PVC	11-111	1,532	82	63.2	3-13-80	San Angelo, Choza	

Table 2.--Chemical analyses of water from selected test holes sampled in the North Croton Creek area

(COUNTY = 269 - King, 433 - Stonewall; FT = feet; MG/L = milligrams per liter; AC-FT = acre-feet; MICROMHOS = micromhos per centimeter at 25°C; DEG C = degrees Celsius)

LOCAL IDENT-I-FIER	STATION NUMBER	COUNTY	SAMP-LING DEPTH (FT)	DATE OF SAMPLE	SILICA, DIS-SOLVED (MG/L AS SIO2)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)
OBS 7	332318100021001	433	32.0	78-11-02	16	1100	930	10000	170
			50.0	78-11-02	17	2300	3100	31000	400
OBS 9	332419100041101	269	82.0	78-11-02	21	1000	950	8500	160
			98.0	78-11-02	18	1400	2500	15000	280
OBS 12	332618100071801	269	35.0	78-10-19	10	460	250	260	34
			59.0	78-10-19	5.7	1600	3100	17000	410
OBS 16	332738100115801	269	63.0	78-10-11	16	650	160	470	44
			80.0	78-10-11	16	1700	560	3400	140
			94.0	78-10-11	12	5200	3200	12000	450
OBS 17	332652100104001	269	59.0	78-10-11	24	720	160	1100	40
			66.0	78-10-11	18	1300	780	5000	150
			80.0	78-10-11	6.3	3200	6100	46000	1000
OBS 20	332428100114901	269	56.0	78-10-12	22	640	200	140	15
			75.0	78-10-12	9.4	3500	3500	15000	400
OBS 23	332327100060401	433	35.0	78-10-17	12	370	170	100	31
			58.0	78-10-17	11	480	180	31	45
			72.0	78-10-17	9.4	500	470	2600	120
OBS 25	332038100062001	433	42.0	78-10-16	6.7	260	1200	2500	120
			52.0	78-10-16	6.7	380	2500	11000	240
OBS 27	332153100014801	433	52.0	78-10-18	20	500	86	790	38
			70.0	78-10-18	12	300	290	3900	87
			86.0	78-10-18	12	340	400	6100	110
			105	78-10-18	9.7	1500	1200	18000	230
OBS 29	332603100044501	269	29.0	78-10-18	15	590	150	48	11
			48.0	78-10-18	13	780	310	1000	47
OBS 32	332744100091801	269	55.0	78-11-01	25	640	230	360	28
			67.0	78-11-01	20	680	640	1700	95
			74.0	78-11-01	15	1400	1000	4500	160
			90.0	78-11-01	6.3	3000	5300	[illegible]	790
OBS 36	332925100094301	269	61.0	78-11-01	11	560	230	840	50
			70.0	78-11-01	15	920	350	1600	62
OBS 41	332631100161201	269	35.0	78-10-10	12	400	140	330	37
			85.0	78-10-10	8.2	7600	3100	49000	770

Table 2.--Chemical analyses of water from selected test holes sampled in the North Croton Creek area--Continued

LOCAL IDENT-I-FIER	BICAR-BONATE (MG/L AS HCO3)	CAR-BONATE (MG/L AS CO3)	CARBON DIOXIDE DIS-SOLVED (MG/L AS CO2)	ALKA-LINITY (MG/L AS CACO3)	SULFATE DIS-SOLVED (MG/L AS SO4)	CHLO-RIDE, DIS-SOLVED (MG/L AS CL)	FLUO-RIDE, DIS-SOLVED (MG/L AS F)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (MG/L)	SOLIDS, DIS-SOLVED (TONS PER AC-FT)	HARD-NESS (MG/L AS CACO3)
OBS 7	80	0	6.4	66	5000	17000	<.1	34300	46.6	6600
	84	0	17	69	5200	53000	.1	95200	129	19000
OBS 9	200	0	13	164	4900	14000	.4	29800	40.5	6400
	150	0	19	123	5600	30000	.0	54900	74.7	14000
OBS 12	92	0	5.9	75	2300	310	.3	3670	4.99	2200
	92	0	9.3	75	4400	35000	.5	61600	83.8	17000
OBS 16	210	0	21	172	2200	1200	.9	4850	6.60	2300
	238	0	48	195	2000	8300	.9	16300	22.2	6600
	220	0	70	180	2100	46000	.8	69500	94.5	26000
OBS 17	360	0	36	295	1800	2000	.3	6020	8.19	2500
	358	0	45	294	2400	10000	.3	19900	27.1	6500
	230	0	147	189	3900	94000	.7	155000	211	33000
OBS 20	230	0	37	189	1900	320	.8	3350	4.56	2400
	184	0	47	151	3300	37000	.2	63000	85.7	23000
OBS 23	160	0	13	131	1600	59	.9	2420	3.29	1600
	170	0	17	139	2200	220	.7	3250	4.42	1900
	160	0	16	131	2900	4500	.4	11200	15.2	3200
OBS 25	170	0	6.8	139	5000	4400	.3	13600	18.5	5600
	130	0	8.3	107	6000	21000	.6	41300	56.2	11000
OBS 27	350	0	112	287	1700	980	.4	4290	5.83	1600
	110	0	44	90	3900	4300	.3	12800	17.4	1900
	120	0	61	98	3900	8100	<.1	19100	26.0	2500
	62	0	99	51	4700	31000	.3	56700	77.1	8700
OBS 29	200	0	16	164	1800	110	1.3	2820	3.84	2100
	200	0	20	164	2300	2200	.9	6750	9.18	3200
OBS 32	360	0	58	295	2000	670	.8	4130	5.62	2500
	370	0	75	303	2800	3300	.5	9420	12.8	4300
	340	0	68	279	1900	10000	.2	19200	26.1	7600
	230	0	58	189	4100	77000	.4	128000	174	29000
OBS 36	230	0	29	189	2000	1300	.6	5110	6.95	2300
	230	0	18	189	2300	3300	.6	8670	11.8	3700
OBS 41	78	0	3.9	64	1100	44	.4	2100	2.86	1600
	110	0	44	90	1500	100000	1.2	163000	222	32000

Table 2.--Chemical analyses of water from selected test holes sampled in the North Croton Creek area--Continued

LOCAL IDENT-I-FIER	HARD-NESS, NONCAR-BONATE (MG/L CACO3)	SODIUM PERCENT	SODIUM AD-SORP-TION RATIO	SPE-CIFIC CON-DUCT-ANCE (MICRO-MHOS)	PH FIELD (UNITS)	TEMPER-ATURE, WATER (DEG C)	IODIDE, DIS-SOLVED (MG/L AS I)	BROMIDE DIS-SOLVED (MG/L AS BR)
OBS 7	6500	76	54	51000	7.3	20.2	1.7	88
	18000	78	99	130000	6.9	20.1	5.5	180
OBS 9	6200	74	46	41500	7.4	19.8	1.6	120
	14000	70	56	76800	7.1	19.8	2.8	46
OBS 12	2100	20	2.4	4430	7.4	18.8	.03	1.1
	17000	68	57	85100	7.2	19.1	2.1	75
OBS 16	2100	30	4.3	6610	7.2	20.4	.10	1.1
	6400	52	18	26300	6.9	20.2	.66	73
	26000	49	32	99000	6.7	20.6	4.7	380
OBS 17	2200	49	9.7	8970	7.2	20.4	.05	1.5
	6200	62	27	33600	7.1	20.8	.75	83
	33000	74	110	181000	6.4	20.2	7.3	710
OBS 20	2200	11	1.2	3900	7.0	21.0	.04	2.0
	23000	58	43	87300	6.8	20.7	3.0	230
OBS 23	1500	12	1.1	3360	7.3	19.7	.01	.7
	1800	3	.3	4210	7.2	19.4	.02	.3
	3100	63	20	17500	7.2	19.4	.30	1.4
OBS 25	5500	49	15	18900	7.6	19.8	.15	.8
	11000	67	45	56800	7.4	19.8	1.1	62
OBS 27	1300	51	8.6	5990	6.7	19.2	.07	.8
	1900	81	39	19900	6.6	19.6	.36	.3
	2400	83	53	28500	6.5	19.7	.75	62
	8600	81	84	76500	6.0	20.0	.05	46
OBS 29	1900	5	.5	3120	7.3	19.8	.01	.2
	3100	40	7.7	10100	7.2	19.8	.17	3.2
OBS 32	2300	23	3.1	5310	7.0	19.5	.03	1.0
	4000	45	11	15500	6.9	19.4	.30	1.3
	7300	56	22	29900	6.9	19.4	.75	40
	29000	73	94	151000	6.8	19.5	4.9	400
OBS 36	2200	43	7.5	7560	7.1	18.4	.14	3.8
	3600	48	11	12600	7.3	18.5	.28	4.4
OBS 41	1500	31	3.6	4020	7.5	21.2	.00	.6
	32000	77	120	193000	6.6	21.0	6.2	590