HYDROGEOLOGY OF THE TRI-BASIN AND PARTS OF THE LOWER REPUBLICAN AND CENTRAL PLATTE NATURAL RESOURCES DISTRICTS, NEBRASKA

By J.M. Peckenpaugh, J.T. Dugan, R.A. Kern, and W.J. Schroeder

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For readers who may prefer to use metric (International System) units rather than the inch-pound units, the values used in this report may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
acre	0.0040	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot	0.3048	meter
foot per mile (ft/mi)	0.3048	meter per mile
foot per day (ft/d)	0.3048	meter per day
square foot per day (ft^2/d)	0.0929	square meter per day
inch	25.4	millimeter
mile	1.609	kilometer
square mile (mi^2)	2.509	square kilometer
degree Fahrenheit (°F)	(°F -32)/1.8	degree Celsius

Sea level: In this report "sea level" refers to the 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 of 1929."

DEFINITION OF HYDROGEOLOGIC TERMS
(From Peckenpaugh and Dugan, 1983)

Aquifer--A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Base flow--The component of total streamflow attributable to ground-water discharge into the stream channel.

Confined aquifer--An aquifer that is overlain by a confining bed that restricts the vertical movement of water from or to the aquifer; water levels in wells that are screened within the aquifer stand above the confining bed.

Consumptive-irrigation requirements (CIR)--The amount of water required to meet evapotranspiration demand of a plant and to maintain soil moisture at an arbitrary level after soil mosture and infiltrated precipitation have been drawn upon.

Crop coefficient--The monthly ratio of actual to potential evapotranspiration based on field experiments.

Deep percolation--Water that leaves the soil zone and goes into the underlying part of the unsaturated zone.

Discharge from an aquifer is the transfer of water from the aquifer to the unsaturated zone or to the land surface.

Evapotranspiration (ET)--The combined process of evaporation from free water and bare soil surfaces and transpiration by plants.

Evapotranspiration salvage--The reduction in the amount of evapotranspiration from the aquifer resulting from a lowering of the water table.

Flux--The rate of water movement into, out of, or through the aquifer.

Hydraulic conductivity (K)--A measure of the volume of fluid that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic head, or head--An expression for the potential energy of a fluid, frequently expressed as the water-level altitude.

Infiltration (I)--The part of precipitation and applied surface water that enters the soil zone.

Isotropic--All significant properties of the aquifer are independent of direction.

Low-flow measurements--Low-flow measurements made during periods when surface-water runoff is at a minimum.

Nonhomogeneous--The hydrologic properties of the aquifer vary throughout the aquifer.

Permeability of a rock or soil is a measure of its ability to transmit a fluid such as water under a hydraulic gradient.

Potential evapotranspiration (PET)--The amount of water that would evaporate from bare soil and transpire by plants if neither were under moisture stress.

Recharge to an aquifer is that part of deep percolation that reaches the aquifer.

Saturated zone--That part of the water-bearing material in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.

Soil zone--The unconsolidated mineral and organic material from the land surface to the depth reached by the plants' root systems.

Specific yield of a rock or soil is the ratio of volume of water that the rock or soil, after being saturated, will yield by gravity to the volume of the rock or soil.

Surface runoff--The component of runoff that enters the stream channel by flowing over the land surface.

Transmissivity (T)--A product of the thickness of the saturated zone and the hydraulic conductivity of that zone.

Unconfined aquifer--An aquifer not overlain by a confining bed, also referred to as a water-table aquifer.

Underflow--The lateral movement of ground water across a specified boundary.

Unsaturated zone--The interval between the soil zone and the water table, including the capillary fringe.

Water table--The surface in a ground-water body (unconfined aquifer) at which the water pressure is atmospheric.

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ABSTRACT

The hydrogeologic system in south-central Nebraska, which has been altered by surface- and ground-water irrigation, has been described and modeled to evaluate quantitatively the effects of management practices on water levels, streamflow, and surface-water seepage.

Since the early 1940's when the Central Nebraska Public Power and Irrigation District began operation south of the Platte River in south-central Nebraska, seepage from this surface-water irrigation system has resulted in ground-water level rises of as much as 110 feet above the water levels in 1940 in the northwestern part of the study area. Ground-water irrigation has increased substantially throughout the study area since the 1940's; nevertheless, only minor water-level declines have occurred over much of the study area.

The depth to water ranged from less than 1 foot in several locations to 350 feet in the northwest corner of the study area for the 1940 to 1981 time period. The saturated thickness of the aquifer decreased from west to east and from north to south and ranged from near zero along the southern boundary of the study area to greater than 600 feet in the northwest corner for the 1940 to 1981 time period.

Transmissivity and specific yield of the aquifer indicated little change during the 1940 to 1981 time period, even though the saturated thickness of the aquifer increased in the northern part of the study area. Transmissivity ranged from 100 to 20,000 square feet per day in 1940, and from 100 to 25,000 square feet per day in 1981. Specific yield ranged from 0.08 to 0.26 for the entire time period.

The hydrogeologic system was subdivided into four components: surface-water system, soil zone, unsaturated zone, and saturated zone. Computer programs were developed or obtained to represent the hydrologic regime in each component except the unsaturated zone.

A two-dimensional, finite-element, ground-water flow model (RAQSIM) was developed to represent the hydrogeologic systems in this 5,600 square-mile study area. The model was calibrated for the time period 1940 through the spring of 1981. A comparison of the computed and measured 1981 water levels was favorable. In most of the study area, the differences between computed and measured water levels were less than 10 feet. In the southern part of the study area, water-level differences of 15 to 20 feet occurred. An examination of hydrographs from eight observation wells showed similar trends between the observed and computed water levels during the calibration period.

The ground-water flow model was used to simulate a management alternative that consisted of no additional irrigation development beyond the 1981 level. Projected water levels indicated maximum rises above the 1981 computed water levels in the northwestern part of the study area of 40 feet by the year 2000 in a 50 square-mile area and 60 feet by the year 2020 in a 12 square-mile area.

INTRODUCTION

The use of surface water for irrigation and the subsequent development of ground-water resources for irrigation has brought stability and increased productivity to agriculture in south-central Nebraska. Surface-water irrigation has been practiced along the Platte River since the 1890's. In the early 1940's and 1950's, the Central Nebraska Public Power and Irrigation District (CNPPID) and the U.S. Bureau of Reclamation (USBR) developed surface-water irrigation projects in the area between the Platte and Republican Rivers (fig. 1). The use of ground water for irrigation has also increased significantly since the 1950's because of limitations on the availability of surface water and because of the widespread availability of ground water.

The development of surface-water irrigation along the Platte River and in the CNPPID has resulted in extensive ground-water-level rises as much as 110 feet above the levels in 1940. This has created both benefits (less water lift for ground-water users) and costs or damages (water logging of certain areas and changes in vegetation). Conversely, ground-water-level rises along the Republican River caused by seepage from Frenchman-Cambridge Irrigation District and Nebraska-Bostwick Irrigation District are not extensive and generally are less than 5 feet.

Ground-water-level declines caused by ground-water irrigation usually do not exceed 5 feet. However, the potential for additional ground-water-level declines does exist for several reasons. First, seepage from the surface-water systems appears to have been balanced recently by ground-water pumping in these areas. Second, in some areas where surface-water seepage does not occur, ground-water pumping exceeds recharge from irrigation return flow and precipitation. Finally, additional ground-water development is probable throughout the study area.

The possibility of future ground-water-level declines and potential changes in both the surface-water and ground-water systems led to an agreement between the Nebraska Natural Resources Commission, the Lower Republican Natural Resources District (NRD), and the U.S. Geological Survey for a quantitative hydrogeologic study of the area. The results of this study are to serve as a basis for evaluating the hydrology of the area and the effects of various management practices.

Purpose and Scope

This report details the results of a study (1) to describe and study the hydrogeologic system of the area and (2) to develop and demonstrate a capability for evaluating quantitatively the effects of management practices on ground-water levels, streamflow, and surface-water seepage losses in the study area.

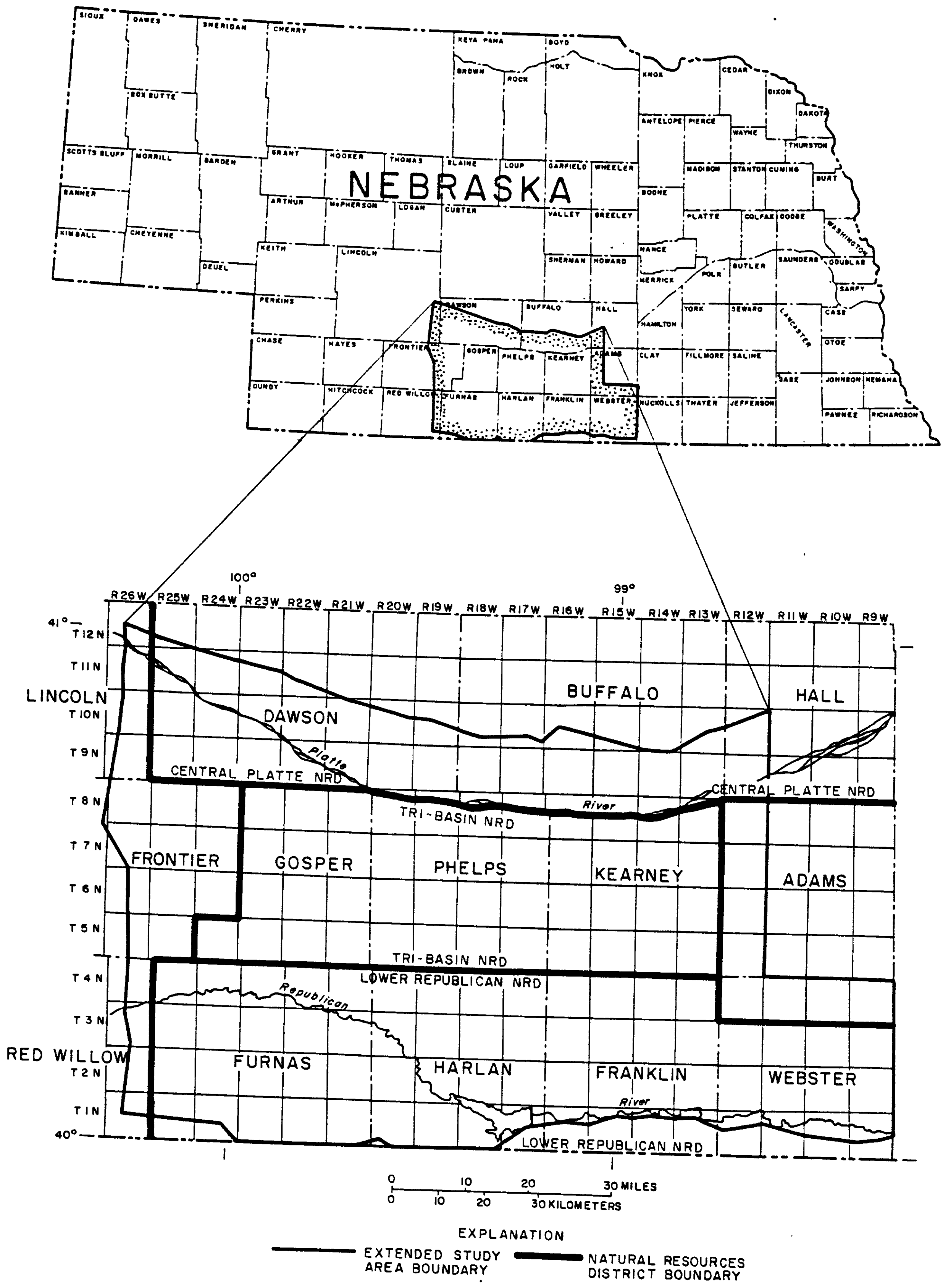


Figure 1.--Location of study area.

The scope of this study includes the development of a ground-water-flow model that uses new and previously available data. The water balance in different components of the hydrologic system--the surface-water system, soil zone, and saturated zone--were analyzed by using mathematical programs. Output from these programs are used in a ground-water-flow model of the saturated zone, which simulates the effects of changes in recharge and discharge on ground-water levels and streamflow. The surface-water system is included in the model only to the extent necessary to determine the effects of surface water on recharge to the ground-water reservoir or of ground-water discharge to the surface-water system. Also, the unsaturated zone was not analyzed by use of the mathematical programs because movement of water in the unsaturated zone was treated as being directly between the soil zone and the saturated zone.

New field data collected for this study include the following: (1) Twenty-three test holes were drilled to a few feet below the base of the Ogallala Formation or the oldest Quaternary deposits, if the Ogallala Formation was not present. (2) Mass water-level measurements were made in the spring of 1981 and additional measurements were made in the fall of 1981 and spring of 1982. (3) Water from different parts of the aquifer at 68 different locations was sampled and analyzed. (4) A land-use map for the study area was developed for 1980 conditions. (5) Eighteen water-use sites were studied for 2 to 3 years to collect data on the amount of water pumped for different crops, soils, and climatic conditions.

Available hydrologic and geologic data from previous studies were reviewed and reassessed. Both the new and existing data were used in calibrating the model and in developing management alternatives.

In addition to this report, which covers the items mentioned above in the purposes of the study, two reports have been published on different components of this investigation. One report (Hiergesell, 1984) describes the logs of 23 test holes that were drilled for this study. The second report (Bartz and Peckenpaugh, 1986) lists and describes some of the data collected for this investigation.

Previous Studies

In several previous investigations the geology and hydrology of the area were examined. Two of these investigations cover a large part of the study area and provide historic records such as water levels. Several other reports describe geologic and hydrologic aspects of the Republican Valley and adjacent areas. Reports on smaller areas provide information on special problems of local interest. Recently, studies have been performed where ground-water flow models have been developed covering part of the study area.

Lugn and Wenzel (1938) investigated the entire study area except those parts of Furnas and Harlan Counties south of the Republican River. They described the hydrology and geology of the Platte Valley from Dawson County eastward through Hall County. Their work on the undissected uplands south of the Platte River (the major part of this study) consisted of describing the geology of the area and evaluating the ground-water conditions by measuring water levels in existing wells and by preparing a 1931-32 water-level configuration map.

Johnson (1960) updated Lugn and Wenzel's study with a report describing the undissected uplands south of the Platte River in south-central Nebraska. He appraised the water content, thickness and water-yielding capacity of the aquifer, direction and rate of ground-water movement and discharge or pumpage from the aquifer. He also developed a 1948-52 water-level configuration map.

Several studies were conducted in the southern part of the study area covering either all or parts of Red Willow, Furnas, Harlan, Franklin, and Webster Counties. Condra (1907) performed a hydrogeologic investigation of the above counties. Waite, Reed, and Jones (1944) briefly discussed the geology of the same area; however, the main emphasis of their report was a description of test-hole logs in the Republican Valley. Bradley and Johnson (1957) discussed the geology and ground-water hydrology of a narrow area along the Republican River from central Harlan County westward to the Nebraska-Colorado border. Miller and others (1964) described the geology of Franklin and Webster Counties.

The Conservation and Survey Division, University of Nebraska-Lincoln, has published ground-water reports on Kearney (1948), Phelps (1953), and Franklin (1957) Counties. These reports contain geologic cross sections and water-level configuration maps. The U.S. Bureau of Reclamation has prepared reconnaissance reports on the Lower Plum Creek damsite (1947), Fort Kearney Unit (1971), and an environmental impact statement on CNPPID's E-65 system project improvements (1975).

Several studies were performed by the U.S. Geological Survey on the flood plain and terraces north of the Platte River. Waite and others (1949) presented maps showing the net changes in water levels from 1930 to 1939 and from 1939 to 1946 for the Platte Valley from North Platte to Fremont, Nebraska. Keech (1952) described the ground-water resources of the USBR's Wood River Unit from near Kearney to Wood River, Nebraska. Schreurs (1956) described the geology and ground-water resources of Buffalo County and parts of Dawson and Hall Counties. Keech and Dreeszen (1964) provided a 1961 water-level configuration map of Hall County.

Bentall (1975a and 1975b) described the physiography, geology, soil, and agriculture of the Platte Valley, and the hydrology of the Platte Valley, respectively, as they related to a proposed surface-water diversion project.

Recently, hydrogeologic studies have been performed in parts of the study area using ground-water flow models. Marlette and Lewis (1973) and Marlette, Lewis, and Keasling (1974) discussed the development and results of a study using a ground-water flow model for the Platte Valley in Dawson County. Charley and others (1973) investigated CNPPID's E-65 system project improvements by use of a ground-water flow model. Lappala, Emery, and Otradovsky (1979) used a ground-water flow model in a study of the entire Platte River basin, which included part of the area covered by this report. Peckenpaugh and Dugan (1983) used ground-water modeling procedures in a study that covered the Platte Valley on the north side of the Platte River.

Method of Study

The hydrogeologic system was subdivided the into four components--surface-water system, soil zone, unsaturated zone, and saturated or ground-water zone. Computer programs were developed or obtained to represent the hydrologic regime in each of the components except the unsaturated zone.

A digital finite-element, ground-water-flow model and associated data were developed to represent the hydrogeologic conditions in the area. The Regional Aquifer Simulation Model (RAQSIM) (Cady and Peckenpaugh, 1985) was the finite-element program selected to be the flow model. The hydrogeologic data needed to describe the characteristics of the ground-water system include, but are not limited to, transmissivity, specific yield, base of the aquifer, and elevation of the water table. Recharge and consumptive irrigation-requirement (CIR) information are needed to generate the data on deep percolation and discharge required for input to the ground-water flow model.

Some hydrogeologic data for the model were obtained from previous investigations and some new data were collected. Numerous logs of test holes and irrigation wells were obtained both from published reports and unpublished data. In addition, 23 new test holes (Hiergesell, 1984) were drilled for this study to obtain additional information on the aquifer characteristics and geology. Ground-water samples from 68 different sites were collected and analyzed to supplement existing water-quality information. Eighteen water-use sites were studied for 2 to 3 years to obtain information on the amount of water pumped for different crops, soils, and climatic conditions (Bartz and Peckenpaugh, 1986). Data from the water-use sites, plus additional data on recharge and CIR were obtained either from existing files or generated, in part, through the use of computer programs. The flow model was calibrated using the above data, and management alternatives were simulated with the calibrated model.

Well Numbering System and Altitude Control

Well numbers are based on the land subdivisions within the U.S. Bureau of Land Management's survey of Nebraska. The numeral preceding N (north) indicates the township, the numeral preceding W (west) indicates the range, and the numeral preceding the terminal letters indicates the section in which the well is located. The terminal letters denote, respectively, the quarter section, the quarter-quarter section, the quarter-quarter-quarter section, and the quarter-quarter-quarter-quarter section. They are assigned in counterclockwise direction beginning with "A" in the northeast corner of each subdivision. If two or more wells are located in the same section, they are distinguished by adding a sequential digit to the well number. Thus, a well inventoried in SW1/4, SW1/4, SE1/4, NW1/4, sec. 24, T.5 N., R.18 W. would be assigned the number 5N-18W-24BDCC. This example is shown in figure 2.

Altitudes (land-surface datum) for most wells were determined from 7-1/2 minute series topographic maps (scale 1:24,000) with 5- or 10-foot contour intervals, which were available for the entire study area. Altitudes for some wells, particularly long-term observation wells, were obtained by instrument survey.

Acknowledgments

The authors appreciate the assistance and cooperation during this study by personnel of the Lower Republican, Tri-Basin, and Central Platte Natural Resources Districts and by personnel of the Central Nebraska Public Power and Irrigation District.

PHYSICAL SETTING

The physical setting of the study area can be described by its physiography, geology, climate, soils, natural vegetation, and land use. These features have been important in shaping both the ground- and surface-water developments and the distribution and extent of irrigated and dryland agriculture in this area.

Location

The study area of 5,600 square miles is located in south-central Nebraska. Although the original area of interest was located between the Platte and Republican Rivers and the eastern and western boundaries of the Tri-Basin and Lower Republican NRDs, the study area was extended to include all the area shown in figure 1, in order to better simulate the hydrogeologic system.

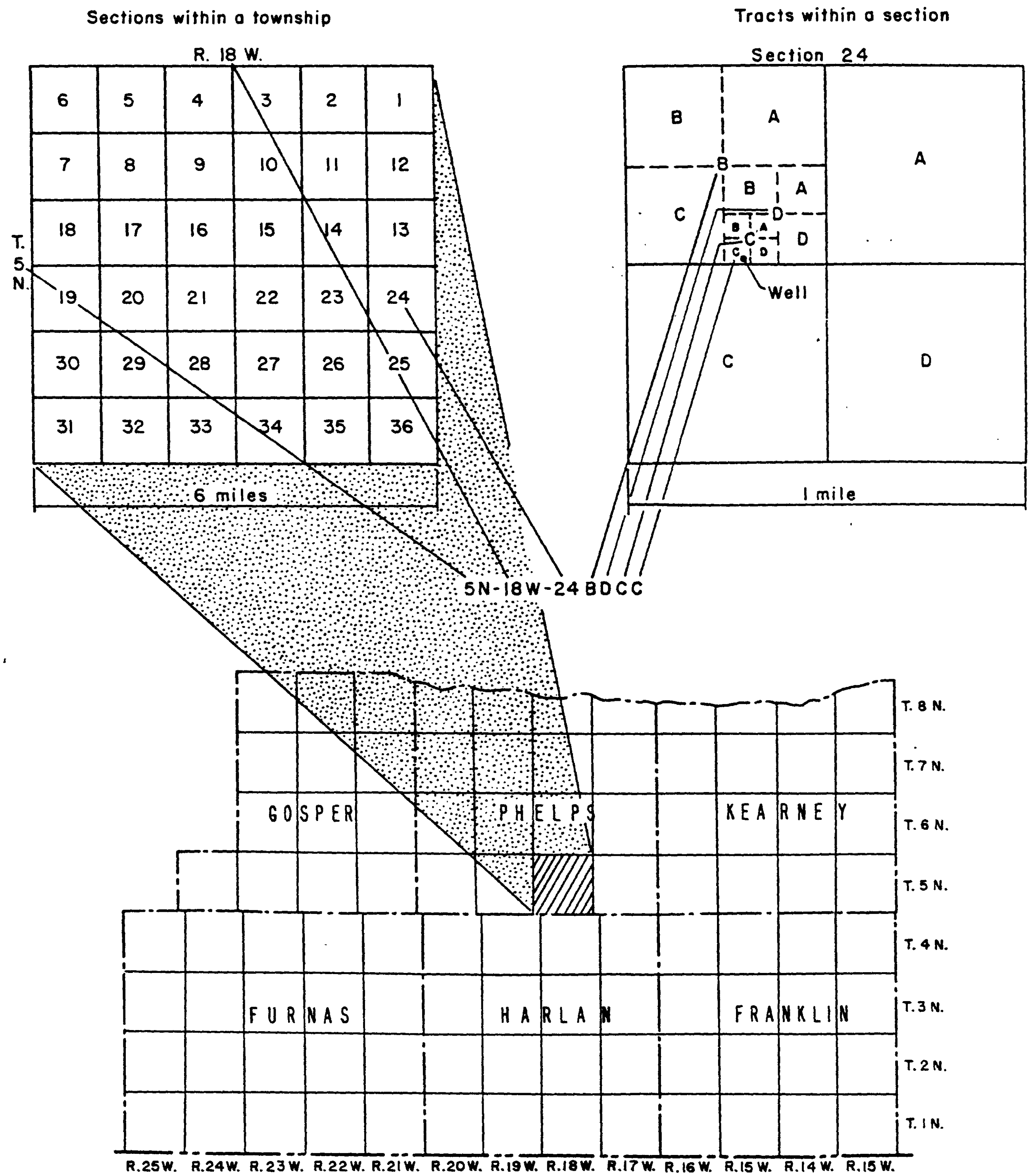


Figure 2.--Well numbering system.

The extended study area, which coincides with the modeled area, extends to the Nebraska-Kansas border, except from eastern Harlan County through Franklin and Webster Counties where the aquifer in these areas is not continuous and, therefore, could not be modeled. The other areas, where the southern boundary of the study area falls north of the Nebraska-Kansas border, were delineated by the distribution of test holes.

Parts or all of 14 counties comprise the study area (fig. 1). The counties and NRDs included in the study area are: Gosper, Phelps, and Kearney Counties in the Tri-Basin NRD; Furnas, Harlan, Franklin, and Webster Counties in the Lower Republican NRD; Dawson, Buffalo, and Hall Counties in the Central Platte NRD; and Lincoln, Frontier, Red Willow, and Adams Counties in the Twin Platte, Middle Republican, and Little Blue NRD's.

Physiography

The study area lies in two physiographic sections of the Great Plains Province (Fenneman, 1931). The northern part is in the High Plains Section, locally known as the Loess Plains. The southern part, encompassing the drainage system of the Republican River, is in the Plains Border Section, locally known as the Loess Hills and Canyons or Republican River Breaks. The boundary between the two sections, which corresponds approximately to the drainage divide between the Republican and Platte Rivers, is not distinct and has been subject to a variety of interpretations, although the characteristics of the two landscapes are distinctly different.

The Loess Plains, which has a nearly flat to slightly rolling surface, is underlain by a relatively undissected part of the Ogallala Formation. This surface consists of a moderately thick mantle of silty, eolian deposits or loess. While the surface of the Loess Plains appears to be largely flat, there is a significant regional slope from west to east. Elevation ranges from over 2,600 feet in Gosper County to less than 1,900 feet in Webster County, an average slope of 10-15 feet per mile.

A major characteristic of the Loess Plains is the lack of external drainage over much of the area. Most of the drainage is into numerous small closed basins or depressions that range in size from a few acres, with depths of 1 foot or less, to several square miles, with depths exceeding 20 feet. Until recently, these depressions were catch basins for spring rains and they remained inundated most of the year. Over the last 20 to 30 years, many of these basins have been leveled or artificially drained. A few of the larger basins are still maintained as wetland sanctuaries for migratory waterfowl. These depressions, frequently called rainwater basins, buffalo wallows, or lagoons, are believed to be deflation basins caused by wind erosion on the Loess Plains (Thornbury, 1962).

The Platte Valley to the north blends almost imperceptibly into the Loess Plains. The Platte River is largely superimposed on the Loess Plains in this region. The true flood plain of the Platte River is only a few miles wide on the south side of the river, but as much as 10 miles wide on the north side of the river in Buffalo County.

Sandhills outliers occur south of the Platte River on the Loess Plains in Phelps, Kearney, and Adams Counties. These sandhills consist of short, somewhat choppy dunes that probably orginated from sand blown out of the Platte Valley. Two other anomalous sandhills areas occur in south-central Kearney and north-central Franklin Counties and in east-central Kearney and west-central Adams Counties, coinciding approximately with the Thompson Creek and Sand Creek basins, respectively.

The Loess Hills and Canyons is characterized by a discontinuous or absent Ogallala Formation that was largely removed by erosion prior to loess deposition. The northern part of the Loess Hills and Canyons is the dissected edge of the Loess Plains where the Ogallala Formation is present but discontinuous, resulting in small but numerous tablelands. Farther south in the study area where the Ogallala Formation is usually absent, the tablelands gradually change to a more rounded topography, particularly south of the Republican River in Franklin and Webster Counties. The topography is generally not steep, but is characterized by rather complex drainage patterns. The closed basins found on the Loess Plains are largely absent throughout the Loess Hills and Canyons.

The entire area of Loess Hills and Canyons is mantled by loess. Flat-topped hills or tablelands with rather broad, shallow, flat-bottomed canyons coincide with the somewhat thicker loess deposits in the northern areas. Where the loess thins south of the Republican River, the topography becomes more rounded as the underlying bedrock surface assumes more topographic control. Outcrops of Ogallala Formation and Cretaceous units, the Pierre Shale and underlying Niobrara Formation, occur south of the Republican River, particularly along the bluffs above the valley where the loess mantle is absent.

Approximately 50 percent of the Loess Hills and Canyons in the study area is native rangeland. However, nearly all of the tablelands and some of the broader canyons are cultivated. Many of the larger tablelands have been developed for irrigation where adequate ground water occurs.

A distinct area that geologically and geographically belongs to the Loess Plains but is similar topographically to the Loess Hills and Canyons is a highly dissected area in the extreme northwestern part of the study area, particularly in southwest Dawson County. Here the natural drainage system that flows into the Platte River has eroded the loess mantle of the Loess Plains into rather steep bluffs and escarpments. In some cases the underlying Ogallala Formation is exposed.

The topographic positions of the Platte and Republican Rivers are significant to the physiography of the study area. The Platte, as mentioned previously, is largely superimposed on top of the Loess Plains with very little valley incision or tributary development, resulting in minimal dissection of the Loess Plains. The Republican River and its tributaries, which are in the Loess Hills and Canyons, are well entrenched, occupying a position 200 or 300 feet lower than the Platte River. This difference is apparent in the degree of areal erosion or dissection of Loess Hills and Canyons.

Geology

The land surface in the study area consists of unconsolidated Quaternary deposits, except along valleys where streams have eroded through the Quaternary materials. This erosion is most evident in the southern part along the Republican River and its tributaries.

Quaternary deposits are composed of sands, gravels, silts, and clays of fluvial origin and sands, silts, and clays of eolian origin. The thickness of these deposits varies from zero along the valley sides of the Republican River and its tributaries to about 390 feet in the uplands of northwestern Gosper County. Quaternary deposits thin toward the south. South of the Republican River these deposits form a thin mantle on older bedrock units. Also, the Quaternary deposits decrease in thickness from west to east across the study area.

During the Quaternary Period, several episodes of fluvial and eolian deposition were followed by periods of erosion and soil formation. These events were related to advancing and retreating or melting of continental ice sheets in eastern Nebraska. These ice sheets blocked the valleys of eastward flowing streams and diverted their flow southward and southeastward along the ice margins.

The diversion of these streams caused a lowering of stream gradients and a reduction in their sediment-carrying capability. The streams aggraded their valleys and alluvial plains developed in front of the ice sheets. After the ice retreated or melted, the sediment load of these streams decreased and the level to which the streams could erode valleys into the alluvial plains was lowered. The resulting erosion produced a new landscape of valleys and uplands.

Within each depositional sequence, the lower part is generally coarse-textured sands and gravels, while the upper part is fine-textured silts and clays. At some locations these fine-textured sediments have been eroded; thus, the sand and gravel deposits of one sequence occur vertically adjacent to those of another sequence or are separated by only thin layers of silt and clay.

Upper Quaternary dune sand covers parts of northern Phelps and Kearney Counties and the area adjacent to Thompson Creek in Franklin County. In several areas, the dune sand has been reworked from existing sand deposits to form areas of rough topography.

Colluvium, consisting primarily of reworked loess, mantles most terraces in the study area. Its deposition probably alternated with deposition of silt and fine sand blown from the loess-mantled uplands. The colluvium thins from the margin of the uplands toward the terraces and flood plains.

The Ogallala Formation of Tertiary age lies immediately below the Quaternary deposits in much of the study area. The Ogallala Formation has been completely removed by erosion in eastern Kearney County, in central and southern Franklin County north of the Republican River, and in Webster County north of the Republican River, except for an outlier in the northeastern corner. The Ogallala Formation also has been completely eroded along parts of the Republican River valley and the valleys of its tributaries. The thickness of the Ogallala Formation within the study area ranges from zero in the areas previously mentioned to over 300 feet in the southwestern corner of Dawson County.

The Ogallala Formation consists primarily of calcareous silt, silty or sandy clay, and fine- to medium-grained sand. The sand is consolidated into friable sandstone in some locations. These materials often are interbedded with marly zones, and a basal gravel is present at several locations.

The Ogallala Formation can be grouped into three units: Undifferentiated silt, clay, and sand (the most common unit, which was described above); quartzite; and "mortar beds". The quartzite consists of sand and silt that was cemented by secondary accumulations of silica. The mortar beds consist of sand and silt that was cemented by secondary accumulations of calcium carbonate. Both the quartzite and mortar beds are largely discontinuous lenticular bodies. At a few places where both units are present, the mortar beds overlie the quartzite. Both units are well consolidated; thus, they form ledges when exposed on the sides of valleys.

Cretaceous bedrock units, unlike the Quaternary deposits and Ogallala Formation, are not considered hydrologically important to this study. These units, which directly underlie the Ogallala Formation or the Quaternary deposits where the Ogallala is not present, are thick beds of shale with some thinner beds of shaley chalk and chalk.

Six general hydrogeologic sections (fig. 3 and 4a-f) show the variability of the hydrogeology of the Quaternary deposits and the Ogallala Formation that comprise the aquifer in the study area. The Quaternary deposits and Ogallala Formation are not separated hydrologically.

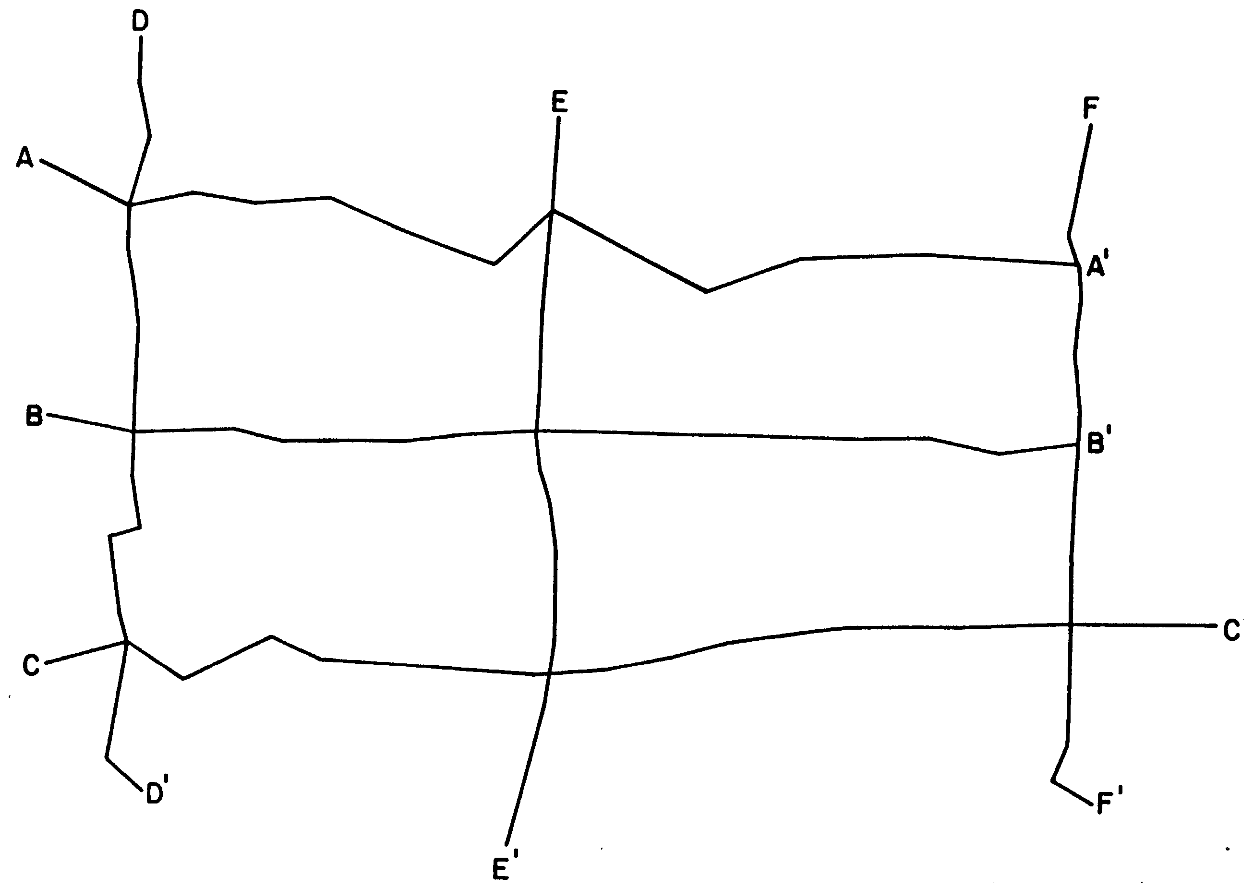


Figure 3.--Location of generalized hydrogeologic sections.

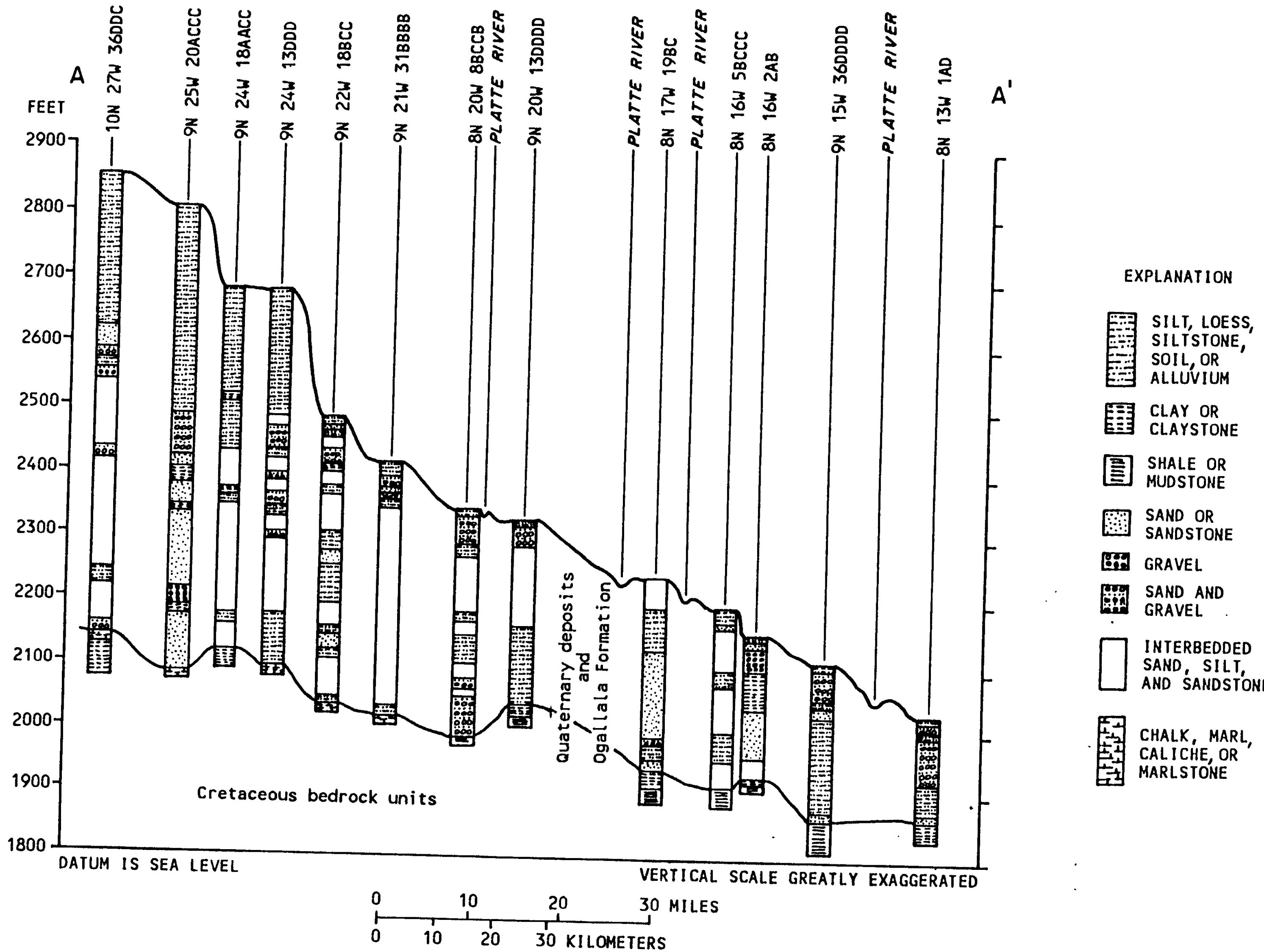


Figure 4.--Generalized hydrogeologic section, Part A, A-A'.

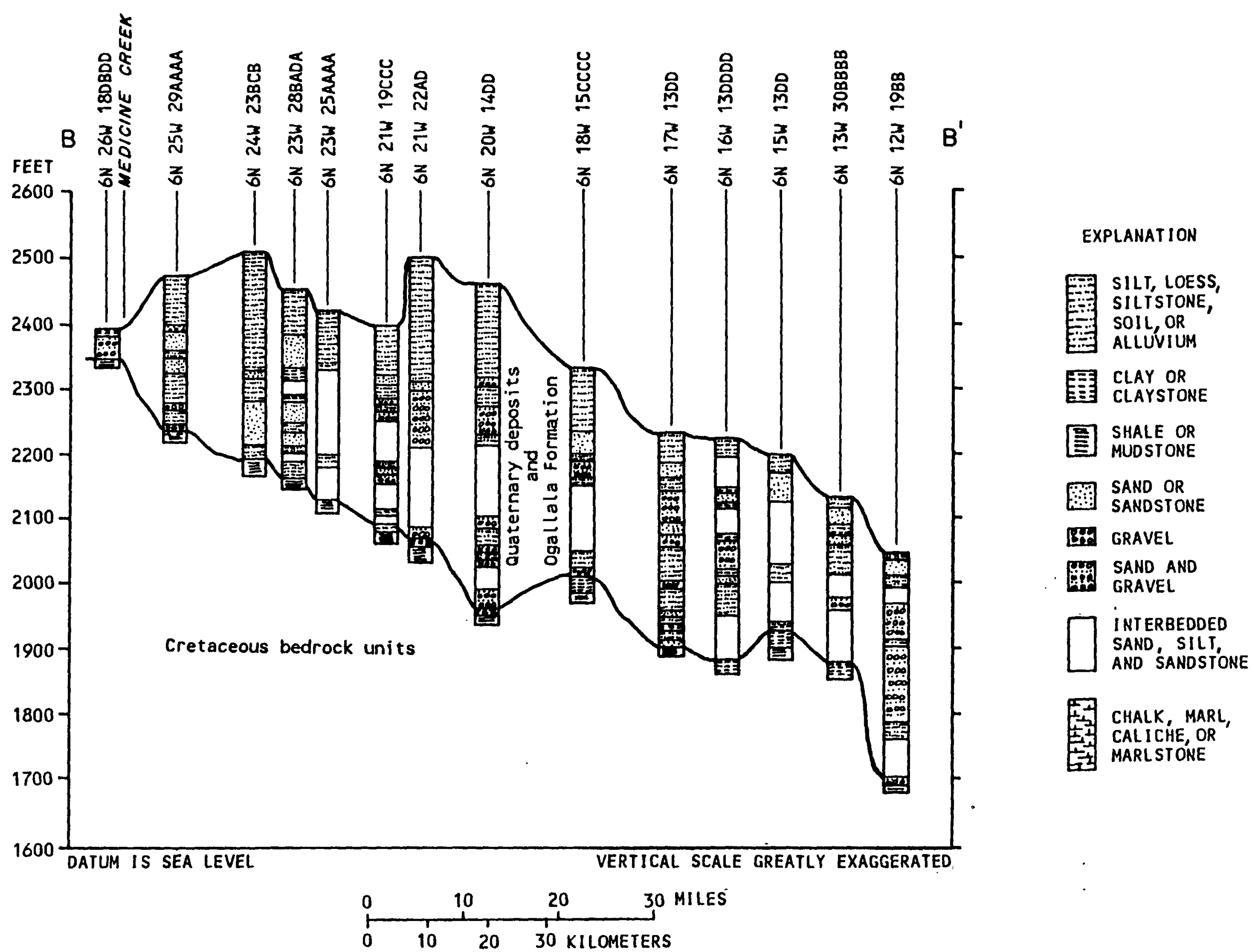


Figure 4.--Generalized hydrogeologic section, Part B, B-B'.

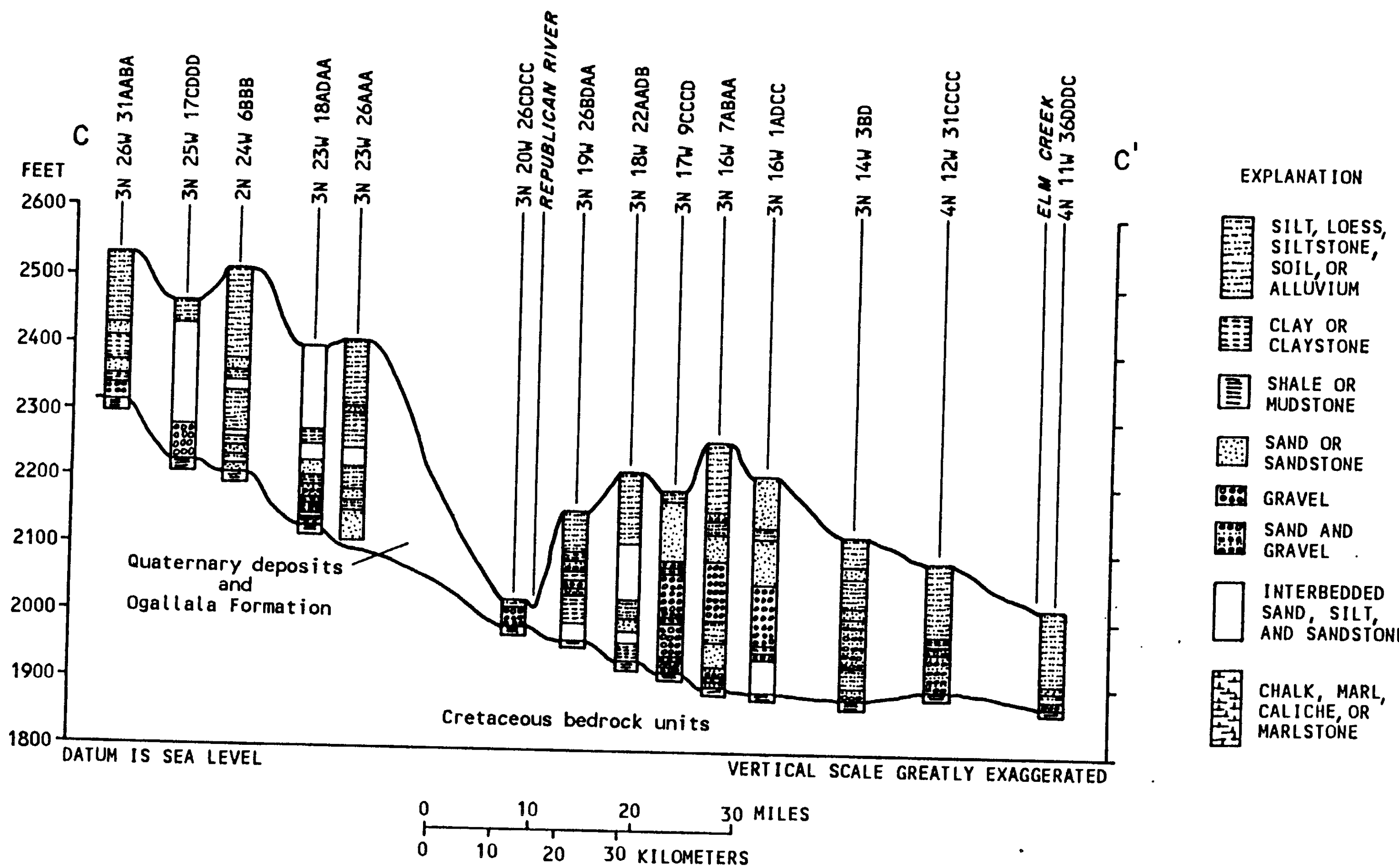


Figure 4.--Generalized hydrogeologic section, Part C, C-C′.

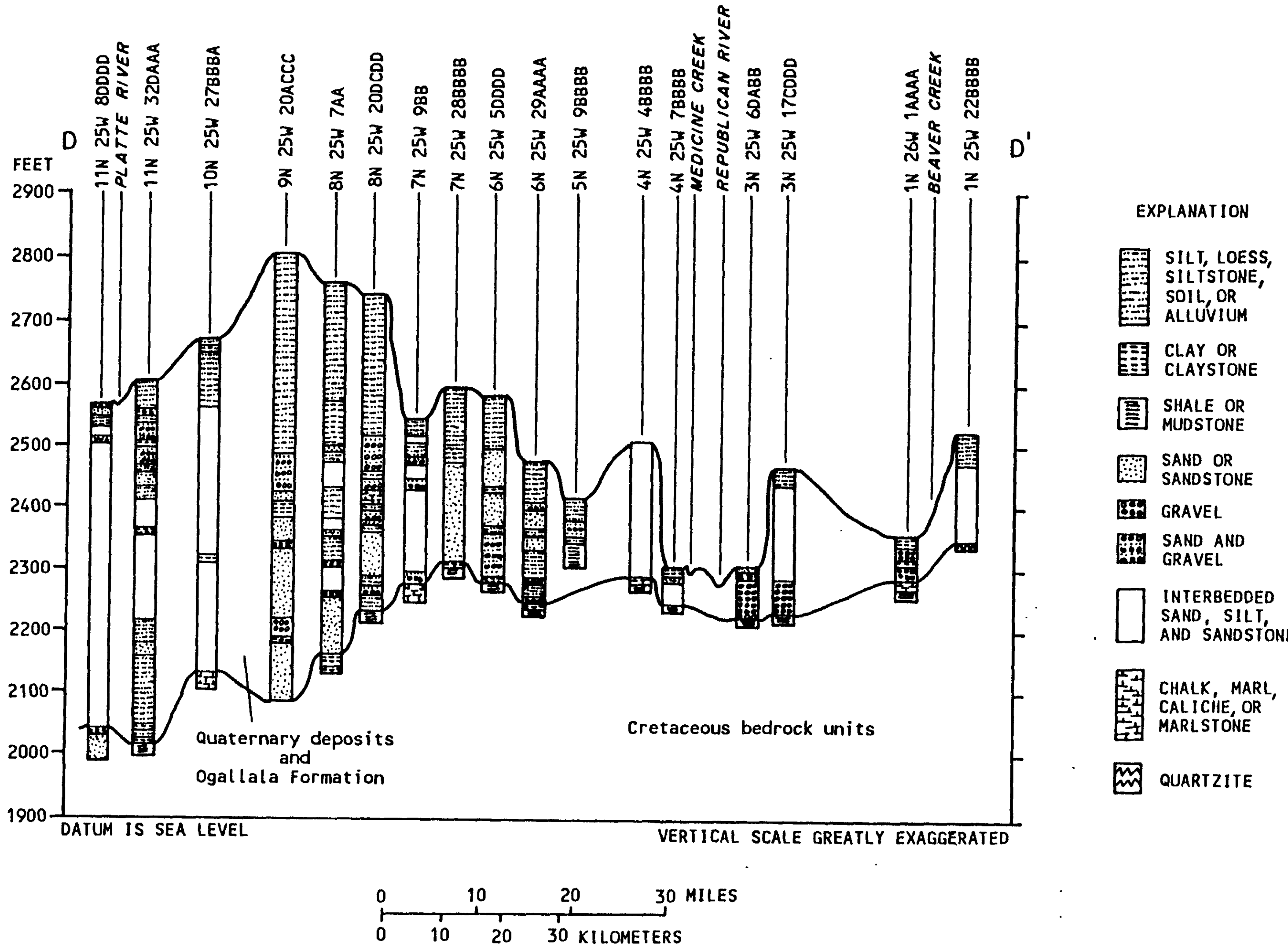


Figure 4.--Generalized hydrogeologic section, Part D, D-D'.

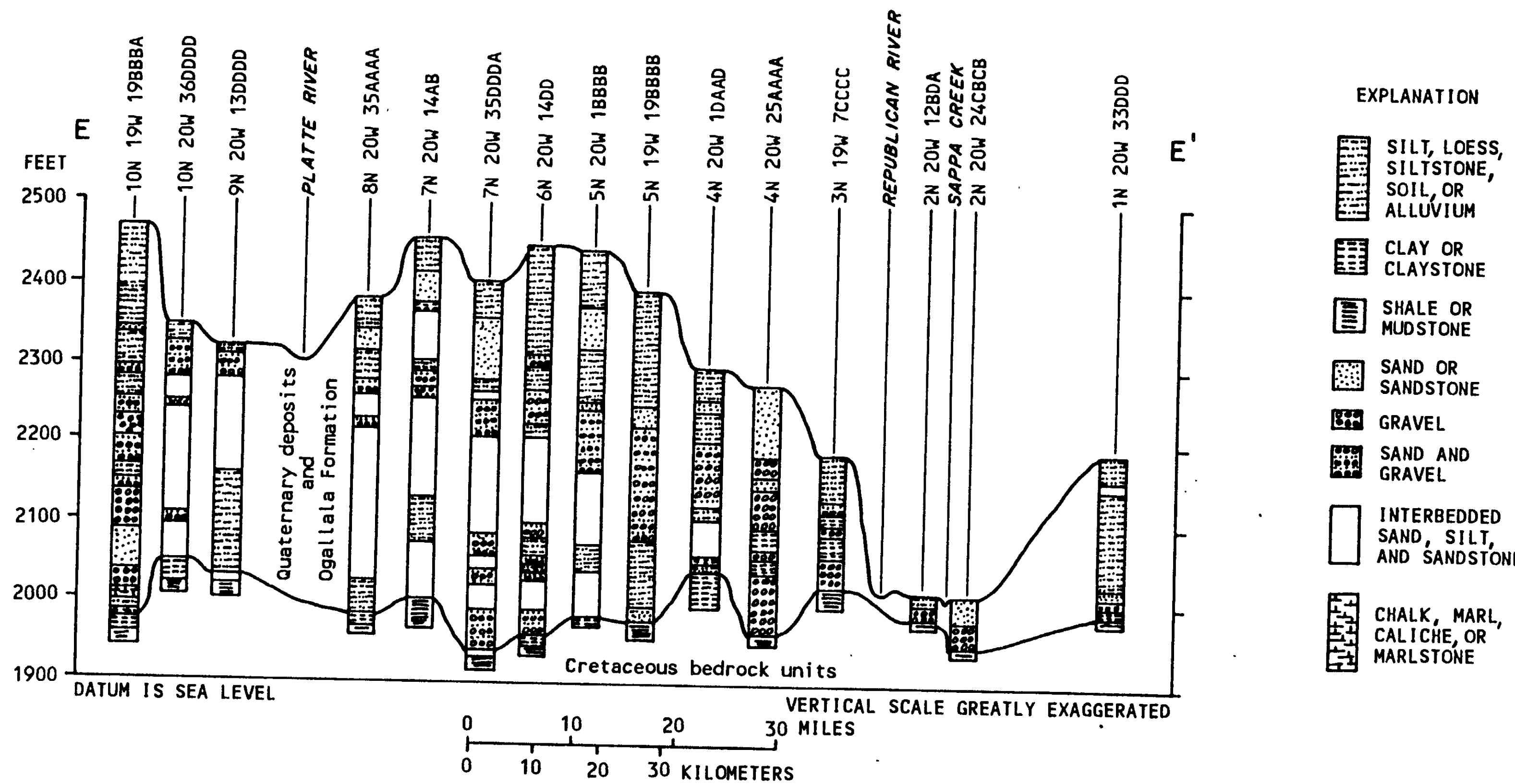


Figure 4.--Generalized hydrogeologic section, Part E, E-E'.

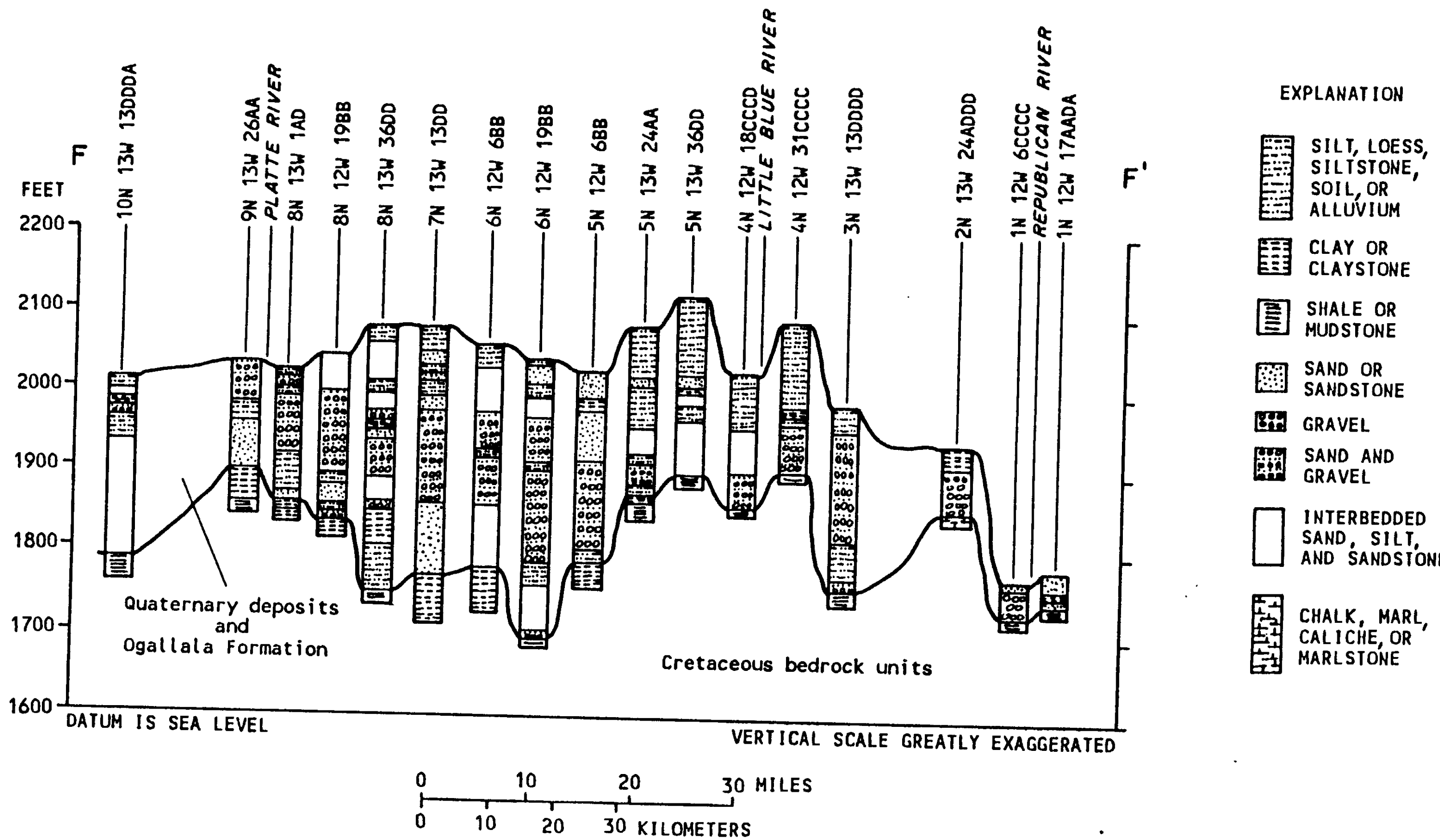


Figure 4.--Generalized hydrogeologic section, Part F, F-F′.

Climate

The climate of the study area is classified as subhumid continental, characterized by cold winters, hot summers with moderate amounts of precipitation and no distinct dry season. As with all midlatitude continental climates, strong seasonal temperature contrasts occcur. Precipitation is not evenly distributed seasonally, and annual variation may be significant. In some years the climate is more semiarid than subhumid.

Little spatial variation in temperature occurs throughout the study area. For example, at Holdrege, Nebraska, the mean January temperature, usually the coldest month, averages 23.7° F, with an average daily range of 21.7° between the high and low temperatures. The warmest month, July, averages 76.9° F, with a daily range of 26.6° (National Oceanic and Atmospheric Administration, 1983). Temperature extremes are less than -20°F in the winter and greater than 110°F in the summer.

The frost-free season, or growing season, ranges from 150 to 160 days in the study area between the first week in May and October 5-10 (Lawson and others, 1977, p. 30). Frost dates, however, may occur as much as a month either before or after these dates. The growing season is sufficient for a wide variety of crops.

Average annual precipitation ranges from approximately 20 to 26 inches across the study area. However, the coefficient of variation is approximately 25 percent of the average, which means it reasonably can be expected that precipitation will range from 18 to 30 inches in any given year. In approximately 2 years in 10, the study area receives less than 18 inches of precipitation annually, an indication of the frequency of severe drought conditions for this region.

Severe drought years occasionally occur in a series, such as the 1890's, 1930's, 1950's, and somewhat in the 1970's. These long-term drought periods have detrimental effects on crops, natural vegetation, and available water resources. In the study area, the more severe droughts frequently are accompanied by hot, dry, continental tropical air masses that cause an even greater demand for water by crops and vegetation, resulting in even greater evapotranspiration rates.

In the study area, 75 to 80 percent of the annual precipitation occurs during the warm season (April through September), which closely corresponds to the growing season. The 20 to 25 percent that occurs in the cool season (October to March), however, is often more effective in replenishing soil moisture and providing ground-water recharge, because evapotranspiration rates are small.

Warm season precipitation largely results from convective activity or thunderstorms and squall lines, which cause wide variations in spatial patterns of rainfall. Large amounts of precipitation may occur in isolated locations, while other areas may receive little or none during the same storm period. However, data for cool-season precipitation for the period of record indicates greater statistical differences from year to year than does warm season precipitation. This is related to the variability in cyclonic storm tracks from year to year. Long-term droughts are usually associated with extended periods of deficits in cool-season precipitation, when soil moisture is not replenished.

The overall demand or need for water in a particular climatic region is indicated by potential evapotranspiration. Using the Jensen-Haise (1963) method of calculation, annual potential evapotranspiration averages from 47 to 50 inches of water in the study area, increasing from east to west. Because annual precipitation averages about 50 percent of potential evapotranspiration there are extended periods in which soil-moisture deficits likely will occur.

Approximately 90 percent of the annual potential evapotranspiration is confined to the warm season. During this period soil-moisture deficits normally occur despite the greater incidence of warm-season precipitation. During the cool season, precipitation and potential evapotranspiration rate are much more favorable, resulting in increased soil moisture and water available for recharge. Annual potential evapotranspiration during severe drought years is as much as 25 percent greater than the average in the study area. This corresponds to a greater incidence of sunshine, less humidity, higher temperature, and more frequent occurrence of drying winds.

Soils

Soils are significant to hydrology because of their ability to transmit or store water. Physical characteristics of the soils, such as permeability and soil slope, affect the volume of precipitation that may be captured. The ability of the soil to retain or store water for use by plants, often expressed as the soil's available water capacity, is largely a function of the soil's texture. The predominant parent material for the area is eolian loess, which tends to produce soils of moderate to low permeability and high available water capacity.

Soil variations (fig. 5) that exist in the study area are associated largely with topographic differences (fig. 6). The soils can be subdivided into (1) silt loam to silty clay loams of the undissected uplands (soil group A); (2) loams to silty clay loams of the dissected uplands (soil groups B, C, and F); (3) fine sandy loam to fine sand of the uplands (soil groups E and H);and (4) variable soils of the flood plains and terraces (soil groups D and G).

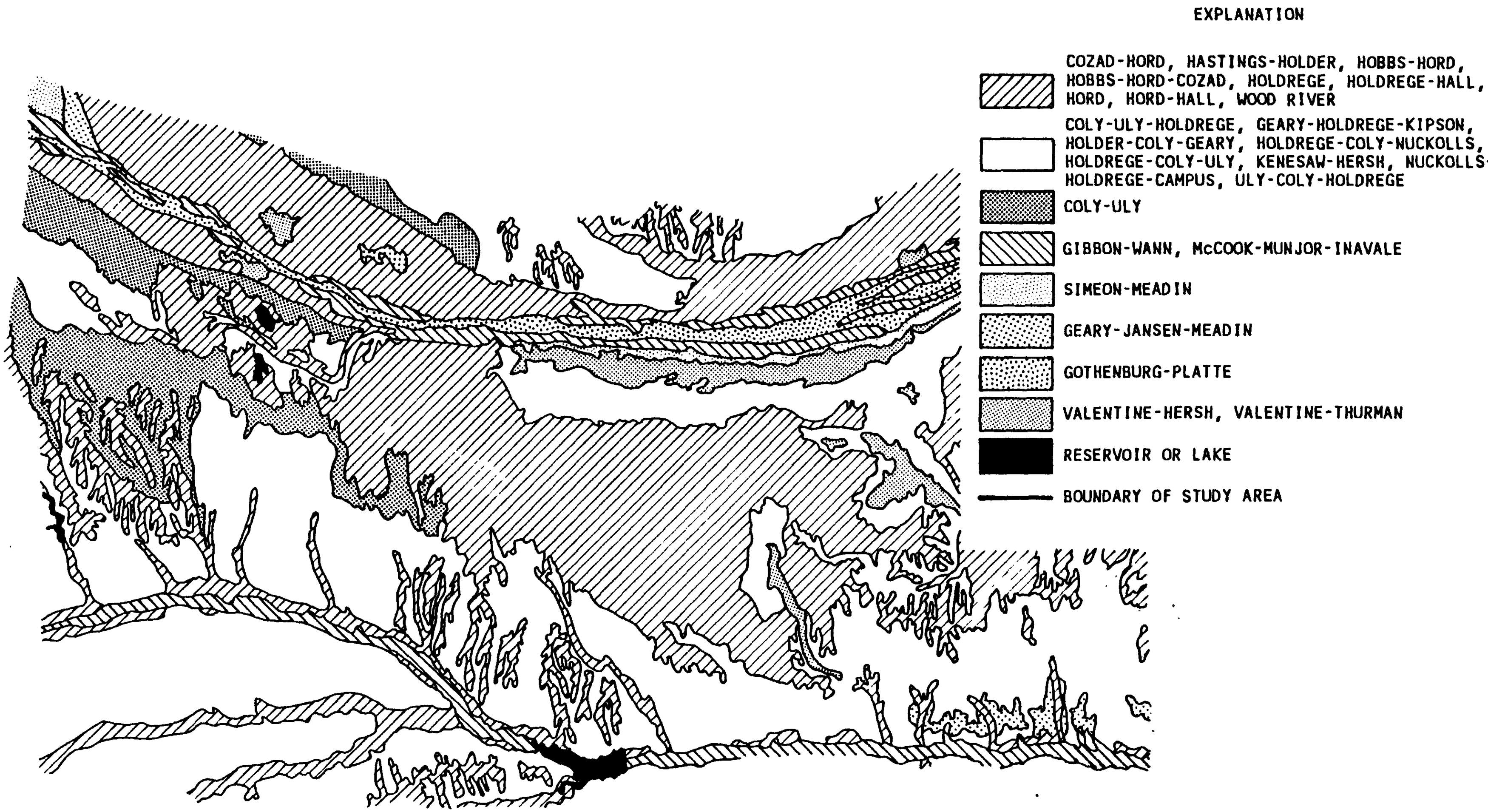


Figure 5.--Distribution of soil groups.

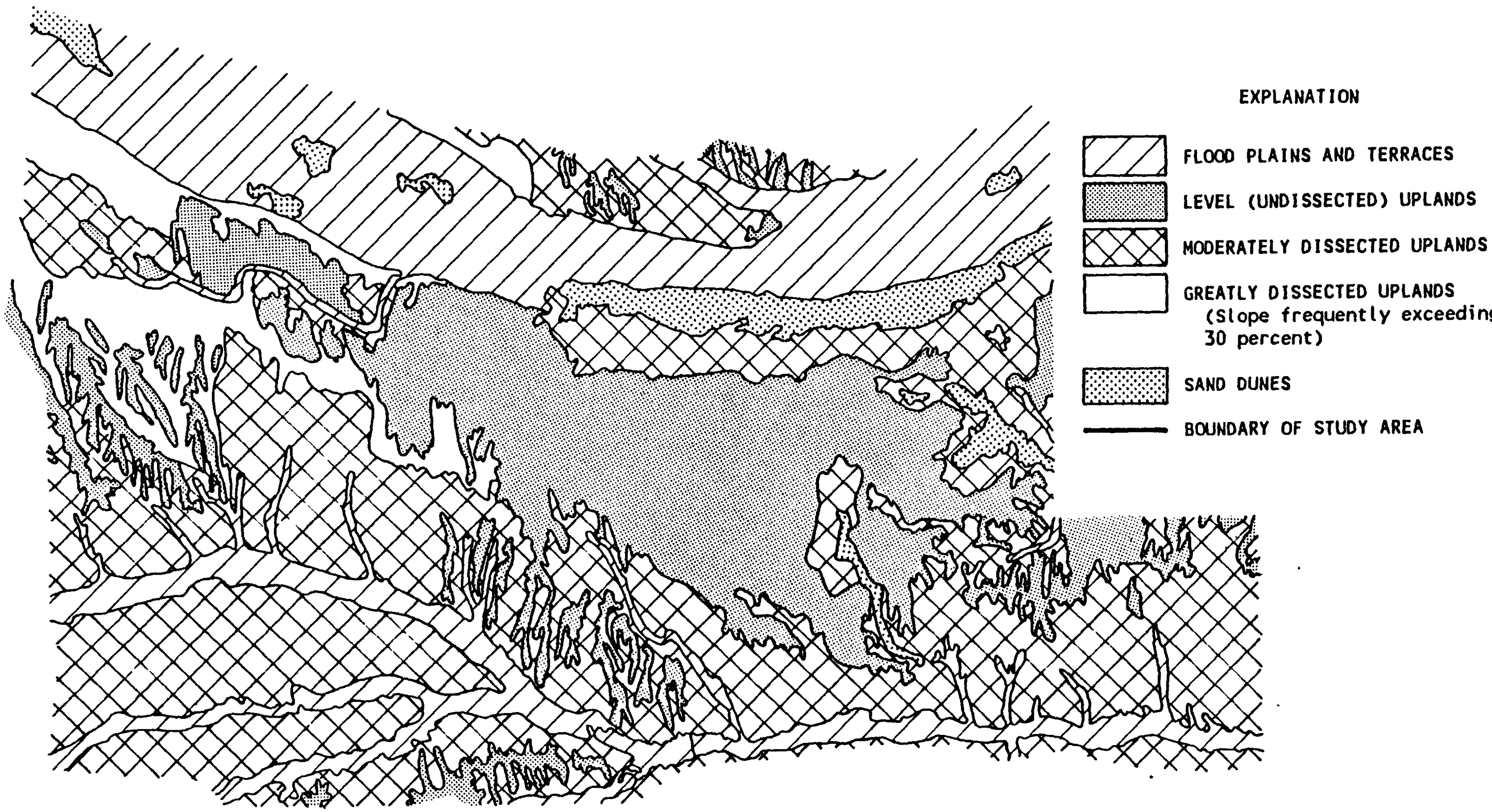


Figure 6.--Distribution of topographic types.

Silt loam to silty clay loams of the undissected uplands (soil group A) belong to two major soil associations. The predominant association is the Holdrege, which is moderately permeable with a high available water capacity and slightly rolling slope (table 1). In the eastern part of the study area these upland soils belong to the Hastings-Holder association, which are somewhat finer grained and heavier than the Holdrege association, which makes them less permeable. In the western part of the study area the undissected upland remnants are predominantly mantled by the Holdrege-Hall association, which is very similar to the Holdrege association, but is slightly less sloping.

Very similar to the soils of the undissected uplands are the soils of the higher terraces (group A), which are also derived from loess parent material and have little or no slope, but occur at a slightly lower topographic position. Three different soil associations (Hord, Hord-Hall, and Cozad-Hord), which are nearly identical in their physical properties, comprise these high terrace soils. For the purposes of this study, they can be grouped with the undissected upland soils of loess origin.

The silt loam to silty clay loam soils of the dissected uplands are also of loess origin. Seven soil associations of the dissected area can be grouped together (group B), because they have moderate permeabilities, high available water capacities, and steep, rolling slopes. They are Geary-Holdrege-Kipson, Holder-Coly-Geary, Holdrege-Coly-Nuckolls, Holdrege-Coly-Uly, Nuckolls-Holdrege-Campus, and Uly-Coly-Holdrege. Similar to these soils, but with slightly steeper slopes, is the Coly-Uly-Holdrege association occurring in small, scattered areas in the western and southern parts of the study area. The steepest sloped soils of the study area belong to the Coly-Uly association (group C) occurring principally in small areas in the northwestern part of the study area associated with steep bluffs and escarpments along the Platte River. This soil group has slopes exceeding 50 percent.

The sandy loam to sandy soils (group H) occupy only a small part of the study area and are developed largely on eolian sand deposits. The major area of sandy upland soil parallels the Platte River valley on the south side of the Platte River and belongs to the Valentine-Hersh and Valentine-Thurman associations, which are highly permeable with low available water capacities and rolling slopes. Small outliers of this soil occur in Franklin and Kearney Counties.

Another association of sandy soils, the Simeon-Meadin (group E), composed of sandy sediments rather than eolian sands is found on the terraces along the south side of the Platte River. These soils are the most permeable in the study area and have the lowest available water capacity.

Serving as a transition soil between the sandy and loessial soils is the Kensaw-Hersh association, which is a sandy loam with permeabilities and available water capacities similar to the loessial upland soils. Because this soil has similar hydrologic characteristics to the loessial soils of the dissected uplands, it is included with soil group B.

Table 1.--Soil groups and their hydrologic properties

[In/in, inch per inch; in/hr, inch per hour]

Soil group	Association	Topographic characteristics and position	Parent material	Texture	Average available water capacity (In/in)	Average perme-ability (In/hr)	Slope range (Percent)
C	Coly-Uly	Dissected uplands	Loess	Silt loam	0.22	1.31	3 - 60
B	Coly-Uly-Holdrege	Dissected uplands	Loess	Silt loam to silty clay loam	.21	1.30	3 - 30
A	Cozad-Hord	Terraces and foot slopes	Loess and alluvium	Silt loam	.19	1.30	0 - 3
B	Geary-Holdrege-Kipson	Dissected uplands	Loess - weathered shale	Silt loam to silty clay loam	.20	1.26	1 - 20
F	Geary-Jansen-Meadin	Dissected uplands	Loess - sand sediments	Sand to silty clay loam	.14	7.60	3 - 30
D	Gibbon-Wann	Flood plain (seasonally high water table	Alluvium	Fine sandy loam to silt loam	.19	2.94	0 - 20
G	Gothenburg-Platte	Flood plain (seasonally high water table)	Alluvium	Loam to sand	.05	17.60	0 - 3
A	Hastings-Holder	Undissected uplands	Loess	Silt loam to silty clay loam	.21	.99	0 - 9
A	Hobbs-Hord	Flood plains - low terraces	Alluvium - loess	Silt loam	.20	1.48	0 - 3
A	Hobbs-Hord-Cozad	Flood plains, terraces, foot slopes	Alluvium - loess	Silt loam	.20	1.58	0 - 3
B	Holder-Coly-Geary	Dissected uplands	Loess	Silt loam to silty clay loam	.20	1.29	0 - 30
A	Holdrege	Undissected uplands	Loess	Silt loam to silty clay loam	.20	1.30	0 - 6
B	Holdrege-Coly-Nuckolls	Dissected uplands	Loess	Silt loam to silty clay loam	.21	1.31	0 - 30
B	Holdrege-Coly-Uly	Dissected uplands	Loess	Silt loam to silty clay loam	.20	1.30	1 - 30
A	Holdrege-Hall	Undissected uplands	Loess	Silt loam to silty clay loam	.20	1.18	0 - 3
A	Hord	Terraces and foot slopes	Loess	Silt loam	.21	1.30	0 - 3
A	Hord-Hall	Terraces	Loess	Silt loamto silty clay loam	.21	1.13	0 - 3
B	Kenesaw-Hersh	Uplands and terraces	Loess and eolian sands	Fine sandy loam to silt loam	.19	2.03	0 - 15
D	McCook-Munjor-Inavale	Flood plains	Silty to sand alluvium	Fine sand to silt loam	.16	5.47	0 - 3
B	Nuckolls-Holdrege-Campus	Dissected uplands	Loess and weathered sandstone	Loam to silty clay loam	.18	1.30	1 - 30
E	Simeon-Meadin	Uplands - terraces	Sandy sediments	Sand to loamy sand	.06	14.68	0 - 3
B	Uly-Coly-Holdrege	Dissected uplands	Loess	Silt loamto silty clay loam	.21	1.30	3 - 30
H	Valentine-Hersh	Dissected uplands	Eolian sands	Sand to loamy sand	.10	10.42	0 - 17
H	Valentine-Thurman	Dissected uplands	Eolian sands	Sand to loamy sand	.08	12.88	0 - 17
A	Wood River	Terraces	Silty and clayey alluvium	Silt loam to silty clay (saline-alkaline)	.19	.95	0 - 2

Source: From Dugan (1984).

Another transitional soil is the Geary-Jansen-Meadin association (group F) formed in loess and sandy sediment in certain locations in the southeastern part of the study area. Its hydrologic properties are intermediate between sandy and loessial soils.

The soils of the flood plains and low terraces are predominantly loams to loamy sands with moderate to high permeabilities and moderate to low available water capacities. The McCook-Munjor-Inavale and Gibbon-Wann associations (group D) occupy the flood plains of the Platte and Republican Rivers, and the Gothenburg-Platte association (group G) occurs only in the Platte River flood plain. The soils of the Platte River flood plain have higher water tables than those of the Republican River flood plain.

The soils in the flood plains of the tributaries to the Republican, Platte, and Little Blue Rivers are not truly flood plain soils; they are more characteristic of terrace soils. The Hobbs-Hord-Cozad and Hobbs-Hord associations occupy these areas and have characteristics quite similar to the undissected upland loess soils, thus are included in soil group A.

A somewhat unusual terrace soil is the Wood River association found north of the Platte River. These soils have moderate overall permeabilities, but contain a very restrictive horizon, with permeability of less than 0.15 inch per hour. This is the result of a massive subsoil structure because of saline or alkaline conditions. It is grouped with soil group A because of its limited occurrence.

More specific information on soils can be obtained from individual county soil surveys published by the U.S. Department of Agriculture, Soil Conservation Service. The hydrologic properties of the soils of the study area are discussed by Dugan (1984).

Native Vegetation

The native vegetation of the study area is dictated largely by the climate. The subhumid to semiarid climate of this region, characterized by long periods of deficient soil moisture, results in a grassland regime. Grasses generally have large consumptive water requirements but are able to withstand the long periods of deficient soil moisture. This type of grassland generally is classified as mixed prairie--a combination of tall-, mid-, and short-grass communities, which are principally perennial species.

Topography or slope plays a significant role in the distribution of these grassland communities. Slope affects the amount of precipitation that infiltrates the soil; thus, the availability of soil moisture. Also, the slope direction affects the grassland community that is present. Generally south-facing slopes have more soil-moisture loss as a result of greater solar radiation. On hilltops and these south-facing slopes, the short-grass communities generally dominate. The bottom of small canyons or draws, lower slopes, and low terraces generally are dominated by a combination of tall and mid-grasses. On the lower side slopes, a combination of short and mid-grass communities exist in a transitional zone.

The short-grass community is dominated by two drought-resistant species--blue grama and buffalo grass. These species are dormant when soil moisture is in extremely short supply. They are considered warm season grasses that thrive when soil moisture is adequate from late May until early July. These grasses have a very dense lateral root system in the upper 12-18 inches of soil, with vertical development as deep as 60 inches. They are extremely palatable to cattle. Blue grama reaches a height of 3-5 inches and the shorter buffalo grass, 1-4 inches. These short grasses thrive in silty to clayey soil but not in sandy soil.

The mid- and tall-grass communities typically reach heights of 18 inches to 3 feet in the study area. The predominant species in this community are big bluestem, side-oats grama, western wheatgrass, switchgrass, and Canada wild rye (Weaver and Albertson, 1956). The mid- and tall grasses in south-central Nebraska, particularly bluestem, often occur as isolated bunchgrass within the more prominent short-grass community. These mid- and tall grasses can be divided into cool and warm season species based on their primary growth season. Cool and warm season species have different seasonal consumptive water requirements corresponding to their growth periods. The cool season species include western wheatgrass and Canada wild rye. The warm season species include big and little bluestem and side-oats grama. The mid- and tall grasses generally are characterized by less lateral root development than the short grasses within the upper 18 inches. This is common to the taller true prairie species that do not need extensive lateral development to capture moisture in their normally wetter domain. They exhibit greater vertical and oblique root development than the short grasses. Frequently, tall grass root systems extend vertically between 5 and 6 feet, and occasionally as much as 7 feet (Weaver and Albertson, 1956).

Many other herbaceous nongrass species occur in the mixed prairie of the study area. These occur as isolated or small groups among the grassland communities. They include plains milkweed, soapweed (yucca), ragweed, primrose, prairie rose, goldenrod, sunflower, and others. These nongrass types of mixed prairie mostly are perennial, with deep root systems (often exceeding 8 feet) and relatively large water requirements.

The sandy soils of the study area have grassland communities that differ from those of the loess soils. Species such as sand dropseed, sand bluestem, sand reed, needle-and-thread, and other grasses that thrive in sand are prevalent. Short-grass species such as blue grama and buffalo grass are not present.

Along streams and rivers, woodlands are prevalent. Phreatophytes such as willows and cottonwoods border the larger, permanently flowing streams. The larger flood plain and ephemeral tributaries often contain introduced species such as American and red elm, hackberry, and red and green ash. Other small areas of woody vegetation occur in small canyons or "draws" in the dissected areas where soil-moisture conditions are favorable. These primarily consist of thickets of scrub vegetation such as wild plum and chokecherry. Woodlands, however, account for only a small part of the study area--less than 5 percent.

Land Use

Land use is significant to hydrology because of the extensive consumption of soil moisture through transpiration by growing plants. The consumptive water requirements of different plants or vegetation, which will be discussed later, vary considerably according to plant type.

Land use in the study area affects the spatial patterns of consumptive water use. Ninety percent or more of the land in the study area is devoted to agriculture, with the remainder considered undifferentiated land use, including urban areas, woodlands, roads, and highways. In this study, the consumptive water use of nonagricultural land is considered the same as that of grassland.

Agricultural land uses can be divided into two categories--cultivated or cropland and pasture or rangeland. Presently, about 55 percent of the agricultural land in the study area is cultivated and 40 percent is pasture or rangeland (grassland). This relation has not been static during the study period from 1940 to 1981. Table 2 indicates an overall increase of land under cultivation within the study area during this period. This change is related largely to economic conditions requiring more intensive land use, changing agricultural technology, principally in irrigation techniques, and government agricultural programs. Also, the recent emphasis on specialization in cash-grain farming, principally corn produced with irrigation, with the attendant decrease in general farming, has created less need for rangeland for livestock.

Table 2.--Summary of land use for the study area for 10-year intervals from 1940 to 1980

Year	Percent of cultivated land	Percent of irrigated cultivated land	Percent of cultivated land in				
			Row Crop	Sorghum	Small grain	Tame hay	Fallowland
1940	47.0	0.3	31.4	17.7	29.3	5.3	16.1
1950	56.3	10.6	35.6	5.9	33.8	9.9	14.8
1960	53.3	27.5	29.9	16.3	22.9	11.9	19.0
1970	49.4	37.7	30.5	13.0	19.2	12.4	24.9
1980	55.2	55.7	45.8	15.3	16.6	9.7	12.6

Land-use patterns are not homogeneous throughout the study area. Eight counties shown in table 3 illustrate the spatial differences within the study area. Topography and suitability for irrigation account for many of the differences in land use. Kearney and Phelps Counties, which are almost entirely undissected tablelands with large percentages of land suitable for irrigation, are currently more than 75 percent cultivated. A significant increase in land under cultivation has occurred in these two counties since 1940 because of the increased emphasis in cash-grain farming, particularly corn. Also significant is the fact that nearly 75 percent of the total cropland of these two counties was irrigated in 1980, compared to approximately 0.2 percent in 1945. Nearly 70 percent of all cultivated land is in row crops, mainly corn, and approximately 98 percent of the corn was irrigated in 1980.

Agriculture is more diversified in the other six counties listed in table 3. The land in these counties is mainly dissected tableland that is potentially less irrigable. Cultivated land accounted for slightly more than 50 percent of the total land in 1980. Thus pasture and rangeland devoted to cattle grazing are still significant in these counties. Crop production currently is well balanced among row crops, small grains, and sorghum. Corn production, however, showed a great increase from 1965 to 1980, as more cropland was irrigated. More than 40 percent of the combined cropland of these six counties is now irrigated. Winter wheat accounts for nearly all of the small grain production in these six counties.

Changes in crop types have occurred throughout the study period (tables 2 and 3). Row-crop production, mainly corn, has increased; while small grain, essentially winter wheat, has declined. Soybeans, included as a row crop, have increased throughout the study area in the last 10 years, but still account for only about 5 percent of the row-crop production. Grain sorghum production has shown significant spatial changes within the study area. Declines in grain sorghum are evident in the principal irrigated areas (Dawson, Kearney, and Phelps Counties), but steady or increased production is apparent in the counties with less irrigation. Grain sorghum is a more reliable feed-grain crop under dryland conditions than corn. Forage production, mostly alfalfa, increased greatly from 1940 to 1960, but has decreased gradually since 1960. Fallow, or idle land, peaked in the 1960's, but has declined significantly since then.

DESCRIPTION OF THE HYDROGEOLOGIC SYSTEM

The hydrogeologic system is divided into four components for this study: Surface water, soil zone, unsaturated zone, and saturated zone or ground water. Procedures and computer programs have been developed to represent the hydrologic regime in three of these components; however, suitable data and an appropriate computer program are not available to represent the unsaturated zone.

Table 3.--Land use for principal counties in the study area for 5-year intervals from 1940 to 1980

Year	Percent of cultivated land	Percent of irrigated cultivated land	Percent of cultivated land in				
			Row Crop	Sorghum	Small grain	Tame hay	Fallowland
			FRANKLIN COUNTY - 371,000 acres in county				
1940	43.1	0.0	27.4	24.4	34.3	1.2	12.6
1945	50.6	0.0	50.6	7.6	35.9	2.4	3.5
1950	52.2	1.7	32.7	10.1	35.8	9.2	12.2
1955	45.5	8.1	21.2	23.3	26.2	11.6	17.7
1960	46.3	20.2	22.4	21.8	26.7	6.7	22.4
1965	40.3	23.5	15.0	23.7	25.6	6.4	29.4
1970	42.5	31.3	25.0	17.3	23.0	6.2	28.5
1975	42.3	42.0	33.4	25.7	19.2	4.3	15.8
1980	43.2	49.7	39.8	26.4	20.1	4.2	9.5
			FURNAS COUNTY - 467,600 acres in county				
1940	49.4	0.0	32.5	18.8	26.7	3.1	19.0
1945	53.1	0.0	45.0	5.6	31.7	3.5	14.3
1950	56.4	1.8	27.2	6.8	33.6	5.0	27.2
1955	46.9	9.8	18.3	12.3	30.0	9.2	29.9
1960	50.9	13.0	17.2	20.3	28.9	5.7	27.7
1965	51.6	13.7	8.0	22.1	27.3	6.6	36.0
1970	50.4	18.3	16.0	16.7	26.5	6.9	34.0
1975	53.6	21.9	15.9	17.9	29.0	6.3	30.9
1980	58.6	26.2	18.2	17.5	28.6	5.5	30.2
			GOSPER COUNTY - 298,500 acres in county				
1940	39.1	0.0	35.4	21.1	22.3	3.4	17.8
1945	48.8	0.1	55.6	6.4	28.8	2.8	6.3
1950	49.4	6.2	32.9	8.6	34.3	5.4	18.8
1955	43.5	15.6	24.2	13.2	27.6	10.4	24.6
1960	48.7	20.9	24.0	24.3	22.2	7.3	22.2
1965	42.8	23.1	14.0	21.9	23.6	8.1	32.4
1970	42.5	36.6	28.2	15.0	21.1	7.3	28.4
1975	43.0	48.3	37.7	14.5	20.0	6.9	20.9
1980	44.1	60.0	44.6	17.3	18.1	5.7	14.3

Table 3.--Land use for principal counties in the study area for 5-year intervals from 1940 to 1980--Continued

Year	Percent of cultivated land	Percent of irrigated cultivated land	Percent of cultivated land in Row Crop	Sorghum	Small grain	Tame hay	Fallowland
			HARLAN COUNTY - 369,000 acres in county				
1940	46.6	0.0	29.9	18.8	30.6	2.3	18.3
1945	56.5	0.0	44.9	4.5	38.8	3.4	8.3
1950	58.9	1.7	28.7	5.2	38.9	4.1	23.1
1955	46.9	6.8	19.5	10.2	32.3	8.6	29.5
1960	54.3	10.6	16.4	21.1	28.9	5.5	28.2
1965	49.7	13.9	8.7	22.0	27.3	7.5	34.6
1970	48.9	27.9	20.4	19.1	23.9	6.1	30.5
1975	48.6	32.1	25.7	23.9	24.1	4.9	21.9
1980	51.2	46.5	30.8	23.2	23.1	5.1	17.8
			KEARNEY COUNTY - 328,500 acres in county				
1940	61.8	0.0	25.4	10.9	46.6	2.0	15.0
1945	66.7	0.1	43.8	2.6	48.3	3.3	1.9
1950	69.2	12.9	32.0	4.0	47.3	5.2	11.4
1955	69.2	23.0	31.3	12.2	31.0	8.7	16.8
1960	72.7	38.7	34.9	14.3	28.4	4.8	17.6
1965	66.5	41.2	26.6	14.2	28.6	6.1	24.5
1970	71.3	51.7	41.6	9.1	22.4	5.1	21.8
1975	71.2	60.7	56.0	11.2	16.4	4.8	11.6
1980	82.9	71.4	64.4	10.0	12.1	3.7	9.8
			PHELPS COUNTY - 351,600 acres in county				
1940	50.4	0.1	33.0	11.2	33.8	2.2	19.8
1945	64.6	0.3	52.2	3.3	41.2	2.4	1.5
1950	66.3	20.2	37.5	3.6	42.1	4.7	12.1
1955	59.1	32.3	38.7	8.3	31.8	9.5	11.8
1960	68.0	44.5	40.1	12.6	23.5	5.4	18.4
1965	63.5	50.8	31.3	15.6	21.2	6.2	25.5
1970	61.3	60.5	47.1	5.8	17.5	7.2	22.3
1975	65.3	73.1	68.6	7.5	7.9	6.1	9.9
1980	74.9	84.1	77.5	7.5	5.8	4.2	5.0

Table 3.--Land use for principal counties in the study area for 5-year intervals from 1940 to 1980--Continued

Year	Percent of cultivated land	Percent of irrigated cultivated land	Percent of cultivated land in				
			Row Crop	Sorghum	Small grain	Tame hay	Fallowland
			DAWSON COUNTY - 632,100 acres in county				
1940	41.3	2.0	39.5	14.2	14.9	17.7	13.6
1945	50.0	.8	50.7	4.6	20.4	22.4	1.8
1950	48.8	29.1	47.9	1.9	18.1	26.7	5.3
1955	46.2	47.0	46.5	2.7	10.1	34.8	5.8
1960	46.4	58.7	51.5	5.6	7.9	29.9	5.0
1965	45.6	47.4	37.5	6.5	5.7	36.5	13.9
1970	43.5	54.6	44.8	1.7	4.0	34.5	14.9
1975	46.7	65.4	54.7	1.5	3.2	33.6	7.0
1980	46.8	77.2	66.4	1.0	2.8	27.6	2.1
			WEBSTER COUNTY - 368,900 acres in county				
1940	44.6	0.0	22.9	12.8	37.3	1.7	14.2
1945	55.3	0.0	50.2	9.7	33.0	3.5	3.6
1950	54.7	.6	38.8	9.7	33.5	6.8	11.8
1955	43.9	2.6	20.8	24.0	25.1	14.9	15.1
1960	46.5	7.5	16.8	31.1	24.0	10.0	18.1
1965	40.9	8.5	8.2	28.1	28.2	11.1	24.4
1970	39.8	15.1	16.0	25.5	24.0	10.1	24.5
1975	40.7	19.3	20.5	27.0	26.8	9.5	16.3
1980	46.9	27.2	21.0	28.3	27.4	8.0	15.2

Surface-Water System

The surface-water system consists of streams, reservoirs, canals, and drains. These components of the surface-water system often are interrelated. Canals and drains provide passageways either for diversion from or return flow to streams, and reservoirs store water that is delivered by streams or diverted to streams.

Streams

Two major stream systems, the Platte and Republican Rivers, are in the study area. The Platte River has three natural tributaries within the study area: Wood River, which flows into the Platte outside the study area; Plum Creek, which flows through the northern part of the area and joins the Platte River in Gosper County; and Dry Creek, which flows into the Platte River in Kearney County. The Republican River has several tributaries in the study area. Some of the major ones are: Medicine and Thompson Creek on the north side and Sappa, Beaver, and Prairie Dog Creeks on the south side.

Figure 7 shows the location of live reaches of the streams, or perennial streams, in the study area. The live reaches are the segments of the stream that are interconnected with the saturated zone and which have perennial base flow. Intermittent stream reaches that flow only part of the year are not shown on this figure.

Stream reaches can either gain water from or lose water to the ground-water system. Some reaches of the Platte and Republican Rivers gain water from the ground-water system at certain times of the year, but lose water to the ground-water system at other times.

Figure 8 contains schematics of the surface-water system showing the perennial streams, canal diversions, canal returns, selected drains, and stream-gaging sites along the Platte and Republican Rivers. The average annual flows at the stream-gaging sites, and the average annual canal diversions and returns are shown on this figure. The maximum period of record used in this study for these values is from September 1, 1939, through May 31, 1981. When data were not available for the maximum period of record, the available period of recorded data were used.

Base flows were computed for stream-gaging sites where flows were not regulated by upstream reservoirs. Table 2 in the data report for this study (Bartz and Peckenpaugh, 1986) contains a listing of the average base flows for the above sites based on average flows for October, November, and December. This table also contains average annual flows at all gaging stations in or near the study area.

Four low-flow-measurement studies (seepage runs) were performed in the study area starting during April 1980 and ending during October 1982. The purpose of these studies was to determine the contribution of ground-water seepage to streamflow. Figure 5 of the data report (Bartz and Peckenpaugh, 1986) delineates the area of the low-flow measurements. The low-flow measurements are published in U.S. Geological Survey Water-Resources Data, Nebraska, water years 1980 through 1983.

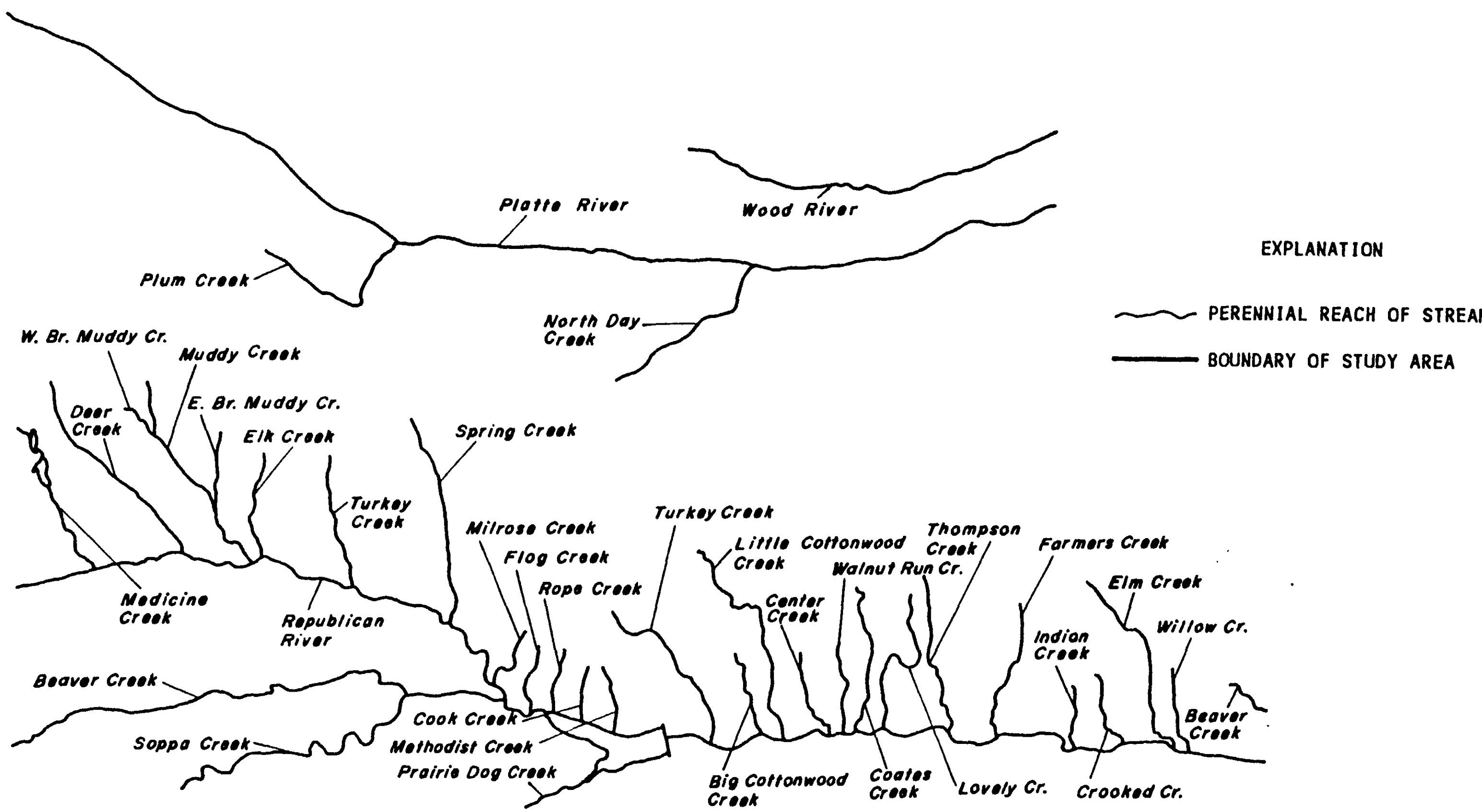


Figure 7.--Location of perennial streams.

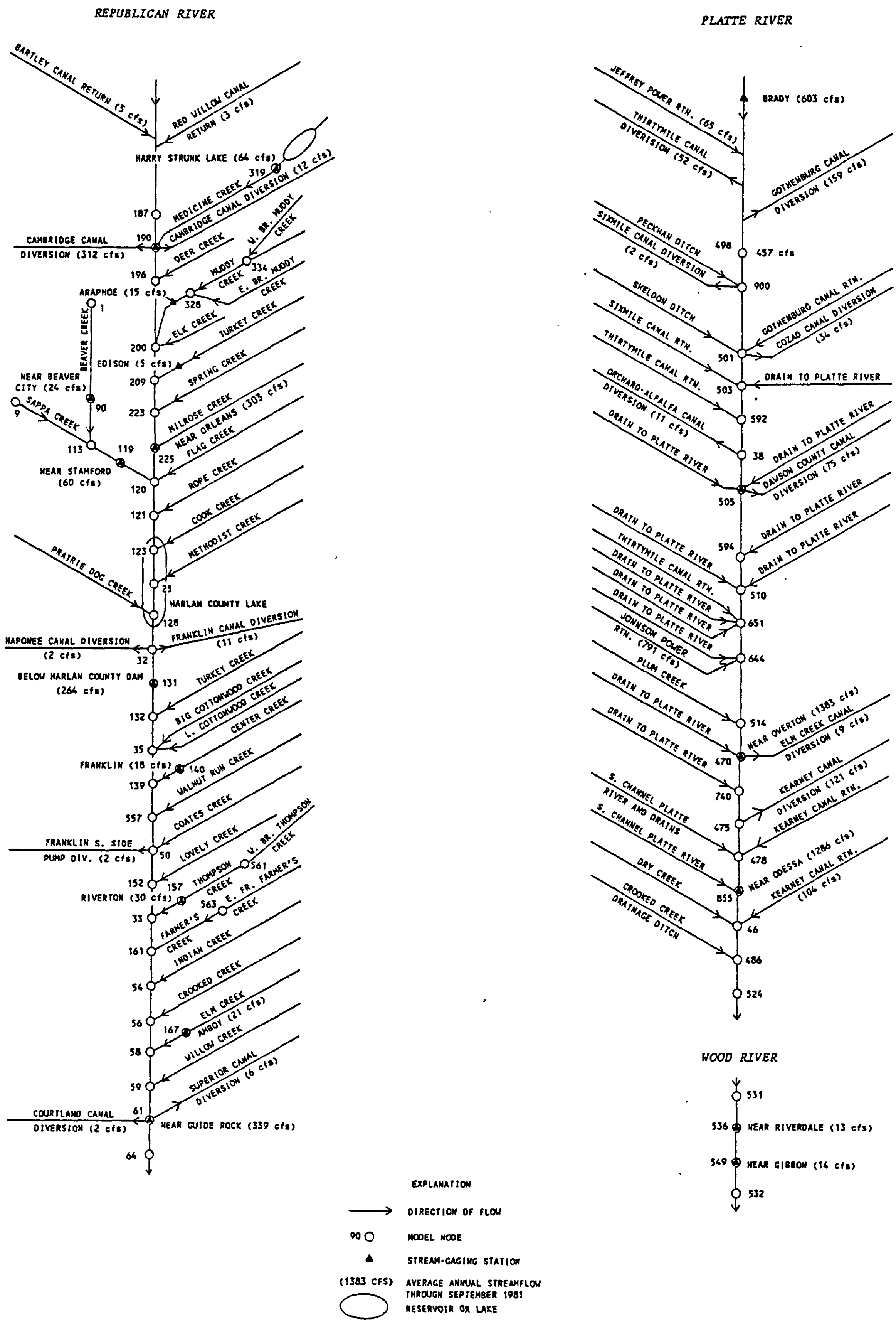


Figure 8.--Surface-water system and average annual flows at selected sites.

Additional surface water for irrigation has been diverted into the study area. This has resulted in a rise in the water table, an increase in base flow, and a resultant upstream migration since the early 1940's of the point where stream reaches become perennial. This is true for many Platte River tributaries that are on the river's south side and for Republican River tributaries that are on the river's north side. Conversely, flow has decreased in Sappa, Beaver, and Prairie Dog Creeks, which are on the south side of the Republican River, because of increased ground-water and surface-water development along their drainages. The effects of ground-water development along the Platte and Republican Rivers are masked by the regulation of flow from upstream reservoirs.

Canals

Nineteen canals currently provide surface water for irrigation in the study area (fig. 8 and 9). These canals can be divided into three groups. In the first group, eight major canals divert water from the Platte River for irrigating substantial acreages. These canals, in downstream order of diversion from the Platte River, are: Tri-County Supply, Thirtymile, Gothenburg, Sixmile, Cozad, Orchard and Alfalfa, Dawson County, and Kearney. In additon to these, the Elm Creek Canal diverted water from the Platte River for surface-water irrigation until it was abandoned in 1963. Prior to 1974, the Gothenburg Canal was used to provide cooling water for electric power generation. Water from the Kearney Canal is used for irrigation and to provide cooling water for electric power generation.

Central Nebraska Public Power and Irrigation District canals comprise the second group. The Tri-County Supply Canal diverts water from the Platte River east of North Platte, Nebraska, about 18 miles west of the study area. This canal supplies substantial amounts of water to the CNPPID's irrigation system. Some irrigation water is supplied directly from the Tri-County Supply Canal, but the E-65, E-67, and Phelps County Canals, which are supplied from the Tri-County Supply Canal, distribute most of the irrigation water to the northern part of the study area.

The U.S. Bureau of Reclamation operates the Frenchman-Cambridge and Nebraska-Bostwick Divisions along the Republican River. Eight canals in these divisions form the third group. Red Willow, Bartley, and Cambridge Canals in the Frenchman-Cambridge Division obtain water from the Republican River and from upstream reservoirs. Five canals in the Nebraska-Bostwick Division carry water from Harlan County Lake or the Republican River to irrigate land in the study area. These canals, in downstream order of diversion and their water source are: Franklin and Naponee from Harlan County Lake, Franklin South Side Pump from the Republican River, and Superior and Courtland from the Republican River.

The Johnson Power Return is CNPPID's return to the Platte River. It carries water from CNPPID's hydroelectric plant and additional flow required to meet downstream diversions. It also supplied cooling water for the Canaday plant when it was in operation.

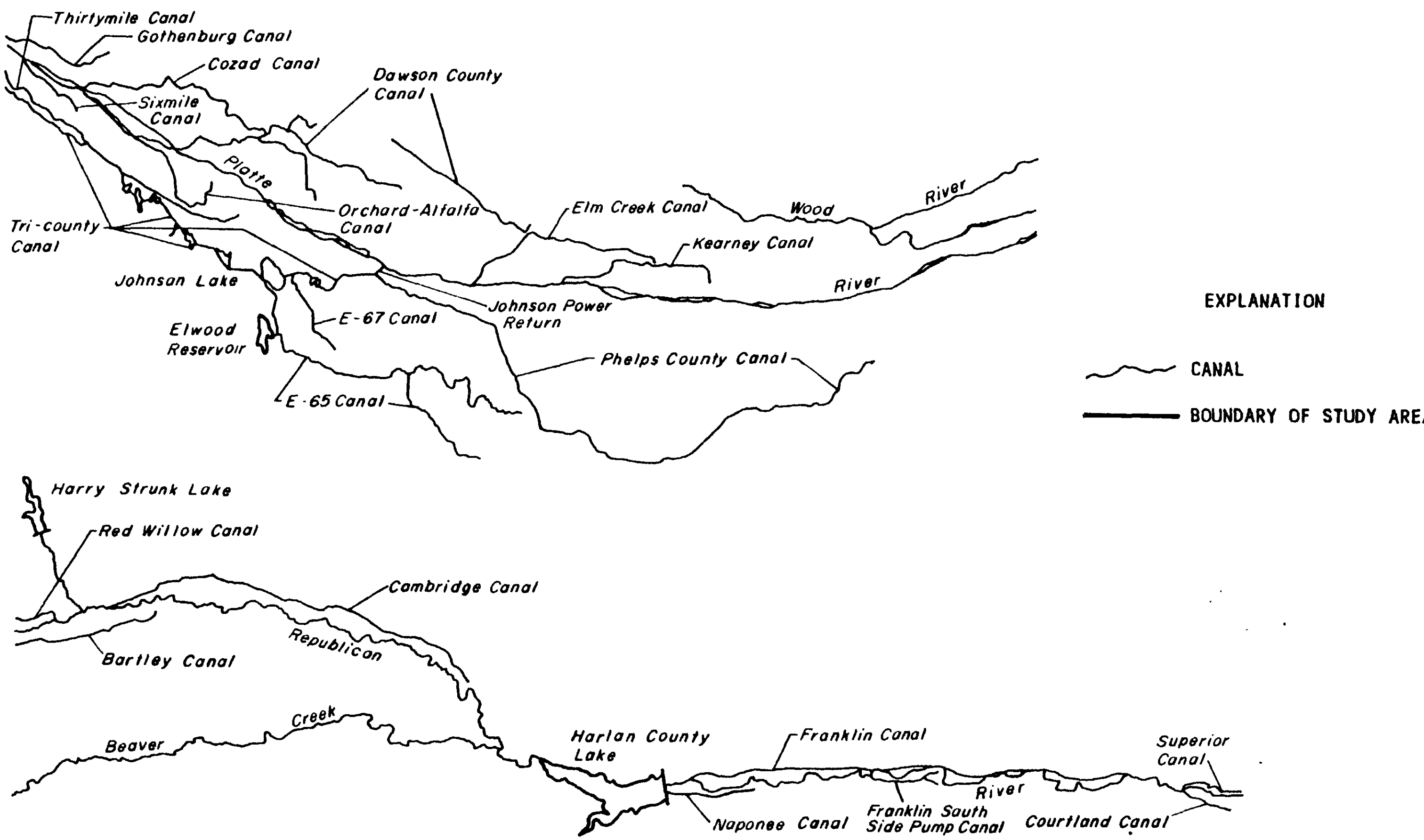


Figure 9.--Location of major irrigation canals.

Figure 10 delineates the locations of surface-water irrigated areas in 1980. Table 4 contains information on the areas irrigated from each canal and the average amount of water diverted or returned from each canal. These data are computed for the period September 1939 through May 1981, unless the canal was operated for a shorter period. For modeling purposes, the canal diversions were compiled for the nonirrigation season from September 1 through May 31 and for the irrigation season from June 1 through August 31. These data are available in the data report for this study (Bartz and Peckenpaugh, 1986).

Table 4.--Average annual canal diversions, returns, and irrigated acres from September 1939 to 1981

[Use of water: I, irrigation; P, power generation. Model node locations are shown on figure 8. Dashes indicate no specific return or diversion exists.]

Canal	Model node			Average annual diversion		Average annual return (Acre-feet)	Average irrigated acres
	Water use	Diversion	Return	Irrigation (Acre-feet)	Power (Acre-feet)		
Jeffrey Power Return	P	(1)	(1)	------	------	46,840	------
Thirtymile	I	(1)	592	37,834	------	------	10,665
Gothenburg	I,[2]P	(1)	501	35,220	80,000	68,580	2,295
Sixmile	I	900	503	1,471	------	------	1,135
Cozad	I	501	---	24,621	------	------	7,776
Orchard and Alfalfa	I	38	---	8,333	------	------	1,535
Dawson County	I	505	---	54,358	------	------	7,794
Johnson Power Return	P	(1)	644	------	------	573,400	------
Elm Creek	I	470	---	6,850	------	------	3,000
Kearney	I,P	475	46	12,922	74,990	74,990	2,405
Bartley	I	(1)	---	3,313	------	------	6,219
Red Willow	I	(1)	---	2,502	------	------	1,991
Cambridge	I	190	---	8,670	------	------	12,762
Naponee	I	32	---	1,107	------	------	1,199
Franklin	I	32	---	7,971	------	------	10,915
Franklin Southside	I	50	---	1,152	------	------	1,478
Superior	I	61	---	4,280	------	------	560
Courtland	I	61	---	1,658	------	------	384
Tri-County Supply	I,P	(4)	---	[5]4,815	------	------	5,694
Phelps County	I	(4)	---	59,032	------	------	(6)
E-65	I	(4)	---	35,961	------	------	(6)
E-67	I	(4)	---	4,369	------	------	(6)

1 Outside study area.
2 Power generation discontinued in 1974.
3 Abandoned in 1963.
4 Diversion occurred within the Central Nebraska Public Power and Irrigation District's surface-water system; therefore, node value is not given.
5 Values for 1981 only.
6 For Phelps, E-65, and E-67 canals, the irrigated acres are combined. The combined irrigated acres are: 1941 - 26,320; 1946 - 74,434; 1955 - 104,261; 1965 - 122,058; 1975 - 122,628; and 1981 - 129,375.

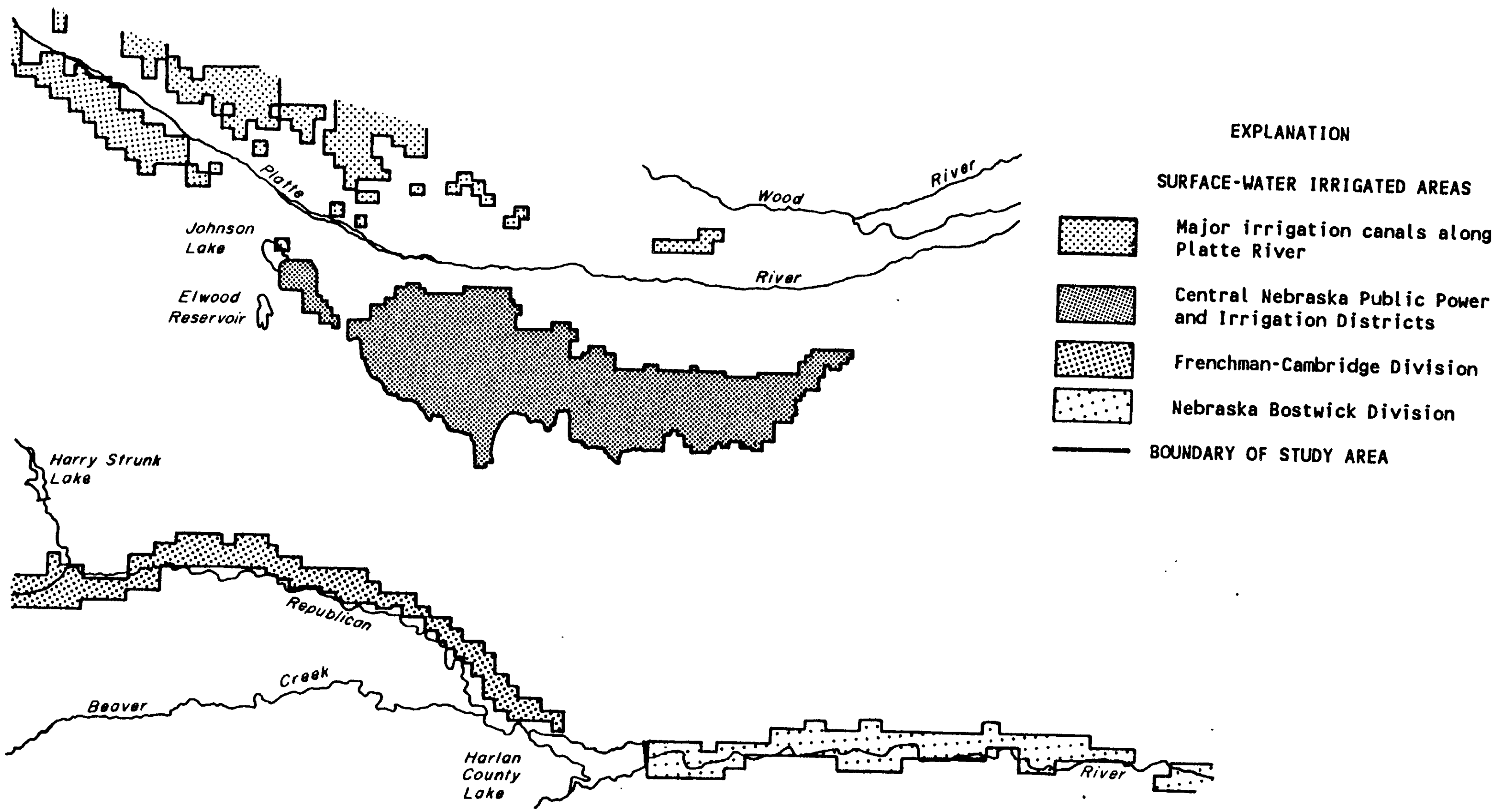


Figure 10.--Location of surface-water irrigated areas for 1980.

Lakes or Reservoirs

Four lakes or reservoirs in the study area provide water for irrigation. Table 5 contains information on reservoir size, initial date of operation or impoundment, and average annual seepage losses. It is worth noting that the seepage losses per surface area are much greater for Johnson Lake and Elwood Reservoir than for Harry Strunk and Harlan County Lakes. This is attributable to greater permeability of materials beneath Johnson Lake and Elwood Reservoir than the other two lakes.

The data report by Bartz and Peckenpaugh (1986) contains an explanation of the procedures used to compute the seepage losses from the reservoirs. Also, table 8 of that report lists the annual seepage losses for the four reservoirs.

Drains

The ground-water flow model, discussed later in this report, demonstrated that the drains along the Platte River valley are critical factors in determining the water levels in the area. Therefore, the drains are treated as a part of the surface-water system.

The drains in the study area are used to stabilize water levels and to carry excess surface water to the streams. For this study, only drains along the Platte River were added to the surface-water system.

The drains along the Republican River valley were not added to the surface-water system, because they were not found to be a critical factor in determining water levels in the southern part of the study area.

Soil Zone

The soil zone component of the hydrogeologic system consists of the soil extending from the land surface down to the base of the plants' root systems. Water from precipitation and applied irrigation that infiltrates the soil zone is either stored in the soil zone or removed by evapotranspiration, by deep percolation to drains or streams where it is carried away as surface runoff, or by percolation to the underlying unsaturated zone or directly to the saturated zone if no unsaturated zone exists.

Hydrologic Properties of the Soils

The soils in the study area have been delineated into eight soil groups (fig. 5) based on hydrologic properties of the soils. Each group was classified according to topographic position, slope, soil texture, available water capacity, and average permeability. Table 1 provides a listing of the hydrologic properties for the soil groups.

Table 5.--Seepage losses and surface area for lakes and reservoirs in the study area

Reservoir	Date of impoundment	Surface area (acres)	Average net seepage (acre-feet)	Average seepage per surface area (feet)
Johnson Lake	1942	2,500	38,398	15.4
Harry Strunk Lake	1950	1,850	7,581	4.1
Harlan County Lake	1952	13,338	24,044	1.8
Elwood Reservoir	1978	1,150	29,181	25.4

The rate at which water can be absorbed at the land surface is called the infiltration rate. Soils with higher permeabilities usually have greater infiltration rates and lower surface runoff rates than soils with lower permeabilities. Infiltration rates are influenced by the amount of water in the soil zone, the vegetation cover, the intensity of rainfall,and soil temperature (whether the ground is frozen). Infiltration rates are important in determining the amount of water that will move into the soil zone and the amount that will be surface runoff.

The available water capacity and the average permeability are critical in determining the amount of water stored in the soil and the amount that percolates downward to the saturated zone. Soils with higher permeabilities permit water to move downward more rapidly than soils with lower permeabilities. The available water capacity, which is the capacity of the soil to hold water, is low for soils with high permeabilities. Thus, soils with high permeabilities and low available water capacities have a greater potential for recharging the saturated zone. Conversely, soils with low permeabilities and high available water capacities will hold more water in their soil profiles and will have less potential for recharging the saturated zone.

Water Requirements of the Vegetation

Different plants have different water requirements; therefore, it is necessary to distinguish land uses between natural and cultivated vegetation and between the types of cultivated crops. Water requirements of the land-use groups in table 2, in decreasing order, are: Alfalfa (alfalfa and other tame hay); row crops (corn, soybeans, sugar beets, and potatoes); pasture and range (including urban lands, farmsteads, roads, and woodlands); sorghum; fallow; and small grain (wheat, oats, barley, and rye).

Flow Into and Out of the Soil Zone

Precipitation and water applied by irrigation to the soil zone is discharged from the soil zone by evapotranspiration, surface runoff, and deep percolation.

Monthly precipitation data from 39 weather stations, 31 weather stations under the administration of the National Oceanic and Atmospheric Administration (NOAA) and 8 weather stations under the administration of the CNPPID, for the period January 1940 through December 1981, were compiled for this study. Missing precipitation data were estimated from two or three nearby weather stations using a simple linear interpolation technique. Locations of 38 weather stations are shown on figure 11. One station (No. 29) is approximately 6 miles east of the study area. The average precipitation for each station is listed in table 6.

Surface and ground water are used for irrigating lands in the study area. Figures 9 and 10 show the location of major canals and surface-water irrigated areas, respectively. An indication of the ground-water irrigated lands can be obtained from the number and distribution of registered irrigation wells (fig. 12 for 1940 and fig. 13 for 1980) and the acres irrigated per well, by county for 5 years from 1940 to 1980 (table 7).

The amount of surface water applied for irrigation depends on land use, soils, climatic conditions, and system-operating procedures. The U.S. Bureau of Reclamation computes and removes canal seepage losses from their published diversions for their canals along the Republican River. Thus, the amount of water they list as being diverted, is applied as irrigation water. For the other canals, a part of the diverted water is lost to seepage or recharge to the ground-water system. For the major canals along the Platte River, it is estimated that 50 percent of diverted water is applied for irrigation and the other 50 percent is seepage back to the aquifer. Phelps, E-65, and E-67 Canals use 35 percent of their diversions for irrigation. The remainder is seepage back to the aquifer. CNPPID computes seepage losses for the Tri-County Supply Canal. Therefore, all the water diverted from this canal for the stated purpose of irrigation along the canal is used for irrigation.

The primary component of discharge from the soil zone is evapotranspiration (ET). The Jensen-Haise procedures for calculating potential evapotranspiration were used for this study. These procedures are described by Jensen and others (1969) and Cady and Peckenpaugh (1985). The calculation of actual evapotranspiration uses potential evapotranspiration data with appropriate crop coefficients, which are the monthly ratios of consumptive water requirements to potential evapotranspiration. Additional details on the ET procedures are given in the section on Recharge and Discharge programs.

The other components of discharge from the soil zone are deep percolation (recharge) and surface runoff, which are also discussed further in the section on Recharge and Discharge programs.

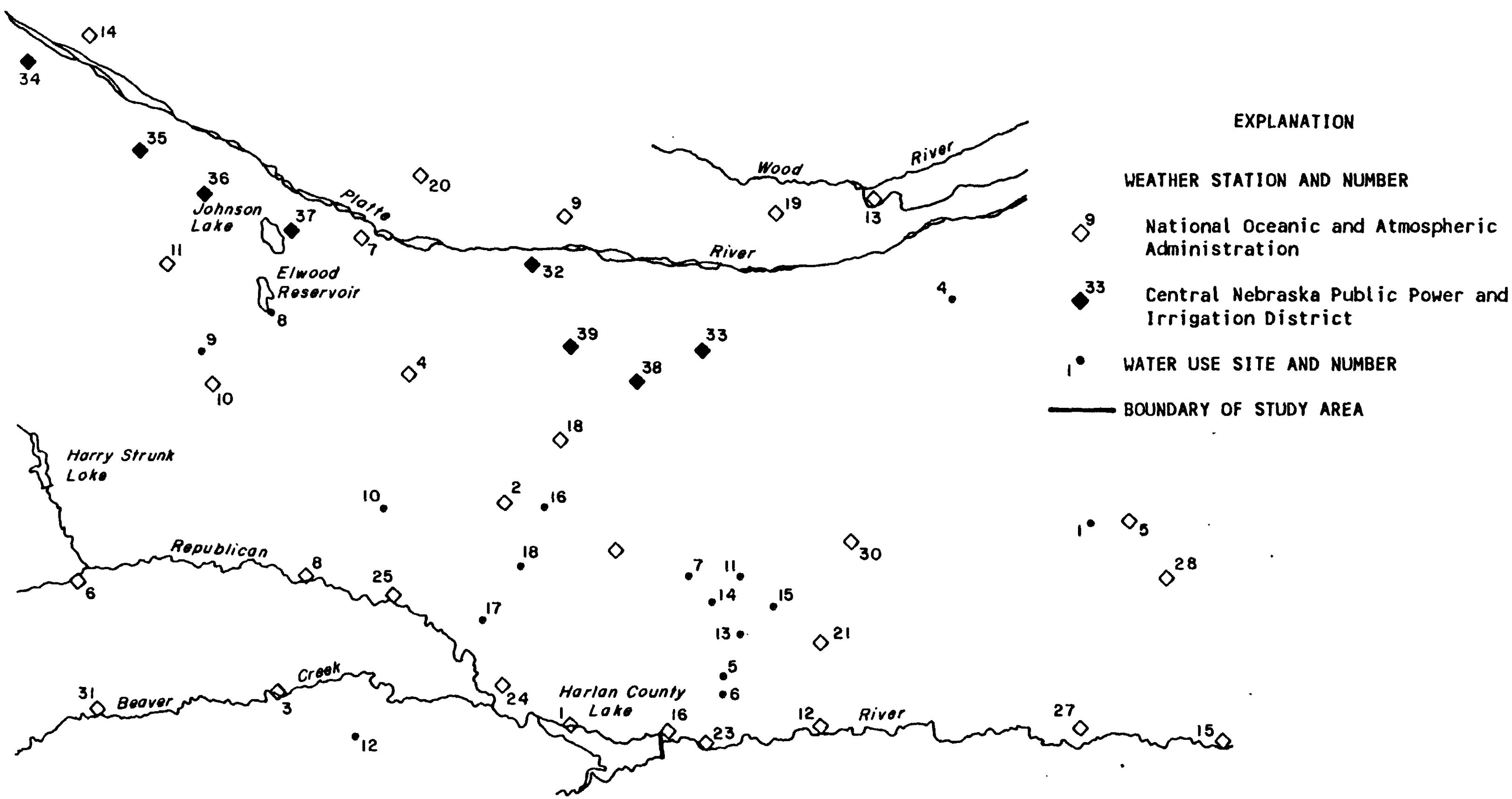


Figure 11.--Location of weather stations, and water-use sites.

Table 6.-- Average annual precipitation for weather stations in and near the study area

[CNPPID is Central Nebraska Public Power and Irrigation District]

Weather station	Identi-fication number on figure 11	Average annual precipi-tation 1940-81 (inches)	Weather station	Identi-fication number on figure 11	Average annual precipi-tation 1940-81 (inches)
Alma	1	22.65	Macon	21	23.95
Atlanta	2	22.59	Minden	22	24.55
Beaver City	3	22.84	Naponee	23	23.74
Bertrand	4	22.46	Orleans	24	22.45
Blue Hill	5	24.96	Oxford	25	19.95
Cambridge	6	22.15	Ragan	26	23.04
Canaday	7	21.40	Red Cloud	27	25.88
Edison	8	21.01	Rosemont	28	24.75
Elm Creek	9	20.93	Superior 1/	29	27.15
Elwood	10	21.48	Upland	30	24.65
Eustis	11	20.89	Wilsonville	31	21.95
Franklin	12	23.75	CNPPID 2E	32	21.57
Gibbon	13	22.59	CNPPID No. 3	33	22.77
Gothenburg	14	21.31	CNPPID No. 17	34	20.02
Guide Rock	15	26.40	CNPPID No. 21	35	20.20
Harlan County Lake	16	22.32	CNPPID No. 22	36	19.57
Hastings	17	26.40	CNPPID No. 23	37	19.84
Holdrege	18	24.50	CNPPID No. 35	38	22.48
Kearney	19	24.21	CNPPID No. 36	39	21.80
Lexington	20	21.98			

1/ Weather station not shown on figure 11.

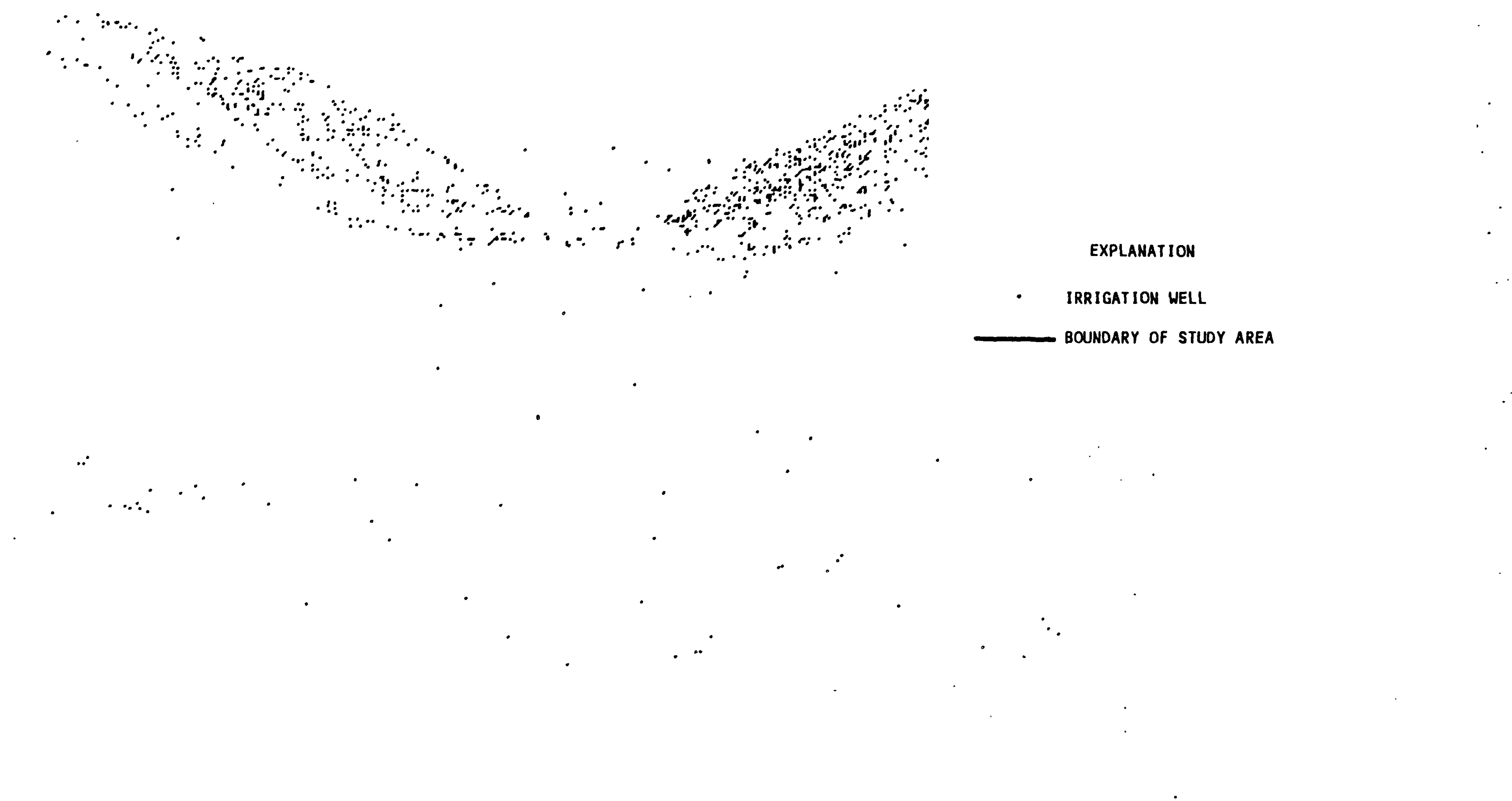


Figure 12.--Distribution of registered irrigation wells drilled through January 1, 1940.

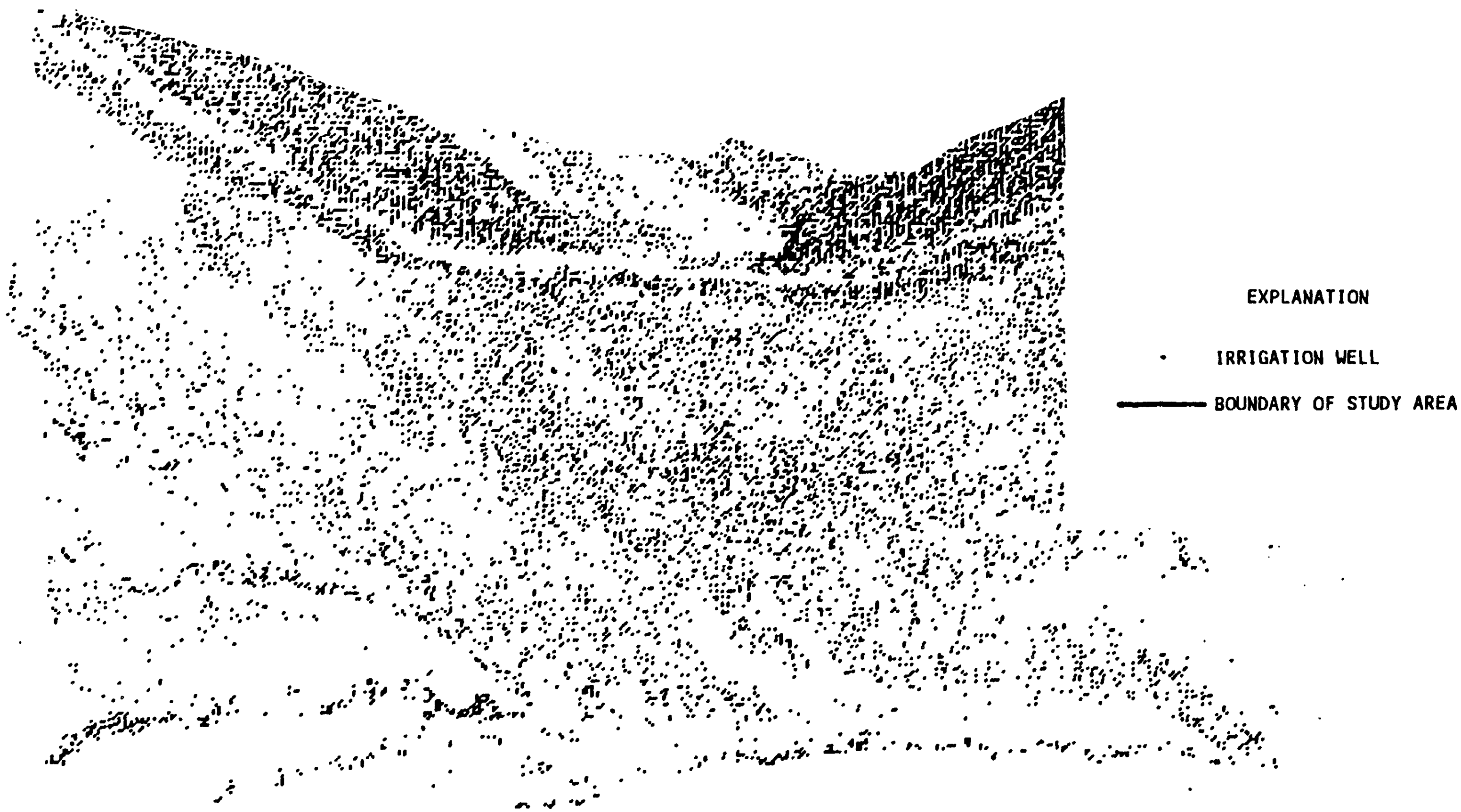


Figure 13.--Distribution of registered irrigation wells drilled through January 1, 1980.

Table 7.--Registered irrigation wells and average acres irrigated per well by county for 5-year perods from 1940 to 1980

Period	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well	Number of wells	Acres irrigated per well
	ADAMS COUNTY		BUFFALO COUNTY		DAWSON COUNTY		FRANKLIN COUNTY	
1940	18	58	440	55	432	40	6	50
1945	46	58	624	55	643	40	15	50
1950	109	58	874	55	965	44	34	60
1955	337	78	1,416	52	1,657	52	111	68
1960	649	82	1,853	53	2,193	39	213	74
1965	780	83	2,013	52	2,290	32	276	73
1970	1,067	80	2,234	59	2,441	39	362	76
1975	1,375	84	2,580	62	2,755	47	538	85
1980	1,707	95	2,969	71	3,050	55	759	78
	FRONTIER COUNTY		FURNAS COUNTY		GOSPER COUNTY		HALL COUNTY	
1940	2	40	17	50	11	50	374	30
1945	2	40	26	50	24	50	788	30
1950	5	44	40	51	32	57	1,095	28
1955	56	80	112	47	75	62	1,521	63
1960	97	92	198	48	135	61	2,142	57
1965	134	86	230	40	170	58	2,322	61
1970	247	102	314	52	263	75	2,559	74
1975	507	98	449	56	451	80	2,889	83
1980	632	102	601	56	557	93	3,265	94

Table 7.--Registered irrigation wells and average acres irrigated per well by county for 5-year perods from 1940 to 1980--Continued

Period	Number of wells	Acres irri-gated per well	Number of wells	Acres irri-gated per well	Number of wells	Acres irri-gated per well	Number of wells	Acres irri-gated per well
	HARLAN COUNTY		KEARNEY COUNTY		LINCOLN COUNTY		PHELPS COUNTY	
1940	4	50	50	30	117	40	61	30
1945	15	50	97	30	157	40	85	30
1950	33	52	200	28	240	44	117	30
1955	113	56	394	63	403	52	262	30
1960	183	63	615	57	535	39	498	32
1965	243	64	731	61	631	32	647	35
1970	431	72	952	74	741	39	951	54
1975	620	72	1,262	83	1,082	47	1,323	83
1980	787	80	1,549	94	1,523	55	1,592	89
	RED WILLOW COUNTY		WEBSTER COUNTY					
1940	22	30	8	30				
1945	55	30	8	30				
1950	67	30	22	30				
1955	130	36	67	33				
1960	160	61	123	34				
1965	224	87	144	40				
1970	296	88	213	52				
1975	514	75	300	69				
1980	716	64	422	81				

Unsaturated Zone

The unsaturated zone extends from the bottom of the soil zone to the saturated, or ground-water zone. Water in the unsaturated zone may move laterally, downward, or upward; it may also be stored for limited periods. The physics of water movement in the unsaturated zone is complex. For this study, the unsaturated zone is treated as a conduit through which water moves either upward or downward, with no storage. Major assumptions are that all the water percolating through the soil zone reaches the ground-water zone, that water moving up from the ground-water zone through the unsaturated zone reaches the soil zone, and that lateral movement of water in the unsaturated zone is insignificant.

Saturated Zone

The saturated (ground-water) zone, which will be referred to as the aquifer, extends from the water table to the base of the aquifer, usually the bottom of the lowest coarse-grained materials (sand or gravel) above the Cretaceous bedrock.

Boundaries of the Aquifer

Water levels and changes in water levels over time define the upper surface of the aquifer. The base of the aquifer does not change with time or water-level conditions.

Water Levels

The water table, which forms the upper boundary of the aquifer, fluctuates in response both to short-term and long-term variations in recharge and discharge, or both.

Figure 14 shows the configuration and elevation of the water table in 1940, prior to surface-water development. This map was developed from 1940 water levels and the earliest available water levels near 1940. The configuration shown in the upland areas (fig. 6) represents approximately 1965 water levels, which are the earliest available water levels in the uplands.

The next map showing the configuration and elevation of the water table (fig. 15) was developed from mass water-level measurements in the study area during the spring of 1981. For more information on these water levels, consult the south-central area data report (Bartz and Peckenpaugh, 1986).

An examination of the water-level configuration maps of 1940 (fig. 14) and 1981 (fig. 15) shows significant rises in water levels since 1940 in the northern part of Gosper, Phelps, and Kearney Counties, with a maximum rise of 110 feet in northern Gosper County. These rises have been caused primarily by seepage into the aquifer from CNPPID's canals and also a lesser extent by seepage from other canals on the south side of the Platte River. Differences are less between the 1940 and 1981 water levels in the southern part of the study area.

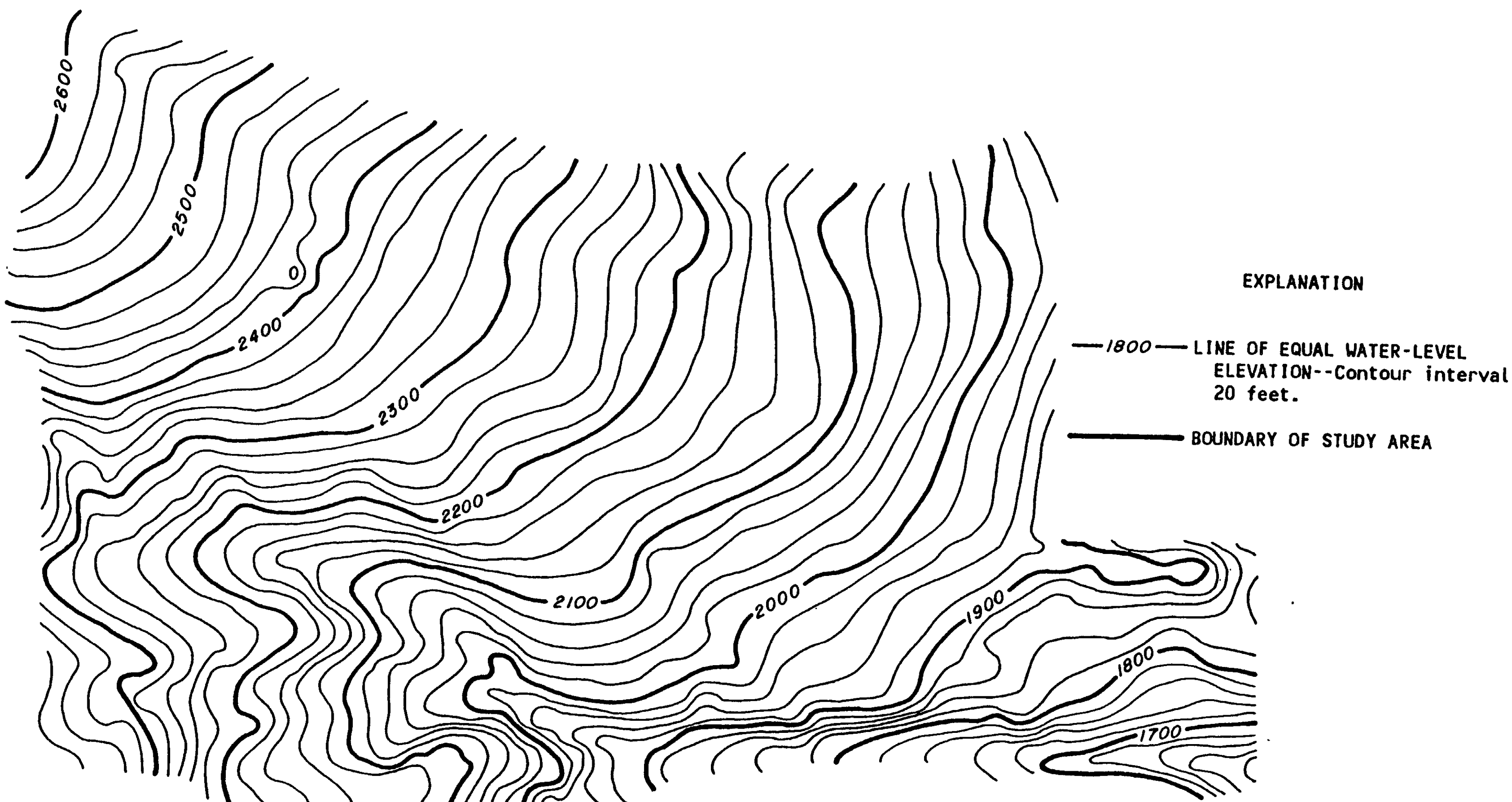


Figure 14.--Configuration and elevation of water table, 1940, prepared from measured water levels.

Figure 15.--Configuration and elevation of water table, spring 1981, prepared from measured water levels.

Depth to Water

The depth to water in 1940 is shown in figure 16, and the depth to water in the spring of 1981 is shown in figure 17. The depth-to-water maps were prepared by subtracting the land-surface elevation from the 1940 and 1981 water levels (fig. 14 and 15) at selected points.

For both time periods, the depth to water ranges from zero at several locations to slightly more than 350 feet in the uplands of Dawson County on the south side of the Platte River. In 1981 in northern Gosper and Phelps Counties, the depth to water was from 80 to 110 feet closer to the surface than in 1940. In other parts of the study area, the depth to water increased slightly from 1940 to 1981. This increase in depth to water occurred in areas where ground water has been developed and discharge exceeds recharge.

Base of the Aquifer

The configuration and elevation of the base of the aquifer are shown in figure 18. The base of the aquifer slopes generally toward the east, with a decrease in elevation from 2,350 feet in the west to 1,600 feet in the east.

Channels in the Cretaceous bedrock are present in the area. Those filled with permeable materials are shown on the map of the base of the aquifer (fig. 18). Channels containing fine-grained, less permeable materials are not included in the aquifer and are not shown on the map.

Saturated Thickness

The saturated thickness of an unconfined aquifer is the interval from the base of the aquifer to the water table. Figures 19 and 20 show the saturated thickness of the aquifer for 1940 and 1981, respectively. From 1940 to 1981, the saturated thickness increased in the northern part of the study area. The maximum increase was about 110 feet in northern Gosper County. As mentioned earlier, this was the result of surface-water seepage from CNPPID canals filling the previously unsaturated loess material. The saturated thickness of the aquifer for both time periods decreases from west to east and from north to south. For both time periods, the saturated thickness of the aquifer ranges from greater than 600 feet in the northwest corner of the study area to near zero in southern Harlan and Franklin Counties.

EXPLANATION

—20— LINE OF EQUAL DEPTH TO WATER FROM LAND SURFACE, IN FEET--Contour interval varies.

BOUNDARY OF STUDY AREA

Figure 16.--Depth to water from land surface, 1940.

Figure 17.--Depth to water from land surface, spring 1981.

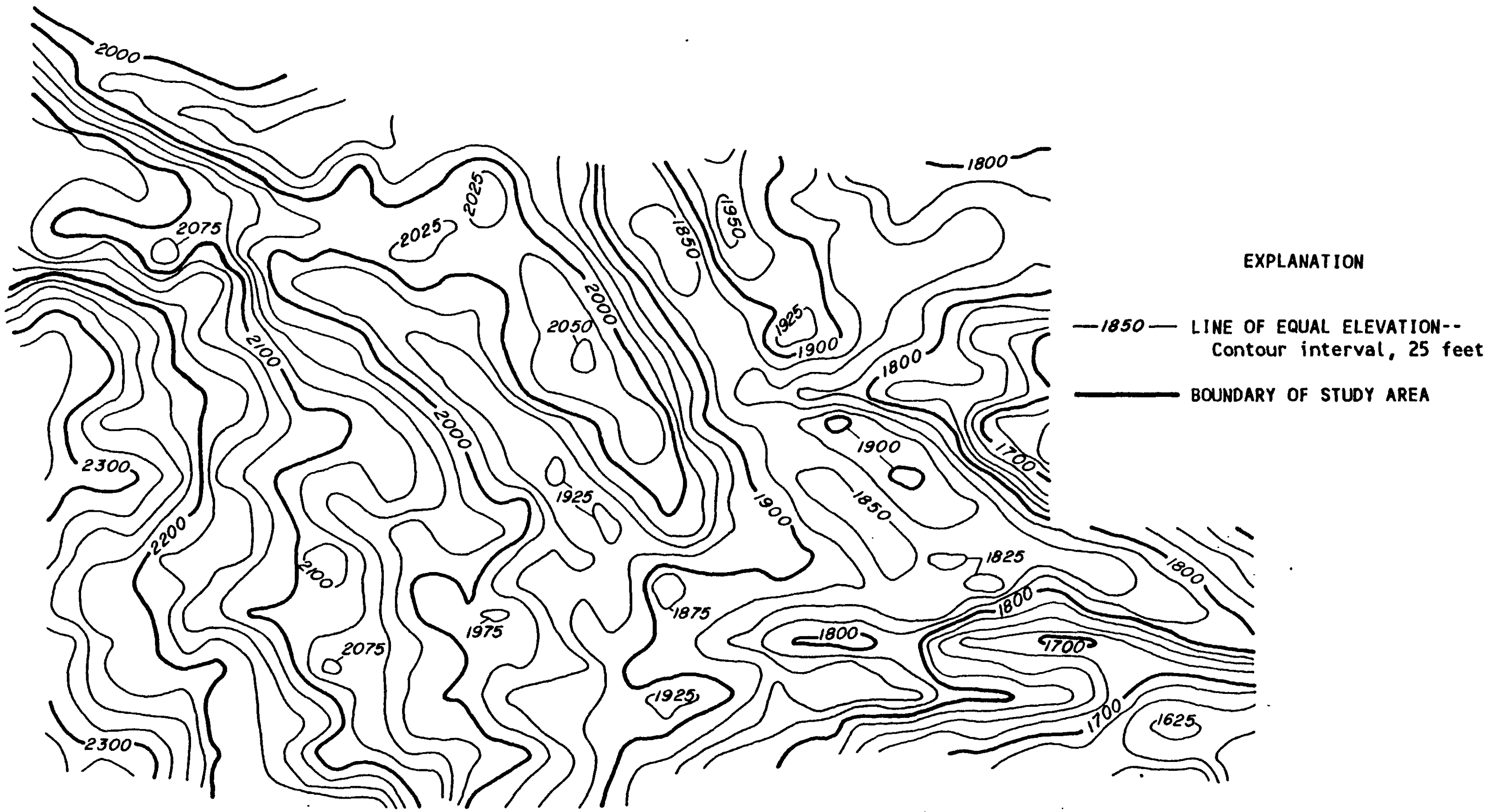


Figure 18.--Configuration and elevation of the base of the aquifer.

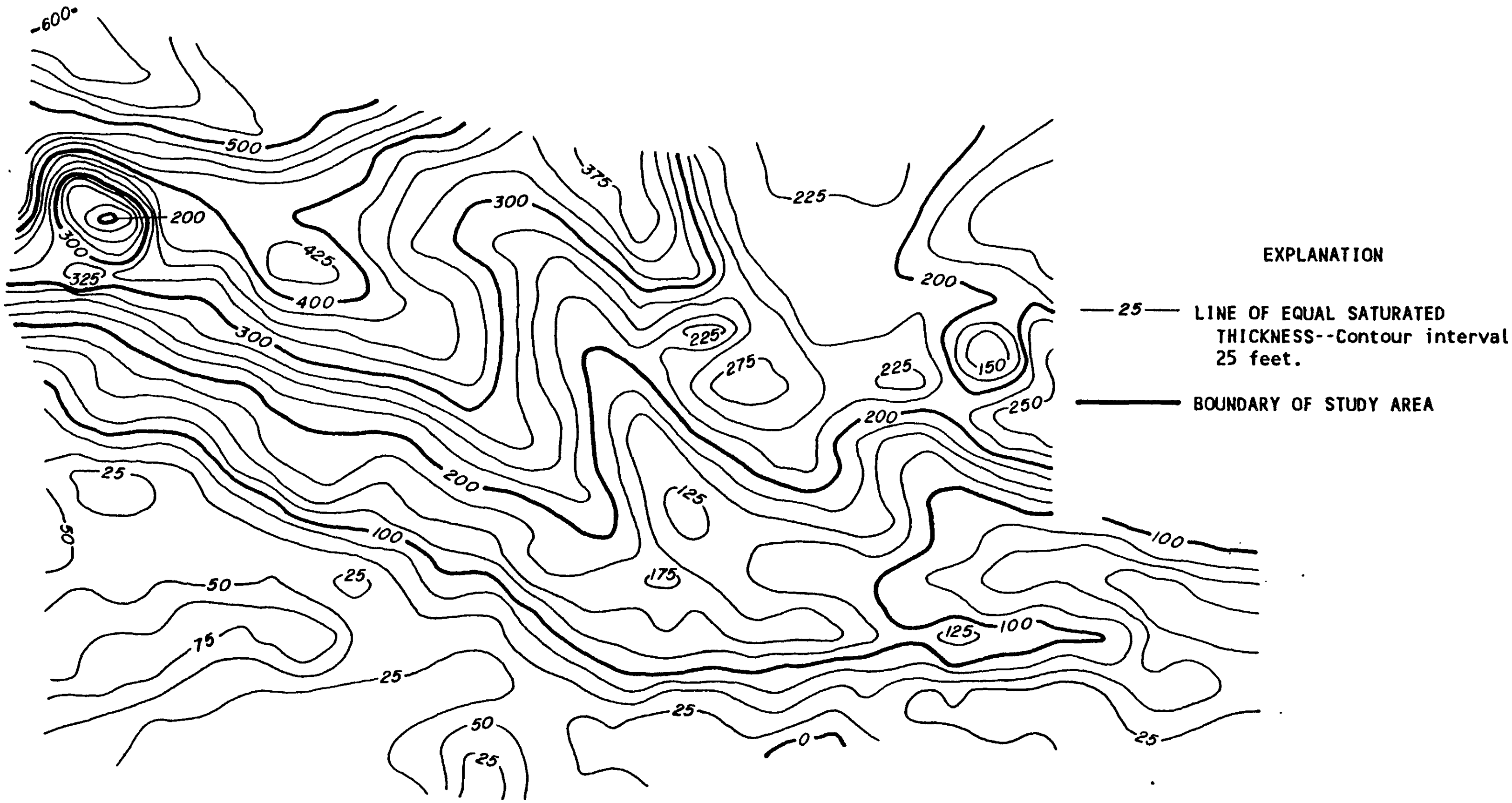


Figure 19.--Saturated thickness of the aquifer, 1940.

EXPLANATION

—150— LINE OF EQUAL SATURATED THICKNESS--Contour interval, 25 feet.

——— BOUNDARY OF STUDY AREA

Figure 20.--Saturated thickness of the aquifer, spring 1981.

Hydraulic Characteristics

The hydraulic properties of the aquifer, transmissivity and specific yield, indicate the ability of the aquifer to transmit and store water.

Computation of Hydraulic Properties

At this point, a brief explanation of the grid system used in this study is necessary for two reasons. First, the grid system and the hydraulic properties of the aquifer are interrelated. Second, it is easier to understand the procedures used in developing the hydraulic properties of the aquifer if the grid system is understood.

Logs from 410 test holes were selected to represent the hydraulic properties of the aquifer throughout the study area. An additional 160 interpretive test holes were developed or "interpreted" from the 410 test holes that comprise the 45 east-west and north-south cross sections. Six of these cross sections are delineated in figure 4a-f.

The test-hole locations, 410 test holes and 160 interpretive test holes, were the initial nodes for this study area. However, these 570 nodes or locations were not sufficient to produce an adequate water-level configuration map. Therefore, additional locations were selected from the hand-contoured, measured 1981 water-level configuration map until the computer-generated water levels matched closely the hand-contoured water levels. An additional 343 nodes were selected to produce a "reasonable" agreement between the two water-level maps. Figure 15 is the final product of this process.

These same 913 nodes (570 test holes and 343 additional nodes) delineated on figure 21, with the intersection of two or more lines, form the basis of the finite-element grid system used in this study. The finite elements are the smallest areas within the model that can represent the different hydrogeologic, hydraulic, and water-use features of the study area. Finite elements (fig. 21) are formed by connecting either three (triangular) or four (polygonal) nodes. For additional information on the construction of finite elements and on the uses of both finite elements and nodes, the reader is referred to the documentation report on RAQSIM by Cady and Peckenpaugh (1985).

The distribution of test holes and interpretive test holes did not adequately represent the finite elements. Several finite elements lacked test holes or interpretive test holes as nodes within their three or four node structures. Therefore, finite elements were grouped to form larger triangles or polygons that had test holes or interpretive test holes as their nodes or corners. This new grouping, which was named material elements, was developed so that no finite elements would be subdivided between material elements and so that a single material element did not include both topographic types of uplands and topographic types of flood plains and terraces (fig. 6). Each finite element is assigned to the material element in which it is located. The distribution of material elements is shown on figure 22.

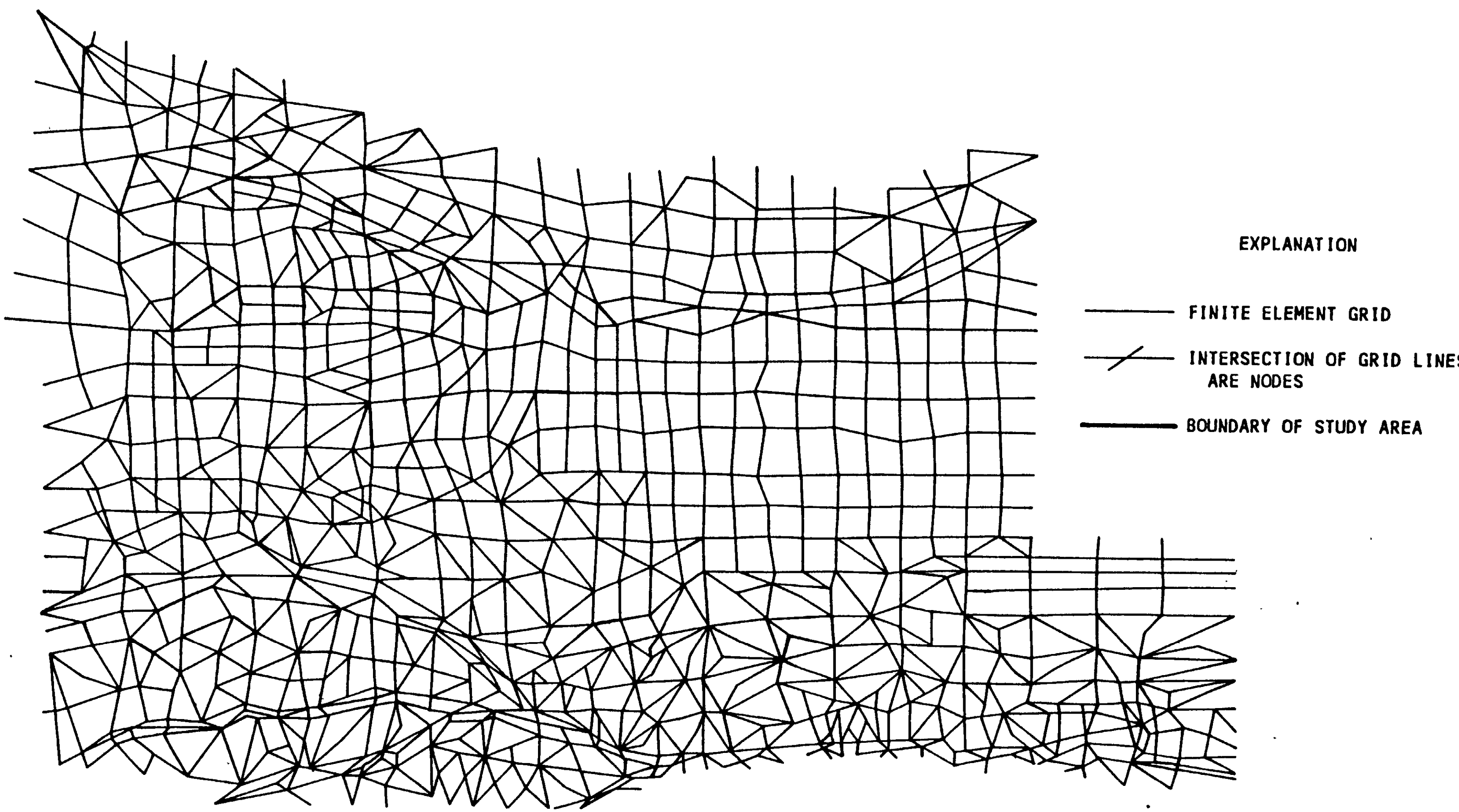


Figure 21.--Finite-element grid.

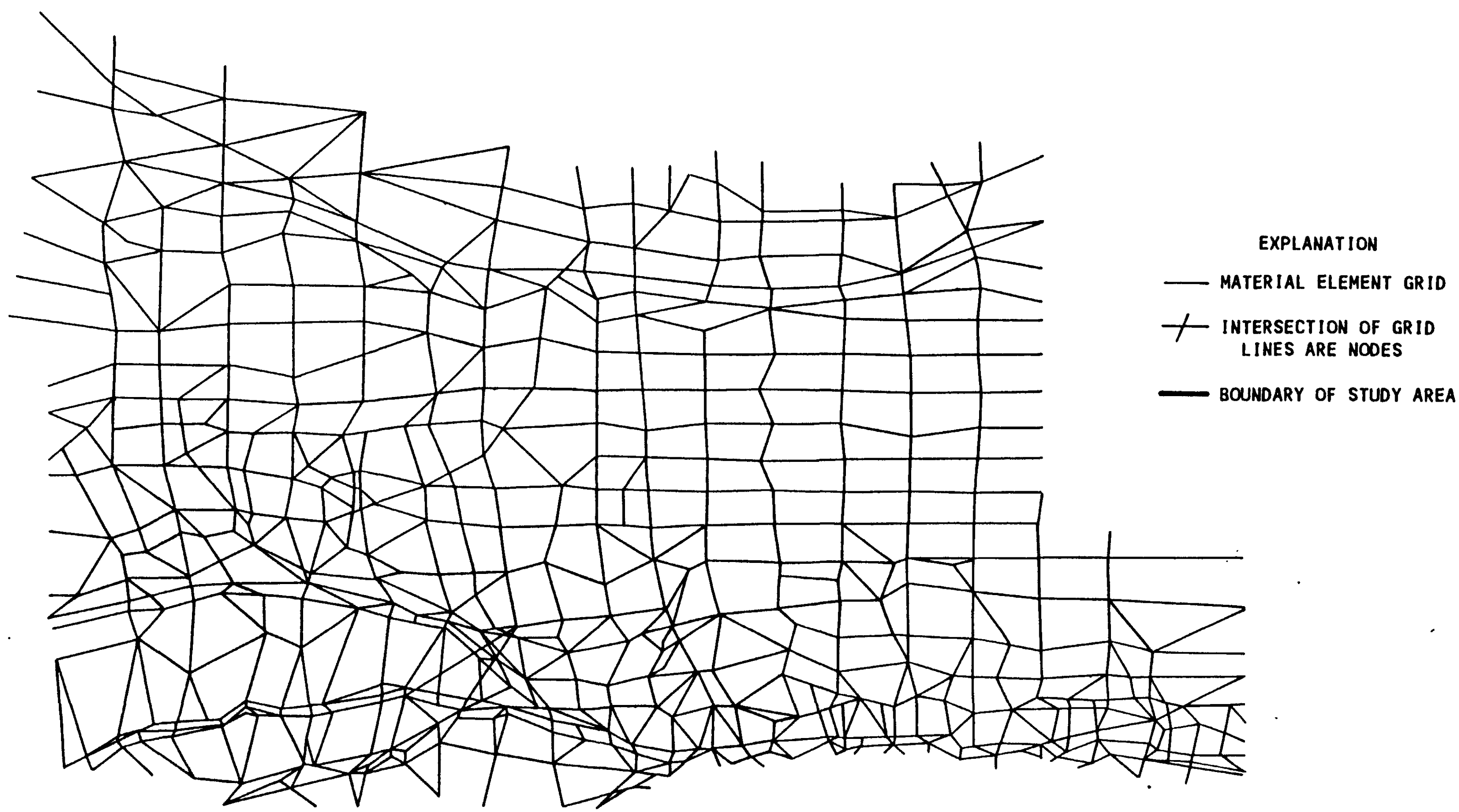


Figure 22.--Material element grid.

The hydraulic properties of the aquifer are computed for each material element by a computer program, METS (material elements transmissivity and storage). The results from METS are used within RAQSIM where transmissivity (T) and specific yield (Sy) values are assigned to individual finite elements as the saturated thickness within the finite elements changes.

METS, which was developed for this study, computes a table of T and Sy values using the logs from the 410 test holes and 160 interpretive test holes. For each lithologic unit within the test-hole logs, hydraulic conductivity (K) and Sy values from table 8 or 9 were assigned according to the grain size of the material comprising the unit and to its degree of sorting or silt content. The METS Program uses these K and Sy values to compute T and Sy at selected interval thicknesses for each node (test hole) included in the material element. For this study, the interval thickness was chosen as 50 feet. Therefore, the selected interval thicknesses from the base of the aquifer to the land surface (a distance of 205 feet) would be 0, 50, 100, 150, 200, and 205 feet.

The METS Program has a procedure that operates as follows for each material element: The T and Sy values at selected interval thicknesses for each node (1 to 4 nodes per material element) are combined into single values of T and Sy at selected interval thicknesses for the entire material element. The final product of this program is a table of T and Sy values at selected interval thicknesses for each material element.

Some adjustments were made in the K and Sy values used in the METS Program. Hydraulic conductivity and specific yield values from tables 8 and 9 were adjusted based on aquifer test data, specific capacity data for irrigation wells, and the results of simulations with the ground-water-flow model.

Transmissivity and specific yield maps were prepared from results of the ground-water-flow model, RAQSIM, using the table of T and Sy values. RAQSIM computes the T and Sy values for each finite element based on the current average saturated thickness for all the nodes in that finite element. It does this for the initial and final T and Sy values and for each time the changes in water levels and, therefore, saturated thicknesses exceeded a maximum limit of 25 feet. The T and Sy values are computed according to the following procedures: (1) RAQSIM selects the correct material element for each finite element; (2) RAQSIM reads the table of T and Sy values, and at the appropriate material element it compares the finite element's saturated thickness with the interval thickness in the table. It selects the T and Sy values that bracket the saturated thickness of the finite element. (3) RAQSIM computes the T and Sy values by linear interpolation between the bracketed values. The T and Sy values are then plotted using a contouring plotting program.

Table 8.--Hydraulic conductivity and specific yield estimated from description of materials comprising a lithologic unit

Grain-size class or range from sample description	Hydraulic conductivity, in feet per day[1]						Specific yield[2] (percent)
	Estimated from degree of sorting			Estimated from silt content			
	Poor	Moderate	Well	Slight	Moderate	Large	
FINE-GRAINED MATERIALS:							
Clay	---	-------	---	2.0	---	---	2.0
Silt, slightly clayer	---	-------	---	18	---	---	17.0
Silt, moderately clayey	---	-------	---	11	---	---	11.0
Silt, very clayey	---	-------	---	7.0	---	---	7.0
Silt; loess; sandy silt	---	-------	---	20	---	---	24.0
SANDS AND GRAVELS[3]:							
Very fine sand	13	20	27	23	19	13	21.0
Very fine to fine sand	27	27	---	24	20	13	21.5
Very fine to medium sand	36	41- 47	---	32	27	21	22.4
Very fine to coarse sand	48	-------	---	40	31	24	22.5
Very fine to very coarse sand	59	-------	---	51	40	29	22.4
Very fine sand to fine gravel	76	-------	---	67	52	38	22.3
Very fine sand to medium gravel	99	-------	---	80	66	49	22.2
Very fine sand to coarse gravel	128	-------	---	107	86	64	22.1
Fine sand	27	40	53	33	27	20	22.0
Fine to medium sand	53	67	---	48	39	30	24.5
Fine to coarse sand	57	67- 72	---	53	43	32	25.0
Fine to very coarse sand	70	-------	---	60	47	35	24.5
Fine sand to fine gravel	88	-------	---	74	59	44	24.4
Fine sand to medium gravel	114	-------	---	94	75	57	24.3
Fine sand to coarse gravel	145	-------	---	107	87	72	24.2
Medium sand	67	80	94	64	51	40	27.0
Medium to coarse sand	74	94	---	72	57	42	27.5
Medium to very coarse sand	84	98-111	---	71	61	49	27.4
Medium sand to fine gravel	103	-------	---	84	68	52	27.3
Medium sand to medium gravel	131	-------	---	114	82	66	27.2
Medium sand to coarse gravel	164	-------	---	134	108	82	27.1
Coarse sand	80	107	134	94	74	53	28.0
Coarse to very coarse sand	94	134	---	94	75	57	27.5
Coarse sand to fine gravel	116	136-156	---	107	88	68	27.3
Coarse sand to medium gravel	147	-------	---	114	94	74	27.1
Coarse sand to coarse gravel	184	-------	---	134	100	92	26.8
Very coarse sand	107	147	187	114	94	74	27.0
Very coarse sand to fine gravel	134	214	---	120	104	87	26.5
Very coarse sand to medium gravel	170	199-227	---	147	123	99	26.3
Very coarse sand to coarse gravel	207	-------	---	160	132	104	25.8
Fine gravel	160	214	267	227	140	107	26.0
Fine to medium gravel	201	334	---	201	167	134	25.5
Fine to coarse gravel	245	289-334	---	234	189	144	24.5
Medium gravel	241	321	401	241	201	160	25.0
Medium to coarse gravel	294	468	---	294	243	191	24.0
Coarse gravel	334	468	602	334	284	234	23.0

[1] Hydraulic conductivity values are from an unpublished, undated paper by E.C. Reed and R. Piskin, Conservation and Survey Division, University of Nebraska.
[2] Specific yield values are modified from Johnson (1967).
[3] Reduce hydraulic conductivity by 10 percent if grains are subangular.

Table 9.--Hydraulic conductivity and specific yield for interbedded sand, sandstone, silt, and clay

Lithology[1]	Percent clay and silt	Hydraulic conductivity (feet/day)	Specific yield (percent)
Sand-------------------	< 20	49.0	24.0
Sand-------------------	20 - 40	40.0	22.0
Sand-------------------	> 40	32.0	20.5
Sand = sandstone--------	< 20	34.0	22.5
Sand = sandstone--------	20 - 40	25.5	21.5
Sand = sandstone--------	> 40	24.5	19.5
Sandstone with sand-----	< 20	22.0	19.0
Sandstone with sand-----	20 - 40	21.0	19.0
Sandstone with sand-----	> 40	19.0	17.0
Sandstone and silt------	< 20	23.0	18.0
Sandstone and silt------	20 - 40	14.0	17.5
Sandstone and silt------	> 40	13.0	17.5

[1]Sand: Primarily all sand; may have some sandstone.
Sand = sandstone: Equal amounts of sand and sandstone.
Sandstone with sand: Sandstone is much greater than sand.
Sandstone and silt: Sandstone and silt, with no sand or very small amounts of sand.

Transmissivity

The distribution of transmissivity for 1940 is shown in figure 23 and for 1981 in figure 24. The range in T's for the 1940 time period is approximately 100 to 20,000 ft^2/d (feet squared per day), while the range in T's for the 1981 time period is approximately 100 to 25,000 ft^2/d. Transmissivity values increased from 1940 to 1981, primarily in the northern part of the study area. The transmissivity of the aquifer is a good indicator of potential well yield at a given location. Areas where transmissivity values are large, conditions are favorable for developing wells with high yields.

Specific Yield

The distribution of specific yield for 1940 is shown in figure 25 and for 1981 in figure 26. Specific yield values for both time periods range from 0.08 to 0.26. The specific yield of an aquifer is a good indicator of the volume of water available for use.

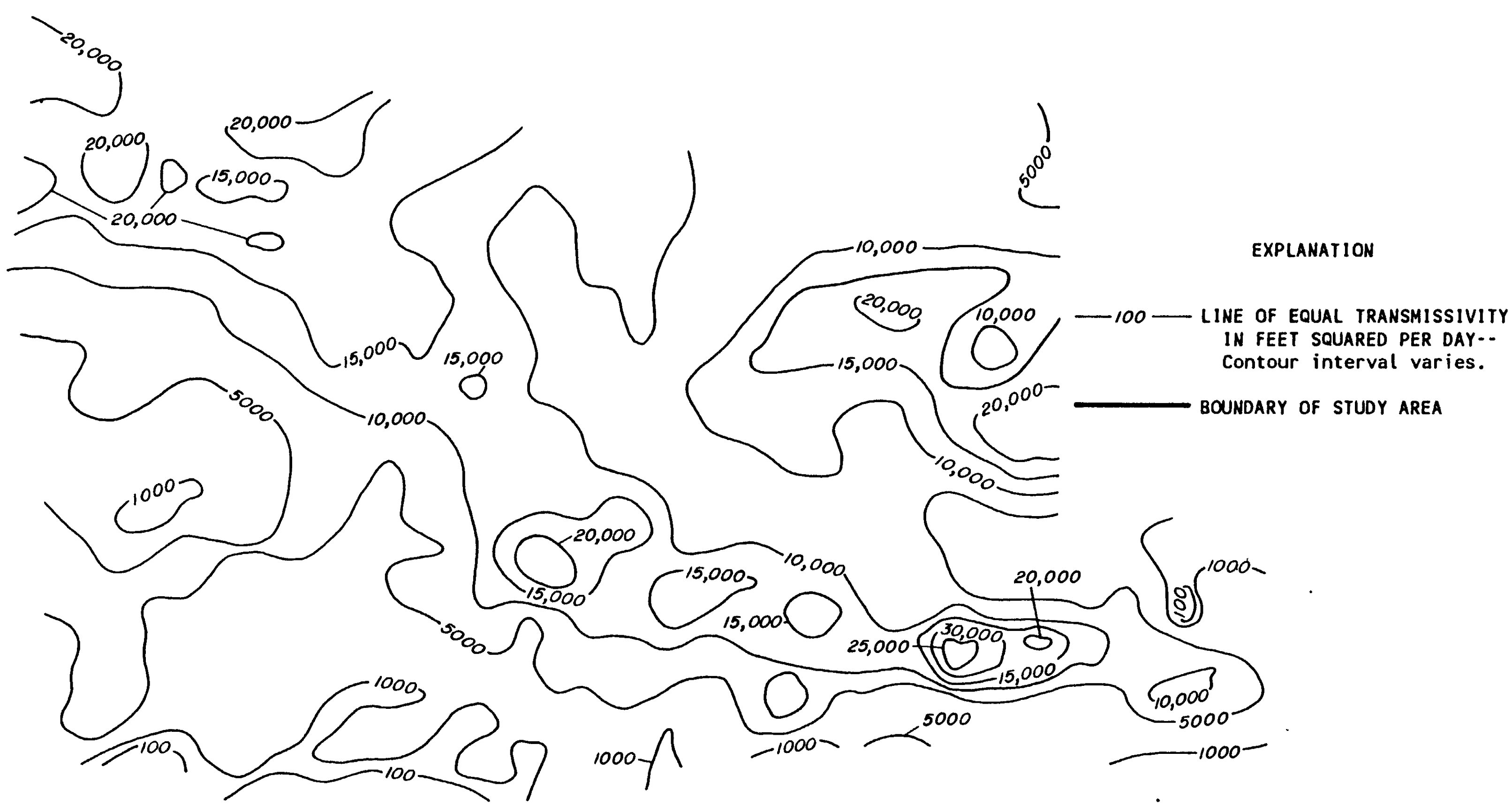


Figure 23.--Transmissivity of the aquifer, 1940.

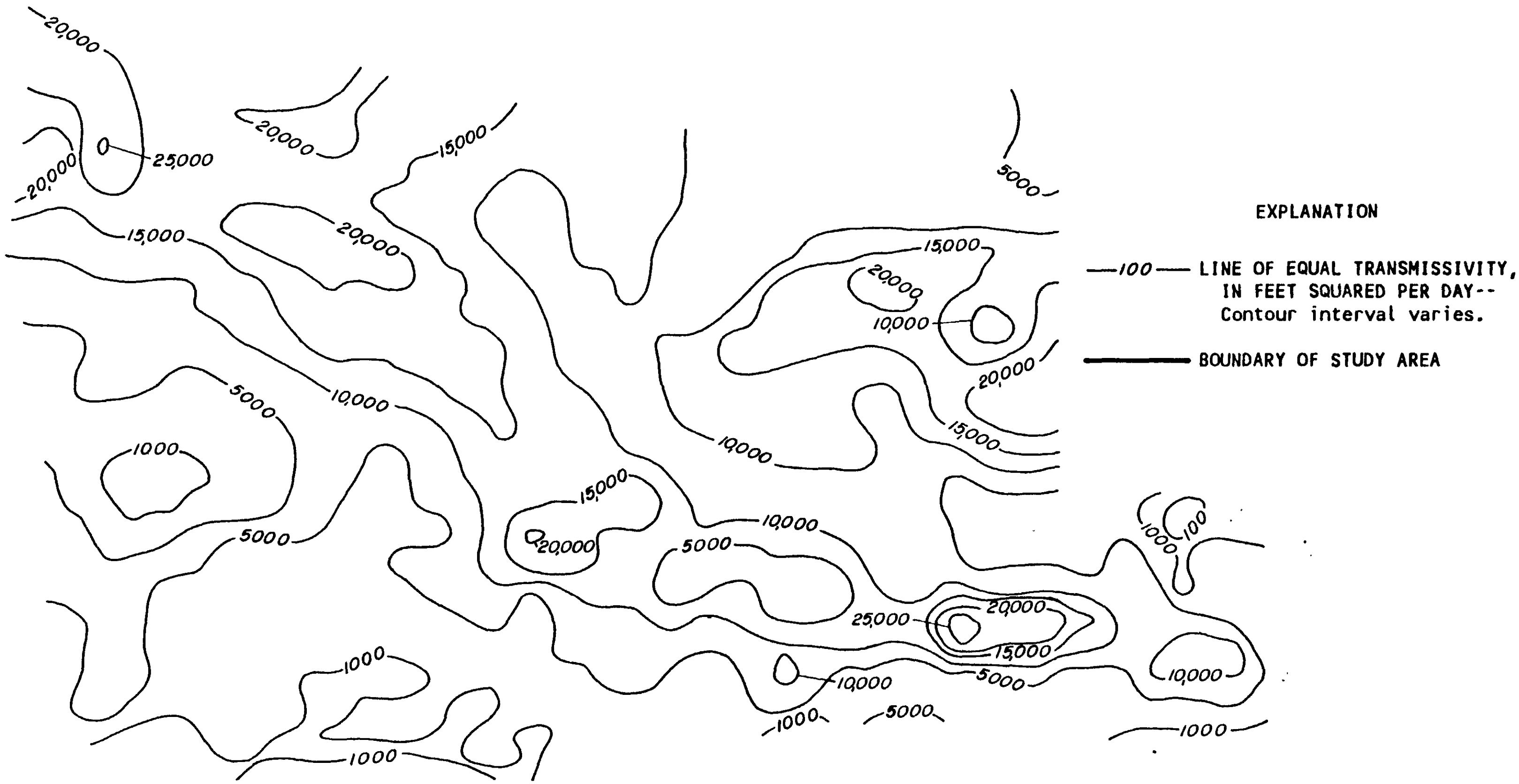


Figure 24.--Transmissivity of the aquifer, spring 1981.

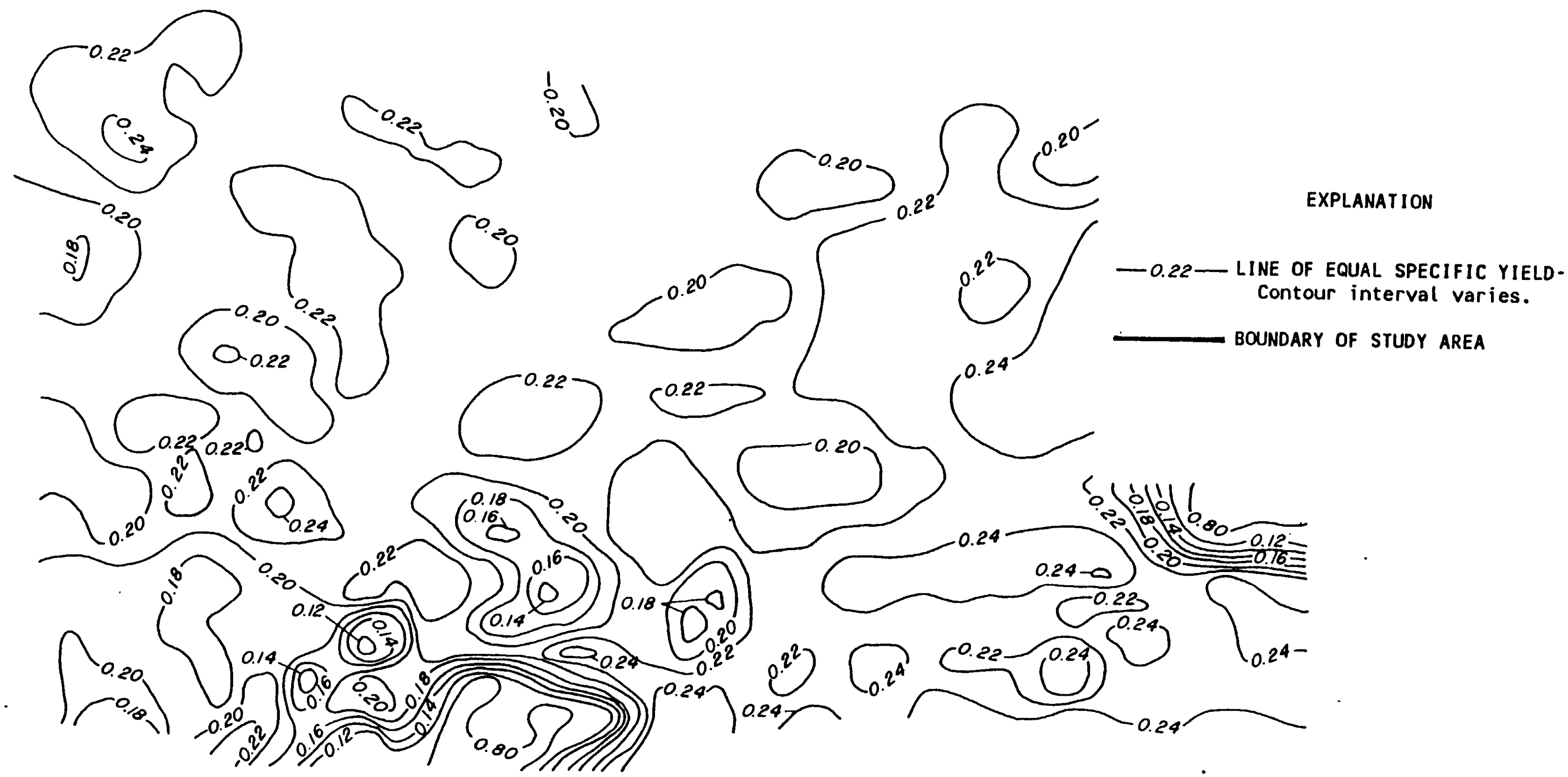


Figure 25.--Specific yield of the aquifer, 1940.

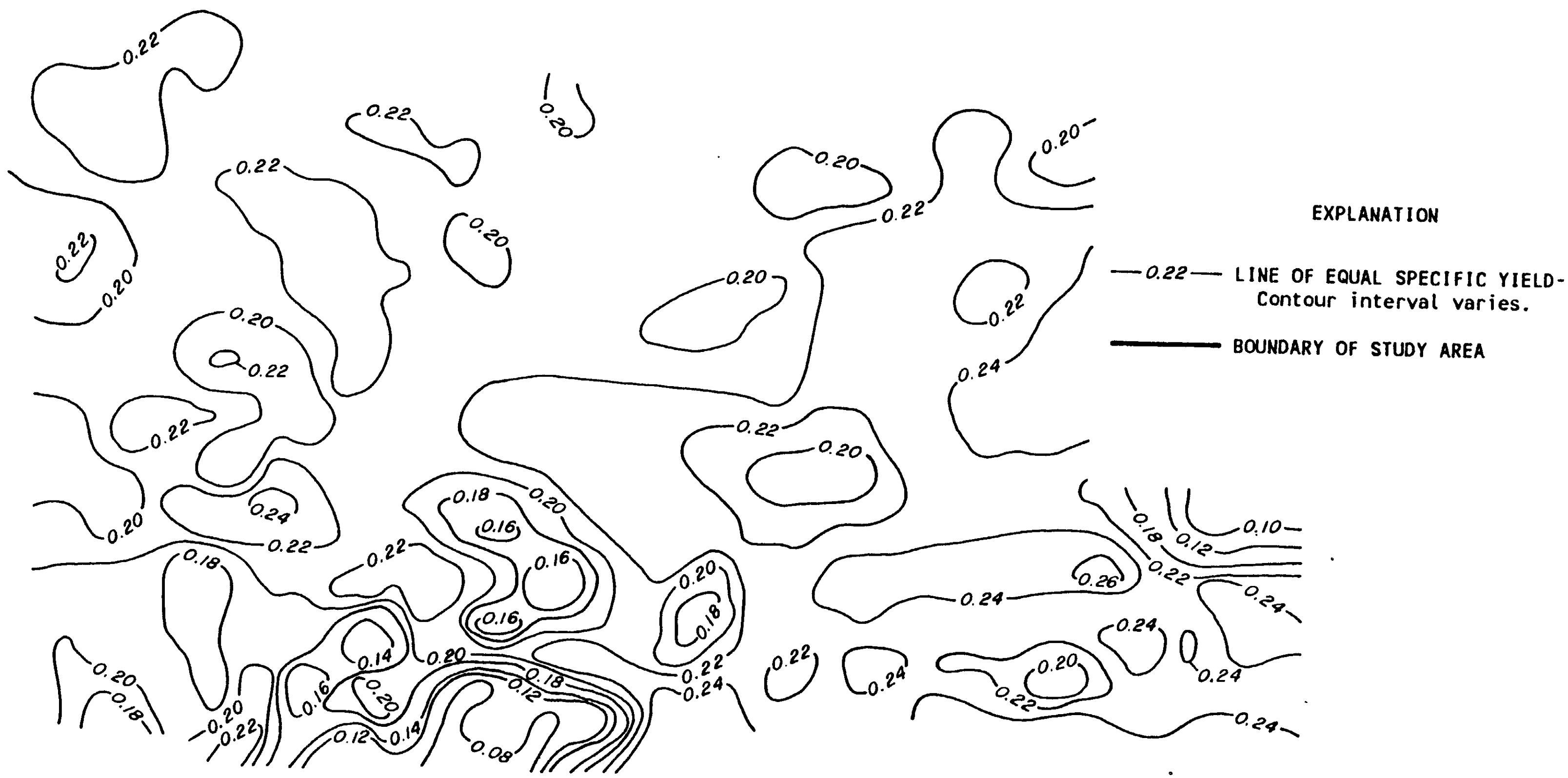


Figure 26.--Specific yield of the aquifer, spring 1981.

Water in Storage

The volume of water in storage is computed by multiplying both the average saturated thickness and the area of the aquifer by average specific yield. (RAQSIM uses the term "mass balance" for this quantity. A detailed discussion of this term can be found in the section on Simulation of the Ground-Water System.) The volume of water in storage was 134,600,000 acre-feet in 1940, and the final (1981) volume of water in storage was 141,200,000 acre-feet. This was an increase of 6,600,000 acre-feet and amounts to an average of 1.84 feet of additional water over the entire study area.

Flow in the Aquifer

Ground water flows in the direction of decreasing hydraulic head, which is approximately normal to the water-table contours (fig. 14 and 15). The regional ground-water flow pattern is modified near discharge and recharge areas. The flow paths will converge in areas of discharge and diverge from areas of recharge.

The velocity of ground-water movement in an aquifer is a function of hydraulic conductivity and the gradient of hydraulic head, which is the potential energy of the water. Velocities usually are very low, and they are defined as follows:

$$\overline{V} = \frac{K}{n} \frac{\partial h}{\partial x_i} \tag{1}$$

where $\overline{V}$ = the average linear velocity, L/T,

K = hydraulic conductivity, L/T,

n = porosity, volume of voids divided by total volume of aquifer; dimensionless,

∂h = total hydraulic head, L,

∂x_i = a coordinate direction, L.

Rates of ground-water movement in the study area range from 15 feet to slightly more than 45 feet per year.

The underflow of ground water into the study area primarily is along the western border of Lincoln, Dawson, Frontier, and Red Willow Counties and along the northern border of Dawson, Buffalo, and Hall Counties. Underflow can be calculated as follows (Lappala, 1978):

$$Q = \sum_{i=1}^{m} - \hat{K}_i b_i w_i \left(\frac{\partial h}{\partial n}\right)_i \qquad (2)$$

where Q = underflow into the study area (+) and underflow out of the study area (-), L^3/T,

i = an index on the interval used,

m = total number of intervals,

$\hat{K}_i$ = average hydraulic conductivity over b_i and w_i, L/T,

b_i = average aquifer thickness over interval i, L,

w_i = width of the interval i, L,

$\left(\frac{\partial h}{\partial n}\right)_i$ = the outward, normal hydraulic gradient along boundary interval i, dimensionless.

The underflow into the study area was determined by the above equation to be approximately 116,700 acre-feet in 1940 and 82,800 acre-feet in 1981.

Outflows from the aquifer are: discharge from domestic, municipal, industrial, and irrigation wells; ET losses from shallow water-table areas; ground-water discharge to the surface-water system; and underflow of ground water to areas outside the study area. ET losses and ground-water discharge to streams are computed by the ground-water flow model. The net recharge or discharge, which is entered into the flow model, will be discussed in the section on Procedures for Estimating Recharge and Consumptive Irrigation Requirements. Underflow of ground water to areas outside the study area occurs along the eastern border of Hall, Adams, and Webster Counties. Underflow of ground water to areas along the southern border of the study area is negligible.

Underflow of ground water along the eastern border was computed using equation 2. Approximately 42,100 acre-feet of ground water was flowing out of the study area in 1940 and 45,000 acre-feet was flowing out of the area in 1981.

Water Quality

Concentrations of dissolved constituents in ground water depend on the hydrogeologic environment through which the water moves or in which the water is stored. The concentration of dissolved constituents in ground water can be modified by conditions in the surface-water system, soil zone, unsaturated zone, or saturated zone. When water percolates through the soil zone and unsaturated zone, numerous reactions may occur between the water and the soil and unsaturated zone material, and soluble chemical constituents may dissolve in the percolating water. The amount of constituent dissolved may depend on their solubility or on other chemical reactions.

Man-generated pollutants also may affect the quality of water in the saturated zone. For example, the movement and storage of surface water into the aquifer in the northern part of the study area has changed the original ground-water quality in this area so that it resembles more closely the water quality of the surface water. Also, the increase in fertilizer usage since the 1950's has affected the water quality in some areas (Spalding and others, 1978).

Chemical Composition and Variations

During the summers of 1980 and 1981, 38 and 30 irrigation wells were sampled, respectively. Thirteen of these wells were sampled previously during the 1970's. The samples collected in 1980 and 1981 are discussed here.

Figure 4 in the south-central area data report (Bartz and Peckenpaugh, 1986) shows the location of these water-sampling sites. The irrigation wells selected for sampling were screened either in the Quaternary deposits or Ogallala Formation. An attempt was made to distribute the sampled wells evenly throughout the study area. All water samples were collected using U.S. Geological Survey sampling methods and techniques. At the time each sample was collected, water temperature, pH, and specific conductance were measured. Other constituents were measured at the U.S. Geological Survey Central Laboratory at Arvada, Colorado. These constituents were calcium, magnesium, sodium, chloride, sulfate, fluoride, silica, boron, iron, manganese, nitrite plus nitrate as nitrogen, alkalinity, pH, and specific conductance. Results of the analyses of the wells sampled in 1980 and 1981 are published in U.S. Geological Survey Water-Resources Data, Nebraska, water years 1980-1981.

Table 10 provides the descriptive statistics and distribution tables for 13 constituents and properties for the water samples measured in 1980 and 1981. The 90th and 10th percentiles in the distribution tables define an effective range of ground-water quality. Constituent values greater than the 90th percentile or less than the 10th percentile are outliers that frequently represent random errors in the data base or represent unusual events that have taken place. The median (50th percentile) is another good indicator of sample distribution, because, unlike the mean, it is not affected by outliers.

Table 10.--Summary of ground-water-quality data, 1980-81
[μS/cm, microsiemens per centimeter at 25° Celsius; mg/L milligrams per liter; μg/L, micrograms per liter]

Water-quality constituent or property	Descriptive statistics					Percent of samples in which values were less than or equal to those shown				
	Sample size	Maximum	Minimum	Mean	Standard deviation	10	25	50	75	90
Specific conductance (μS/cm)	68	1160	170	625	202	432	507	568	751	986
Alkalinity (mg/L as $CaCO_3$)	38	260	160	216	25	179	210	219	240	250
Calcium, dissolved (mg/L as Ca)	68	150	24	85	28	56	68	78	100	140
Magnesium, dissolved (mg/L as Mg)	68	29	2.4	15	5	8.5	11	15	19	22
Sodium, dissolved (mg/L as Na)	68	79	3.4	21	18	7.8	9.6	15	25	47
Potassium, dissolved (mg/L as K)	68	17	3.1	10	2.4	6.6	8.8	9.7	11	12
Chloride, dissolved (mg/L as Cl)	68	52	1.2	15	13	2.7	5.0	11	22	37
Sulfate, dissolved (mg/L as SO_4)	68	280	5.0	67	69	15	19	32	115	190
Fluoride, dissolved (mg/L as F)	68	.6	.1	.3	.1	.2	.2	.3	.3	.4
Silica, dissolved (mg/L as SiO_2)	68	70	23	49	12	33	40	48	61	65
Nitrogen, NO_2+NO_3, dissolved (mg/L as N)	67	12	0	3.0	2.4	.8	1.9	3.0	4.4	6.9
Boron, dissolved (μg/L as B)	68	210	10	73	39	30	50	60	90	141
Solids, sum of constituents, dissolved (mg/L)	68	770	120	398	134	278	320	350	493	615

Suitability of Water for Use

The suitability of water depends on whether it can be used safely for human and animal consumption or other domestic use, or if it can be used for irrigating crops without harm to the crops. Maximum contaminant levels (MCL) for public water supplies have been established by the U.S. Environmental Protection Agency (EPA, 1976). Irrigation suitability guidelines are listed in the U.S. Department of Agriculture Handbook 60 (1954).

Drinking Water Suitability

The EPA maximum contaminant levels for drinking water are applicable for all community water systems. Those for nitrate as nitrogen are applicable to noncommunity water systems. Maximum contaminant levels for constituents measured on samples from the study area are:

Contaminant	MCL, in mg/L
Fluoride	1.4-2.4
Nitrate, as N	10

The fluoride concentrations in water samples from the 68 irrigation wells are all below the MCL; however, for nitrate as nitrogen, 3 samples equaled or exceeded the MCL.

Nitrate as nitrogen equalled or exceeded the MCL in three wells: 11 mg/L in well 1N-16W-14ABBA in Franklin County; 10 mg/L in well 7N-16W-29CA in Kearney County; and 12 mg/L in well 5N-18N-2CCD in Phelps County. All of these concentrations most likely are related to point-source contamination. The descriptive statistics for nitrate as nitrogen are given in table 10. For the unconfined aquifer in the study area, the combined mean concentration of nitrite plus nitrate as nitrogen is 3.0, and it is assumed to be all nitrate-nitrogen.

Irrigation Suitability

Figure 27 shows the range of sodium-adsorption ratio (SAR) and specific conductance (conductivity) for the water samples in the study area. SAR relates sodium concentration to calcium and magnesium concentrations in water. As the sodium concentration increases and calcium and magnesium concentrations decrease, SAR becomes larger. In figure 28, irrigation water that falls into class C1-S1, the lower left area, is the most suitable; and irrigation water classified as C4-S4, in the upper right, is the least suitable. Moving right across the conductivity scale, the salinity increases; while moving upward along the SAR scale, the SAR increases. Water that is classified as S3, S4, C3, and C4 is either not recommended for irrigation or requires special management if used for irrigation.

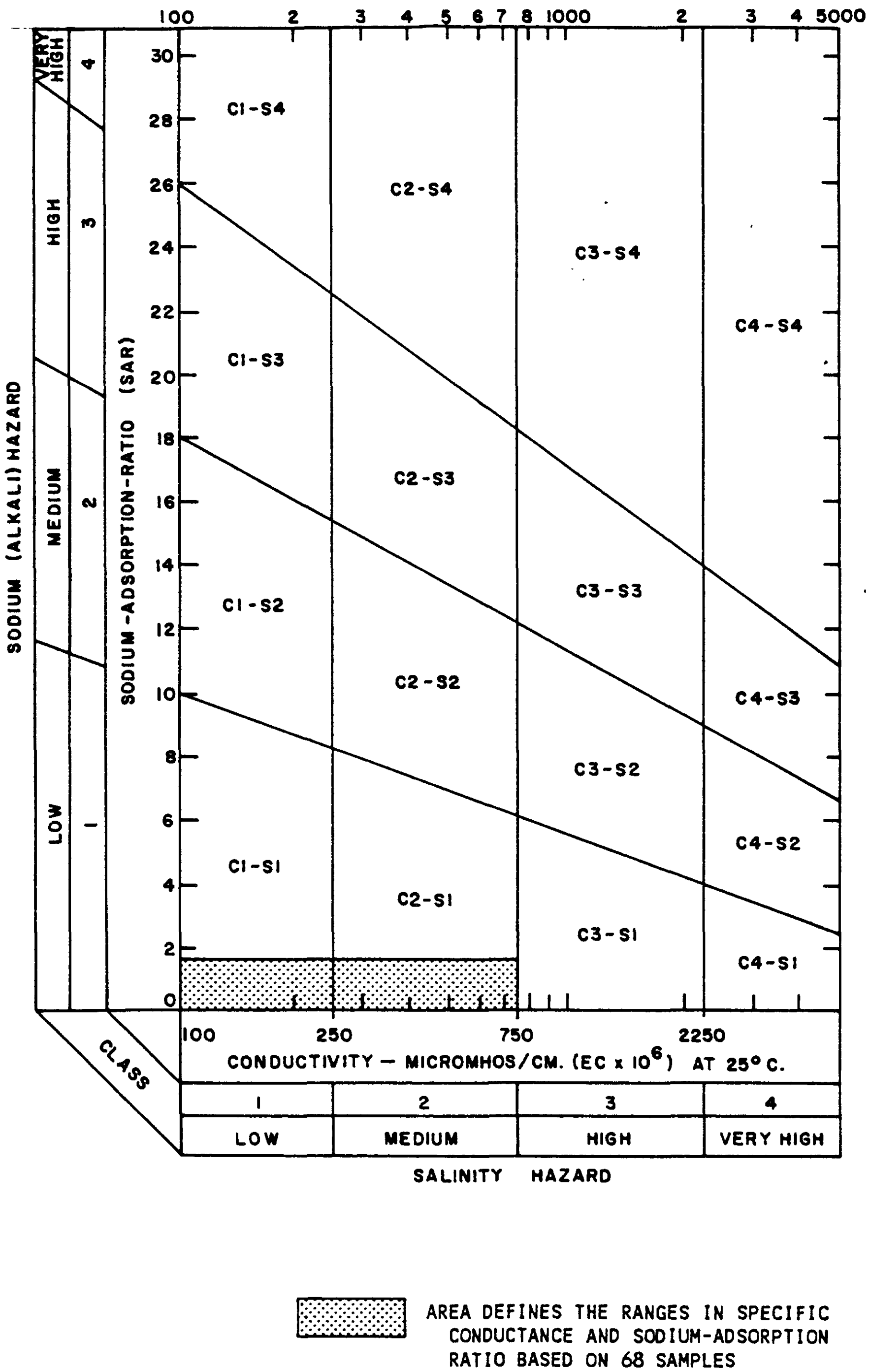


Figure 27.--Range in sodium-adsorption ratio (SAR) and specific conductance for water samples. (modified from U.S. Department of Agriculture, 1954.)

The ranges of SAR and specific conductance for the water samples in the study area fall within the low (S1) for SAR and low and medium (C1 and C2) for conductance. Thus, the water classes are C1-S1 and C2-S1, which indicates the water is safe for irrigation under most conditions.

The maximum boron concentration in the study area is 210 µg/L. This is less than the National Academy of Science (1972) maximum level of 750 µg/L, which should not be exceeded. Thus, boron does not constitute a danger to the crops grown in the study area.

PROCEDURES FOR ESTIMATING RECHARGE AND CONSUMPTIVE IRRIGATION REQUIREMENTS

Procedures were developed to prepare recharge and consumptive irrigation requirement (CIR) data for use in the ground-water flow model, and simplifying assumptions were made with regard to these data. Four interdependent computer programs are used to compute recharge and CIR data.

Soil-Zone Programs

Two computer programs, the Potential Evapotranspiration (PET) Program and the Soil-Moisture Program, are used to represent the movement of water in and through the soil zone. These programs require climatic, soil, and crop data to calculate both the amount of water that will pass through the soil zone to become recharge to the aquifer and the CIR of crops.

The operational procedures and physical basis for these soil-zone programs are discussed by Cady and Peckenpaugh (1985). Only minor modifications in the input and output procedures for these programs were made for this study.

PET (Potential Evapotranspiration) Program

The PET Program computes monthly potential evapotranspiration using the Jensen-Haise method (Jensen and others, 1969). First it calculates total solar radiation by a regression equation that uses percent of possible sunshine from the National Weather Service station at North Platte, Nebr., and maximum solar radiation for each month. Next it computes monthly potential evapotranspiration by using temperature and total solar radiation for the nine weather stations in or near the study area that have temperature data. Potential evapotranspiration data from the above nine weather stations are used to assign potential evapotranspiration values to the other 30 weather stations.

Soil-Moisture Program

The Soil-Moisture Program simulates the infiltration, storage, and removal of water from the soil on a monthly basis in order to compute recharge to the underlying saturated zone. The Soil-Moisture Program requires values for (1) monthly potential evapotranspiration values from the PET Program; (2) crop coefficients (fig. 28), which are the monthly ratios of consumptive water requirements to potential evapotranspiration for row crops, sorghum, alfalfa, small grain, pasture and range, and fallowland; (3) precipitation and infiltration-curve coefficients and infiltration-curve numbers (fig. 29) that are dependent on soils, topography, and land use; (4) available water capacity for eight soil groups in the study area (table 11); and (5) crop root-zone depths.

The results of the Soil-Moisture Program can be presented in a variety of forms, depending on the program options selected. The program gives values for each soil, land use, and weather station in the study area. The output necessary for computing recharge and CIR is either the deep percolation or CIR amounts for irrigated land and the deep percolation for drylands during the irrigation and nonirrigation seasons.

The Soil-Moisture Program can provide study-period averages for each soil, land use, and weather station of the following items: (1) precipitation, (2) infiltration, (3) surface runoff, (4) evapotranspiration, (5) deep percolation on irrigated lands, (6) CIR, and (7) deep percolation on drylands. For this study, there is a possible combination of 178 of these soils, land use and weather station groups. Table 12 presents a representative subset of these data.

The Soil-Moisture Program solves the soil-moisture budget equations for drylands and irrigated lands. For drylands, the soil-moisture budget equation is $ET \geq I - DPD$; where I = infiltration and DPD = deep percolation (recharge) from drylands. The "greater than" symbol represents the conditons where ET exceeds infiltration. When this occurs, the soils have a moisture deficit, and dryland crops or land uses have a water deficiency. For irrigated lands, the soil-moisture budget equation is $ET \geq I + CIR - DPI$; where CIR = consumptive-irrigation requirements and DPI = deep percolation (recharge) for irrigated lands. The "greater than" symbol represents the conditions where ET exceeds infiltration and there is no CIR (during the nonirrigation season). When this condition occurs, the soils have a moisture deficit, and irrigated crops or land uses have a water deficiency.

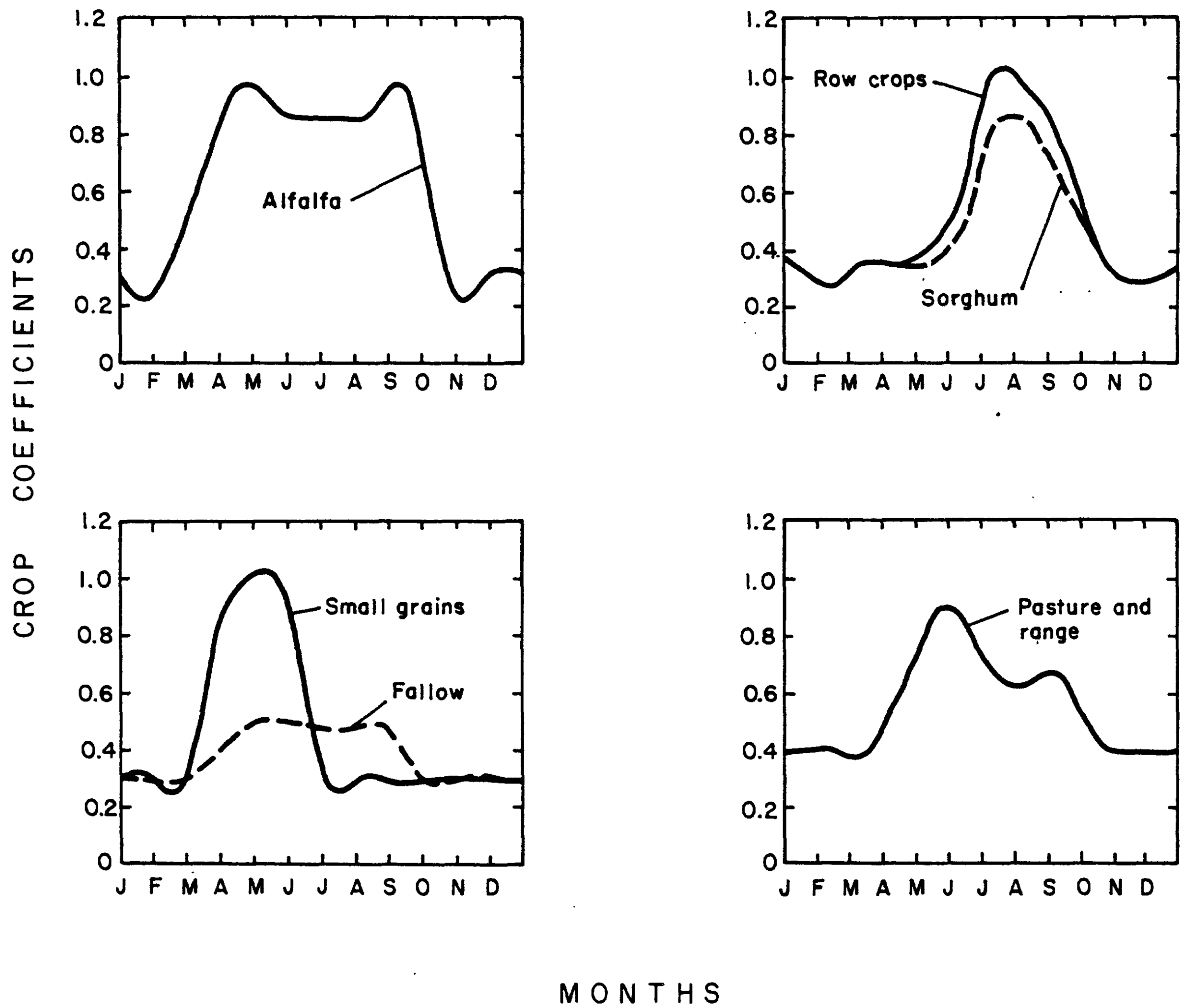
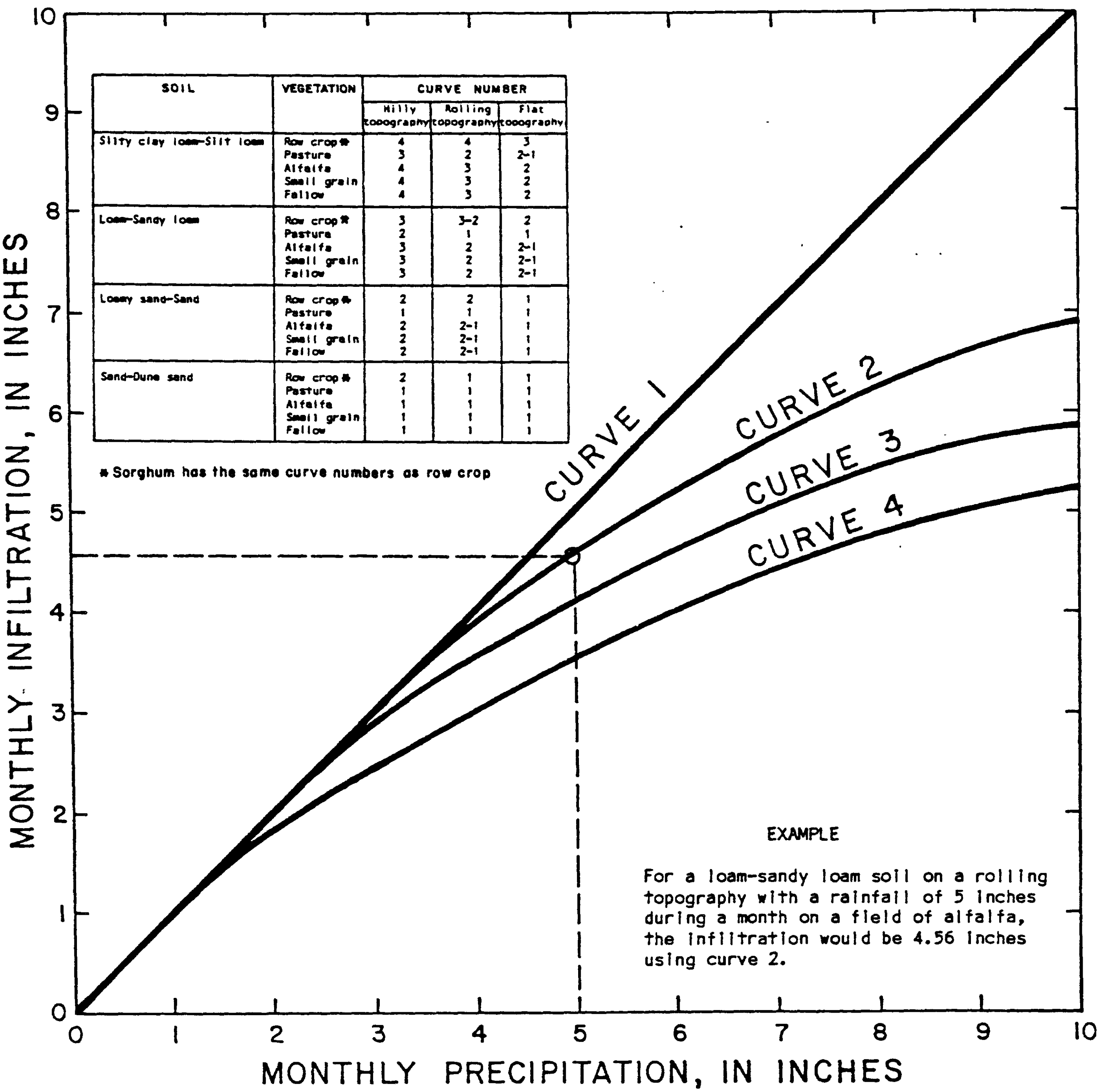


Figure 28.--Crop coefficients for five crop types and fallow land.
(Modified from Cady and Peckenpaugh, 1986.)



SOIL	VEGETATION	CURVE NUMBER		
		Hilly topography	Rolling topography	Flat topography
Silty clay loam-Silt loam	Row crop*	4	4	3
	Pasture	3	2	2-1
	Alfalfa	4	3	2
	Small grain	4	3	2
	Fallow	4	3	2
Loam-Sandy loam	Row crop*	3	3-2	2
	Pasture	2	1	1
	Alfalfa	3	2	2-1
	Small grain	3	2	2-1
	Fallow	3	2	2-1
Loamy sand-Sand	Row crop*	2	2	1
	Pasture	1	1	1
	Alfalfa	2	2-1	1
	Small grain	2	2-1	1
	Fallow	2	2-1	1
Sand-Dune sand	Row crop*	2	1	1
	Pasture	1	1	1
	Alfalfa	1	1	1
	Small grain	1	1	1
	Fallow	1	1	1

* Sorghum has the same curve numbers as row crop

Figure 29.--Monthly precipitation-infiltration for different soils, land use, and topography. (Modified from Cady and Peckenpaugh, 1985.)

Table 11.—Available water capacity and curve numbers for the soil groups

Soil group symbol 1/	Available water capacity (inch per inch)	Curve number for					
		Row crop	Sorghum	Alfalfa	Small grain	Pasture	Fallow-land
A	0.18	2	2	1	2	1	2
B	.18	3	3	2	2	2	3
C	.16	3	3	2	2	2	3
D	.16	1	1	1	1	1	1
E	.08	2	2	1	1	1	2
F	.18	3	3	3	3	2	3
G	.09	1	1	1	1	1	1
H	.07	2	2	1	1	1	2

1/ Table 1 and figure 5 identify the soil associations that comprise each soil group symbol.

Table 12.--Results of soil-moisture program using data for Alma, Elwood, Minden, and Red Cloud weather stations

[P, precipitation; I, infiltration; RO, surface runoff; ET, evapotranspiration; DPI, deep percolation (recharge) from irrigated lands; CIR, consumptive irrigation requirements; DPD, deep percolation (recharge from drylands; P = I + RO; for irrigated lands, ET = I + CIR - DPI; for drylands, ET can exceed I - DPD.]

Map Symbol[1]/	Land use	P	I	RO (Inches)	ET	DPI	CIR	DPD
				ALMA				
A	Row crop	22.7	21.3	1.4	32.8	1.3	11.9	0.8
	Sorghum	22.7	21.3	1.4	28.9	2.4	9.5	1.8
	Alfalfa	22.7	22.7	0.0	39.3	.2	15.5	0.0
	Small grain	22.7	21.3	1.4	23.7	2.8	4.9	1.5
	Pasture	22.7	22.7	0.0	32.2	1.5	9.9	.8
	Fallow	22.7	21.3	1.4	23.9	3.7	5.6	2.3
B	Row crop	22.7	20.2	2.5	32.8	.8	12.5	.5
	Sorghum	22.7	20.2	2.5	28.9	1.8	10.0	1.2
	Alfalfa	22.7	21.3	1.4	39.3	0.0	16.5	0.0
	Small grain	22.7	21.3	1.4	23.7	2.8	4.9	1.5
	Pasture	22.7	21.3	1.4	32.2	.8	10.5	.4
	Fallow	22.7	20.2	2.5	23.9	3.0	5.9	1.6
D	Row crop	22.7	22.7	0.0	32.8	2.3	11.5	1.9
	Sorghum	22.7	22.7	0.0	28.9	3.6	9.2	3.0
	Alfalfa	22.7	22.7	0.0	39.3	.2	15.2	.1
	Small grain	22.7	22.7	0.0	23.7	3.9	4.6	2.7
	Pasture	22.7	22.7	0.0	32.2	1.8	9.8	1.1
	Fallow	22.7	22.7	0.0	23.9	5.0	5.5	3.6
				ELWOOD				
A	Row crop	21.5	20.2	1.3	32.2	1.1	12.1	0.8
	Sorghum	21.5	20.2	1.3	28.4	2.1	9.6	1.6
	Alfalfa	21.5	21.5	0.0	38.5	.1	15.7	0.0
	Small grain	21.5	20.2	1.3	23.3	2.5	5.1	1.3
	Pasture	21.5	21.5	0.0	31.5	1.2	10.0	.7
	Fallow	21.5	20.2	1.3	23.4	2.9	5.4	1.7
B	Row crop	21.5	19.2	2.3	32.2	.7	12.7	.5
	Sorghum	21.5	19.2	2.3	28.4	1.6	10.1	1.1
	Alfalfa	21.5	20.2	1.3	38.5	0.0	16.8	0.0
	Small grain	21.5	20.2	1.3	23.3	2.5	5.1	1.3
	Pasture	21.5	20.2	1.3	31.5	.6	10.6	.2
	Fallow	21.5	19.2	2.3	23.4	2.2	5.7	1.1

Table 12.--Results of soil-moisture program using data for Alma, Elwood, Minden, and Red Cloud weather stations--Continued

Map Symbol[1]/	Land use	P	I	RO (Inches)	ET	DPI	CIR	DPD
				ELWOOD--Continued				
C	Row crop	21.5	19.2	2.3	32.2	.9	12.7	.7
	Sorghum	21.5	19.2	2.3	28.4	1.8	1.2	1.4
	Alfalfa	21.5	20.2	1.3	38.5	0.0	16.4	0.0
	Small grain	21.5	20.2	1.3	23.3	2.7	5.2	1.6
	Pasture	21.5	20.2	1.3	31.5	.8	10.5	.4
	Fallow	21.5	19.2	2.3	23.4	2.4	5.7	1.3
D	Row crop	21.5	21.5	0.0	32.2	2.2	11.7	1.8
	Sorghum	21.5	21.5	0.0	28.4	3.3	9.4	2.8
	Alfalfa	21.5	21.5	0.0	38.5	.1	15.4	0.0
	Small grain	21.5	21.5	0.0	23.3	3.5	4.8	2.4
	Pasture	21.5	21.5	0.0	31.5	1.4	9.9	.9
	Fallow	21.5	21.5	0.0	23.4	4.1	5.4	2.8
				MINDEN				
A	Row crop	21.6	20.3	1.3	29.6	1.8	10.5	1.3
	Sorghum	21.6	20.3	1.3	26.0	2.9	8.3	2.2
	Alfalfa	21.6	21.6	0.0	35.3	.3	13.3	.1
	Small grain	21.6	20.3	1.3	21.2	3.4	4.0	2.2
	Pasture	21.6	21.6	0.0	28.8	2.1	8.6	1.4
	Fallow	21.6	20.3	1.3	21.4	3.7	4.4	2.4
B	Row crop	21.6	19.3	2.3	29.6	1.2	11.0	.8
	Sorghum	21.6	19.3	2.3	26.0	2.3	8.7	1.6
	Alfalfa	21.6	20.3	1.3	35.3	.1	14.4	0.0
	Small grain	21.6	20.3	1.3	21.2	3.4	4.0	2.2
	Pasture	21.6	20.3	1.3	28.8	1.3	9.1	.7
	Fallow	21.6	19.3	2.3	21.4	2.9	4.7	1.7
D	Row crop	21.6	21.6	0.0	29.6	3.1	10.2	2.4
	Sorghum	21.6	21.6	0.0	26.0	4.1	8.2	3.5
	Alfalfa	21.6	21.6	0.0	35.3	.5	13.2	.2
	Small grain	21.6	21.6	0.0	21.2	4.5	3.9	3.5
	Pasture	21.6	21.6	0.0	28.8	2.3	8.6	1.6
	Fallow	21.6	21.6	0.0	21.4	5.0	4.4	3.7
E	Row crop	21.6	20.3	1.3	29.6	3.8	11.4	3.6
	Sorghum	21.6	20.3	1.3	26.0	4.8	9.4	4.4
	Alfalfa	21.6	21.6	0.0	35.3	1.5	12.4	1.2
	Small grain	21.6	21.6	0.0	21.2	5.7	4.4	5.0
	Pasture	21.6	21.6	0.0	28.8	3.7	8.8	3.2
	Fallow	21.6	20.3	1.3	21.4	5.1	4.9	4.3

Table 12.--Results of soil-moisture program using data for Alma, Elwood, Minden, and Red Cloud weather stations--Continued

Map Symbol[1]	Land use	P	I	RO (Inches)	ET	DPI	CIR	DPD
				MINDEN--Continued				
G	Row crop	21.6	21.6	0.0	29.6	4.5	11.0	4.2
	Sorghum	21.6	21.6	0.0	26.0	5.6	9.0	5.2
	Alfalfa	21.6	21.6	0.0	35.3	1.3	12.5	.9
	Small grain	21.6	21.6	0.0	21.2	5.5	4.3	4.7
	Pasture	21.6	21.6	0.0	28.8	3.4	8.8	2.9
	Fallow	21.6	21.6	0.0	21.4	6.0	4.7	5.1
H	Row crop	21.6	20.3	1.3	29.6	4.1	11.5	3.9
	Sorghum	21.6	20.3	1.3	26.0	5.0	9.5	4.7
	Alfalfa	21.6	21.6	0.0	35.3	1.8	12.3	1.4
	Small grain	21.6	21.6	0.0	21.2	5.9	4.4	5.3
	Pasture	21.6	21.6	0.0	28.8	3.9	8.8	3.5
	Fallow	21.6	20.3	1.3	21.4	5.3	5.0	4.6
				RED CLOUD				
A	Row crop	25.9	23.9	2.0	31.6	2.9	10.1	2.1
	Sorghum	25.9	23.9	2.0	27.8	4.4	8.0	3.3
	Alfalfa	25.9	25.9	0.0	37.9	.9	12.1	.2
	Small grain	25.9	23.9	2.0	22.9	4.9	3.6	3.5
	Pasture	25.9	25.9	0.0	31.0	3.7	8.1	2.6
	Fallow	25.9	23.9	2.0	23.0	5.7	4.5	4.2
B	Row crop	25.9	22.5	3.4	31.6	2.1	10.7	1.5
	Sorghum	25.9	22.5	3.4	27.8	3.5	8.5	2.5
	Alfalfa	25.9	23.9	2.0	37.9	.2	13.4	0.0
	Small grain	25.9	23.9	2.0	22.9	4.9	3.6	3.5
	Pasture	25.9	23.9	2.0	31.0	2.3	8.7	1.4
	Fallow	25.9	22.5	3.4	23.0	4.7	4.8	3.2
D	Row crop	25.9	25.9	0.0	31.6	4.7	9.8	3.8
	Sorghum	25.9	25.9	0.0	27.8	6.2	7.8	5.3
	Alfalfa	25.9	25.9	0.0	37.9	1.1	12.1	.4
	Small grain	25.9	25.9	0.0	22.9	6.7	3.4	5.4
	Pasture	25.9	25.9	0.0	31.0	4.0	8.2	2.9
	Fallow	25.9	25.9	0.0	23.0	7.7	4.3	6.2

Table 12.--Results of soil-moisture program using data for Alma, Elwood, Minden, and Red Cloud weather stations--Continued

Map Symbol1/	Land use	P	I	RO (Inches)	ET	DPI	CIR	DPD
				RED CLOUD--Continued				
F	Row crop	25.9	22.5	3.4	31.6	2.1	10.7	1.5
	Sorghum	25.9	22.5	3.4	27.8	3.5	8.5	2.5
	Alfalfa	25.9	22.5	3.4	37.9	.1	14.6	0.0
	Small grain	25.9	22.5	3.4	22.9	3.9	4.0	2.6
	Pasture	25.9	23.9	2.0	31.0	2.3	8.7	1.4
	Fallow	25.9	22.5	3.4	23.0	4.7	4.8	3.2
H	Row crop	25.9	23.9	2.0	31.6	5.4	11.5	5.1
	Sorghum	25.9	23.9	2.0	27.8	6.6	9.4	6.2
	Alfalfa	25.9	25.9	0.0	37.9	2.9	12.0	2.4
	Small grain	25.9	25.9	0.0	22.9	8.4	4.3	7.5
	Pasture	25.9	25.9	0.0	31.0	5.9	8.7	5.2
	Fallow	25.9	23.9	2.0	23.0	7.4	5.0	6.6

1/ Table 1 and figure 5 identify the soil associations that comprise each soil group symbol.

Recharge and Discharge Programs

Because few of the needed recharge and CIR data are measured directly, procedures and programs were developed to estimate these data. The recharge-discharge programs compute net recharge to, or discharge from, the saturated zone for each finite element of the ground-water flow model for a given period of time. These programs use the results of the Soil-Moisture Program and additional data on irrigation and land use.

For this study, the programs for recharge and discharge are composed of two primary programs, the ACRES and PUMP programs. These programs are developed from the PUMP Program of Cady and Peckenpaugh (1985).

Weighting Procedures for Precipitation

Procedures were developed to assign the recharge and CIR data to finite elements in the study area (Dugan and Peckenpaugh, 1985). These procedures replace the Thiessen polygon method, which had been used in some previous ground-water studies to assign these data. The Theissen polygon method often produced uneven recharge and CIR data across polygon boundaries. Smoother and more reasonable recharge and CIR data are obtained by the new procedures, which weight the effects of precipitation from one to three weather stations on the distance of those weather stations from the center of the finite element. Also, the nearer a weather station is to the center of the finite element, the greater the precipitation data from that station affects the values of recharge and CIR used for that finite element.

ACRES Program

The ACRES Program computes the types of land use for each finite element for a selected time period. The product of this program is the number of acres of each land-use type in each finite element that are irrigated or dryland farmed.

A variety of input data concerning the study area were necessary for use in the ACRES program. The following data were used:

(1) A 1980 land-use inventory was performed. The 1980 land-use data for Franklin, Furnas, Gosper, Harlan, Kearney, and Phelps Counties and the areas of study in Dawson and Buffalo Counties were developed by the Nebraska Natural Resources Commission (NNRC) using remote-sensing data and aerial photography. After the above land-use inventory was started, a 1980 land-use inventory of Webster County was developed by the NNRC by using remote-sensing procedures. Data for Adams, Frontier, Hall, Lincoln, and Red Willow Counties were obtained from 1978 land-use maps (unpublished) developed by the U.S. Soil Conservation Service. Lands were classified into eight types. Ultimately, each finite element was assigned a distribution of land-use types.

(2) The distribution of acres irrigated with surface water throughout the study period, 1940 through May 1981, was generated (table 4). The surface-water irrigation system was categorized into three groups (fig. 9 and 10), which are described in the section on Surface-Water System.

Information on surface-water irrigated acreages supplied by the private canals north and south of the Platte River is somewhat limited. The surface-water irrigated acreages from the Platte Level B Study (Lappala and others, 1979), which represents the approximate 1970 acreages, was used for canals on the south side of the Platte River for the entire study period. For private canals on the north side of the Platte River the Platte Level B data was used until 1970. Then surface-water irrigated acres between 1970 and 1981 were computed by using linear interpolation. The 1981 surface-water irrigated acres were based on an unpublished Nebraska Department of Water Resources survey of irrigated acreages north of the Platte River in 1980.

The CNPPID surface-water irrigated acreage was available for each year of operation. However, only 1941, 1946, 1955, 1965, and 1980 were used in the model.

The areas of lands irrigated with water from U.S. Bureau of Reclamation canals along the Republican River are based on the maximum acreages that could be irrigated. To obtain the acreages irrigated each year, the maximum acreages were multiplied by a proportion of the maximum acreages actually irrigated that year. Changes in the number of irrigated acres were assumed to be equally distributed over the entire supply area (U.S. Bureau of Reclamation, written commun., 1981).

(3) The historical land use for the 1940-81 study period was developed for use with the finite element grid. These data were generated by using the 1980 land-use inventory and Nebraska Agricultural Statistics (Nebraska Department of Agriculture, published annually), which lists annual crop acreages by counties.

After some crops were grouped together for simplification, a computer program calculated land uses back in time by using the 1980 land-use inventory as the starting point. The distribution of registered irrigation wells (fig. 12 and 13 and table 7) was used in computing the land uses back in time from 1980. As the numbers and distribution of registered irrigation wells decreased back in time from 1980, acres irrigated by ground water were subtracted from the land-use acres based on acres irrigated per well by county and year as given in table 7. The final product was the land-use value, in acres, by finite element and year from 1940 through 1981. (The 1980 land use was used for both 1980 and 1981.)

PUMP Program

The PUMP Program uses the results from the ACRES Program and additional irrigation data to compute recharge to the aquifer and CIR values for each element in the model. The recharge and CIR values are computed for the nonirrigation pumping period (September through May) and for the irrigation pumping period (June through August). The PUMP Program can be used to compute recharge and CIR values for the calibration period or for the predictive period.

The following data and related assumptions are used in the PUMP Program: (1) The historical land-use data for the 1940-81 study period (results of the ACRES Program); (2) the recharge and CIR for irrigated land and dryland for the nonirrigation and irrigation pumping periods (results of the Soil-Moisture Program); (3) the distribution of the soil groups within the finite elements; (4) the weighting factors for each finite element, which are used for distributing recharge and CIR values; (5) the location of surface-water irrigated lands in the finite elements; (6) the location of reservoirs and seepage from reservoirs within the finite elements; (7) the municipal pumpage that was estimated for communities greater than 500 people, by using an estimate of 300 gallons per capita per day; and (8) the surface-water seepage from canals.

SIMULATION OF THE GROUND-WATER SYSTEM

The development of the ground-water-flow model included the selection of a model that can represent the ground-water system, the generation of hydrogeologic and recharge and CIR data, and the calibration of the model by comparing measured and simulated water levels.

Description of the Ground-Water-Flow Model

The model used in this study to simulate the ground-water system was RAQSIM, a regional aquifer simulation model (Cady and Peckenpaugh, 1985). RAQSIM is a two-dimensional finite-element ground-water-flow model that allows flexibility in choosing boundaries and streams. This model computes transmissivity and specific yield values for the initial time step and at any time that the head change for any node exceeds a user-supplied limit.

The hydrogeologic parameters and water-use data are read into the ground-water-flow model using a system of 913 nodes or 1,013 finite elements (fig. 21). Water-level elevations, base of aquifer, and land-surface elevations are entered for each node. Recharge and CIR data are originally computed for each finite element and then transformed into nodal data by using a computer program before they were entered into the model. Other data, like T and Sy values, are computed within RAQSIM for each finite element.

RAQSIM computes evapotranspiration losses for areas where the depth to water is shallow, within a specified range. Evapotranspiration losses are computed for each time step within the model. Evapotranspiration losses from the ground water are assumed to be represented by the following relation:

$$q_{et(i,k)} = ETr - \frac{ETr}{ETz} (G_i - h_{i,k}). \qquad (3)$$

The terms in this equation have been modified from Trescott and others (1976) and are as follows:

$q_{et(i,k)}$ is the ET from ground water for node (i) and time (k), in feet per day;

ETr is the maximum evapotranspiration rate from ground water, in feet per day;

ETz is the depth below land surface at which ET ceases, in feet;

G_i is the elevation of the land surface, in feet; and

$h_{i,k}$ is the elevation of the water table, in feet.

Equation 3 is linear over the interval $0.0 \leq (G_i - h_{i,k}) \leq ETz$. The terms ETr and ETz are based on the assumption that the ET rate decreases linearly with depth and that ET will cease at some point, regardless of type of soil or crop.

The ET values computed by equation (3) represent ET losses or discharges from the aquifer. ETr and ETz are read into the model in the LAND file, which contains the elevation of the land surface of each node. ETr was selected as -.00205 foot per day, or -9 inches per year, while ETz was selected as 5 feet. These values were chosen based on the work done by Peckenpaugh and Dugan (1983).

Evapotranspiration salvage occurs when the water table is lowered by ground-water pumpage. The amount of ET salvaged equals the difference in ET calculated under pumping conditions and ET calculated in the absence of pumping according to equation 3. A maximum ET salvage of 9 inches will occur if the water level in the absence of pumping is from 0 to 1 foot below the land surface, and if the water level under pumping conditions is 5 feet or more below the land surface.

The treatment of the stream system within RAQSIM allows water to move between the aquifer and stream similarly to what happens in nature. Perennial segments of all streams were subdivided into reaches that are delineated by nodes on each end (fig. 30). The stream reaches were then subdivided into 66 stream systems. These stream systems are the streams shown in the schematic for the surface-water system (fig. 8). Stream reaches may parallel finite elements or they may truncate finite elements.

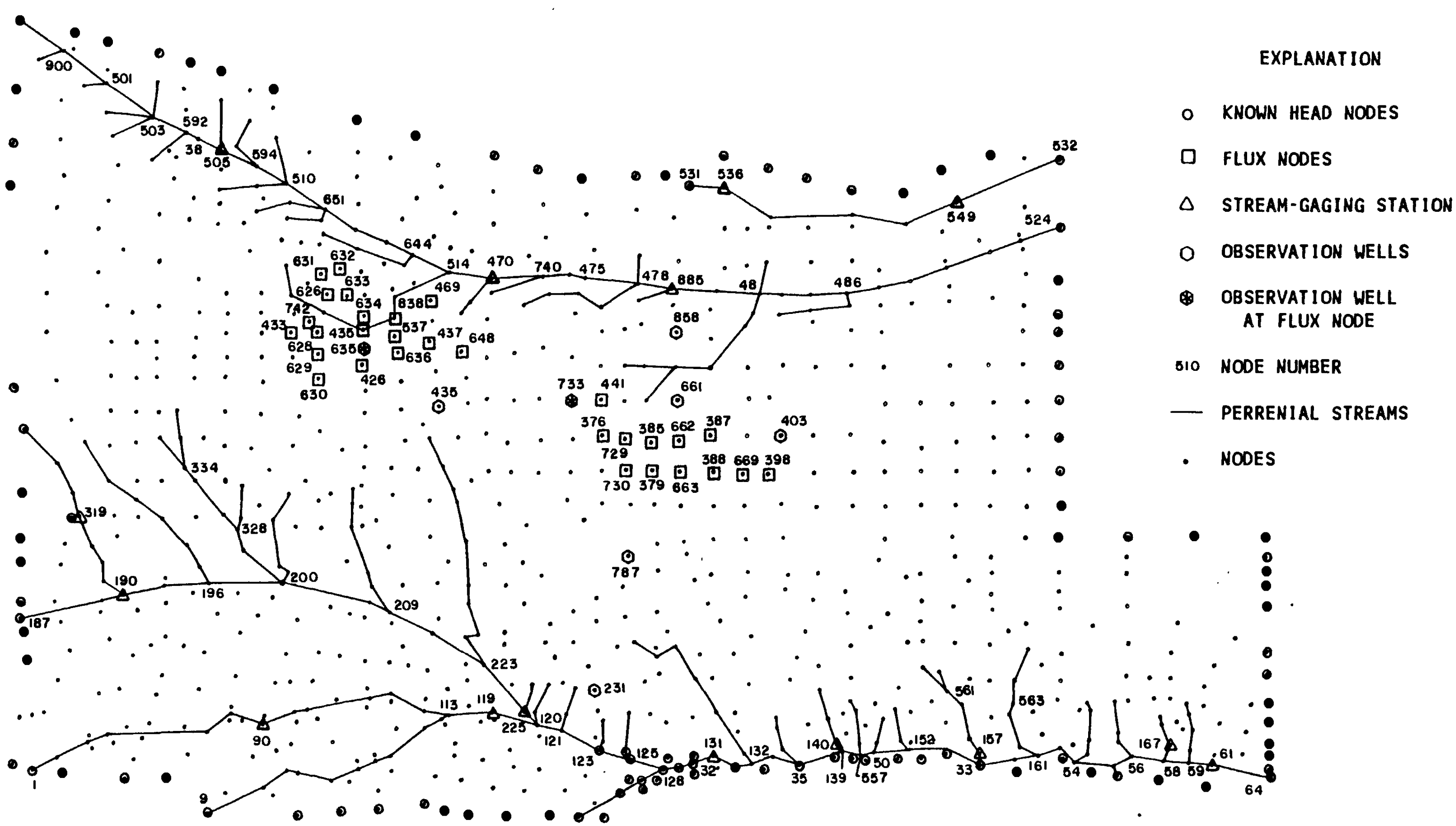


Figure 30.--Stream system.

Nodes where the water levels are not allowed to change, are referred to as known heads. There are 117 known-head nodes in the model. Most of the known-head nodes lie on the boundary of the study area; however, a few occur at reservoir sites. At the known-head nodes, water levels are linearly interpolated between measured water levels in 1940, 1965, and 1981. RAQSIM adds or removes water from these nodes so that water levels at these nodes remain unchanged.

Known-flux nodes were added to the model when it became apparent that the surface-water seepage from CNPPID's surface-water system could not be distributed by the model to match the historical distribution of seepage. This inability to match model seepage with historical seepage is predictable, because information on seepage rates along the different segments of the E-67, E-65, and Phelps County Canals or their laterals was not available, and because seepage data on Johnson Lake is limited. Known-flux nodes were used to provide additional seepage or recharge to the CNPPID area. Table 13 lists the known-flux nodes and the average acre-feet per year of recharge added to the aquifer at these nodes.

Assumptions in the Ground-Water-Flow Model

A variety of assumptions are necessary in developing and running the ground-water-flow model. Some assumptions pertain to the data required in the model, while others pertain to the development and operation of the model. Assumptions pertaining to required data have been previously discussed. The information that follows pertains to assumptions about the development and operation of the ground-water flow model.

1. The ground-water system can be represented as a nonhomogeneous, isotropic, unconfined aquifer. There are areas where the ground-water system responds like a confined aquifer; however, the regional and long-term response is that of an unconfined aquifer.

2. The vertical ground-water flow component is negligible; therefore, ground-water flow is assumed to occur only in the horizontal plane.

3. Irrigation wells are open and penetrate the entire thickness of the aquifer.

4. Underflow does not exist in nodes where the streams are connected to the aquifer.

5. Boundary conditions--known-head nodes and known-flux nodes--represent the aquifer adequately.

6. Pumping rates of irrigation wells are not affected by the saturated thickness of the aquifer until the base of the aquifer is reached. When this occurs, pumping ceases.

Table 13.--Known-flux nodes

Node	Year started	Recharge or seepage (acre-feet per year)	Node	Year started	Recharge or seepage (acre-feet per year)
632	1941	3,034	638	1941	200
631	1941	4,500	467	1941	2,400
626	1941	800	630	1941	250
742	1978	800	733	1941	1,600
628	1978	1,200	441	1941	800
633	1953	1,400	376	1941	100
634	1941	400	729	1941	100
435	1941	400	730	1941	200
629	1941	1,000	385	1941	200
635	1941	900	379	1941	500
630	1941	250	662	1941	23,900
426	1941	250	663	1941	1,200
637	1941	700	387	1941	50
636	1941	300	388	1941	2,100
437	1941	1,000	669	1941	800
646	1941	1,000	398	1941	400

Calibration of the Ground-Water-Flow Model

Calibration of a ground-water-flow model is the process of adjusting model parameters so that the results will be both realistic and valid. This is frequently achieved by trial-and-error adjustments of simulated properties until differences between simulated and measured water levels and flows are within acceptable limits. As part of the calibration procedures, sensitivity analyses of both steady-state and transient conditions should be performed. Steady-state conditions are those for which model results are independent of time and for which the hydrogeologic system is assumed to be in equilibrium. Transient conditions are those for which the model results are dependent on time and the hydrogeologic system does not have to be in equilibrium.

For this study, the ground-water-flow model was calibrated using steady-state procedures to check and adjust, if necessary, transmissivity values, recharge, water levels, and evapotranspiration losses from the ground water. Steady-state and transient procedures were used to perform sensitivity analyses on the input data. The model was calibrated for the 1940-81 time period using transient procedures. Adjustments in data were made until a reasonable fit was obtained between the computed and measured 1981 water levels.

Sensitivity Analyses

Sensitivity analyses were performed to ascertain what effect changes in recharge, transmissivity, and specific yield would have on water levels. The ground-water flow model was run using steady-state conditions with recharge values of 0.25, 0.75, 1.0, 1.25, and 1.75 times the initial recharge, with all other parameters set at their initial values. Water levels rose sharply as the recharge increased from 1.0 to 1.25. A decrease in recharge results in a small decline in water levels.

Using steady-state conditions, the ground-water-flow model was run with transmissivities of 0.25, 0.75, 1.0, 1.25, 1.5, and 2.0 times the initial T values, with all other parameters set at their initial values. Increasing T from 1.0 to 1.25, 1.50, and 2.0 produces a small decline in water levels. Decreasing T from 1.0 to 0.75 and 0.25 produces small to moderate rises in water levels. The relation between T and water levels is predictable. Increases in T allow the water to move away more rapidly; therefore, small declines in water levels result. Decreases in T prevent the water from moving toward discharge as readily; thus rises in water levels can occur.

Using transient conditions, the ground-water-flow model was run with specific yield (Sy) values of 0.25, 0.75, 1.0, 1.25, and 1.75 times the initial Sy values, with all other parameters at their initial values for a period of 3 years. Water levels declined slightly as specific yield values were increased from 1.0 to 1.25 and to 1.75. Water levels rose slightly as Sy values were decreased from 1.0 to 0.75, and they rose moderately when Sy values were decreased to 0.25. The relationship between Sy and water levels is predictable. As Sy values increase, more water is stored in a given thickness of the aquifer; thus, the overall saturated thickness of the aquifer decreases and water levels decline. The opposite occurs for decreases in Sy; that is, less water is in storage and water levels rise.

A comparison between sensitivity analyses for recharge, T, and Sy indicates that changes in recharge produce different responses in water levels than changes in T and Sy produce. Also, the changes in water levels due to changes in Sy are smaller than those due to changes in T. Thus, the model is more sensitive to changes in recharge and T than it is to changes in Sy. It should be noted that the model would respond with similar changes in water levels if discharge was substituted for recharge. The direction of changes, however, would be reversed.

Steady-State Procedures

When operating the model using steady-state procedures, the 1940 water levels (fig. 14) were used as the initial water levels, and transmissivity values (fig. 23) were computed based on the 1940 saturated thickness (fig. 19). With steady-state conditions, storage was set at zero and the time step was set at 1.0 day.

Steady-state model runs were used both in the sensitivity analysis and in the early calibration procedure to adjust and check both the data and the model. Only data-handling and programming errors in the data--recharge and discharge, transmissivity, and water-level elevations--were adjusted using steady-state procedures. Examples of these errors would be the use of the wrong sign for flow into or out of the aquifer and the incorrect use of a multiplication factor in the PUMP Program.

Transient Procedures

The transient procedures were the main tool in calibrating the ground-water flow model. In operating the model using transient procedures, the 1940 water levels (fig. 14) were the initial ones used, and the computed water levels were compared to the spring 1981 water levels (fig. 15). The model was run during the calibration period, September 1, 1939, through June 1, 1981.

Frequently, the initial water levels are smoothed by running the steady-state procedures to eliminate irregularities caused by measurement, contouring, or coding errors. This was not done, because the recharge-discharge information available (1940 through 1981) did not represent the recharge-discharge data that produced the 1940 water levels. The recharge-discharge data prior to 1940 (1937 through 1940 would be a reasonable period) determine the configuration of the water levels in 1940.

During model calibration, several adjustments in the hydrogeologic and water-use data were made. Sorghum was separated from other row crops, because water requirements for sorghum are significantly smaller than for corn, the predominant row crop. Because the land use in the southern counties contains large quantities of sorghum and correspondingly smaller amounts of irrigated corn (see table 2), without this change the pumpage in these southern counties would have been too great. This problem became apparent after reviewing the pumpage at the 18 water-use sites (Bartz and Peckenpaugh, 1986).

Changes were made in the available water capacities for some soil groups and in the curve numbers for certain soil and land-use categories (table 11). This required another run of the Soil-Moisture Program and all programs that used the results from the Soil-Moisture Program.

Some changes were made in hydraulic conductivity and specific yield values, which are used in the METS Program. These changes did not produce significant changes in water levels.

It became apparent after the above changes and an examination of the test-hole logs and water levels that T and Sy values in northeastern Webster County and in the area west of Harlan County Lake were not correct. The Ogallala Formation in the area west of Harlan County Lake apparently contains more of the quartzite and mortar-bed units, which have lower T and Sy values than the typical Ogallala Formation that is present south of the Republican River. Thus, T and Sy values were decreased for this area. The area in northeastern Webster County coincides with a bedrock high (fig. 18), which results in a thinner aquifer in this area. Thus, it was necessary also to decrease T and Sy values in this area.

T and Sy values in these areas were decreased by employing another feature of RAQSIM. T and Sy values can be computed by using the table of transmissivity and specific yield values, or one or both of these values can be set to any value in the finite-element file. For these areas and a few other small areas, T and Sy were set to smaller values in the finite-element file.

In selected areas south of the Republican River where T and Sy values were small, pumpage was decreased by 50 percent. This action was taken because pumpage values were computed independently from the aquifer's ability to produce and in these areas the aquifer's water yield was reduced. Figure 31 shows the finite elements where pumpage was reduced. All of these areas are south of the Republican River in the uplands (fig. 6).

Calibration of the ground-water-flow model was considered completed after these changes were made, because computed 1981 water levels (fig. 32) compared favorably with measured 1981 water levels (fig. 15). Lines of equal water-level elevation from computed and measured 1981 water levels show good agreement, especially in the northern half of the study area. South of the Republican River, the computed and measured values compared favorably in most areas. In Franklin County, the computed 1981 water levels are higher than measured water levels; however, the lines of equal water-level elevations have similar patterns.

Figure 31.--Elements with reduced irrigation pumpage.

Figure 32.--Configuration and elevation of the water table, 1981, from computed water levels.

The differences between computed and measured 1981 water levels are shown in figure 33. For much of this study area, the differences are within plus or minus 10 feet of measured water levels. The differences are less than 10 feet in most of Dawson, Gosper, Phelps, and Kearney Counties. Differences increase to 15 feet or more in some areas of these counties. In the southern part of the study area, there are large areas where differences between computed and measured 1981 water levels are 10 feet or less; and there are much smaller areas where the differences are 15 to 20 feet.

Maximum computed water-level declines of 50 feet occur in northeastern Webster County and declines of 40 feet occur in the area west of Harlan County Lake (fig. 33). As mentioned earlier, T and Sy values were decreased to reduce the declines. It is believed that current differences can be attributed to inadequate data on the hydraulic properties of the aquifer. Also, for the area of northeastern Webster County, water-level data are sparse, and difficulties may have occurred in accurately locating observation wells because of the rough topography. Thus, incorrect water-level data may be causing some of these differences.

An average, squared, weighted residual analysis (Ralph Cady, personal commun., 1984) was performed on the 1981 computed and measured water levels as a check on calibration of the model. This analysis involved the following: (1) subtracting the measured from the computed 1981 water levels at each node; (2) squaring the differences and multiplying this by the area represented by the node within the element; (3) adding this value for all active nodes; (4) dividing this sum by the total active study area; and (5) taking the square root of the result. The average, squared, weighted residual for the active nodes, excluding the known head nodes, was 10.93 feet. This represents an error of about one contour interval. The measured 1940 and 1981 water-level configuration maps were originally developed with 10-foot contour intervals. This magnitude of error is acceptable, considering the size of finite elements and the quality of hydrogeologic and water-use input data.

Model-generated streamflows are compared to measured streamflows in table 14. Computed streamflows are calculated streamflows based on hydrogeologic conditions for the time period of March 1 to June 1, and measured streamflows are the mean for the month of May. Also, only stream-gaging stations that measure unregulated streamflows were listed in table 14. An examination of the computed and measured streamflows shows a reasonable match between these values.

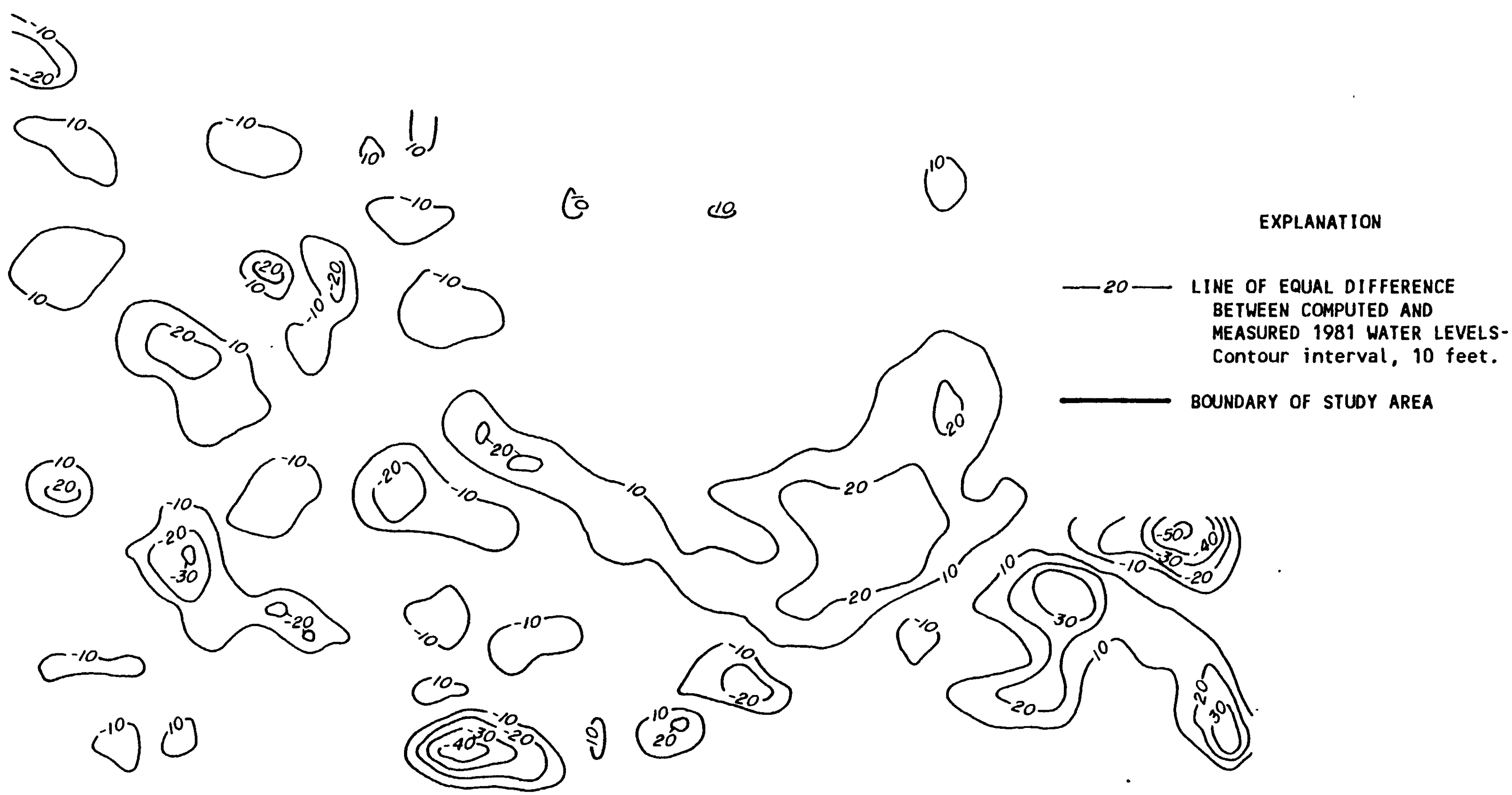


Figure 33.--Configuration of the difference between computed and measured 1981 water levels.

Table 14.--Comparison of measured streamflow, in cubic feet per second, to flow computed by the model
[Dashes indicate no value read or reported.]

Node	Gaging station reference site	Year (June 1)	Measured streamflow	Computed streamflow
200	Muddy Creek at at Arapahoe	1955	10	16
		1960	18	18
		1965	7	17
		1970	9	21
		1975	--	15
		1981	12	15
209	Turkey Creek at Edison	1955	--	13
		1960	--	14
		1965	--	13
		1970	--	14
		1975	--	10
		1981	5	7
90	Beaver Creek near Beaver City	1955	0	10
		1960	42	10
		1965	4	6
		1970	2	5
		1975	1	5
		1981	1	2
119	Sappa Creek near Stanford	1955	2	23
		1960	84	28
		1965	13	18
		1970	19	17
		1975	5	15
		1981	0	3
139	Center Creek at Franklin	1955	5	3
		1960	--	4
		1965	--	3
		1970	7	4
		1975	6	5
		1981	7	4

Table 14.--Comparison of measured streamflow, in cubic feet per second, to flow computed by the model--Continued

Node	Gaging station reference site	Year (June 1)	Measured streamflow	Computed streamflow
157	Thompson Creek at Riverton	1955	28	16
		1960	--	18
		1965	--	16
		1970	25	16
		1975	23	17
		1981	23	16
167	Elm Creek at Amboy	1955	--	2
		1960	--	3
		1965	--	2
		1970	--	3
		1975	--	3
		1981	16	3

A final check of the calibration of the model is the computed versus the measured observation-well data. Twenty-three nodes were selected that were near observation wells. The computed water levels at each of these nodes at the end of each time step were written onto a file. Water levels for 14 of these nodes were plotted individually with the appropriate water levels from the observation wells (fig. 34a-h). The computed and measured water levels for all the nodes have similar trends, and the differences between the two water levels are reasonable. Because computed water levels follow the same trends as the measured observation wells, it was concluded that the model is responding adequately to changes in recharge and discharge.

The computational performance of the model was checked by examining the cumulative error, boundary flux at the known-head nodes, and the mass balance. The cumulative error is the difference between all the types of fluxes going into and out of the model and all the types of fluxes going into and out of storage. The cumulative error was -1.65×10^4 cubic feet, which is -1.29×10^{-6} inches distributed over the entire study area. With a cumulative error of this size, it appears that the model is handling the computations adequately.

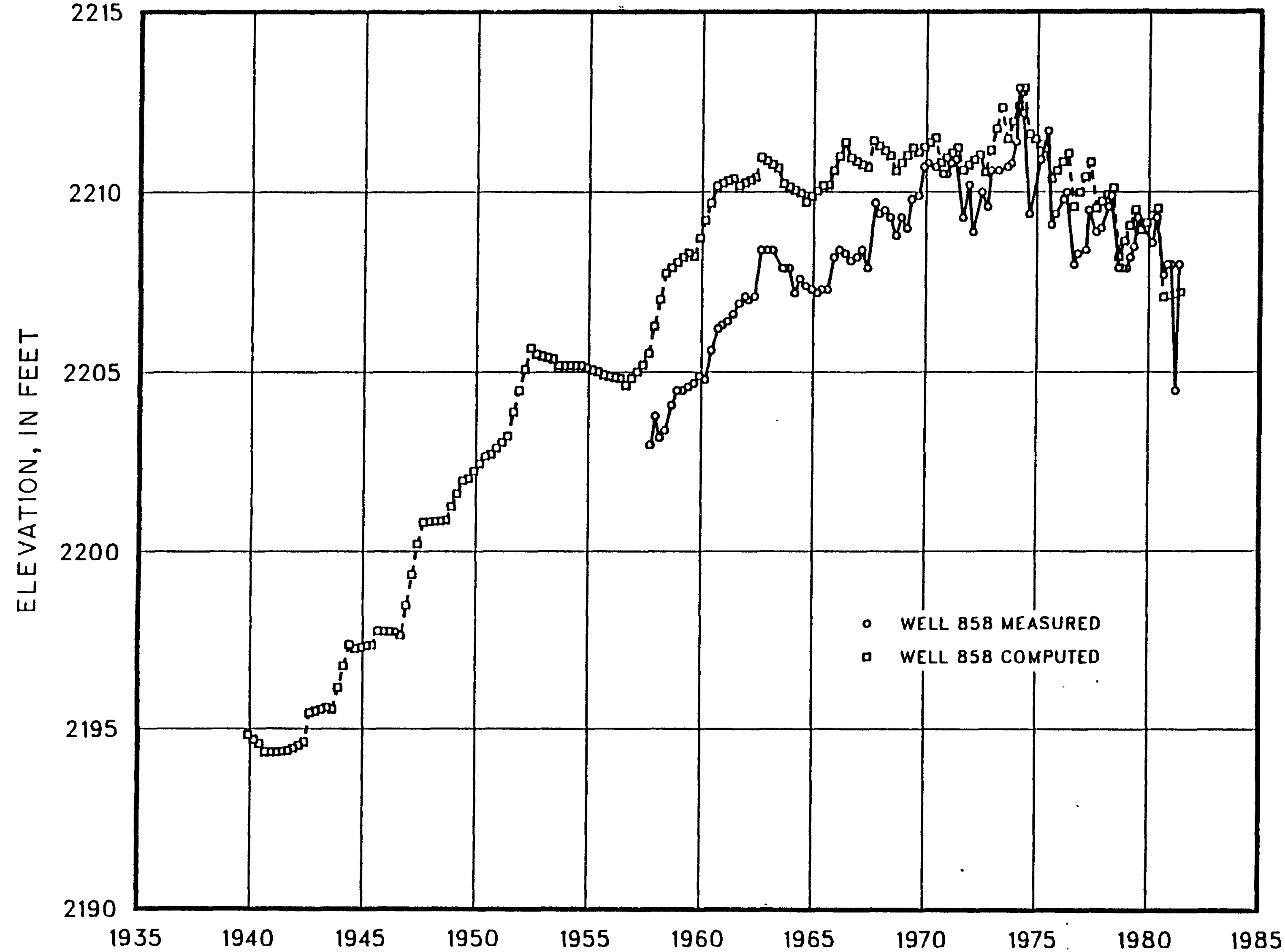


Figure 34-A.--Comparison of water levels computed for selected nodes with water levels measured in observation wells near the node, 1940-81.

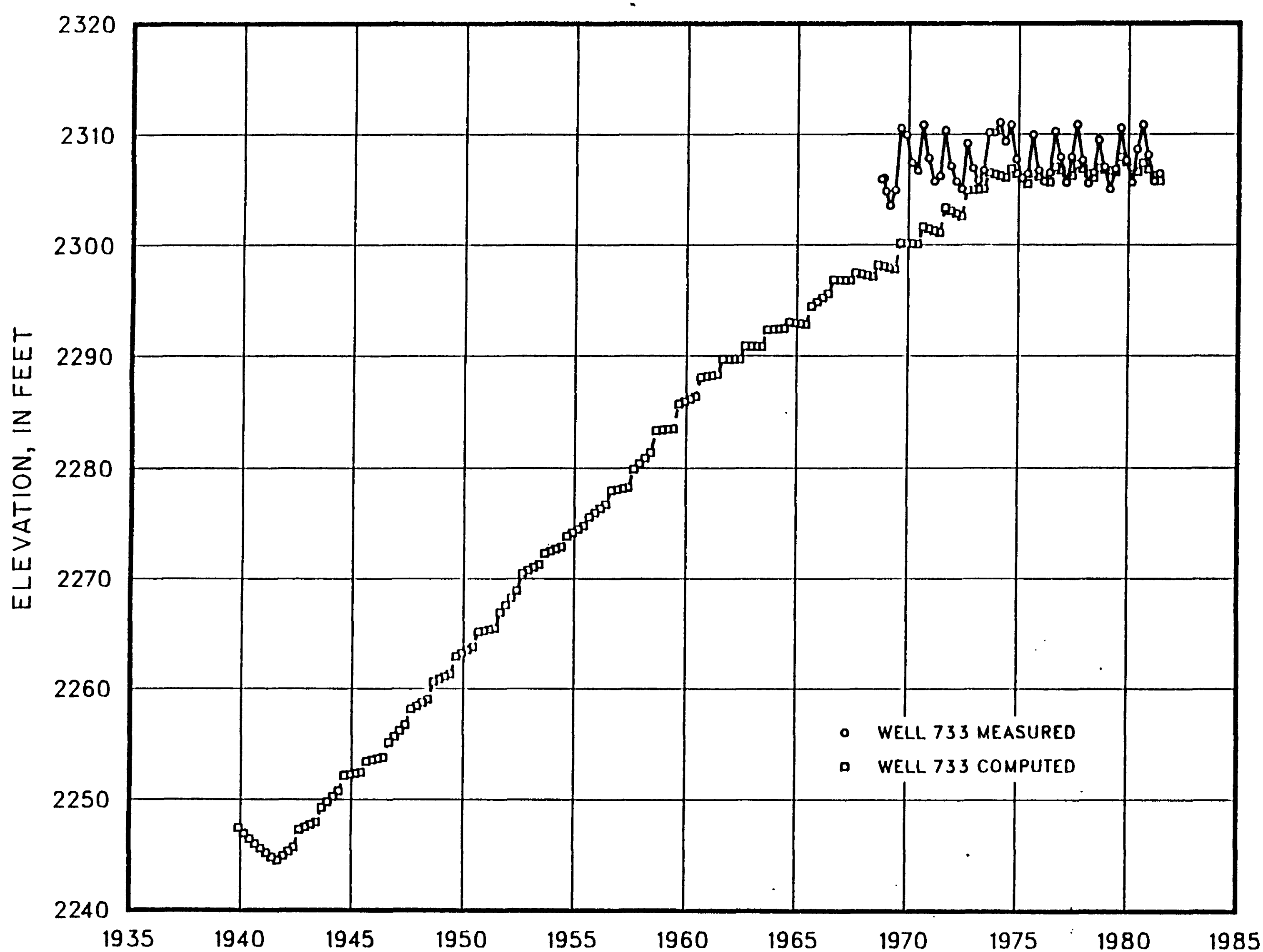


Figure 34-B.--Comparison of water levels computed for selected nodes with water levels measured in observation wells near the node, 1940-81.

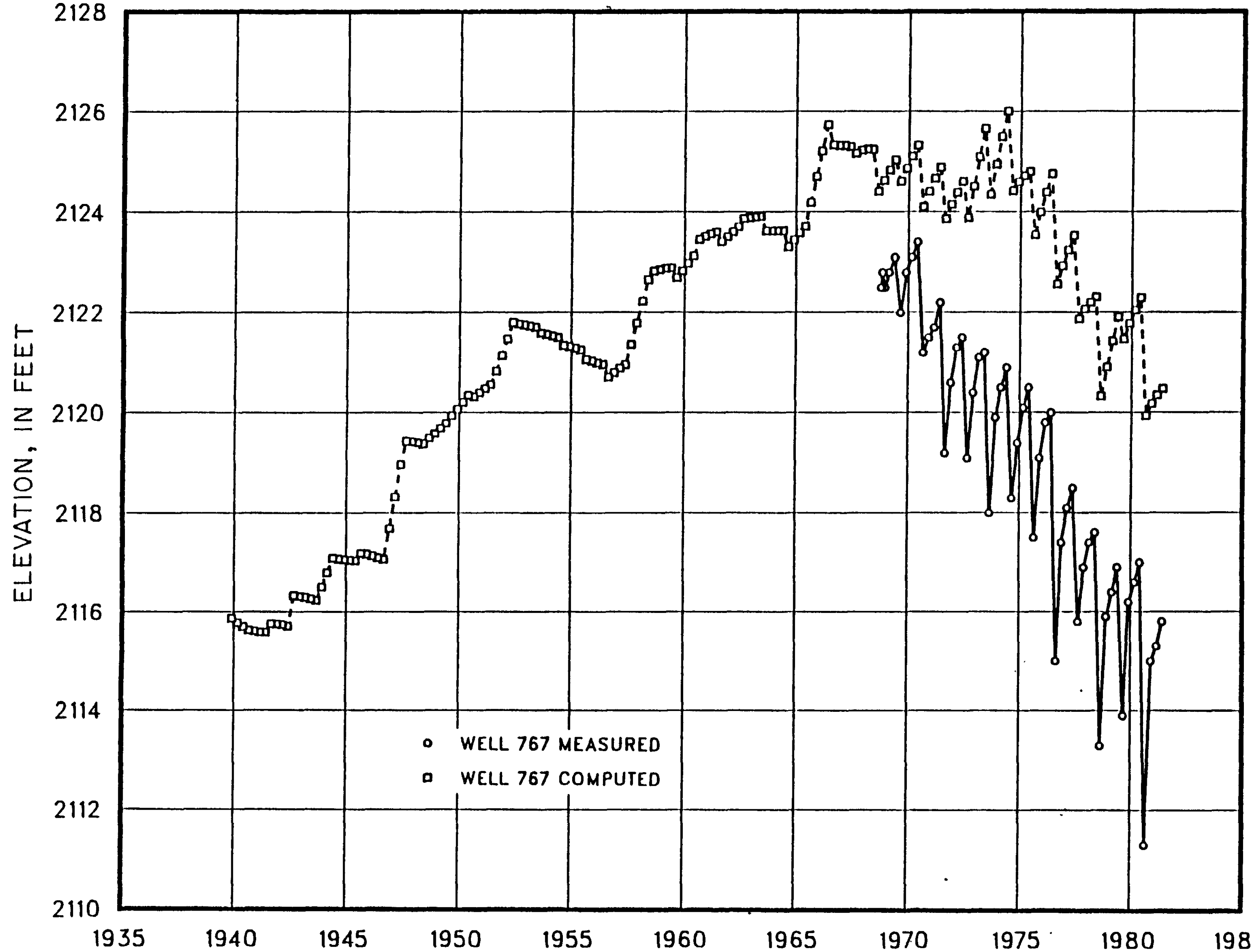


Figure 34-C.--Comparison of water levels computed for selected nodes with water levels measured in observation wells near the node, 1940-81.

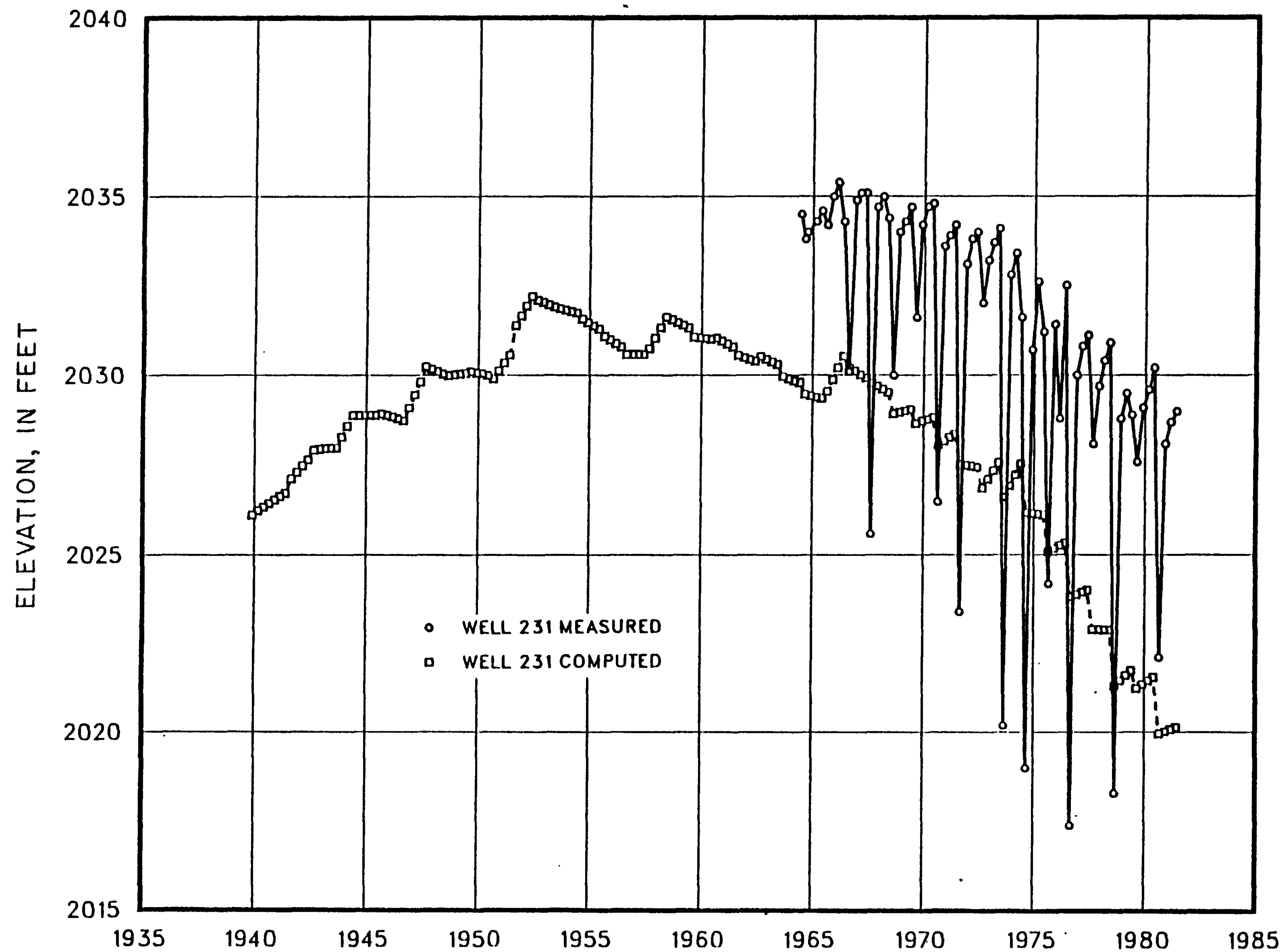


Figure 34-D.--Comparison of water levels computed for selected nodes with water levels measured in observation wells near the node, 1940-81.

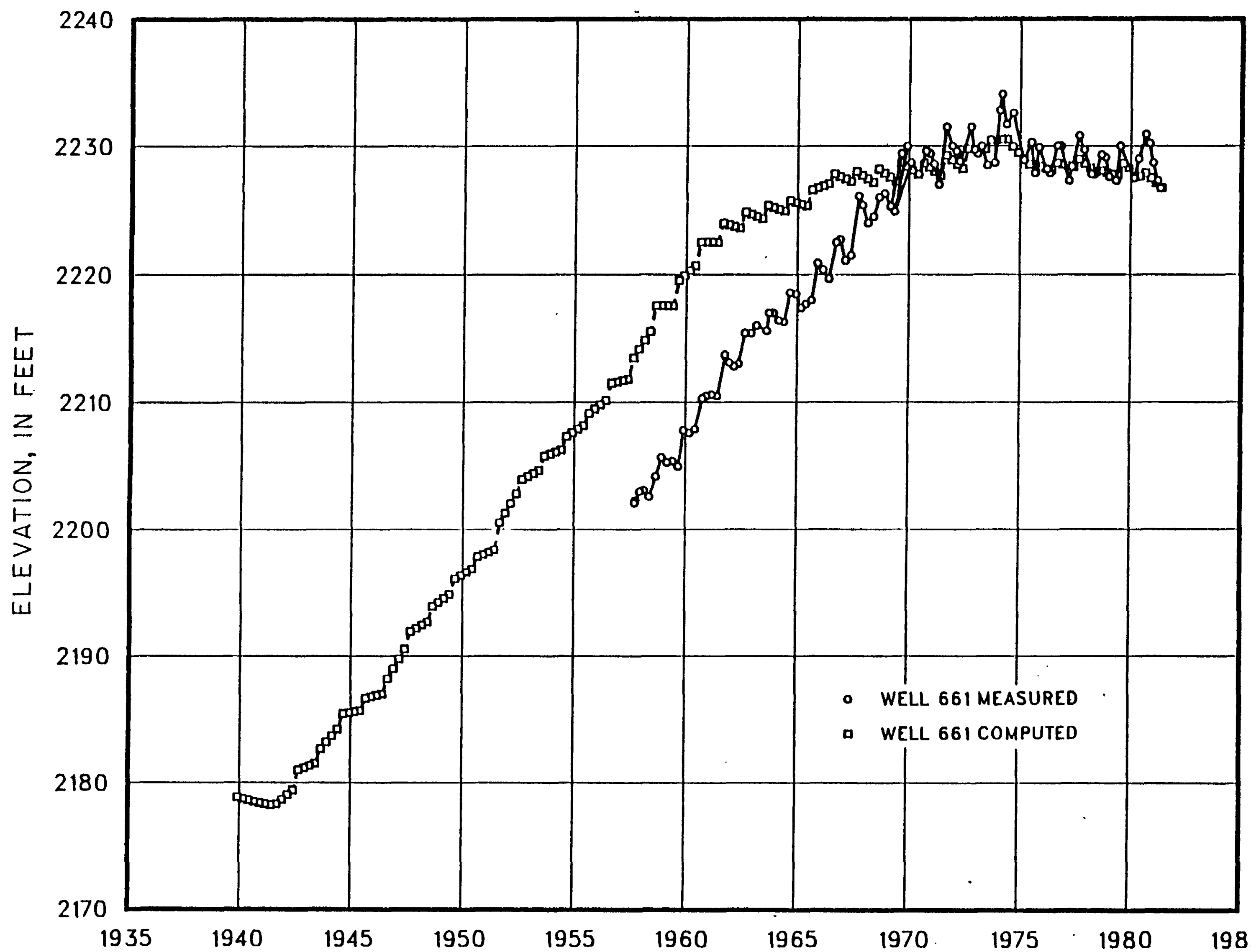


Figure 34-E.--Comparison of water levels computed for selected nodes with water levels measured in observation wells near the node, 1940-81.

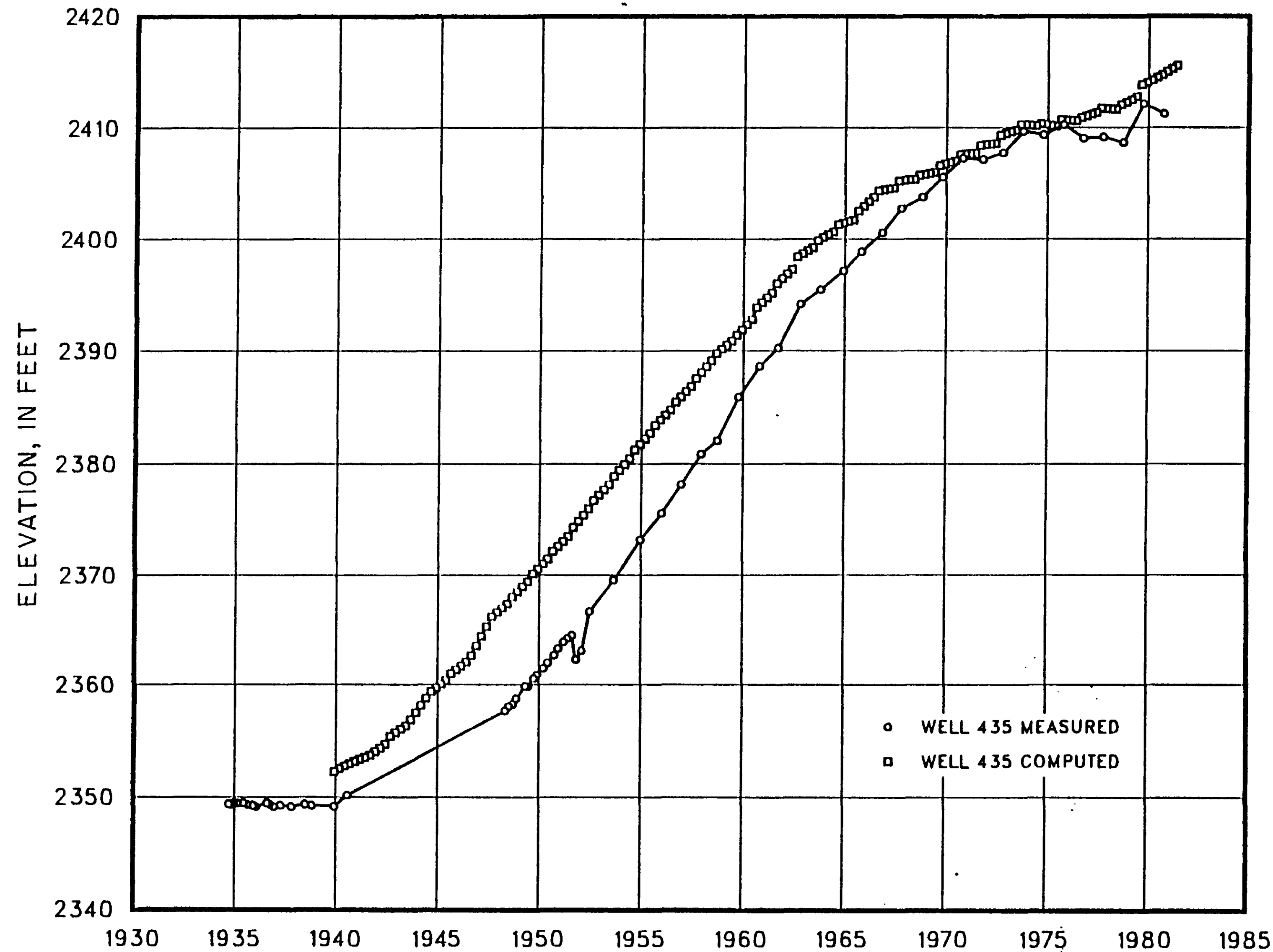


Figure 34-F.--Comparison of water levels computed for selected nodes with water levels measured in observation wells near the node, 1940-81.

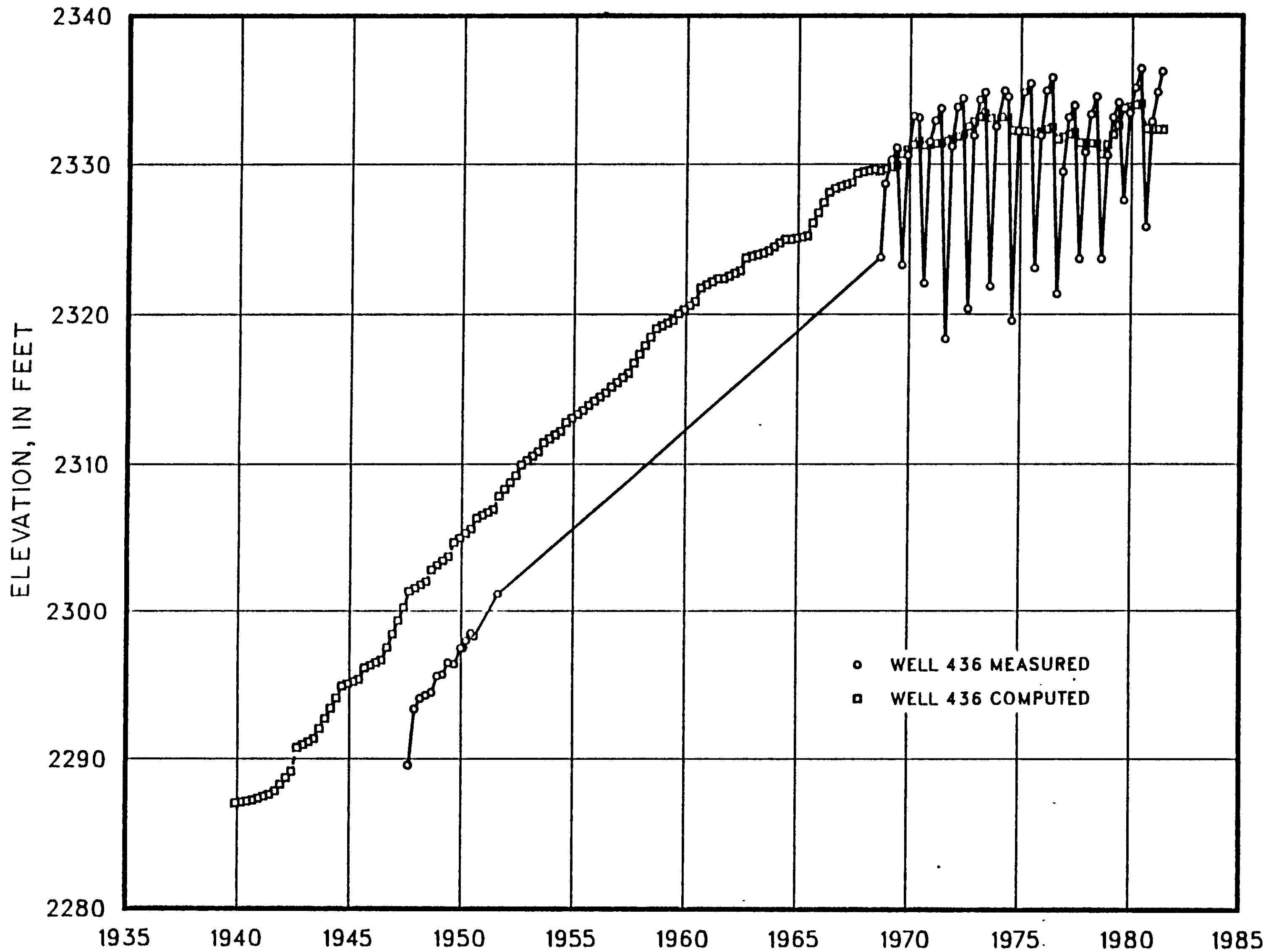


Figure 34-G.--Comparison of water levels computed for selected nodes with water levels measured in observation wells near the node, 1940-81.

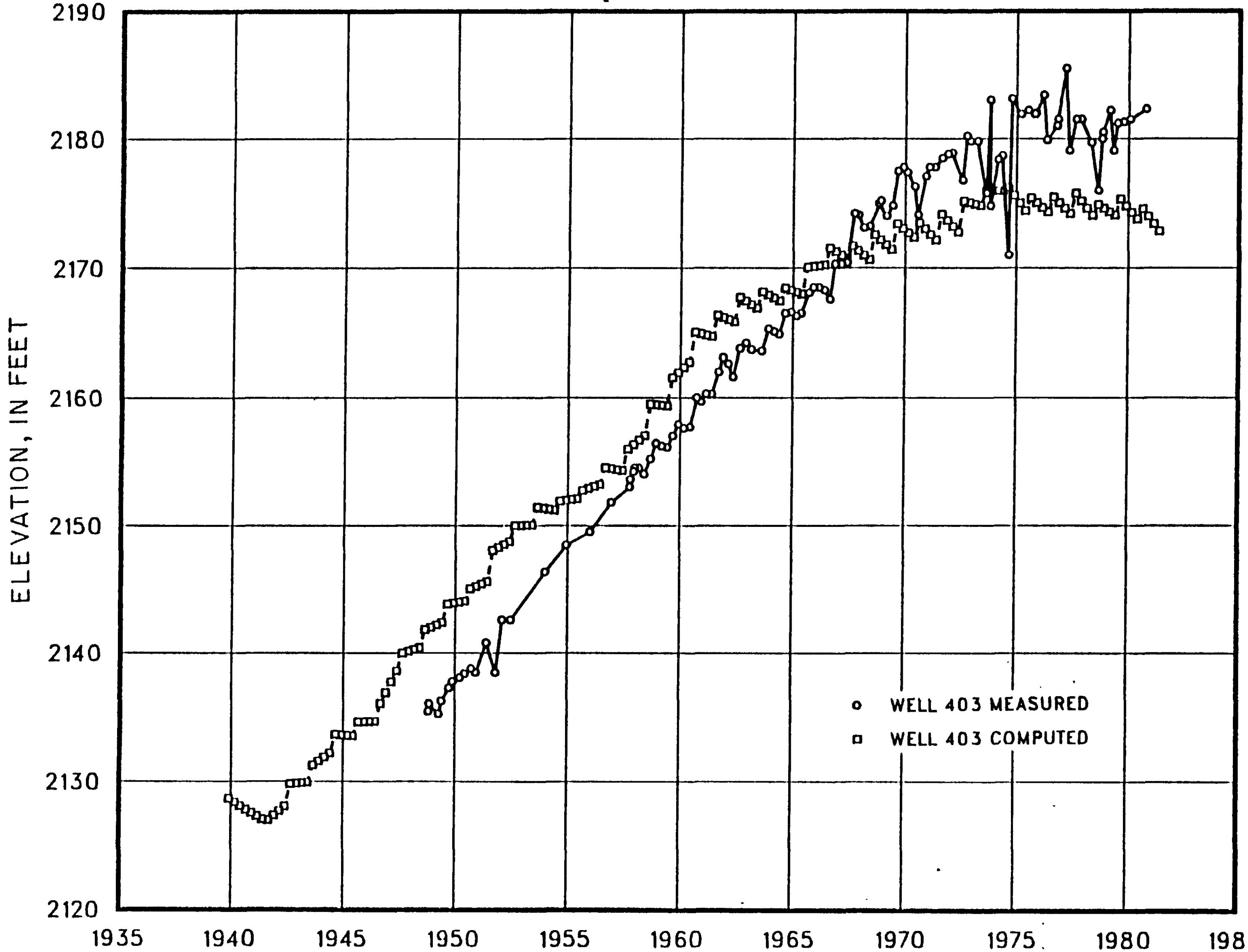


Figure 34-H.--Comparison of water levels computed for selected nodes with water levels measured in observation wells near the node, 1940-81.

The known-head boundary flux, the difference between underflow into the study area and underflow out of the study area, was computed by the model at each time step. The known-head boundary flux in 1940 was 51,700 acre-feet of inflow into the study area and in 1981 the flux was 6,200 acre-feet of outflow from the study area. These values compare favorably with the net underflow values of 74,700 acre-feet of inflow in 1940 and 37,900 acre-feet of inflow in 1981, which were computed using the hydrogeologic data and equation (2) on page 69. The agreement between the model values and the computed values using equation (2) indicates that the model is not adding or removing excessive amounts of water at the known-head nodes to balance conditions within the interior nodes of the model.

The mass balance or volume of water stored in the aquifer was computed by the model at each time step. The mass (Sy multiplied by saturated thickness) is initialized at each node before the first time step by integrating the Sy over the initial saturated thickness. However, for each additional time step, the cumulative mass is calculated by adding or subtracting the fluxes moving in and out of the aquifer. After the last time step, Sy is integrated over the final saturated thickness to compute integrated mass. The difference between the cumulative mass and the integrated mass is the error. For the model calibration, the cumulative mass is 6.149×10^{12}, integrated mass is 6.152×10^{12}, and the mass balance error is 3.070×10^{9} cubic feet. The mass balance error distributed over the entire study is 0.24 inches.

Potential Uses and Limitations of the Model

The model can be used to evaluate a variety of management alternatives. However, careful development and application of the management alternatives must be followed or the results will be incorrect. There also are limitations on what the model can predict with reasonable accuracy, even if good techniques are used. For example, the improvements in irrigation efficiency since the early 1940's would be a useful item to include in the ground-water flow model. However, the ability to handle this item adequately is not available; therefore, many of the improvements in irrigation efficiency have not been included in this model.

The model can be used to examine the effects of a variety of ground-water development rates, irrigation-application rates, surface-water irrigation projects, and streamflow changes on the hydrogeologic system. Ground-water development alternatives might include: no additional development, cutbacks in development, and development at different rates or different areas.

The model cannot be used to evaluate management alternatives that it was not designed to handle. This model is not capable of handling a number of physical problems; an example is the relation between streamflow and bank storage. (Bank storage is the water stored in the stream banks when the stage rises above the water table in the bank.)

APPLICATION OF THE MODEL TO MANAGEMENT ALTERNATIVES

The ground-water flow model can be used to simulate several management alternatives or plans. These management alternatives are primarily based on hypothetical land-use development schemes. However, only one management alternative--no additional irrigation development beyond the 1981 level--will be presented in this report.

To simulate this management alternative, additional data were developed to run this predictive simulation. The recharge and discharge values for the calibration period were replaced with data for the predictive period. Predicted recharge and discharge values were computed in the PUMP Program for the period June 1, 1981, through May 31, 2020. The climatic data of the calibration period (Sept. 1, 1939, through May 31, 1981) were used to generate the predicted recharge and discharge values. For example, June 1, 1940, through August 31, 1940, climatic data were used to represent the climate for the period June 1, 1981, through August 31, 1981. The 1981 ground-water irrigation rates were held constant throughout the predictive period. Surface-water values for the predictive period were the 1978 through 1981 averages for canal diversions, canal seepage, total surface-water irrigated acres, and seepage from reservoirs or lakes. Other values, such as the flow at known-flux nodes and the heads at known-head nodes, were held at 1981 values.

Known-head nodes completely bound the ground-water model; therefore, users of this model must be careful not to substantially increase the pumpage near the boundaries. Large amounts of pumpage along the boundaries may cause errors in the water levels at these sites, as the known-head nodes and not the aquifer supply most of the additional pumpage.

The model was run with recharge and discharge values for the predictive period. Figure 35 shows the changes from computed 1981 to 2000 water levels, and figure 36 shows the changes from computed 1981 to 2020 water levels. Table 15 compares computed streamflow on June 1, 1981, with projected streamflow on June 1, 2000, and June 1, 2020. The only gaging stations listed in this table are those for which flows are not regulated. An examination of this table indicates that significant flow depletions for Turkey and Beaver Creeks (nodes 209 and 90) are projected by the years 2000 and 2020. The other five gaging stations are not projected to have significant streamflow depletions.

Figure 35, the projected water-level rises and declines by June 1, 2000, assuming no new additional irrigation development after 1981, shows the water-level changes over the study area. Major water-level changes occur in two areas. Water-level rises exceeding 10 feet, with a maximum rise of 40 feet, occur in northern Gosper County, covering an area of about 250 square miles. A much larger area east of the rise has water-level declines that exceed 10 feet, with a maximum decline of 20 feet. By the year 2020 (fig. 36) these rises and declines have increased their areas and magnitudes. The maximum rise is 60 feet, while the maximum decline is 30 feet. No additional areas of either significant rises or declines have developed by the year 2020.

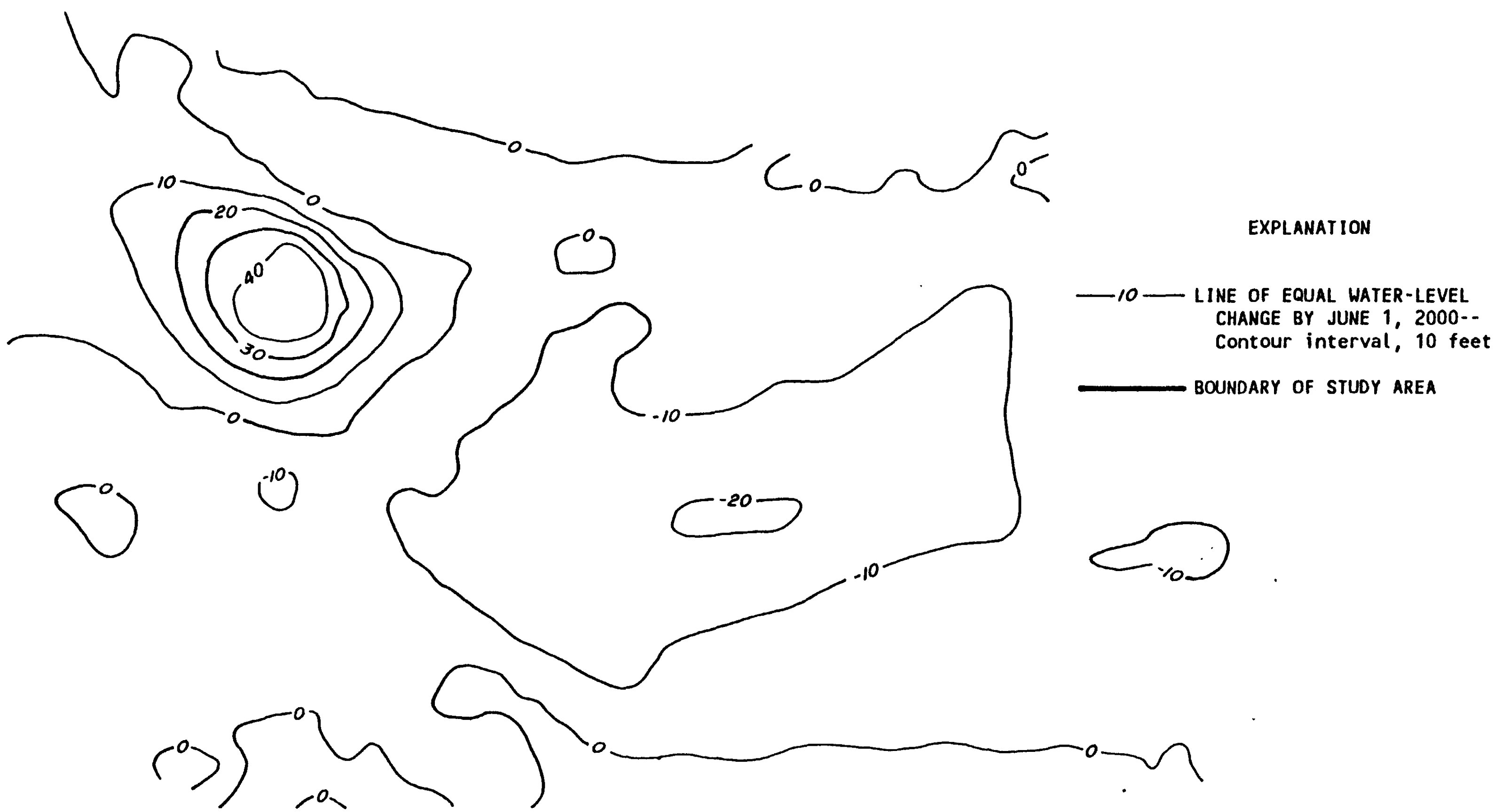


Figure 35.--Projected water-level changes by June 1, 2000, assuming no additional irrigation development after 1981.

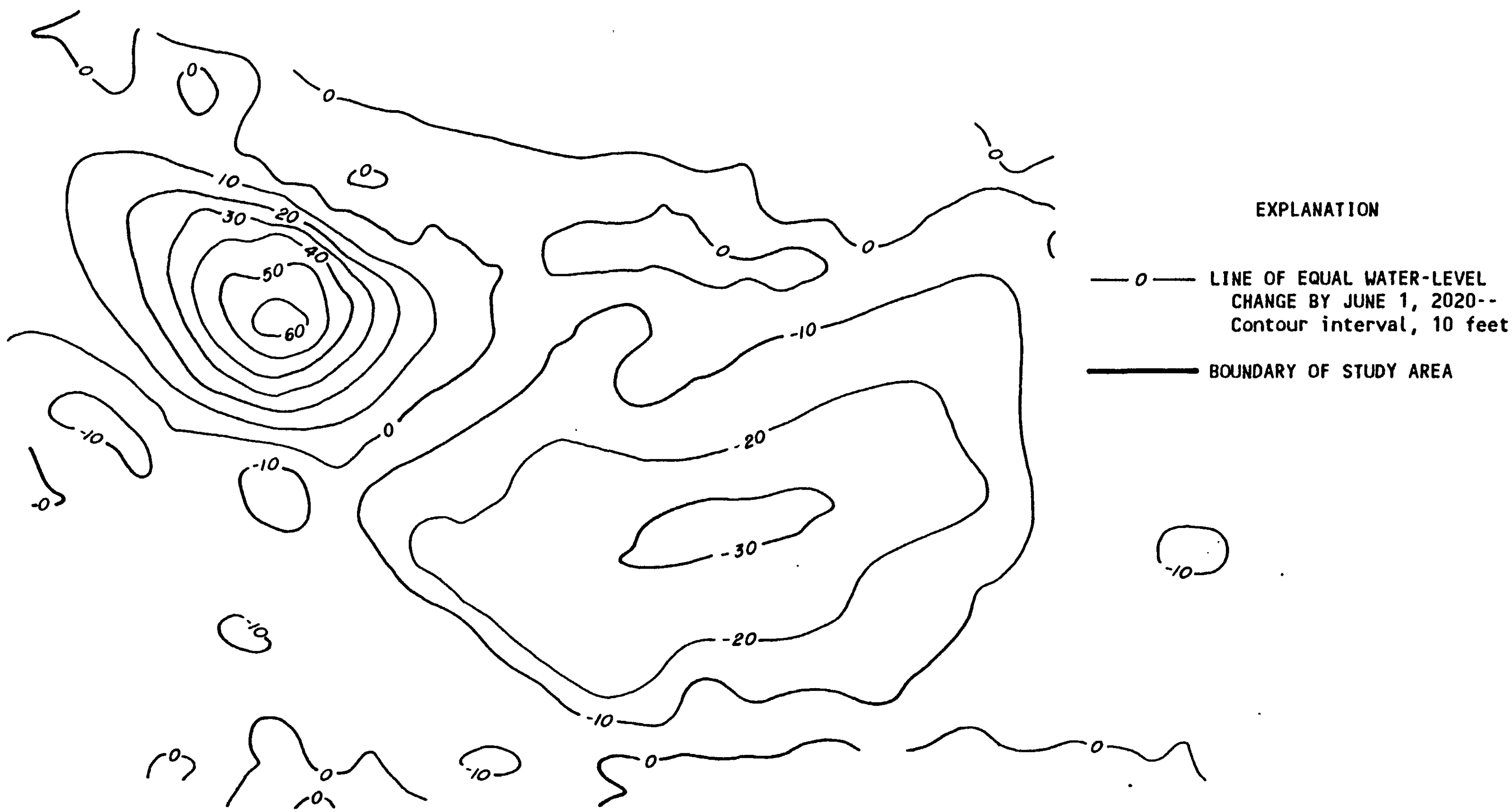


Figure 36.--Projected water-level changes by June 1, 2020, assuming no additional irrigation development after 1981.

Table 15.--Projected streamflows for years 2000 and 2020 compared to computed streamflow for June 1, 1981, in cubic feet per second

Node	Gaging station reference site	Model computed streamflow June 1, 1981	Projected streamflow June 1, 2000	Projected streamflow June 1, 2020
200	Muddy Creek at Arapahoe	15	11	11
209	Turkey Creek at Edison	7	2	1
90	Beaver Creek near Beaver City	2	1	0.26
119	Sappa Creek near Stanford	3	5	2
139	Center Creek at Franklin	4	3	2
157	Thompson Creek at Riverton	16	14	12
167	Elm Creek at Amboy	3	2	2

The known-head boundary flux, which was computed by the model for the year 2020, was 25,200 acre-feet of outflow from the study area. This value does not differ significantly from the model-generated known-head boundary flux in 1981 of 6,200 acre-feet of outflow from the study area. Thus, the model is not using the known-head nodes to remove or add water that is being generated or used within the interior nodes of the model.

A check of the computational performance of the predictive model was made by examining the cumulative error and the mass balance. The cumulative error was 1.218×10^4 cubic feet, which is 9.52×10^{-7} inches distributed over the entire study area. With a cumulative error of this size, it appears that the model is handling the computations adequately.

The mass balance for the predictive period was favorable. The cumulative mass is 6.012×10^{12} cubic feet, the integrated mass is 6.012×10^{12} cubic feet, and the error is 2.687×10^8 cubic feet. This mass balance error distributed over the entire study area is 0.02 inches.

SUMMARY AND CONCLUSIONS

The purposes of this study were to describe the hydrogeologic system of the area and develop a finite-element, ground-water-flow model that could evaluate, quantitatively, the effects of management practices on water levels, streamflows, and surface-water seepage.

Ground-water rises of as much as 110 feet have occurred in the northern part of the study area since 1940 as a result of seepage from the surface-water irrigation system of canals and reservoirs. Ground-water irrigation has increased significantly throughout the study area since the 1940's, but only minor water-level declines have occurred over much of the study area.

The depth to water and saturated thickness of the aquifer increased as much as 80 to 110 feet in the northern part of the study area from 1940 to 1981 because of the increased seepage from surface-water irrigation. However, the ranges in the depths to water and the saturated thickness of the aquifer did not change during the 1940 to 1981 time period, except in the northern part of the study area. The depth to water ranged from less than 1 foot in several locations to a maximum of 350 feet in southwestern Dawson County. The saturated thickness of the aquifer, which generally decreased from west to east and from north to south across the study area, ranged from less than 1 foot in Harlan and Franklin Counties to greater than 600 feet in the northwest corner of the study area.

The transmissivity and the specific yield of the aquifer changed very little in the study area during the 1940 to 1981 time period, even though the saturated thickness of the aquifer increased in the northern part of the study area. The transmissivity ranged from 100 to 20,000 ft^2/d in 1940 and from 100 to 25,000 ft^2/d in 1981. The specific yield ranged from 0.08 to 0.26 for the entire time period.

The ground-water-flow model, after being calibrated, produced similar results between measured and computed water levels. In most of the northern half of the study area the differences between computed and measured 1981 water levels are less than 10 feet, with water-level differences of 15 feet in a few areas. In the southern half of the study area, there are large areas where the differences in water levels are less than 10 feet, and much smaller areas where differences are 15 to 20 feet. An examination of hydrographs from eight observation wells showed similar trends between the observed and computed water levels during the calibration period, with differences ranging from 0 to 10 feet.

The model was tested by simulating a management alternative that consisted of no additional irrigation development beyond the 1981 level. The projected water levels for the years 2000 and 2020 indicated a few significant differences from the computed water levels for 1981. By the year 2000 the maximum rise in water levels was 40 feet in an area of about 50 square miles in northwestern Gosper County. The maximum decline in water levels was 20 feet in an area of about 30 squaremiles where Phelps, Kearney, Harlan, and Franklin Counties meet. In the year 2020 the maximum rise in water levels had increased to 60 feet in an area of about 12 square miles in northwestern Gosper County. The maximum water-level decline was 30 feet in an area of about 70 square miles in southwestern Kearney and northwestern Franklin Counties.

The verification of computational performance (cumulative error) and the mass balance (volume of water stored in the aquifer) were favorable for both the calibration and predictive runs. The cumulative error, in inches, distributed over the entire study area was -1.29×10^{-6} for the calibration run and 9.52×10^{-7} for the predictive run. The mass balance errors distributed over the entire study area were 0.24 inch for the calibration run and 0.02 inch for the predictive run.

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