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Geologic and Hydrologic Characteristics of the Ogallala and Peripheral Aquifers in Western Kansas

by

Howard G. O'Connor
Thomas J. McClain

Kansas Geological Survey
1930 Constant Avenue
University of Kansas
Lawrence, KS 66047-3726

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Geohydrology Section
Kansas Geological Survey
Lawrence, Kansas 66044

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Introduction

Purpose and Scope of Investigation:

This study is one part of a plan by the Economic Development Administration to "study the depletion of the Ogallala aquifer and to develop plans to increase water supplies in the High Plains Region." Specifically, this study is to describe the geology, hydrology, and the groundwater resources of the Ogallala and peripheral aquifers in a 32-county area of western Kansas, including information on precipitation, recharge, movement of groundwater, water quality, and interrelationships among aquifers. A series of maps was to be prepared, using 1977 as the base year, showing 1) bedrock contours and bedrock geology, 2) water table or potentiometric surface, 3) saturated thickness of the Ogallala aquifer, 4) depth to water, and 5) areas of natural groundwater discharge and areas of above average recharge. A series of tables was to be prepared showing available information on 1) specific capacity, 2) transmissivity, 3) hydraulic conductivity, and 4) storage coefficient for wells. Representative hydrographs were to be prepared for each county as well as tables and textual discussion to describe existing and potential point, nonpoint, and natural-source water-quality problems. The tabular materials and maps were to be supplemented by a brief interpretative report.

Location and Extent of Area:

The area of study includes about 28,560 square miles (Batschelet, 1942) in a 32-county area of western Kansas (Fig. 1) divided into three subregions: Northwest Kansas Subregion, West-Central Kansas Subregion, and Southwest Kansas Subregion.

Essentially all of the area of the Ogallala aquifer having a significant saturated thickness is included in the study area.

Methods of Investigation:

The plan for this investigation was to review and compile information on the geology and hydrology of the Ogallala and peripheral aquifers in western Kansas based on the published literature and on unpublished information in agency files or being acquired in current investigations. The principal sources of information include information published by the U.S. Geological Survey as Water Supply Papers, Hydrologic Investigation Atlases, Professional Papers, Water-Data Reports and Open-File Reports; information published by the Kansas Geological Survey as Bulletins, Journals, Basic Data Series, Chemical Quality Series, Groundwater Series, Irrigation Series, and Map Series publications. Unpublished data in the files of the Kansas Geological Survey were also reviewed, and the public file of several thousand water well records maintained by the Survey as legislated under the Kansas "Groundwater Exploration and Protection Act" was used as a source of data.

Related publications of the Kansas Department of Health and Environment, Kansas Water Resources Board, the Division of Water Resources of the Kansas Board of Agriculture, Kansas State University Extension, and other local, state, and federal agencies were reviewed.

The data from many separate sources were integrated into a series of maps, tables, hydrographs, and other illustrations for all of the study area and the three subregions, supplemented by an interpretative report.

Acknowledgements:

The authors wish to acknowledge the assistance of Cihat Basocak, Mark Silks, Wayne Premo, and Ronald McDowell, research assistants, who researched publications, compiled and tabulated data, prepared material for tables, plotted information on maps, and assisted in interpretation of data. The work could not have been completed on schedule without their exemplary assistance.

Tom McClain accepted primary responsibility for supervision and compilation of the plates and hydrographs in the report; Howard O'Connor had primary responsibility for the organization and writing of the manuscript, tables, and other illustrations.

Geologic Framework

Stratigraphy:

The oldest rocks considered in this study are those of the Lower Permian Blaine Formation (Table 1). Older rocks in western Kansas do not contain fresh water. The Blaine is not known to yield significant quantities of groundwater to wells and is considered to be highly mineralized throughout the study area where it underlies the Ogallala aquifer (Gutentag, Lobmeyer, and Slagle, 1980). It is a formation easily identifiable on geophysical logs and is useful in interpretation of regional structure. The thickness, physical character, and water-bearing characteristics of rocks younger than the Blaine Formation are summarized in Table 1.

Permian rocks are characterized by red siltstones and shales, very fine grained sandstones and beds of gypsum, anhydrite, and halite. These rocks underlie all of the 32 counties in the study area, but directly underlie the Ogallala aquifer only in parts of Morton, Stevens, Seward, Haskell, Meade, and Clark counties (Pl. 1A,B). The rocks crop out at the surface in eastern Meade County and in Clark County.

Jurassic rocks are characterized by grayish and greenish shales, very fine to medium-grained sandstone and some thin limestone beds (Table 1). The rocks outcrop locally in Morton County and underlie parts of Stevens, Seward, Grant, and Haskell counties and most of the area west of a line drawn from the southwest corner of Kansas northeastward to the northeast corner of Phillips County (Merriam, 1963; Weeks and Gutentag, 1981). Plate 1B shows the area in which Jurassic rocks directly underlie the Ogallala aquifer in parts of Morton, Stevens, Seward, Meade, Grant, Haskell, and Gray counties.

Lower Cretaceous rocks (Table 1) consist of gray, black, and varicolored shales, claystones, and fine- to medium-grained sandstone beds. These rocks directly underlie the Ogallala aquifer in parts of Morton, Stevens, Meade, Clark, Stanton, Grant, Haskell, Gray, Ford, Hamilton, Kearny, and Finney counties (Pl. 1B) and occur below Upper Cretaceous rocks in the northern part of the study area.

Upper Cretaceous rocks are largely light and dark gray and black shale, chalk, and limestone (Table 1) which directly underlie the Ogallala aquifer in parts of Hamilton, Kearny, Finney, Gray, Haskell, and Ford counties and all of the counties in the West-Central and Northwest Kansas subregions (Pl. 1B).

Tertiary rocks of Miocene and Pliocene age comprise the Ogallala Formation and consist of clay, silt, sand and gravel, and caliche, generally unconsolidated but locally cemented by calcium carbonate or silica. The Formation also contains thin fresh-water limestone beds, volcanic ash beds, and diatomaceous marl.

The Ogallala Formation was deposited on an eastward-sloping surface of moderate relief (Pls. 2A,B) by streams flowing eastward from the Rocky Mountains. Deposits gradually filled the pre-Ogallala valleys and formed an alluvial plain. Limestones locally were deposited in fresh-water lakes formed on the constructional surface (Frye and Leonard, 1952; Merriam, 1963; Zeller, 1968).

Recent work by Boellstorff (1978) and Thomasson (1979) suggest parts of the deposits which have been called Ogallala in Kansas and originally considered as Pliocene in age are of Miocene age (>5 million years).

Quaternary Pleistocene age deposits (Table 1) are extensively exposed at the surface in western Kansas and include both eolian, or wind-blown deposits (dune sand and loess), and fluvial deposits of silt, clay, sand, and gravel (alluvium).

Periodic rejuvenation of streams in the area following deposition of the Ogallala Formation resulted in extensive erosion and redeposition of Ogallala deposits during the Pleistocene. In southwestern Kansas Ogallala deposits were extensively eroded and redeposited by streams, perhaps partly as a result of dissolution and subsidence of underlying Permian salt beds.

Undifferentiated, but largely fluvial, deposits more than 500 feet thick, similar in lithology to the Ogallala deposits, occur locally in southwest Kansas between the Bear Creek Fault and the Crooked Creek-Fowler Fault (Pl. 1B). In contrast, Pleistocene fluvial deposits in west-central and northwest Kansas are generally thinner.

Late Pleistocene wind-blown deposits of silt (loess) are extensive in western Kansas (Kansas Geological Survey, 1964; Frye and Leonard, 1952). The deposits are thickest in northwestern Kansas and thin southward. Extensive tracts of Late Pleistocene dune sand deposits occur in southwestern Kansas, especially along the south side of the Arkansas River and along the Cimarron River.

Geologic Structure:

The structure of the Permian, Jurassic, and Cretaceous rocks that underlie western Kansas has a significant affect on the direction of groundwater flow in the confined or bedrock aquifer systems.

Merriam (1963) has compiled a series of regional structural maps contoured on top of the Stone Corral Formation (Permian), top of the Dakota Formation (Lower Cretaceous), and on the base of the Niobrara Chalk. Keene and Bayne (1977) show the structure on top of the Lower Cretaceous rocks (Dakota Formation) in Kansas and the major structural features. The major features from the Colorado-Kansas boundary eastward include 1) the Los Animas

Arch (east flank), 2) the Western Kansas Basin, 3) the Cambridge Arch, 4) the Central Kansas Uplift, and 5) the Salina Basin. Gutentag, Lobmeyer, and Slagle (1980) prepared a structure map on top of the Permian Blaine Formation for southwest Kansas showing the important Bear Creek Fault and the Crooked Creek-Fowler Fault, also shown in this report (Pl. 1B).

The hydrologic significance of the structures as shown in the maps is that these rock units dip or slope generally northeastward 10-20 feet per mile, locally more northerly or more easterly. The rocks are at higher elevations to the west and southwest of the Kansas-Colorado border.

There are several named anticlines and synclines which, for purposes of this discussion, are relatively unimportant. Two faults in southwest Kansas (Bear Creek Fault in Hamilton, Stanton, Grant, and Kearny counties; Crooked Creek-Fowler Fault in Meade and Ford counties) have important geologic and hydrologic significance. The faults (Pl. 1B) represent the boundary areas in which dissolution and removal by groundwater of evaporites within and below the Permian Blaine Formation have occurred (Irwin and Morton, 1969). The faults are partly defined on the present land surface by a line of sinkholes and filled sinks suggesting dissolution of the evaporites is continuing. The great thickness (300-782 feet) of Miocene-Pliocene and Pleistocene deposits in this area suggests dissolution of the Permian evaporites may have been active since Miocene time.

Bedrock Surface:

Consolidated rocks of Permian, Jurassic, and Cretaceous age underlie the Tertiary and Quaternary rocks (Table 1) in western Kansas and are referred to as bedrock in this report. The bedrock surface is an erosional surface (Pls. 1A,B; 2A,B) sloping generally in an easterly or east-northeasterly direction in northwestern Kansas and generally eastward in west-central Kansas, and is a more complex erosional surface in southwestern Kansas. There is a general slope of about 1,000-1,500 feet from the west boundary eastward across each of the three subregions. In southwestern Kansas there is a major southward-trending erosional channel in the bedrock surface beginning near the Scott-Finney boundary trending southward and southeastward across central Finney and southwestern Gray County into Meade County to the Crooked Creek-Fowler Fault. Another less prominent bedrock erosional channel trends southeastward across Seward County to the Crooked Creek-Fowler Fault and roughly coincides with the present Cimarron River drainage. The local bedrock relief, which may be as much as 250 feet, is affected by faulting, geologic structure, dissolution, and subsidence features and the nature of the bedrock lithology or resistance to erosion.

Permian rocks form the bedrock surface along the southern boundary, but northward a belt of Jurassic rocks and/or Lower Cretaceous rocks form the bedrock surface. Upper Cretaceous rocks are the bedrock surface in west-central and northwestern Kansas (Pls. 1A,B).

Surface Topography:

Western Kansas is in the High Plains section of the Great Plains physiographic province of Fenneman (1931). It is a broad, nearly treeless, grass-covered plain that slopes gently eastward from an elevation of about 4,100 feet in western Wallace County to about 2,000 feet elevation along the eastern boundary (Schoewe, 1949; U.S. Geological Survey, 1963). Thus, the topography slopes generally eastward at an average rate of 10-15 feet per mile.

The greatest local relief is along the Smoky Hill River Valley and may be as much as 300 feet. Numerous undrained depressions ranging in diameter from a few feet to several miles dot the plain's surface throughout most of the area. Locally, south of the Arkansas River and along the Cimarron River, the surface is characterized by the irregular hummocky surface of sand dunes.

Regional Hydrology

Groundwater Occurrence:

Groundwater suitable for domestic, irrigation, municipal, and industrial use occurs in western Kansas both in unconfined and confined aquifers. The most important of these is the largely unconfined Ogallala aquifer. The Ogallala aquifer is defined to include the rocks of the Ogallala Formation together with the overlying saturated undifferentiated Pleistocene deposits, which are hydraulically connected and form a single groundwater reservoir. Plates 3A and B, 4A and B, and 5A and B show respectively the 1977 altitude and direction of slope of the water table, the 1977 depth to water below land surface in the Ogallala aquifer, and the 1977 saturated thickness of the Ogallala aquifer. Some unconfined groundwater also occurs in the alluvium along the major stream valleys.

The Permian, Jurassic, and Cretaceous bedrock (Pl. 1A and B) which underlies western Kansas includes beds of sandstone having pore space between grains through which groundwater can percolate, beds of chalk that are fractured and partly dissolved by percolating groundwater through which groundwater can move, and beds of gypsum and anhydrite that have been partially dissolved to form an aquifer. Except where bedrock aquifers are exposed at the surface or are overlain and hydraulically connected by unconfined groundwater in one of the unconsolidated aquifers the water in the bedrock aquifers is generally confined or artesian groundwater. The aquifers are described in more detail under the description by subregions of western Kansas aquifers.

Precipitation:

Western Kansas has a semi-arid continental climate, abundant sunshine, low humidity, and brisk wind movement. Winters are moderate and summers are often hot. The mean annual precipitation in the study area ranges from less than 17 inches to about 25 inches (Fig. 2). Locally precipitation may be less than 6 inches in dry years or more than 36 inches in wet years. About three-fourths of the precipitation falls during the growing season.

The mean annual surface runoff in the study area (Fig. 3) ranges from less than 0.1 inch to about 1.1 inches (U.S. Geological Survey, 1978a).

Groundwater Recharge:

Recharge is the addition of water to a groundwater body or to an aquifer. Although some groundwater moves into Kansas from adjacent areas, chiefly Colorado, from points of higher hydraulic head to points of lower hydraulic head in Kansas, the most important source of recharge is local precipitation on the 32 western Kansas counties in this study area.

The recharge rates have been estimated for a 9-county area of northwestern Kansas (Jenkins and Pabst, 1975) to average about 0.25 inch per year. McClain and others (1975) estimate annual recharge from precipitation in Gove, Logan, and Wallace counties to be in the magnitude of 15 to 30 acre-feet per square mile or 0.28 to 0.56 inches per year. Meyer, Gutentag, and Lobmeyer (1970) estimate the long-term average recharge from Finney County to be less than 0.5 inch per year. Gutentag and Stullken (1976) estimate recharge on non-irrigated land in Lane and Scott counties to be 1 percent of the precipitation during the growing season (i.e., ±0.15 inch per year).

Figures compiled by Meyer, Gutentag, and Lobmeyer (1970) for Finney County and by Gutentag and Stullken (1976) for Lane and Scott counties indicate about 10 percent of the irrigation water applied during an irrigation season may become recharge through the return flow of irrigation water. Gutentag, Lobmeyer, and Slagle (1980) estimated recharge from precipitation on dry land in southwest Kansas to average about 0.15 inch per year. The estimated or calculated recharge values for all of western Kansas, therefore, range from about 0.15 to about 0.56 inch per year. An approximation of the recharge from irrigation return flow and from precipitation on the area overlying the Ogallala and peripheral aquifers is given in Table 2. Non-irrigated or dry land overlying the Ogallala aquifer is estimated to have an average annual recharge rate of 0.3 inch. This includes recharge from ephemeral streams, depressions, and sand dune tracts which have higher than average recharge. For irrigated land above the Ogallala aquifer the recharge, including that from precipitation and irrigation return flow, is estimated to be 10 percent of an average application of 21 inches, or 2.1 inches annually. The recharge figures do not include subsurface inflow or recharge from the Arkansas or Cimarron rivers.

Jordan (1977) indicates there can be large streamflow losses during flood flows along western Kansas streams and cites four examples of transmission losses on the Arkansas River between gaging stations at Syracuse and Garden City. In this 53-mile segment of river valley he cites four flood events of 3 to 7 days duration between 1951 and 1965 in which the river lost amounts ranging from 11,460 to 82,000 acre-feet of water to the underlying unsaturated aquifer. Jordan cites Bear Creek, Whitewoman Creek, and Sand Arroyo Creek as examples of other ephemeral western Kansas streams that on the average have flow in them only a few days per year, within which all flood flows except the very highest are entirely absorbed.

The U.S. Geological Survey (1975) indicated 163,500 acre-feet of water entered southwest Kansas as streamflow in the Arkansas and Cimarron rivers in 1974. Because of declining water levels along these stream valleys much of the streamflow is lost by influent seepage to adjacent groundwater bodies and does not flow out the east side of the study area.

Areas of western Kansas in which recharge is above normal (Fig. 4) include the dune sand tracts, the large undrained depressions or basins such as the Scott-Finney depression, and the streams that flow in stream channels overlying unsaturated sand and gravel deposits, typical of streams overlying the Ogallala aquifer.

The quantity of influent seepage from streams crossing the Ogallala aquifer in western Kansas is changing, and there currently are no good figures available to indicate how much recharge occurs from streams.

Groundwater Discharge:

Groundwater is discharged by pumpage from wells, by effluent seepage to streams where the streams intersect the water table, and by subsurface flow out of the study area. Some water is lost by transpiration and evaporation but it is a minor amount because the water table in most of the area is too far below the land surface to be affected by evaporation and transpiration (Pl. 4A,B). An approximation of the amount of groundwater pumped from the Ogallala aquifer can be derived by using the 1977 irrigated acreage multiplied by an average irrigation application rate. Table 3 shows the 1978 irrigated acreage in western Kansas by counties and subregions. This includes acreage irrigated by water pumped from wells in alluvium, from bedrock aquifers, and surface water as well as water from the Ogallala aquifer, and a small increase in acreage between 1977 and 1978. The 1977 irrigated acreage in western Kansas from the Ogallala aquifer is calculated to be about 2,500,000 acres. Most irrigators in western Kansas apply 1.5 to 2.0 acre-feet of water per acre of irrigated land. Assuming an average application of 1.75 acre-feet (21 inches) of water per acre would indicate about 4,375,000 acre-feet of water was pumped from the Ogallala aquifer in 1977.

Gutentag, Lobmeyer, and Slagle (1980) indicate groundwater discharge to streams in southwestern Kansas. The 20-year (1943 to 1962) base flow (groundwater contribution) of the Cimarron River at Mocana, Oklahoma, is 33,400 acre-feet per year and of Crooked Creek near Nye, Kansas, is 8,800 acre-feet per year (Busby and Armentrout, 1965).

Figures reported for the Arkansas River near the Ford-Gray boundary by Meyer, Gutentag, and Lobmeyer (1970) and McGovern and Long (1974) indicate that, historically, about 11,300 acre-feet per year of groundwater is discharged as base flow across Gray County. More recent records of flow of the Arkansas River at Dodge City in Ford County (U.S. Geological Survey, 1979, 1980) indicate there is no flow in the Arkansas River most of the year. The total annual Arkansas River flow at Dodge City in 1977 was 292 acre-feet and 1,250 acre-feet in 1978, suggesting that very little groundwater discharges to the Arkansas River above Dodge City or leaves the area as base flow because of declining water levels caused by pumping from the Ogallala and peripheral aquifers.

Groundwater discharge to streams in western Kansas is shown by the points at which a base flow begins (Fig. 4). Quantities discharged for 1977 are not available, but they are known to have been declining in recent years.

In addition to groundwater discharge to streams, some groundwater leaves the area as subsurface flow, largely to the east into the Great Bend Prairie area of south-central Kansas. As area water levels decline, the amount of subsurface flow out of the area declines also.

Groundwater in Storage:

The amount of groundwater in storage in each of the counties and in each subregion has been determined by measuring the volume of saturated aquifer in each county as shown on Plates 5A,B and applying an appropriate storage coefficient. The results are given in Table 4. In 1977 the Northwest Subregion had approximately 51,484,000 acre-feet of groundwater in storage, West-Central Subregion approximately 17,791,000 acre-feet and the Southwest Subregion contained approximately 175,208,000 acre-feet, for a combined storage of 244,483,000 acre-feet in the Ogallala aquifer in western Kansas.

Groundwater Quality:

Groundwater in the Ogallala aquifer is generally of excellent quality as indicated by several hundred analyses. Basically, the water is a Ca-Mg-HCO_3 type of water in most of western Kansas. The water quality with respect to the maximum values for drinking water (U.S. Public Health Service, 1962) for dissolved solids, sulfate, chloride, nitrate, and total hardness is well below recommended limits except for hardness, which may be slightly greater than the recommended 150 mg/l maximum. Locally, as in the Scott-Finney depression, the area north of the Arkansas River in parts of Finney and Kearny counties, and south-central Meade County, the waters have increased amounts of dissolved solids, sulfates, and chloride (Hathaway and others, 1975, 1977, 1978a, 1978b, 1979; O'Connor, Waldorf, and Dulas, 1978). Selected chemical analyses of water from the Ogallala aquifer in the three subregions are given in Table 5.

The groundwater quality with respect to the Ogallala and other aquifers is discussed in more detail under the three subregions.

Western Kansas Aquifers

Northwest Kansas Subregion

Ogallala Aquifer:

Bedrock contour surface and bedrock geology:

The nine counties that comprise the Northwest Kansas Subregion are shown in Figure 1. Plate 1A shows the bedrock geology below the base of the Ogallala aquifer and Plate 2A shows the elevation of the base of the Ogallala aquifer or the elevation of the bedrock erosional surface.

In all of the Northwest Kansas Subregion, Upper Cretaceous rocks directly underlie the Ogallala aquifer. The Niobrara Chalk ranges from a few feet thick below the Ogallala in southwestern Graham County to more than 650 feet thick in southern Sherman and Thomas counties. It lies directly below the Ogallala in nearly all of Norton, Phillips, and Graham counties and the eastern parts of Decatur and Sheridan counties. In Cheyenne, Rawlins, Sherman, and Thomas counties and parts of Decatur and Sheridan counties, the Pierre Shale directly underlies the Ogallala. The rocks thicken and dip northwestward; they are more than 1,500 feet thick in northwest Cheyenne County (Merriam, 1963).

The erosional surface on these Cretaceous rocks slopes generally eastward from an elevation of about 3,800 feet in southwestern Sherman County and shows irregularities indicating that a network of eastward-trending streams were established on the erosional surface when Ogallala deposition began. This surface ranges from about 3,800 feet elevation along the Colorado border and slopes eastward to about 2,000 feet elevation in Phillips County. The erosional surface slopes eastward 1,400 to 1,800 feet across the area at an average rate of about 12 to 13 feet per mile.

Water table or potentiometric surface:

The water table surface, as shown on Plate 3A, is a relatively smooth, generally eastward-sloping surface without the many small irregularities of the bedrock surface. Along the Colorado border the water table has an elevation of about 3,500 to more than 3,850 feet and slopes generally eastward to 2,050 to 2,250 feet elevation in eastern Phillips and Graham counties (Pl. 3A). The water-table slope averages 11 to 12 feet per mile eastward. One may note that some water table contours trend across the present stream drainage as nearly straight lines, but eastward along these streams the water-table contour lines begin bending upstream as they cross the stream. The point at which the contour lines bend upstream indicates that the water table intersects the stream in that general area and from that point eastward there is generally some leakage or groundwater discharge toward or into the stream. For example, South Beaver Creek intercepts the water table at about the 3,300-foot contour line in northeastern Sherman County (Pl. 3A) and from about that point eastward groundwater leaks toward the stream and the stream has a base flow.

Saturated thickness:

The saturated thickness of water-bearing materials in the Ogallala aquifer is shown for the Northwest Subregion on Plate 5A. The saturated thickness represents the difference between the elevation of the water table and the elevation of the base of the Ogallala aquifer. The greatest saturated thickness is in Sherman and Thomas counties where small areas have more than 200 feet of saturation. Hydrographs of 82 observation wells in Sherman County indicate a maximum saturated thickness of 217.65 feet (well 7-39W-30CCB) in 1977 (U.S. Geological Survey, 1977). Large parts of this subregion have 100 to 200 feet of saturated aquifer.

Depth to water:

Plate 4A shows the depth to the water table from land surface. The greatest depth to water is more than 200 feet in parts of Cheyenne and Rawlins counties. Depth to water ranges from 100 to 200 feet in almost all of the upland areas of the subregion and is less than 50 feet along the stream valleys. Within the stream valleys, the depth to water level decreases to zero at streams at and below the points the streams intersect the water table. The greatest depth to water as reported in records of 48 observation wells in Cheyenne County was 243.88 feet (U.S. Geological Survey, 1977) in well 2-38W-27DAD.

Groundwater storage:

Transmissivity and storage coefficients:

There is little published information on the transmissivities and storage coefficients for the Ogallala aquifer in the Northwest Subregion. Prescott (1953) reported transmissivity and hydraulic conductivity determined from three pumping tests in Sherman County. The results are summarized in Table 6. Transmissivity values range from 34,000 to 396,000 ft^2/day. Bayne and Ward (1969) estimated specific yield for the unconsolidated aquifers of Kansas and, for northwest Kansas, estimated a specific yield of 0.2 for the Ogallala aquifer. For this area the specific yield is equivalent to the storage coefficient, as essentially all water comes from gravity drainage rather than compression of the aquifer and expansion of the water. In computing the quantity of groundwater in storage (Table 4), a revised storage coefficient of 0.17 was used for the nine counties in the Northwest Subregion.

Water quality:

Hathaway and others (1979) collected and analyzed water samples from 265 pumping irrigation wells in seven of the nine counties in the Northwest Subregion in July 1978. Selected chemical analyses from that study are included in Table 5. The analyses of water from the Ogallala aquifer indicate the water is a calcium bicarbonate to calcium-magnesium-bicarbonate-type water. In the western part of the Subregion, where Pierre Shale is the bedrock, the water tends to be dominantly a $Ca-Mg-HCO_3$ type water whereas in the eastern part of the Subregion, where Niobrara Chalk is the bedrock, the water tends to be a $Ca-HCO_3$ type water. Specific conductance of Ogallala water is generally less than 750 μMho's; sodium adsorption ratio (SAR) is generally less than 1.5. For irrigation use the waters generally have a medium salinity-low alkali hazard classification and thus are not expected to produce detrimental effects in the soil as a result of long-term irrigation. Values of dissolved solids, sodium + potassium, sulfate, chloride, and nitrate are generally well below the recommended maximum for drinking water standards. Total hardness of the waters generally is above or near the recommended maximum value of 150 mg/l for drinking water. Ogallala aquifer water may be characterized generally as excellent quality water for irrigation and domestic and other uses.

Point source pollution problems have been summarized by O'Connor, Waldorf, and Dulas (1978). In 1977 there were 40 commercial cattle feedlots, 30 commercial hog feedlots, and 2 dairy feedlot operations, 12 cities using septic tank systems and 9 cities using waste stabilization ponds for disposal of domestic sewage, and 15 Department of Transportation rest stop areas that used waste stabilization ponds, septic tank systems, or open pit toilets for sewage disposal. LeGrand (1964) developed an empirical point-count system applicable to unconfined alluvial water-table aquifers for evaluating and rating the possibilities of pollution. Using the LeGrand system the possibilities of groundwater pollution generally rate in the "very improbable" or "impossible" categories for pollution from municipal and animal wastes. Provided good well siting and well construction practices are followed there is little hazard of any significant bacterial contamination of the Ogallala aquifer. The low precipitation and recharge rates, high evaporation rates, topography, soils, geology of the unsaturated zone, depth to water table, and distances between waste-disposal sites and groundwater-withdrawal sites are all factors to be considered and in the Northwest Subregion these factors are generally very favorable for protection of the Ogallala aquifer.

Industrial pollution has not been evaluated but the Subregion does not have a large industrial base and the same beneficial factors of low precipitation and recharge rates, generally very favorable depth to water table, favorable geology and soils, etc., all tend to reduce the potential for groundwater pollution but not to completely eliminate the risk. Each potential industrial source of pollution must maintain good housekeeping practices and use reliable safe practices for handling and disposal of potentially polluting materials. The potential pollution hazard to the Ogallala aquifer from primary petroleum production is believed very small, provided good practices are followed in handling and disposal of brine produced with the oil and gas and provided good casing cementing practices through the fresh water zones and good plugging practices on test holes and abandoned wells are followed. Secondary and tertiary production practices may involve more potential for pollution of the fresh-water aquifer.

Hathaway and others (1979) indicate little evidence of groundwater pollution from agricultural fertilizers and agricultural practices thus far, although the long-term results of irrigation and the return flow of some irrigation water (combined with declining water levels) suggest that an increase in some of the more mobile constituents such as chloride, nitrate, and possibly phosphate, as well as an increase in dissolved solids may be expected. The potential for long-term changes in the chemical quality of Ogallala aquifer water, that is, increases in some of the dissolved constituents, will probably be greater from irrigation and irrigation return flow than from any other activity in this Subregion.

There is very little natural-source water-quality problem in the Northwest Subregion with respect to the Ogallala aquifer.

Groundwater-level changes:

Hydrographs of one or more representative wells in the Ogallala aquifer in each county are shown in Appendix A. Water levels fluctuate in response to changes in discharge and recharge. In 1977 the water levels declined an average of about 1.9 feet in the six western counties of this Subregion (U.S. Geological Survey, 1978b) and less in other areas since less irrigation is taking place in the three eastern counties. The average decline for the period 1966 to January 1978 was 8.26 feet for the six counties. The maximum water-level declines in these six counties the period 1950-1977 was 47.35 feet (well 8-40W-25AAC). This represents a decline in water levels of 30.16 percent, from a saturated thickness of 156.00 feet in 1950 to a saturated thickness of 110.84 feet in 1977. This is essentially the historical period during which extensive irrigation developed. The reader is referred to a series of water-level reports published by the Kansas Geological Survey and the U.S. Geological Survey for detailed statistical data on the several hundred observation well records for this Subregion.

Water-level declines result in greater pumping lifts, greater pumping costs, reduced saturated thickness of the aquifer, and decreased yield of wells. The average recharge to the Ogallala aquifer in the Northwest Subregion from precipitation and irrigation return flow is estimated to have been 222,050 acre-feet in 1977 (Table 2). The irrigation pumpage is estimated to be about 686,000 acre-feet (Table 2). In addition to irrigation pumpage there are relatively small additional amounts of groundwater pumped for domestic, municipal, and industrial use.

Alluvium:

The alluvium along the principal stream valleys in the Subregion ranges in thickness from about 25 to 70 feet and consists of sand, gravel, silt, and clay. Where 30 feet or more of saturated sand and gravel is present, wells yielding 300-1,000 gpm may be obtained. The alluvium receives recharge from direct precipitation, from influent flow from streams where the water table is below the stream surface, and from groundwater discharge from the Ogallala aquifer where the water table in the alluvium is below and hydraulically connected to the Ogallala water table. In addition, the Pierre Shale and Niobrara Chalk discharge some water to the valley alluvium where the bedrock is weathered and yields small amounts of water. The groundwater in the alluvium is of poorer quality than Ogallala water and generally has higher dissolved solids, hardness, calcium, sodium, sulfate, chloride, specific conductance, and SAR values. In many of the valleys the dissolved solids and sulfate levels of the groundwater tend to increase in a direction down the valley. Generally groundwater from the alluvium is not as suitable for irrigation or municipal use as water from the Ogallala aquifer because of its greater mineralization.

Depth to water is relatively shallow in the alluvial valleys. Most streams have sand and gravel bottoms that absorb water readily during periods of stream flow whenever the water table is at or below the surface of the stream. Jordan (1977) cites examples of significant stream-flow losses during flood flows on Beaver Creek, Prairie Dog Creek, and Sappa Creek.

Bedrock Aquifers:

Upper Cretaceous Rocks:

Pierre Shale Aquifer: The Pierre Shale is exposed locally along the stream valleys in Cheyenne County and underlies the Ogallala aquifer in the western part of the Subregion. Although the Pierre Shale is not significant as an aquifer, some groundwater does move through the Pierre where it is weathered at or near the surface (Table 1). It yields very small supplies (0-3 gpm) locally to wells. The water is very hard and high in calcium sulfate derived from gypsiferous beds in the Pierre.

Niobrara Chalk Aquifer: Niobrara Chalk directly underlies the Ogallala aquifer in the eastern part of the Subregion. It is not a source of large quantities of groundwater in this Subregion, although 0-10 gpm yields may be obtained locally. The water is generally a calcium bicarbonate type water, although some wells tend toward the calcium sulfate type water. Water occurs mostly in fractures. It is important primarily for stock and domestic wells in those areas where the Ogallala aquifer is thin or absent.

Codell Sandstone Aquifer: Not much information is available about the quantity or quality of groundwater from the Codell Sandstone member of the Carlile Shale. Prescott (1955) reports that one well, 380 feet deep, in Graham County penetrated the Codell sandstone and obtained some water from this aquifer. He also indicates that the water had dissolved solids of 768 ppm and was of the sodium bicarbonate type. Hattin (1962) summarizes information about the Codell as a fine to very fine grained silty sandstone or sandy siltstone ranging in thickness from a featheredge to about 19 feet, being thickest in northern Ellis County. It has not been tested adequately in the Subregion to make a good evaluation of its potential for water supply, but based on the limited information available it may supply 1-10 gpm of water to wells suitable for livestock use, but probably of quality too poor for domestic, irrigation, or other uses. It is of minor importance as an aquifer in the Northwest Subregion.

Lower Cretaceous Rocks:

Undifferentiated Sandstone Aquifer: The Lower Cretaceous rocks comprise the Dakota Formation, Kiowa Formation, and the Cheyenne Sandstone in a downward sequence (Table 1). Each unit contains beds of fine- to medium-grained sandstone that yields significant amounts of groundwater to wells in parts of Kansas. Keene and Bayne (1977) compiled available information about water supplies in Lower Cretaceous rocks, but had no data from these units in the Northwest Kansas Subregion. They indicate the depth to the top of the Lower Cretaceous sandstone aquifer ranges from about 500 feet in southeastern Phillips County to about 2,600 feet in western Cheyenne and Sherman counties. About 100-300 feet of sandstone beds are included in the three formations. Thickness of Lower Cretaceous rocks ranges from slightly more than 200 feet in southeast Phillips County to more than 800 feet in southern Graham County (Merriam, 1963). Keene and Bayne indicate groundwater from Lower Cretaceous rocks probably has dissolved solids between 500 and 1,000 mg/l in southeastern Graham County, but the dissolved solids content increases to perhaps more than 10,000 mg/l in northern parts of the Subregion. They indicate the water is a mixed sodium-calcium-bicarbonate water in southeastern Graham County, but is a sodium chloride type water in most of the Subregion. Leonard (1952) reports water from the Dakota Formation in Phillips County to be too mineralized for domestic, livestock, or irrigation use. The Lower Cretaceous sandstone aquifer is not adequately tested for quality of water and potential well yields. It may be unsuitable for domestic, stock, irrigation, or other uses in much of the Subregion because of its chemical quality. Yields of 10-500 gpm or more may be available to properly constructed wells.

West-Central Kansas Subregion

Ogallala Aquifer:

Bedrock Contour Surface and Bedrock Geology:

The nine counties that comprise the West-Central Subregion are shown in Figure 1. Plates 1A and 1B show the bedrock geology below the base of the Ogallala aquifer and Plates 2A and 2B show the elevation of the base of the Ogallala aquifer, or the elevation of the bedrock erosional surface.

In all of the West-Central Kansas Subregion Upper Cretaceous rocks directly underlie the Ogallala aquifer. The Niobrara Chalk directly underlies the Ogallala aquifer in all of the Subregion except the northwest part of Gove, the north half and part of the southwest quarter of Logan, and almost all of Wallace County and ranges from a featheredge to more than 750 feet in thickness, being thickest in Wallace County. It is overlain by the Pierre Shale in Wallace and parts of Logan and Gove counties. The Pierre ranges in thickness from 0 to more than 800 feet, being thickest in northwestern Wallace County (Merriam, 1963).

The erosional surface on the Cretaceous rocks below the Ogallala aquifer slopes generally eastward from elevations ranging from about 3,870 feet along the Colorado border to elevations of about 2,190 feet in northeastern Trego County. The erosional surface below the Ogallala slopes eastward about 1,680-1,200 feet across the West-Central Subregion at a rate of about 9-12 feet per mile. The Ogallala aquifer is split into two parts by post-Ogallala erosion along the Smoky Hill River. Two interesting features are the bedrock depressions in southwestern Wallace County and the southward-trending bedrock depression through central Scott County. Two of the closed bedrock depressions in Wallace County are more than 50 feet deep and may represent downfaulted bedrock blocks bounded by faults or areas in which solution of underlying rocks, perhaps Permian salt beds, has occurred, allowing sinks to form in the bedrock surface. The Scott County depression continues southward into southwest Kansas and represents the headward end of a major pre-Ogallala erosional channel which can be traced southeastward into Meade County. The many irregularities on the pre-Ogallala erosional surface attest to the development of a drainage network of streams before deposition of the Ogallala Formation.

Water Table or Potentiometric Surface:

The water table, as shown on Plate 3A for the area north of the Smoky Hill River Valley, is a relatively smooth eastward-sloping surface ranging from an elevation of about 3,880 feet along the Colorado boundary to about 2,200 feet in eastern Trego County. The water table south of the Smoky Hill River Valley slopes generally eastward to central Scott County (Scott Basin) and then slopes in a more northeasterly direction into Lane and Ness counties (Pl. 3B). The water-table slope averages about 9.7 to 12.5 feet per mile across the West-Central Subregion.

Except for the Smoky Hill River, most of the streams are ephemeral and are above the water table.

Saturated Thickness:

The saturated thickness of the Ogallala aquifer is 100 feet or less except for an area in southwestern Wallace County where more than 250 feet of saturation occurs and in an elongate north-south basin through central Scott County where locally there is more than 150 feet of saturation (Pls. 5A,B). The greatest saturated thickness reported (U.S. Geological Survey, 1978b) in observation wells was 270.78 feet in well 14-42W-22BDD in southwestern Wallace County. There are extensive areas in the West-Central Subregion where the saturated thickness is 50 feet or less.

There have been significant declines in saturated thickness in this Subregion. In Wichita County, for example, of 82 observation wells with long-term records (1950-1977), 49 have had declines in saturated thickness of 40 percent or greater, with as much as 75 percent decline locally (U.S. Geological Survey, 1978b). In Scott County, similar declines have occurred between 1950 and 1978. In one well (20-33W-5BAB) the saturated thickness has declined 79 percent, from 58 feet in 1950 to 12 feet at the end of 1977.

Depth to Water:

The depth to water below land surface is shown on Plates 4A and 4B. The greatest depth to water is more than 200 feet in a small area of southwestern Wallace and northwestern Greeley counties. Over a large part of the Subregion, the depth to water is 100-150 feet.

The greatest depth to water as reported in hydrographs of observation wells in the Subregion is 245.35 feet (U.S. Geological Survey, 1978b) in well 15-42W-32BDA.

Groundwater Storage:

Transmissivity and Storage Coefficients:

There is only a small amount of published information on the hydraulic properties of the Ogallala aquifer for this Subregion. Prescott and others (1954) described the results of four pumping tests in Wichita County, and Bradley and Johnson (1957) compiled information on one pumping test in Wichita County and four pumping tests in Scott County. Johnson (1958) reported information on four pumping tests in Logan County. Information on the specific capacities of wells, transmissivity, and hydraulic conductivity from these tests is given in Table 6. Transmissivity values range from 15,000 to 365,000 ft^2/day.

An appropriate storage coefficient for the Ogallala aquifer is difficult to determine. Bayne and Ward (1969) used specific yields of 0.2 and 0.15 for different parts of the West-Central Subregion. If these values are used for a percentage of the area to which they are applied, an average specific yield of

0.17 to 0.18 is obtained for the Subregion. Dunlap, Kume, and Thomas (1980), utilizing all the data available for a groundwater model in Wichita County, determined a storage coefficient or specific yield of 0.17. In this report 0.17 is used for storage coefficient, with some assurance that it is probably within 10 percent of the correct value.

The quantities of groundwater in storage (Table 4) have been computed from Plates 5A and 5B using a 0.17 storage coefficient.

Water Quality:

Hathaway and others (1975, 1979) collected and analyzed water samples from a large number of pumping irrigation wells in Wallace, Logan, Gove, Greeley, Wichita, Scott, and Lane counties. Selected chemical analyses from these studies are included in Table 5. The chemical analyses of water from the Ogallala aquifer indicate the water is a calcium bicarbonate to calcium-magnesium bicarbonate water in most of the Subregion. The dissolved solids content of the waters increases to the Scott Basin area of south-central Scott County. The salinity, calcium, and sulfate content of the water also increases in the Scott Basin (well 20-32W-7CBA, Table 5). The occurrence of saline water of high SO_4 content coincides with an area of saline soils (Sallee and Hamilton, 1965). Eastward from Scott County the waters again are calcium bicarbonate type (Table 5). SAR values are generally less than 1.5. The waters generally have a medium salinity, low alkali hazard classification for irrigation use except for the Scott Basin. In most of the Subregion the waters are of good quality for domestic, municipal, and industrial use, except for hardness, which is generally greater than U.S. Public Health Service (1962) recommended values. For more detailed analyses of the water quality, the reader is referred to Hathaway and others (1975, 1979).

Point-source pollution problems have been summarized by O'Connor, Waldorf, and Dulas (1978). There were 72 large cattle feedlots and 17 hog feedlots, six cities using septic tank systems for sewage disposal, 11 cities using waste-stabilization lagoons, and two Department of Transportation highway rest stop areas using waste-stabilization lagoons. Each of these are potential point sources of pollution to the groundwater supplies.

However, when assessed for pollution potential by the LeGrand (1964) point-count system for unconfined alluvial water-table aquifers, the pollution potential is generally very minimal. The low precipitation and recharge rates, high evaporation rates, topography, soils, geology of the unsaturated zone, depth to water table, and distances between waste disposal sites and withdrawal sites are generally very favorable in this area for protection of the Ogallala aquifer.

Because of the many favorable rating factors, any point sources of pollution that may cause groundwater pollution are likely to be very local and not have a significant effect on the Subregion water quality.

Industrial pollution has not been evaluated, but the Subregion does not have a large industrial base and the same favorable factors of geology and climate are applicable. Good housekeeping practices and reliable and safe handling and disposal practices for toxic and hazardous wastes are important in preventing potential industrial pollution of the Ogallala aquifer.

Hathaway (1975) reported locally high levels of PO_4 values in some water samples from the Ogallala aquifer, which may reflect fertilizer contamination. At this time, the levels of the more mobile constituents such as chloride, nitrate, and phosphate as well as increases in dissolved solids in waters sampled do not indicate a significant groundwater pollution problem from agricultural practices. The long-term results of irrigation and return flow of irrigation water to the aquifer, combined with a declining water table and decreasing saturated thickness of the aquifer, suggest that the long-term effects of irrigation may result in an increase in some of the dissolved constituents and a decline in the water quality.

There are no significant natural-source quality problems in the West-Central Subregion except those associated with saline soils in the Scott Basin.

Groundwater-Level Changes:

Hydrographs of one or more representative wells in the Ogallala aquifer in each county are shown in Appendix A. In 1977 the water levels declined about 2 feet compared with 3 feet in 1976 and an average annual decline of 1.5 feet for the period 1966-1977 for Greeley, Lane, Scott, southern Wallace, and Wichita counties (U.S. Geological Survey, 1978b). The average water-level decline therefore for this 12-year period was about 18 feet over the 4-1/2 counties. The water-level changes in these counties probably are representative of changes in Logan, Gove, Trego, and Ness counties. The maximum reported water-level decline (1966-1977) was 45.16 feet in well 16-36W-21CCC in northwestern Wichita County. Since 1950 the water levels in this well have declined 60 feet and the saturated thickness has decreased 50 percent. The greatest decrease in saturated thickness in observation wells is probably in Scott County. Well 20-33W-5BAB had a saturated thickness of 58 feet in 1950 and 12 feet at the end of 1977, for a 79 percent decrease in saturated thickness (U.S. Geological Survey, 1978b).

For nearly all of the Subregion the trend in water levels has been downward and at an increasing rate in recent years as the number of irrigation wells and the amount of pumpage increased. The reader is referred to a series of water-level reports by the Kansas Geological Survey (Pabst and Gutentag, 1977) and the U.S. Geological Survey (1977, 1978b) for more detailed statistical information about water-level changes in observation wells in this area. The effects of water-level declines are increased pumping lifts, increasing pumping costs, reduced well yields, and decreased saturated thickness. In some parts of the Subregion, the decline in water levels, saturated thickness, and well yields have been so great that irrigation is no longer economically feasible.

The average recharge on the area underlain by the Ogallala aquifer in the West-Central Subregion from precipitation and irrigation return flow is estimated to be 180,075 acre-feet in 1977 (Table 2). The irrigation pumpage is estimated to be about 735,000 acre-feet.

Alluvium:

The alluvium in the major stream valleys ranges from about 30-105 feet in thickness and yields supplies of as much as 2,100 gpm (McClain and others, 1975) in the Smoky Hill River Valley and 300-800 gpm in the other tributary valleys. In the Smoky Hill River Valley alluvium the water table lies below and is not hydraulically connected to the Ogallala aquifer except in western Wallace County. Leakage from the Ogallala aquifer to the Cretaceous bedrock and to discontinuous undifferentiated Pleistocene deposits on the valley walls occurs across most of the length of the Smoky Hill Valley. The stream and valley alluvium receives recharge from both the bedrock and the unconsolidated deposits. There is generally less than 50 feet of saturated alluvium in the stream valleys, but locally along the Smoky Hill River, Big Creek, Hackberry Creek, and Lake Creek there is 50-100 feet of saturated alluvium (McClain and others, 1975).

Alluvium along Ladder Creek, Whitewoman Creek, and Sand Creek has a thickness of as much as 50 feet. The deposits are reworked from older unconsolidated deposits and have less silt and clay than Ogallala deposits (Gutentag and Stullken, 1976; Slagle and Weakly, 1976). The alluvium is generally above the water table, but locally is partly saturated and will yield supplies of 250 gpm to wells. During infrequent periods when surface runoff provides flow, the streams are influent and contribute significant recharge to the underlying unsaturated alluvium and the Ogallala aquifer.

In alluvium along stream valleys receiving groundwater contributions from weathered Pierre Shale and Niobrara Chalk and in discontinuous undifferentiated unconsolidated deposits on the valley sides, the groundwater is more mineralized; contains higher amounts of dissolved solids, calcium, sulfate, hardness, and chloride; has higher specific conductance and SAR values; and is not as suitable for irrigation, domestic, municipal, or industrial use.

Alluvium along streams such as Ladder Creek, Whitewoman Creek, and Sand Creek are important mainly as sources of periodic recharge to the underlying Ogallala aquifer. Whitewoman Creek infrequently carries surface runoff all the way to Whitewoman Basin south of Scott City. Thus, infrequently, flood flows accumulate in an undrained basin where the water evaporates or percolates downward to the water table. Saline soils are associated with the basin and the groundwater contributed to the Ogallala aquifer has greater amounts of dissolved solids, calcium, sulfate, and hardness as shown by Hathaway and others (1975).

Bedrock Aquifers:

Upper Cretaceous Rocks:

Pierre Shale Aquifer: The Pierre Shale crops out or is below thin undifferentiated unconsolidated deposits along much of the western part of the Smoky Hill River Valley and its tributaries. It is not a significant aquifer, but the weathered outcrops of dark gypsiferous shale beds yield very small groundwater supplies to wells locally and act to transmit water high in calcium and sulfate toward the valley alluvium.

Niobrara Chalk Aquifer: The Niobrara Chalk underlies the Ogallala or crops out at the surface in all of the Subregion except where it is overlain by Pierre Shale in Wallace, Logan, and Gove counties. It ranges in thickness from a featheredge along the eastern edge of its outcrop in Trego and Ness counties to about 750 feet in Wallace and Logan counties. Weathered outcrops of Niobrara yield very small amounts of water locally but constitute an insignificant aquifer in most of the area where they are exposed or are near the surface. Groundwater from the chalk ranges from a calcium bicarbonate to a calcium sulfate type water.

In southeastern Scott County there are several irrigation wells that yield as much as 1,000 gpm from the Niobrara Chalk, reportedly from fractures and solution openings. In this area, the water is a calcium bicarbonate type with dissolved solids of about 350-400 mg/l and is classed as having a low alkali, medium salinity hazard suitable for irrigation use if moderate leaching occurs (Gutentag and Stullken, 1976).

Codell Sandstone Aquifer: The Codell Sandstone Member occurs at the top of the Carlile Shale (Table 1). It is a very fine grained silty sandstone ranging from a featheredge to about 19 feet in thickness (Hattin, 1962). It yields small supplies (0-10 gpm) of water to wells in Trego and Ness counties. In Trego County the dissolved solids range from 307 to 728 mg/l and the waters may be either of the sodium bicarbonate or calcium bicarbonate type.

Throughout most of the Subregion, the Codell Sandstone is essentially untested, but the very low yields suggest that it probably is not of much significance in most of the area.

Lower Cretaceous and Upper Jurassic Rocks:

Undifferentiated Sandstone Aquifer: Wells have been completed in the Lower Cretaceous sandstone aquifer (Table 1) in Wallace, Logan, Gove, Trego, Wichita, and Greeley counties. The waters are mostly of the mixed sodium-calcium bicarbonate type. Dissolved solids tend to increase northward across the area. Yields are reported to range from 30-300 gpm, but larger yields may be obtainable. Keene and Bayne (1977) summarize available information about water in the Lower Cretaceous rocks and show the direction of groundwater flow to be generally east-northeast across the Subregion. The potentiometric surface is about 3,300 feet elevation in southwestern Greeley County and declines to about 1,950 feet elevation along the east side of Trego County. Depth to top of the sandstone ranges from about 150 feet in eastern Ness County to about 2,200 feet in northwest Wallace County.

The water may not be suitable for irrigation or municipal use because of its high dissolved solids and high sodium, chloride, SAR, and conductivity values and, therefore, water from the Lower Cretaceous aquifer should be tested for suitability before use.

Because of its great depth in much of the area and questionable suitability for certain uses, it has not been adequately tested and is little used in the West-Central Subregion.

The Jurassic rocks lie below the Lower Cretaceous rocks in Wallace, Logan, Gove, Greeley, Wichita, and parts of Scott, Lane, and Trego counties and contain beds of sandstone (Table 1) which may yield small to moderate quantities of water, but are untested in this Subregion. The rocks are known to yield water suitable for irrigation in only a small part of the Southwest Subregion and may contain water too highly mineralized for irrigation, municipal, or industrial use in this area. Testing for quality and quantity will be needed before the Jurassic sandstones can be evaluated.

Southwest Kansas Subregion

Ogallala Aquifer:

Bedrock Contour Surface and Bedrock Geology:

The bedrock geology below the Ogallala aquifer in the Southwest Kansas Subregion is shown on Plate 1B. Rocks of Permian, Jurassic, Lower Cretaceous, and Upper Cretaceous ages lie directly below the Ogallala aquifer. Some of these bedrock units contain permeable water-yielding zones (aquifers) that are in hydraulic connection with the Ogallala aquifer. The Bear Creek Fault and the Crooked Creek-Fowler Fault have important effects on the hydrology of the area.

Plate 2B shows the altitude of the base of the Ogallala aquifer or the configuration of the erosion surface on top of the underlying bedrock. An area in Meade County east of the Crooked Creek-Fowler Fault contains too little data from which bedrock elevation, water table, and saturated thickness maps could be reliably prepared in the thin Ogallala aquifer. This area, therefore, is not contoured. The most striking feature shown is the major drainageway beginning in Scott County, trending southward to near Garden City, then southeastward to the Crooked Creek-Fowler Fault. Other less-pronounced drainage features are a bedrock valley trending through Cimarron and Dodge City nearly parallel to the present Arkansas River, and another bedrock valley trending roughly in the position of the Cimarron River from near Ulysses to the Crooked Creek-Fowler Fault.

The erosional surface slopes southeastward from elevations of a maximum of 3,500 feet along the Colorado border southward and eastward to elevations of less than 2,000 feet near the Oklahoma border.

Displacement along the Bear Creek and Crooked Creek-Fowler faults is as much as 250 feet.

Water Table or Potentiometric Surface:

The water table shown in Plate 3B is a relatively smooth eastward and southeastward-trending surface without the many small irregularities shown on the bedrock surface (Pl. 2B). The water-table elevations range from about 3,500 feet along the Colorado border in Morton County to low points of about 2,150 feet in southeastern Meade and northeastern Clark counties.

Except for Crooked Creek and the lower part of the Cimarron River, nearly all of the streams in the Subregion now lie above the water table and, during infrequent periods when they have storm runoff flowing in them, the streams lose water to the underlying unsaturated unconsolidated rocks and contribute recharge to the groundwater body. The Arkansas River formerly had a base flow, but groundwater pumpage has caused water-level declines along the valley and little or no groundwater now discharges to the river.

There are silt and clay beds interlayered with sand and gravel beds within the Ogallala aquifer. The fine-grained beds retard vertical flow of water and may cause temporary confined conditions and different water levels in wells completed in separate sand and gravel zones. Leakage between pumping seasons tends to reduce or eliminate the differences in head between shallow and deep sand and gravel zones and, in overall performance, the Ogallala aquifer responds as a single unconfined aquifer. Gutentag, Lobmeyer, and Slagle (1980) discuss in detail the water level changes resulting from pumpage.

Saturated Thickness:

More than 600 feet of saturated thickness occurs in the Ogallala aquifer in southwestern Seward County. The range of saturated thickness is shown on Plate 5B. A large part of the Subregion has a saturated thickness greater than 250 feet.

Depth to Water:

The depth to water is shown on Plate 4B. Along the major stream valleys such as the Arkansas River, Cimarron River, and Crooked Creek the water table is generally less than 50 feet deep. Away from the major stream valleys the depth to water increases. Locally as in west-central Haskell County depth to water is more than 300 feet. The great depth to water in parts of Grant and Haskell counties is the result of large water-level declines. Since 1940 water levels have declined as much as 86 feet in Haskell County and as much as 169 feet in parts of Grant County (U.S. Geological Survey, 1978b).

Groundwater Storage:

Transmissivity and Storage Coefficients:

The available pumping-test data for the Southwest Subregion are summarized in Table 6. Transmissivity values (T) range from 1,600 ft^2/day to

590,000 ft^2/day. Storage coefficients (S) range from 0.00011 to 0.22. The small values of S indicate the pumping test was not long enough to allow gravity drainage of water from fine-grained beds that are a part of the Ogallala aquifer, and therefore the values indicate artesian conditions during the pumping test. Over long time periods water will drain from the fine-grained materials in unconsolidated aquifers in response to water-level declines, and storage coefficients of 0.15 to 0.2 are probable. Storage coefficients or specific yield estimated by Bayne and Ward (1969) for the Southwest Subregion ranged from 0.15 to 0.20. A value of 0.17 was used for the area in this study to compute the volume of groundwater in storage (Table 4) and is probably correct within 10 percent.

Water quality:

A total of 490 water samples were collected from pumping irrigation wells in the Southwest Subregion during the month of July in 1975, 1976, and 1977 as part of three studies of irrigation water quality in Kansas (Hathaway and others, 1977, 1978a, 1978b). Selected analyses from these studies are included in Table 5.

The analyses indicate three general types of groundwater occurring in different parts of the Subregion. The unconsolidated aquifer along the Arkansas River Valley from Colorado eastward to northwest Gray County is a saline water of the SO_4 type. It is represented in Table 5 by an analysis from well 24-34W-17BBC. An area north of the Arkansas River contains similar water because of leakage and irrigation return flow of Arkansas River water diverted to this area for irrigation use. The high SO_4 type water associated with the Arkansas River Valley improves in quality in a downstream direction from Lakin to Cimarron as better quality Ca-HCO_3 type water from the sand hills south of the river mixes with and dilutes the dominant SO_4 water. Between Coolidge and the Ford-Gray County boundary, dissolved solids along the Arkansas River decrease from about 3,700 to 500 mg/l (Gutentag, Lobmeyer, and Slagle, 1980).

Large parts of the Subregion are characterized by a $Ca\text{-}HCO_3$ water (Table 5) which, for irrigation purposes, is classed as having a medium to high salinity hazard and a low alkali hazard. Representative analyses are given in Table 5.

In an area of southeast Seward and southwest Meade County, the basal part of the unconsolidated aquifer gains groundwater from the underlying Permian Whitehorse Formation. The bedrock water is of a mixed sodium-magnesium-chloride to sodium chloride type and wells in the Whitehorse Formation have dissolved solids as high as 33,900 mg/l (Gutentag, Lobmeyer, and Slagle, 1980). A well in the Ogallala aquifer having a Na-Cl type water is represented by 33-29W-36AAB in Table 5. The reader is referred to the cited publications for more detailed descriptions of water quality.

Potential point-source pollution problems associated with animal feedlots and municipal and Department of Transportation rest stop sewage disposal systems are summarized by O'Connor, Waldorf, and Dulas (1978). In 1977 there were 101 cattle feedlots, some as large as 50,000 head per feedlot; 29 hog feedlots; and three dairy feedlots in the Subregion. One city used septic tanks for disposal of sewage and 13 cities used waste stabilization ponds for sewage disposal. There were three Department of Transportation rest stop areas that used septic tank sewage disposal and one rest stop used open-pit disposal.

Because of factors cited by LeGrand (1964) - that is, the favorable climate, geology, and depth to water factors - the possibilities for significant pollution are considered "very improbable" or "impossible" provided good well-siting and well-construction practices are followed with respect to point-source pollution and provided the wastes are properly disposed of.

Industrial pollution has not been evaluated, but there is not a large industrial base in the Subregion and the same beneficial factors of climate, recharge rates, geology, and depth to water tend to reduce, although not to eliminate, the potential for groundwater pollution.

Because of the extensive petroleum industry in the area associated with the Hugoton gas field, there is a significant pollution hazard in the handling and disposal of brine produced with oil and gas. Good practices in the cementing of casing through the fresh-water aquifers, good practices in the plugging of deep test holes drilled into the bedrock, and proper plugging of abandoned wells are essential to prevent brine pollution of present and future fresh groundwater supplies in the Ogallala aquifer.

The return flow of irrigation water from 1,688,000 irrigated acres combined with declining water levels, will result in an eventual increase in dissolved solids. Some of the more mobile constituents such as chloride, nitrate, and possibly phosphate may increase.

In the pre-irrigation development period, the heads or potentiometric surface in the bedrock aquifers below the Ogallala aquifer were in equilibrium with the head in the overlying unconsolidated aquifer. Because of regional lowering of water levels in the unconsolidated aquifer an increased rate of upward flow and lateral flow may occur in the bedrock aquifers. Because the Permian, Jurassic, and Lower Cretaceous aquifers typically have water of lower quality and higher dissolved solids, basal parts of the unconsolidated aquifer may locally become more mineralized as a result of increased quantities of poor-quality water flowing from the bedrock aquifers. Krothe and Oliver (1980) cite evidence for deterioration of Ogallala water owing to leaching caused by irrigation return flow and also by upward leakage of poor quality water from underlying Permian rocks in western Kansas and Oklahoma.

There is one area in southeastern Seward County and southwestern Meade County where natural-source salt water from the Permian Whitehorse Formation intrudes into the basal part of the Ogallala aquifer. The upward movement of salty water and influent flow of groundwater to the Cimarron River between U.S. Highway 83 and a sampling point near the Oklahoma border is indicated by stream-flow measurements and the increase in chlorides from 23 mg/l to 650 mg/l downstream (Gutentag, Lobmeyer, and Slagle, 1980).

Additionally, during low to moderate flow, the Arkansas River as it enters Kansas from Colorado commonly contains 2,000-5,000 mg/l of dissolved solids of a mixed type containing sodium, calcium, magnesium, and sulfate. Since the Arkansas River no longer has a base flow through this reach of the river, the dissolved solids are accumulating in the soils and the groundwater body where the water is used for surface irrigation or where it is lost through influent seepage.

Groundwater-Level Changes:

Hydrographs of one or more representative wells in the Ogallala aquifer in each county are shown in Appendix A. The water levels change in response to changes in recharge and discharge rates. In 1977 the water levels declined an average of about 4 feet; in 1976 water levels declined an average of about 5 feet. In the 12-year period 1966-1977 water levels declined about 26.4 feet, exclusive of Ford County where statistical records for the same years are not available. Long-term water-level declines shown in the hydrographs are an indication that discharge is consistently in excess of recharge and reflect the large increases in irrigation pumpage that have occurred in the area since 1950. The areas of greatest decline generally coincide with areas of greatest pumpage. The same amount of water-level decline in different areas may not represent the same amount of groundwater depletion because of differences in the character and thickness of the aquifer. The greatest water-level decline has been in Stanton County where water levels are as much as 172 feet below water levels in 1940 (U.S. Geological Survey, 1978b), and represents a 49 percent decrease in saturated thickness. The reader is referred to a series of water level publications published by the Kansas Geological Survey (Pabst and Gutentag, 1979) and the U.S. Geological Survey (1977, 1978b) for more detailed water level information.

The water-level declines are of importance because they result in greater pumping lifts, greater pumping costs, decreased well yields, and reduced saturated thickness.

The average recharge from precipitation return flow to areas in the Southwest Subregion underlain by the Ogallala aquifer (shown in Plate 5B) is estimated to be 602,725 acre-feet in 1977 (Table 2). Irrigation pumpage is estimated to be about 2,954,000 acre-feet (Table 2).

Alluvium:

The alluvium in the Arkansas River Valley has a thickness of 30-80 feet. Similar thicknesses have been reported for the Cimarron River and Crooked Creek. Irrigation wells pumping from alluvium in the Arkansas River Valley are reported to yield 500-2,400 gpm (Gutentag, Lobmeyer, and McGovern, 1972). Because of declining water levels and increased pumpage, some well yields have greatly declined. In areas along the Cimarron River and Crooked

Creek, many wells are completed in the Ogallala aquifer. Many of the ephemeral streams have only thin alluvium, which lies above the water table, and the streams are important as sources of intermittent recharge during infrequent periods of flow. Jordan (1977) cites seven runoff events in the period 1967-1972 on Bear Creek in which stream flows of 1,140 acre-feet to 10,000 acre-feet were entirely lost by influent seepage in a valley length of 27 miles.

Bedrock Aquifers:

Upper Cretaceous Rocks:

Niobrara Chalk Aquifer: The Niobrara Chalk directly underlies the Ogallala aquifer along the northern parts of Hamilton, Kearny, and Finney counties. In northern Finney and eastern Kearny counties about 45 irrigation wells produce water from the chalk or from the chalk and thin unconsolidated deposits. A permeable zone, 20-40 feet above the base of the Niobrara Chalk, contains a zone of fractures and solution channels that in the period 1968-1972 yielded 500-2,500 gpm. Because of the irrigation development and lowered water levels, yields have been significantly reduced (Gutentag, Lobmeyer, and Slagle, 1980). The water is a mixed calcium-magnesium bicarbonate water similar to that in the overlying Ogallala aquifer. Areas in which the fracture and solution zone is found can best be determined by test drilling, as the highly permeable zone is not present in all of the area.

Lower Cretaceous and Upper Jurassic Rocks:

Undifferentiated Sandstone Aquifer: Undifferentiated sandstone beds of the Dakota Formation, Kiowa Formation, Cheyenne Sandstone, and the underlying Jurassic rocks (Table 1) constitute an important aquifer in parts of the

Southwest Kansas Subregion. The bedrock map (Pl. 1B) shows the distribution of Lower Cretaceous and Upper Jurassic rocks. In these areas the included permeable sandstone beds are hydraulically connected with the Ogallala aquifer. The Jurassic sandstones are known to yield water to wells in Morton and Stanton counties (Gutentag, Lobmeyer, and Slagle, 1980). They are relatively untested in Hamilton and Kearny counties. The Lower Cretaceous rocks have been studied by Keene and Bayne (1977). Their study indicated the water in Lower Cretaceous sandstones is similar in quality to the Ogallala aquifer, generally has less than 500 mg/l dissolved solids, and is a calcium bicarbonate type water except along the northern edge of the Subregion. Wells in the sandstone aquifer have been drilled in Stanton, Grant, Hamilton, Kearny, Finney, Gray, Ford, and Hodgeman counties. Well yields range from about 30 to more than 1,000 gpm. The water becomes more mineralized northward and becomes a mixed sodium calcium bicarbonate water.

The potentiometric surface indicates water moves in a generally easterly or east-northeasterly direction.

Upper Permian Rocks:

Day Creek Dolomite (Gypsum Aquifer): The quality and quantity of groundwater available from Permian rocks is not well known. The thickness, physical characteristics, and water supply are summarized in Table 1. In Morton County there are irrigation wells that obtain yields of 300-1,000 gpm from solution cavities in gypsum and anhydrite beds of the Day Creek Dolomite. The waters are high in dissolved solids, hardness, and are Ca-SO_4 type waters. The water quality becomes more mineralized northward where overlain by Jurassic and Cretaceous rocks. Because the water is highly mineralized, its use for irrigation and other uses is limited.

The Whitehorse Formation occurs below the Ogallala aquifer in parts of Seward and Meade counties and reportedly contains water too mineralized for use (i.e., dissolved solids >30,000 mg/l). Upward leakage of salty water from these beds into the Ogallala aquifer and Cimarron River have been described by Gutentag, Lobmeyer, and Slagle (1980) for southeastern Seward and southern Meade counties.

The hydrology of the Permian aquifers is not adequately known. The relation of the Bear Creek Fault and the Crooked Creek-Fowler Fault as possible avenues of recharge to or discharge from Permian rocks is not known. Much of the salt (halite) in the Blaine Formation has been removed by circulating groundwater in the area between the faults.

Groundwater from the Permian rocks is not believed to be a significant source of additional irrigation water because of its mineralized character.

Summary

The study area includes about 28,560 square miles in 32 western Kansas counties divided into Northwest, West-Central, and Southwest subregions.

Precipitation in western Kansas ranges from less than 17 inches to about 25 inches in the area; mean annual runoff ranges from about 0.1 to 1.1 inches. The Ogallala aquifer is the principal groundwater reservoir in the area and is defined to include the Ogallala Formation and the overlying undifferentiated Pleistocene deposits, which are hydraulically connected and form a single ground-water reservoir.

Bedrock units range in age from Permian (oldest) to Jurassic and Cretaceous and define the lower limits of useable groundwater. The bedrock units may contribute groundwater to the Ogallala aquifer or transmit water

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Table 1. Generalized section of geologic formations and their water-bearing properties.

System	Series	Stratigraphic Unit	Thickness (ft)	Physical Character	Water Supply
Quaternary	Pleistocene	Alluvium	0-105	Stream-laid deposits ranging from silt and clay to sand and gravel that occur in stream valleys.	Well yields range from about 50 to 1,500 gpm (gallons per minute) depending on saturated thickness and lithology of valley filling
		Dune Sand	0-75	Fine to medium quartzose sand with minor amounts of clay, silt, and coarse sand. Deposited by wind into dunes and ridges.	Generally lies above the water table and therefore does not yield water to wells. Serve as important recharge areas because of high infiltration rate and permeable character.
		Loess	0-90	Silt with subordinate amounts of clay and very fine sand deposited as wind blown dust.	Most deposits lie above the water table and yield no water to wells. Locally may yield 0 to 10 gpm where deposits are saturated. Forms areally extensive cover over much of western Kansas through which intermittent recharge occurs.
		Undiff. deposits	0-550	Sand and gravel interbedded with clay, silt, caliche and volcanic ash. Includes fluvial eolian and minor lacustrine deposits.	The sand and gravel deposits of the undifferentiated Pleistocene deposits and the Ogallala Formation are the principal water-bearing deposits in the area, and comprise the Ogallala aquifer. Yields commonly range from 100 to 3,100 gpm.

System	Series	Stratigraphic Unit	Thickness (ft)	Physical Character	Water Supply
Tertiary	Pliocene/ Miocene	Ogallala Formation	0-500	Unconsolidated sand, gravel, silt, clay and caliche, locally cemented by calcium carbonate or silica into mortor beds. Also contains thin fresh water limestones, volcanic ash beds and diatomaceous marl.	
Cretaceous	Upper Cretaceous	Pierre Shale	0-1,600	Consolidated, fissile, black, dark to light gray shale containing concretions, bentonite beds, thin chalk beds and locally thin gypsum.	Generally yields no water to wells. Locally in northwest Kansas yields 0 to 3 gpm to wells where the formation is exposed along stream valleys.
		Niobrara Chalk	0-750	Upper unit (Smoky Hill Chalk Member) consists of yellow to orange yellow chalk and light to dark gray chalky shale. Lower unit (Ft. Hays Limestone Member) consists of white to yellow massive chalky limestone and thin beds of light to dark gray chalky shale.	A minor aquifer (0-10 gpm) in northwest Kansas, but a significant aquifer locally in west-central and southwest Kansas where extensive fractures and solution openings yielded 500-2,500 gpm wells in early irrigation developments. Because of increased irrigation development and water level declines, yields have been reduced by 100 to as much as 2,000 gpm.

System	Series	Stratigraphic Unit	Thickness (ft)	Physical Character	Water Supply
Cretaceous		Carlile Shale	0-330	Upper unit (Codell Sandstone and Blue Hill Shale members) consists of dark-gray to blue-black non-calcareous to slightly calcareous shale. Locally a thin very fine grained sandstone occurs at the top. Lower unit (Fairport Chalk Member) consists of calcareous dark gray shale interbedded with thin limestone, chalky limestones and bentonite layers.	Sandstone may yield 0 to 10 gpm to wells locally. Little or no water obtained from shale and limestone beds.
		Greenhorn Limestone	0-200	Chalky light- to dark-gray limestone and gray calcareous shale interbedded. Contains thin bentonite beds.	Yields little or no water to wells.
		Graneros Shale	0-130	Dark-gray calcareous shale interbedded with black non-calcareous to slightly calcareous shale. Contains thin beds of benotnite and locally thin limestone and fine grained silty sandstone layers.	Yields little or no water to wells.

Table 2. Estimated recharge from precipitation and from irrigation return flow to the Ogallala aquifer and estimated pumpage for irrigation from the Ogallala aquifer in western Kansas, 1977.

		Dry Land		Irrigated Land			
Area	Acreage of Ogallala aquifer (from Plate 5A,B)	Acres	Recharge (acre-feet) 0.3 in/acre	Acres	Irrigation Pumpage (acre-feet) @21 in/acre	Recharge on Irrigated Land (acre-feet) @2.1 in/acre	Total Recharge acre-feet
Northwest Subregion	4,472,000	4,080,000	102,000	392,000	686,000	120,050	222,050
West-Central Subregion	2,478,000	2,058,000	51,450	420,000	735,000	128,625	180,075
Southwest Subregion	5,119,000	3,431,000	85,775	1,688,000	2,954,000	516,950	602,725
Western Kansas Total	12,069,000	9,569,000	239,225	2,500,000	4,375,000	765,625	1,004,850

System	Series	Stratigraphic Unit	Thickness (ft)	Physical Character	Water Supply
	Lower Cretaceous	Undiff. rocks	0-350	Upper unit (Dakota Formation) white, brown and gray fine to medium-grained sandstone; interbedded with gray and varicolored shale; contains lignite beds. Middle unit (Kiowa Formation) dark gray to black shale interbedded with tan and gray sandstone. Lower unit (Cheyenne Sandstone) light to dark gray and brown fine to medium grained sandstone interbedded with dark gray shale.	Yields 30-1,000 gpm available to wells locally in southwest and west-central Kansas. Water quality becomes more mineralized northward from southwest Kansas where Lower Cretaceous rocks are overlain and hydraulically connected to Ogallala aquifer. Relatively untested in northwest Kansas.
Jurassic	Upper Jurassic	Undiff. rocks	0-350	Dark-gray shale interbedded with grayish and bluish green calcareous shale. Contains very fine to medium grained sandstone and some thin limestone beds in lower part.	Yields water to wells in Morton and Stanton counties that also penetrate water yielding Lower Cretaceous sandstone beds. Water may be too mineralized for most uses north of the Arkansas River area where it is untested.
Permian	Upper Permian	Big Basin Formation	0-160	Red and maroon siltstone shale and very fine grained sandstone.	Quantity and quality of ground water from these rocks is poorly known. In general the rocks are believed to yield small quantities of water where they directly underlie the Ogallala aquifer in part of southwest Kansas.

System	Series	Stratigraphic Unit	Thickness (ft)	Physical Character	Water Supply
Permian		Day Creek Dolomite	0-80	White, gray and pink anhydrite and gypsum interbedded with red shale.	Yields large quantities (300-1,000 gpm) of high sulfate water to some wells in Morton County from solution cavities. Untested or non-potable water in other parts of the area.
		Whitehorse Formation	100-350	Red to maroon fine grained silty sandstone, siltstone and shale.	Not known to yield significant amounts of water to wells in southwest Kansas. Water highly mineralized. Provides stock and domestic supplies in the outcrop area of Clark County.
	Lower Permian	Dog Creek Formation	15-60	Maroon shale, siltstone, very fine-grained sandstone, and thin beds of dolomite and gypsum.	Not known to yield significant amounts of potable water to wells in southwest Kansas. Water probably highly mineralized in all parts of western Kansas because of included gypsum, anhydrite and halite beds.
		Blaine Formation	20-150	Generally four gypsum and anhydrite beds separated by red shale. Contains halite beds locally.	

Table 3. 1978 Irrigated Acreage in Western Kansas (Kansas State University Cooperative Extension Service Engineering Newsletter: 1978 Kansas Irrigation Survey, 1978)

Northwest Kansas

Cheyenne	45,000 acres	Sherman	140,000 acres
Rawlins	18,000	Thomas	100,000
Decatur	13,000	Sheridan	83,000
Norton	11,703	Graham	15,127
Phillips	6,725		
		TOTAL	432,555 acres

West-Central Kansas

Wallace	70,000 acres	Greeley	33,000 acres
Logan	10,200	Wichita	158,150
Gove	22,000	Scott	121,600
Trego	3,900	Lane	23,000
Ness	12,000		
		TOTAL	454,550 acres

Southwest Kansas

Hamilton	33,035 acres	Stanton	190,000 acres
Kearny	129,000	Grant	156,000
Finney	326,520	Haskell	222,000
Hodgeman	22,000	Gray	199,633
Ford	85,000	Morton	76,000
Stevens	140,000	Seward	115,000
Meade	123,000	Clark	-------
		TOTAL	1,817,768 acres

Western Kansas Total = 2,704,878 acres

Table 4. Estimated quantity of groundwater in storage in the Ogallala aquifer in Kansas, by counties, and subregions, 1977.

County	Groundwater in Storage (acre-feet)
Northwest Subregion	
Cheyenne	6,591,000
Decatur	2,799,000
Graham	2,798,000
Norton	3,852,000
Phillips	978,000
Rawlins	6,032,000
Sheridan	4,057,000
Sherman	13,883,000
Thomas	10,494,000
Total, Northwest Subregion	51,484,000
West-Central Subregion	
Gove	1,584,000
Greeley	1,385,000
Lane	1,397,000
Logan	1,722,000
Ness	497,000
Scott	3,426,000
Trego	896,000
Wallace	3,659,000
Wichita	3,225,000
Total, West-Central Subregion	17,791,000
Southwest Subregion	
Clark	1,328,000
Finney	19,764,000
Ford	8,120,000
Grant	13,765,000
Gray	13,800,000
Hamilton	1,471,000
Haskell	18,729,000
Hodgeman	656,000
Kearny	8,752,000
Meade	20,216,000
Morton	8,434,000
Seward	24,258,000
Stanton	7,098,000
Stevens	28,817,000
Total, Southwest Subregion	175,208,000
Total, Western Kansas	244,483,000

Table 5. Chemical analyses of groundwater from the Ogallala aquifer in the three subregions of western Kansas (adapted from Hathaway and others, 1975, 1976, 1978, 1979).

Well Location	SiO_2 ppm	Ca ppm	Mg ppm	Na ppm	K ppm	Sr ppm	HCO_3 ppm	SO_4 ppm	Cl ppm	F ppm	NO_3 ppm	Total PO_4 ppm	Fe ppb	Mn ppb	Cu ppb
Northwest Subregion															
Cheyenne County															
3-39W-20DAC	63	34	15	20	7.2	0.6	199	15	4.7	1.4	12		6.0	1.6	0.7
Graham County															
6-25W-33BCB	58	49	18	9.9	5.6	0.7	237	13	3.5	0.7	5.6		6.2	0.4	1.2
Sheridan County															
7-28W-36ABA	49	54	16	16	5.9	0.7	232	24	12	0.7	16		6.7	0.9	0.8
Sherman County															
8-40W-18DBB	53	26	11	40	4.0	0.6	203	24	11	1.5	14		8.8	0.5	0.7
Thomas County															
8-33W-18CCA	48	40	19	24	6.1	0.8	218	24	11	1.5	14		24	0.0	3.0
West-Central Subregion															
Greeley County															
16-39-25CCB	38	43	20	29	4.8	.9	189	56	14	1.5	12		19	6	
Lane County															
17-28W-7BBB	56	54	23	26	6.0	.8	221	53	22	2.5	14		6	2	
Scott County															
17-32W-16BBB	54	55	21	29	5.9	1.1	208	76	16	2.5	16	.10	8	2	
20-32W-7CBA	39	152	66	88	15	3.2	368	407	85	1.4	36	.16	18	7	
Wallace County															
15-41W-5ACB	21	40	15	25	5.0	.7	190	39	9.6	1.1	14	.10	12	2	
Wichita County															
18-36W-29ABB	42	38	14	20	4.1	.8	181	29	12	1.9	15	2.41	8	1	

				Hardness as $CaCO_3$					
Ni ppb	Zn ppb	Temp. °C	Total Solids 180°C ppm	Total ppm	Non-Carbonate ppm	Sp.Cond. µmho at 25°C	SAR	pH	Date Collected
9.4		19.0	270	148	0	375	0.74	7.8	7/24-27/78
5.5		16.0	268	197	2.9	405	0.31	7.7	7/24-27/78
7.0		15.0	298	201	11	470	0.49	7.6	7/24-27/78
3.1		16.0	262	111	0	380	1.65	8.1	7/24-27/78
1.3		15.0	306	179	0.6	445	0.76	7.6	7/24-27/78
13	4	16.0	320	191	36	495	.91	7.7	7/31/74
8	7	16.0	373	230	49	540	.73	7.7	8/1/74
4	3	16.0	388	223	52	650	.84	7.2	7/30/74
63	10	18.0	1044	653	351	1570	1.50	7.1	7/31/74
1	2	16.5	279	163	0	420	.85	7.2	8/1/74
14	0	17.0	273	155	7	430	.70	7.4	7/30/74

Well Location	SiO$_2$ ppm	Ca ppm	Mg ppm	Na ppm	K ppm	Sr ppm	HCO$_3$ ppm	SO$_4$ ppm	Cl ppm	F ppm	NO$_3$ ppm	Total PO$_4$ ppm	Fe ppb	Mn ppb	Cu ppb
Southwest Subregion															
Finney County															
22-33W-36AAA	26	86	43	170	7.6	2.1	289	466	48	1.5	6.7	<0.1	20	.8	1.0
24-34W-17BBC	20	423	158	500	13	4.8	314	2336	206	1.3	38	<0.1	57	8.7	1.6
25-33W-35CCA	20	55	7.4	15	2.7	.4	205	12	3.6	.6	6.7	<0.1	18	.4	1.7
Ford County															
27-26W-21DAA	28	79	11	19	4.0	0.3	221	39	35	0.4	20	<0.1	3.5	0.1	13
Grant County															
28-38W-8BBB	32	81	43	59	4.9	2.8	193	270	44	1.8	17	<0.1	55	8.8	39
Gray County															
26-28W-19ABD	20	55	8.8	21	3.3	.5	200	41	5.4	.6	6.2	<0.1	14	.4	2.8
Hamilton County															
26-42W-22CDB	14	68	16	22	4.0	1.1	174	117	12	.6	3.9	<0.1	34	.4	2.8
Haskell County															
28-33W-21BCC	20	45	8.8	19	2.9	.7	171	46	5.6	1.2	5.6	<0.1	27	2.4	1.0
Kearny County															
24-37W-4CDD	15	35	15	17	3.4	.8	171	46	5.6	1.2	5.6	<0.1	16	.2	1.4
Meade County															
30-29W-28BBB	19	42	9.0	18	3.2	.6	182	25	3.1	.6	12	<0.1	14	.4	3.3
33-29W-36AAB	27	66	21	317	4.4	1.4	226	108	445	1.0	5.0	<0.1	30	.3	1.7
Morton County															
31-40W-1DA	27	41	26	36	4.1	1.4	195	94	19	2.4	10	<0.1	22	3.4	4.8
Seward County															
31-32W-3DAD	21	64	20	34	4.2	1.2	234	82	26	1.0	19	<0.1	28	1.2	1.8
Stanton County															
27-41W-19BAD	18	63	18	27	4.3	1.2	176	125	12	.9	9.0	<0.1	15	1.3	1.1

Ni ppb	Zn ppb	Temp. °C	Total Solids 180°C ppm	Hardness as $CaCO_3$		Sp.Cond. µmho at 25°C	SAR	pH	Date Collected
				Total ppm	Non-Carbonate ppm				
6.4		17.0	1013	394	157	1440	3.73	7.5	7/28-31/75
13		15.0	3936	1710	1453	4800	5.26	7.3	7/28-31/75
8.9		16.5	253	168	0	464	.50	7.5	7/28-31/75
1.6		16.0	346	243	62	572	0.53	7.6	7/25-29/77
1.9		18.0	656	382	224	970	1.31	7.5	7/26-29/76
10		17.0	279	174	10	490	.69	7.6	7/28-31/75
5.1		17.0	381	237	94	504	.62	7.5	7/28-31/75
6.2		19.0	240	149	2	366	.68	7.8	7/26-29/76
9.2		18.0	375	150	10	357	.60	7.6	7/28-31/75
7.8		17.0	221	143	0	370	.66	7.7	7/26-29/76
14		16.0	1097	253	67	2150	8.68	7.6	7/26-29/76
1.4		18.0	340	210	50	550	1.07	7.8	7/26-29/76
7.8		18.0	376	242	51	604	.94	7.7	7/26-29/76
7.8		17.5	352	233	88	580	.77	7.7	7/26-29/76

Well Location	SiO_2 ppm	Ca ppm	Mg ppm	Na ppm	K ppm	Sr ppm	HCO_3 ppm	SO_4 ppm	Cl ppm	F ppm	NO_3 ppm	Total PO_4 ppm	Fe ppb	Mn ppb	Cu ppb
Stevens County															
31-35W-15BAA	25	57	29	49	5.4	1.7	236	149	16	1.3	6.4	<0.1	17	.4	.8
34-38W-2CDB	27	78	23	34	3.7	1.1	170	186	18	.5	11	<0.1	18	3.4	3.6

Ni ppb	Zn ppb	Temp. °C	Total Solids 180°C ppm	Hardness as $CaCO_3$ Total ppm	Hardness as $CaCO_3$ Non-Carbonate ppm	Sp.Cond. µmho at 25°C	SAR	pH	Date Collected
1.1		19.0	454	263	70	670	1.31	7.6	7/26-29/76
.15		20.0	462	291	151	650	.87	7.6	7/26-29/76

Table 6. Specific capacity, transmissivity, hydraulic conductivity and storage coefficient values for wells in western Kansas.

Well Number[1]	Aquifer[2]	Specific Capacity	Transmissivity T	Hydraulic Conductivity K	Storage Coefficient S	Reference[3]
FINNEY COUNTY						
23-34W-36CD	Qal+Qu		64,000	400		KGS Bull. 55
24-31W-27ABC	To+Qu		27,000	235		KGS Bull. 55
24-31W-27BBC	To+Qu		47,500	395		KGS Bull. 55
26-27W-17BD	Qal+Qu		154,185	1,040		KGS Bull. 55
26-28W-10BB	Qal		38,200	1,030		KGS Bull. 55
21-32W-8AB	Qu		84,000	1,300	0.0014	USGS WSP 1891
21-33W-2AC	Qu		62,000	1,500	0.00063	USGS WSP 1891
22-31W-32DB	Qu+To		67,000	1,100	0.048	USGS WSP 1891
24-32W-16AB	Qu+To		72,000	620	0.0017	USGS WSP 1891
24-32W-25BDA	To		29,000	320	0.00062	USGS WSP 1891
24-33W-7BA	Qu+To		40,000	710	0.00057	USGS WSP 1891
24-34W-1DDB	Qu		140,000	2,600	0.14	USGS WSP 1891
26-32W-31CC	Qu+To		90,000	650	0.22	USGS WSP 1891
26-33W-12CA	Qu+To		140,000	920	0.0012	USGS WSP 1891
26-32W-31DDD	QTo		12,000	87	0.22	USGS HA 515
GRANT COUNTY						
27-36W-15DD	Qu+To		153,000		0.00014	KGS Bull. 168
27-37W-29CC	Qu+To		52,000		0.00012	KGS Bull. 168
27-38W-15DA	Qu+To		63,400		0.00023	KGS Bull. 168
27-38W-19CD	Qu+To		590,000		0.0048	KGS Bull. 168
27-38W-22CD	Qu+To		159,000		0.00035	KGS Bull. 168
27-38W-23CA	Qu+To		71,000		0.0021	KGS Bull. 168
27-38W-32BB	Qu+To		188,000		0.0024	KGS Bull. 168
28-36W-11BA	Qu+To		215,000		0.00022	KGS Bull. 168
28-38W-12CB	Qu+To		50,600		0.00028	KGS Bull. 168
28-38W-15CB	Qu+To		119,000		0.00060	KGS Bull. 168
28-38W-27BA	Qu+To		125,000		0.00021	KGS Bull. 168

Well Number[1]	Aquifer[2]	Specific Capacity	Transmissivity T	Hydraulic Conductivity K	Storage Coefficient S	Reference[3]
GRANT COUNTY (cont'd)						
29-35W-15AB	Qu		134,000		0.00038	KGS Bull. 168
29-38W-35DB	Qu+To		45,000		0.00094	KGS Bull. 168
30-37W-2BA	Qu+To		29,000		0.00014	KGS Bull. 168
30-37W-19AA	Qu		56,000		0.00029	KGS Bull. 168
30-37W-26DA	Qu+To		145,000		0.0032	KGS Bull. 168
30-38W-30AC	Qu+To		337,000		0.00044	KGS Bull. 168
GRAY COUNTY						
24-29W-14BA	Qu		8,200	68		USGS HA 517
24-30W-32AC	Qu		3,900	39		USGS HA 517
25-29W-28DB	Qu		1,600	29	0.0003	USGS HA 517
25-30-21DB	Qu		1,600	26	0.0002	USGS HA 517
25-30W-22CA	Qal		13,000	580	0.13	USGS HA 517
25-30W-25AD	Qal		24,000	670	0.17	USGS HA 517
HAMILTON COUNTY						
24-41W-2CC	Qal	45.8	11,300	1,855		KGS Bull. 49
24-41W-3BB	Qal	65.2	546,800	9,113		KGS Bull. 49
24-39W-35BCC	Qu		22,000		0.14	USGS HA 516
24-40-17D	Qu		36,000		0.09	USGS HA 516
26-42W-22DC	Qu		7,500		0.0002	USGS HA 516
HASKELL COUNTY						
27-38W-32CB	Qu+To	48.7	53,954	218		KGS Bull. 61
28-38W-4BB	Qu+To	25.4	23,600	96		KGS Bull. 61
29-38W-35CA	Qu+To	20.0	4,485	13		KGS Bull. 61
30-37W-20BC	Qu or To	29.0	43,573	148		KGS Bull. 61
31-37W-4CB	Qu+To	86.6	147,028	498		KGS Bull. 61
31-37W-10CA	Qu+To	92.5	88,412	305		KGS Bull. 61
33-37W-21BC	Qu+To	6.7	3,853	8		KGS Bull. 61

Well Number[1]	Aquifer[2]	Specific Capacity	Transmissivity T	Hydraulic Conductivity K	Storage Coefficient S	Reference[3]
HASKELL COUNTY (Cont'd)						
27-34W-16DDD	QTu		26,000	180	0.18	USGS HA 515
27-34W-28AAD	QTu		9,000	70	0.01	USGS HA 515
28-31W-2BBC	QTu		35,000	220	0.20	USGS HA 515
28-32W-18BBB	QTu		40,000	200	0.15	USGS HA 515
KEARNY COUNTY						
23-35W-26BB	To+Qu	24.9	79,000	247		KGS Bull. 49
24-35W-23DC	Qal+Qu	55.6	187,000	552		KGS Bull. 49
23-37W-36AAB	QTu		25,000	300	0.11	USGS HA 416
25-36W-18CCA	QTu		196,000	1,440	0.06	USGS HA 416
26-37W-21DDD	QTu		47,000	260	0.0006	USGS HA 416
LOGAN COUNTY						
11-32W-3BD	To	33	49,500	350		KGS Bull. 129
11-33W-14BC	To	11	43,500	520		KGS Bull. 129
11-34W-24CA	To	5	19,500	230		KGS Bull. 129
11-35W-5BB	To	22	47,000	1,150		KGS Bull. 129
SCOTT COUNTY						
17-32W-5AB	To	19.3				KGS Bull. 126
17-33W-28CD	To	21.3				KGS Bull. 126
17-34W-2DC	To	38.8	40,000	440		KGS Bull. 126
18-32W-7AC	To+Qu	49.4	130,000	800		KGS Bull. 126
STANTON COUNTY						
27-40W-25CB	Qu+To		137,000		0.0048	KGS Bull. 168
28-39W-12AC	Qu		40,500		0.00011	KGS Bull. 168
28-39W-20BD	Qu+To		188,000		0.00095	KGS Bull. 168
28-39W-24CC	Qu+To		465,000		0.0094	KGS Bull. 168
28-41W-14AA	Qu+To		352,000		0.059	KGS Bull. 168
29-39W-24DD	Qu+To		58,000		0.0011	KGS Bull. 168
30-40W-24CD	Qu+To+Kd		97,500		0.0013	KGS Bull. 168
30-41W-13CC	To+Kd		137,000		0.044	KGS Bull. 168

Well Number[1]	Aquifer[2]	Specific Capacity	Transmissivity T	Hydraulic Conductivity K	Storage Coefficient S	Reference[3]
SHERMAN COUNTY						
7-39W-20BAD	To	73	396,000	3,300		KGS Bull. 105
8-39W-15CCC	To	20	34,000	266		KGS Bull. 105
8-40-12DBA	To	35	36,000	309		KGS Bull. 105
WICHITA COUNTY						
16-35W-20CCC	To	45	96,000	1,260		KGS Bull. 108
18-35W-34ABB	To	95	365,000	6,800		KGS Bull. 108
18-35W-36BCB	To	85	270,000	5,400		KGS Bull. 108
18-38W-31DBC	To	33	126,000	3,300		KGS Bull. 108
16-35W-31DA	To	22.5	15,000	150		KGS Bull. 126

[1] The well number is derived from the legal location as described in Figure .

[2] Qal, Pleistocene alluvium; Qu, Pleistocene deposits, undifferentiated; To, Ogallala Formation; QTu, Undifferentiated Ogallala aquifer; Kd, Dakota Formation.

[3] KGS, Kansas Geological Survey; USGS, U.S. Geological Survey; WSP, Water Supply Paper; HA, Hydrologic Investigations Atlas.

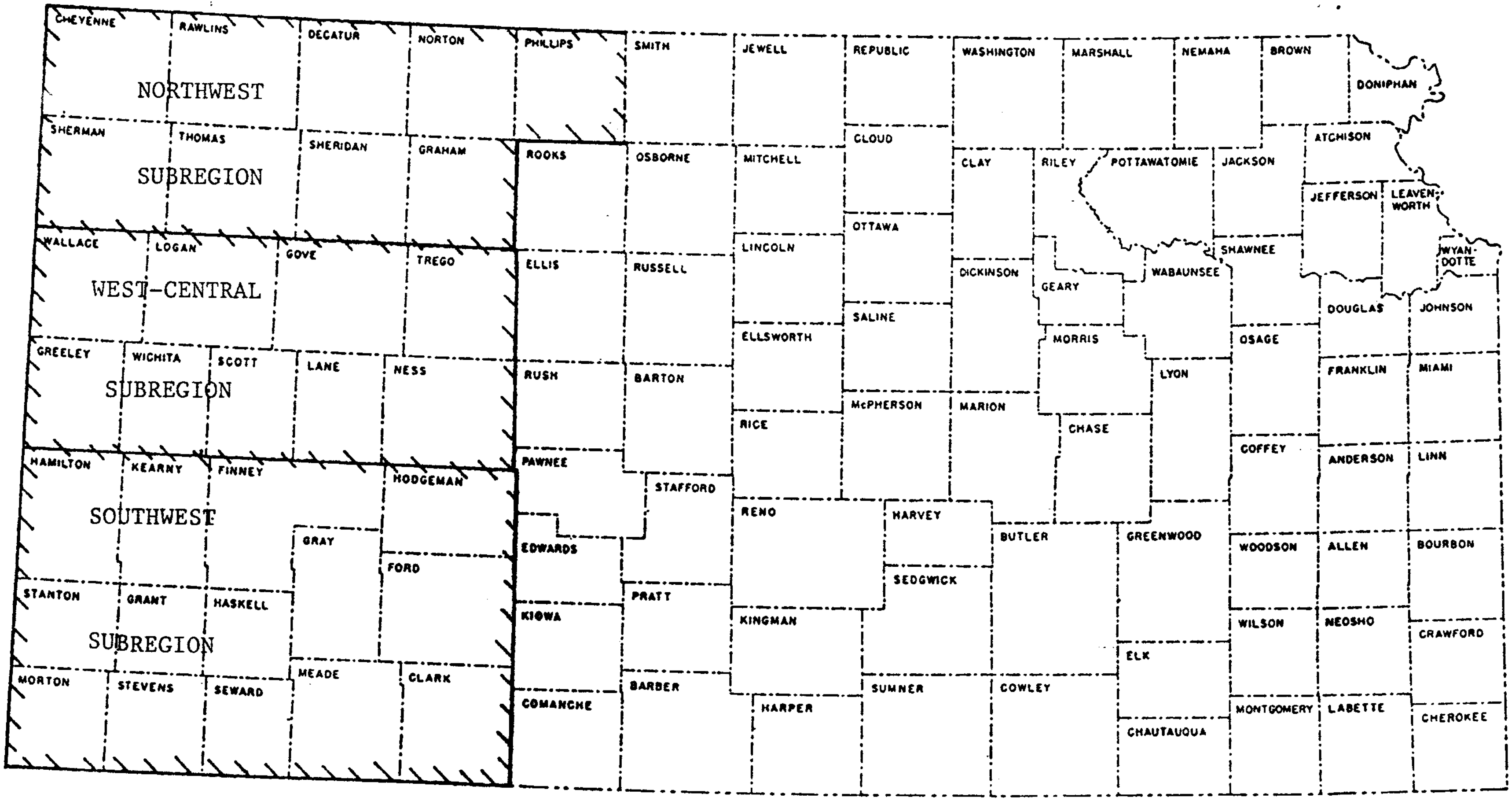


Figure 1. Map of Kansas showing the location of the High Plains Ogallala aquifer study area and the Northwest, West-Central, and Southwest subregions.

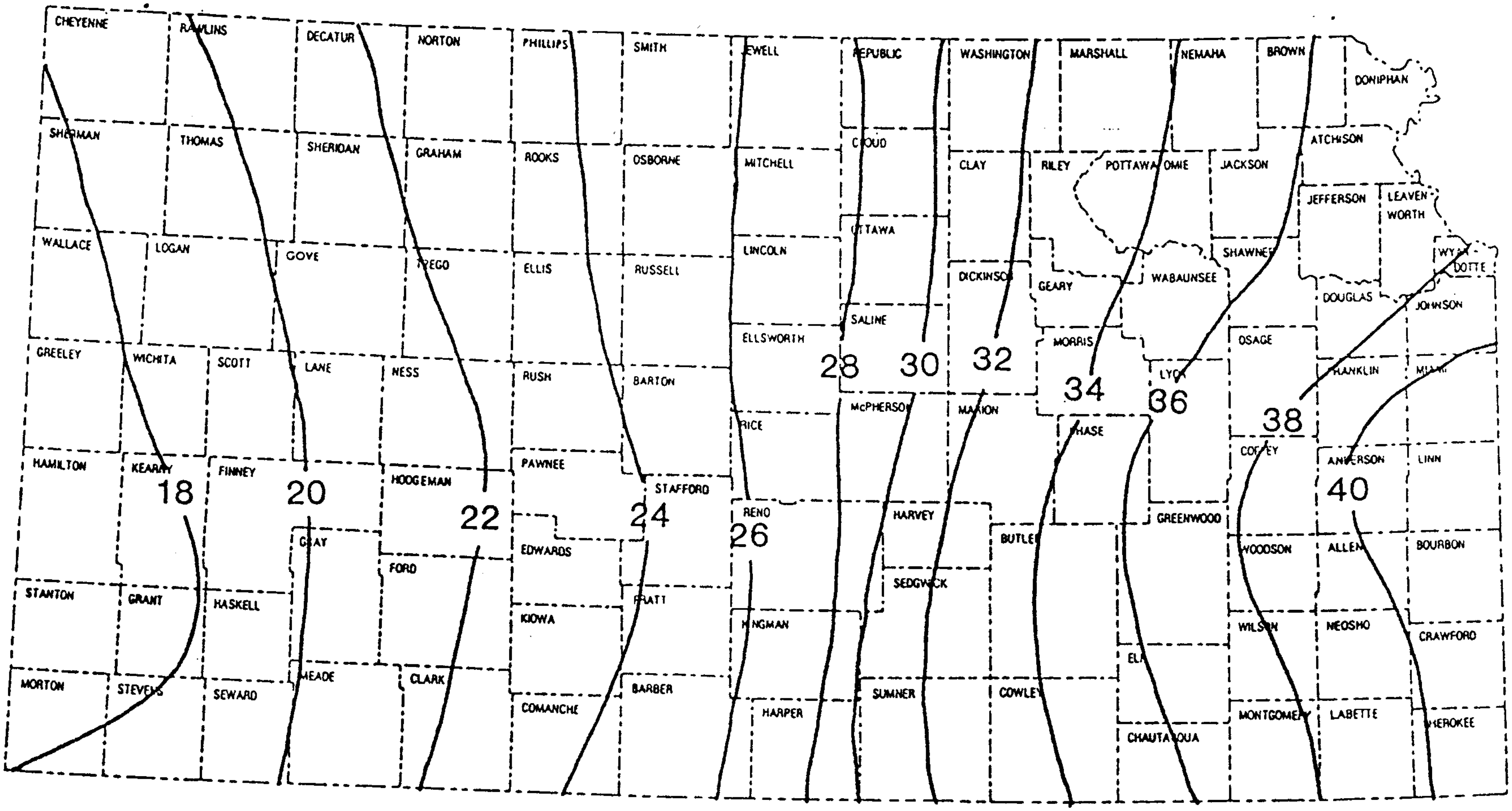


Figure 2. Mean annual precipitation, in inches, 1941-70 (Data from the Kansas Agricultural Experiment Station) (adapted from U.S. Geological Survey, 1978a).

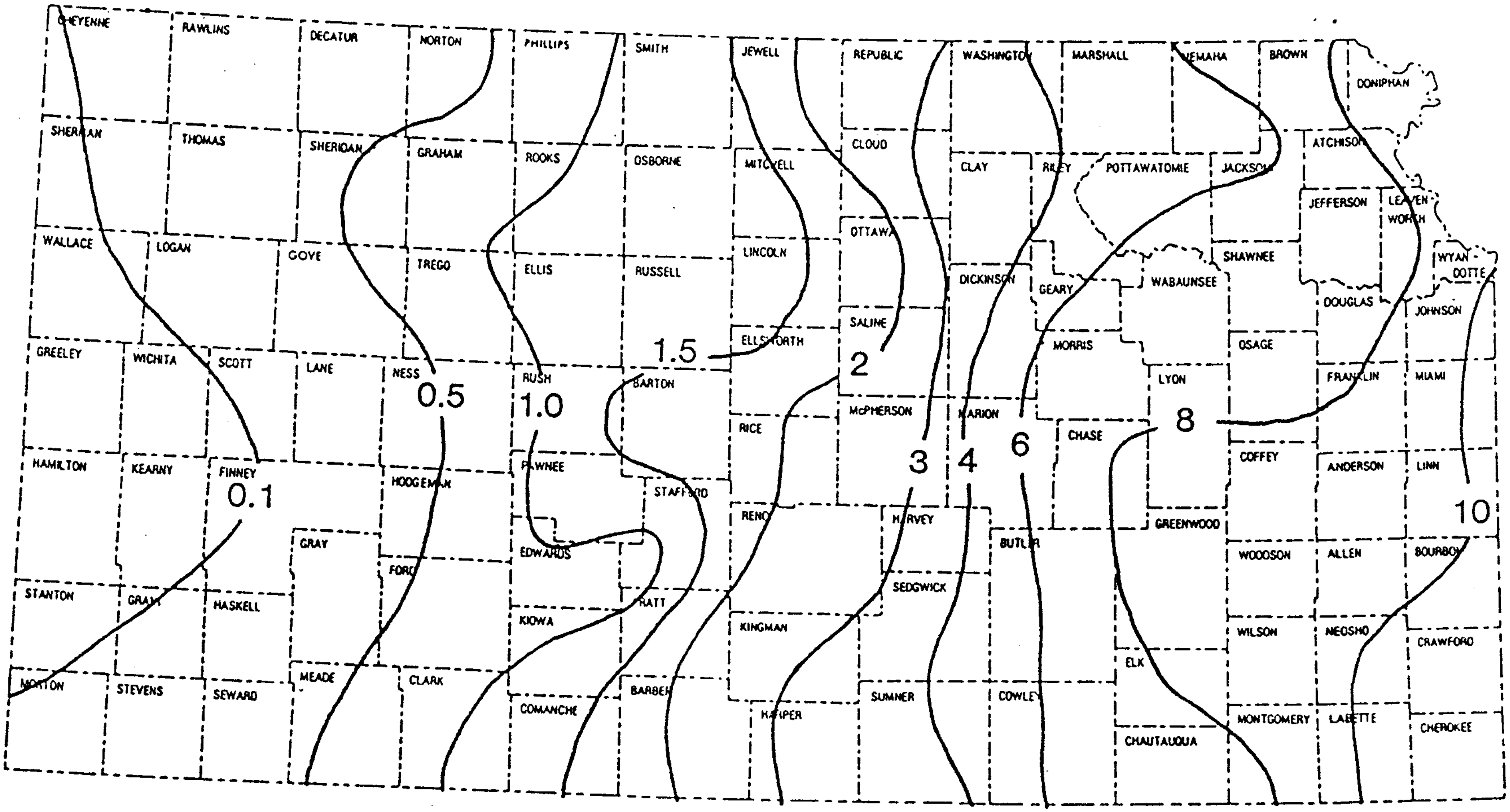


Figure 3. Mean annual runoff, in inches (U.S. Geological Survey, 1978a).

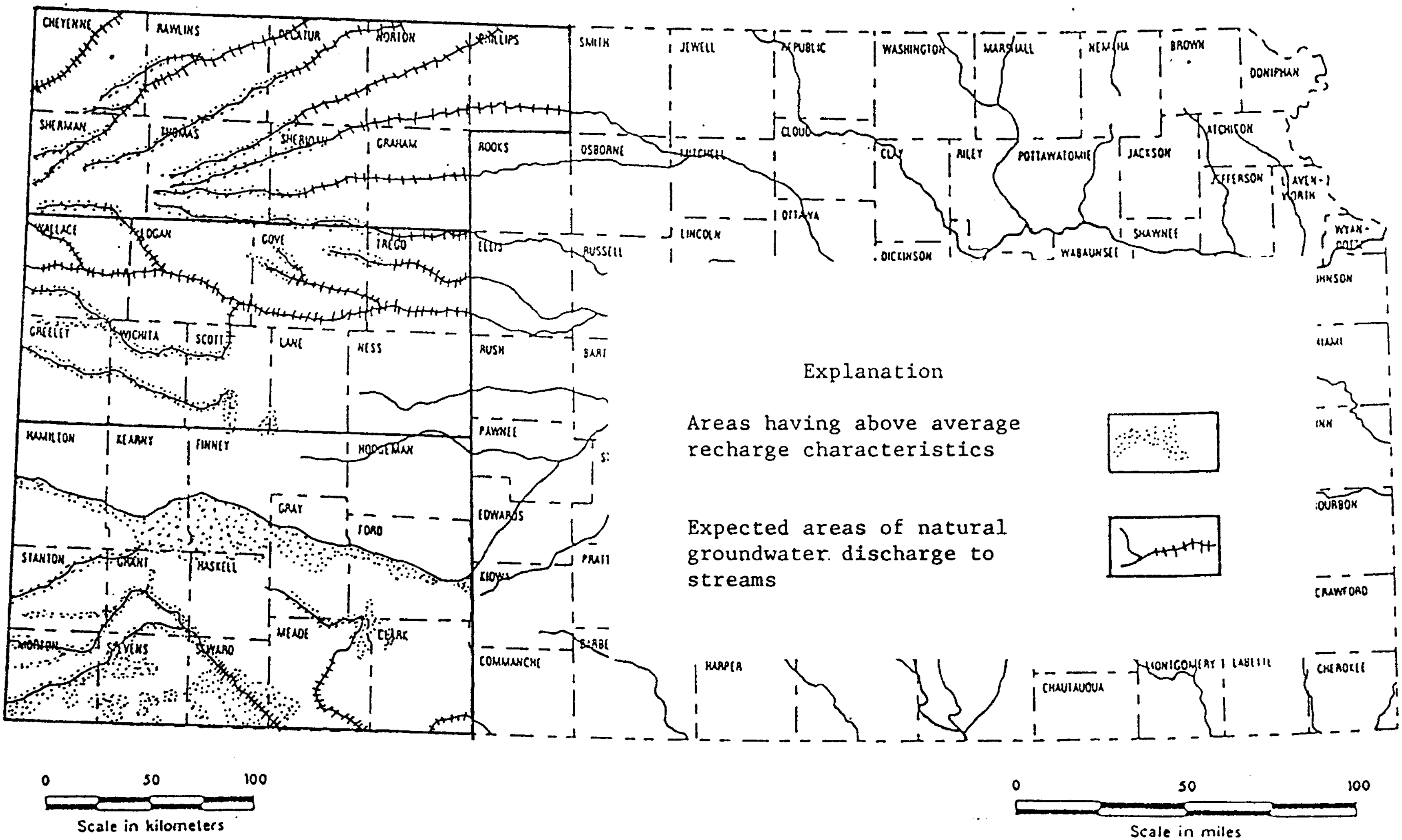
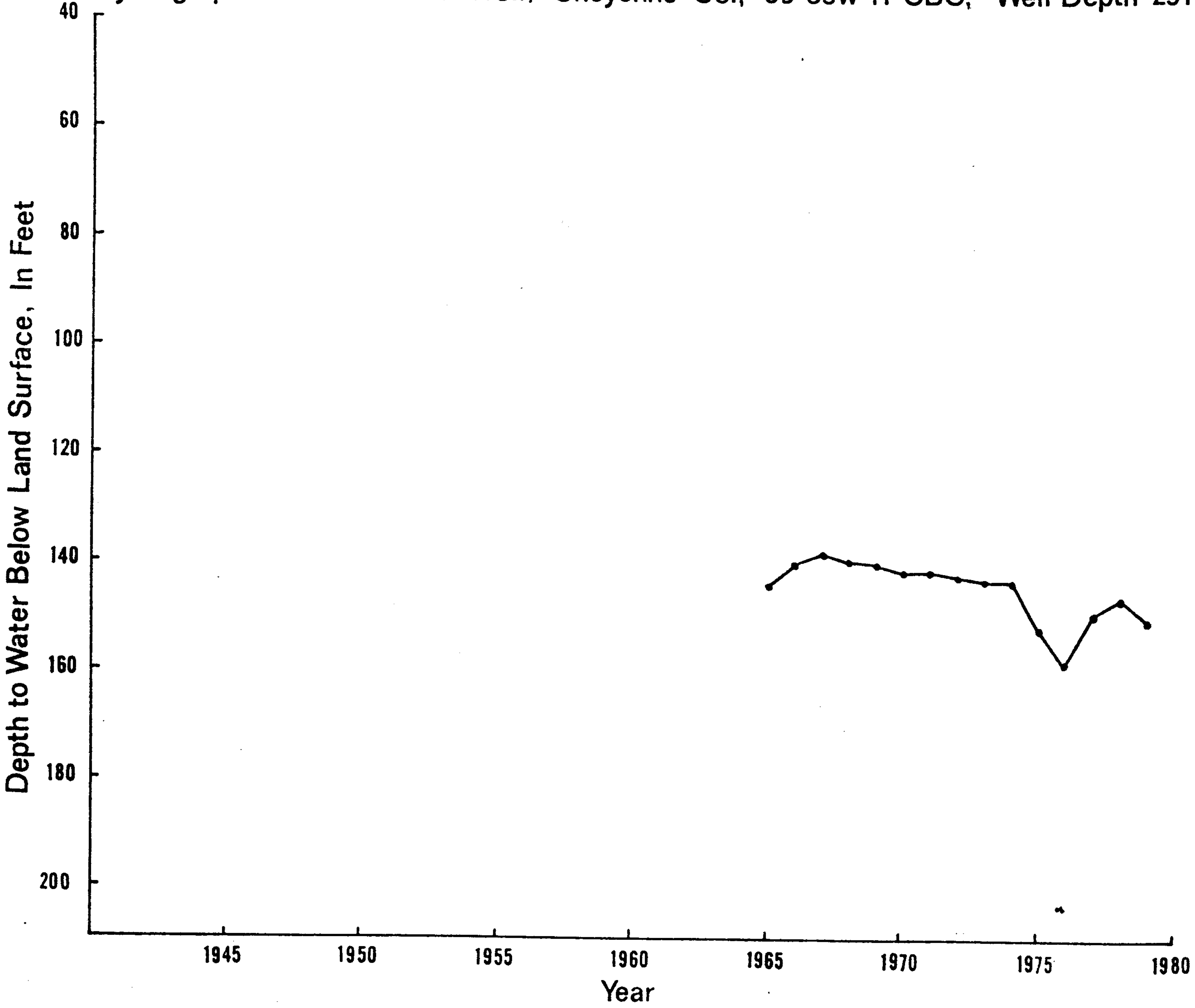
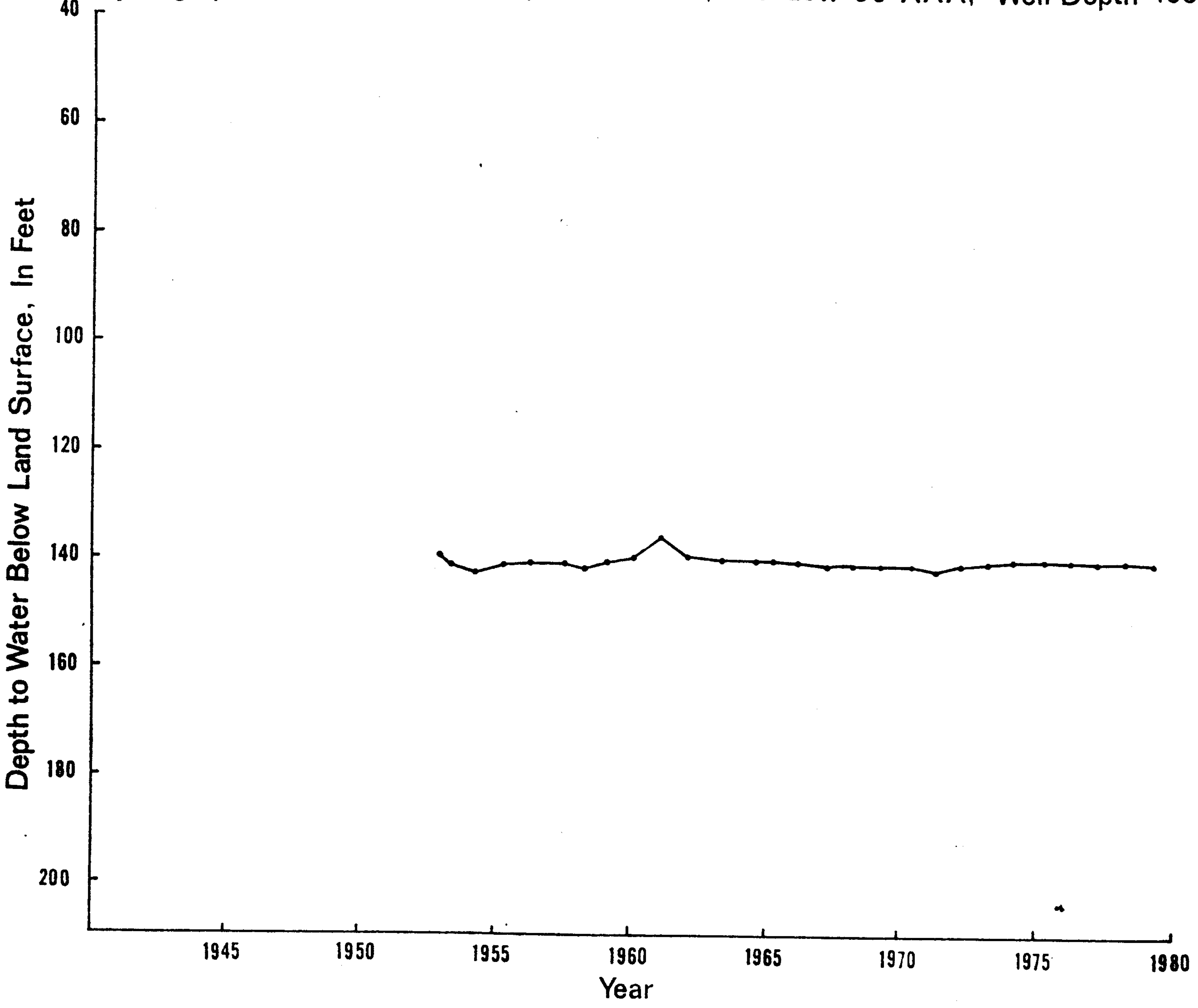


Figure 4. Map showing location of 1) areas having above average recharge characteristics and 2) expected areas of natural groundwater discharge to streams.

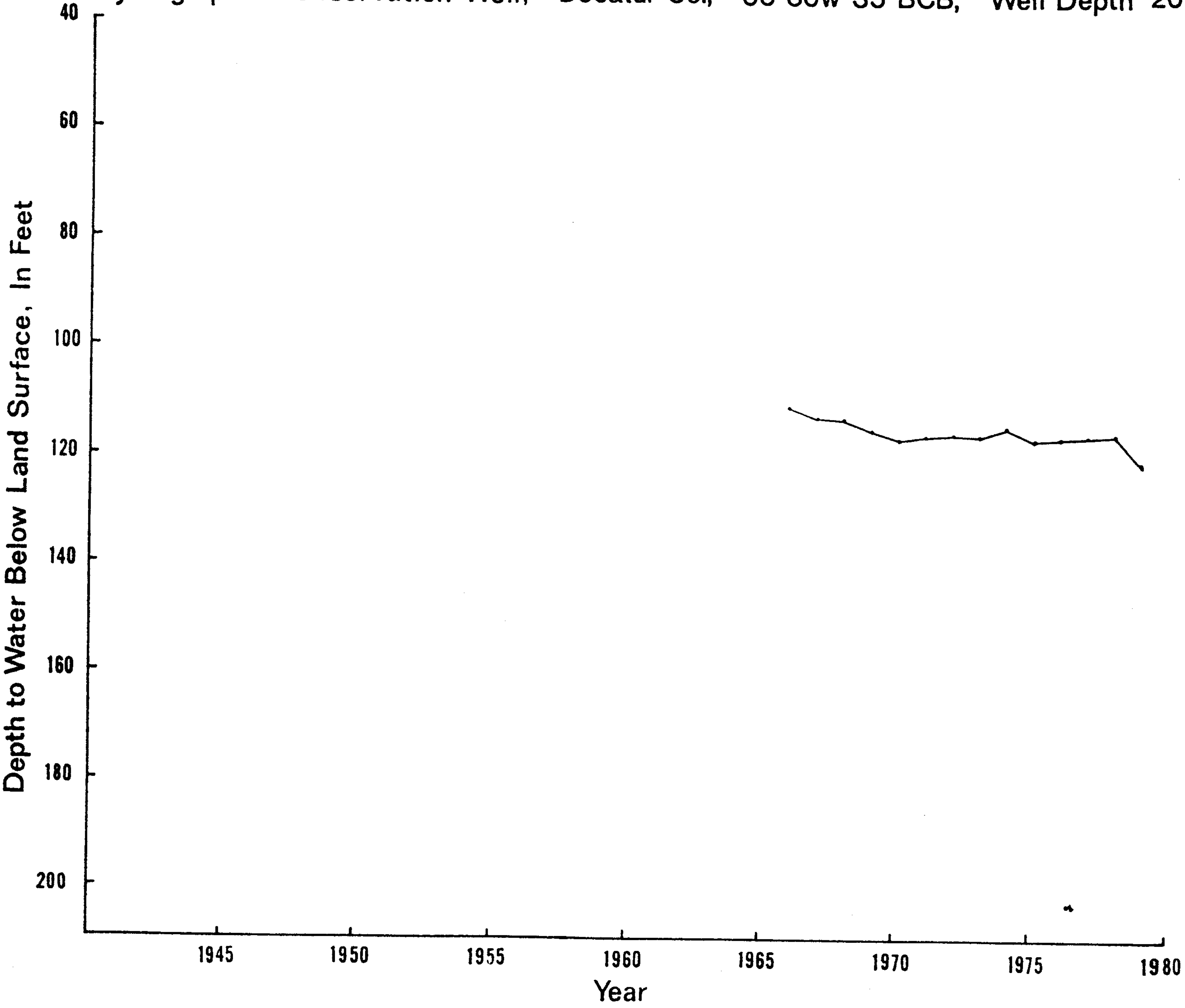
Hydrograph of Observation Well, Cheyenne Co., 05 39w 11 CBC, Well Depth 291′



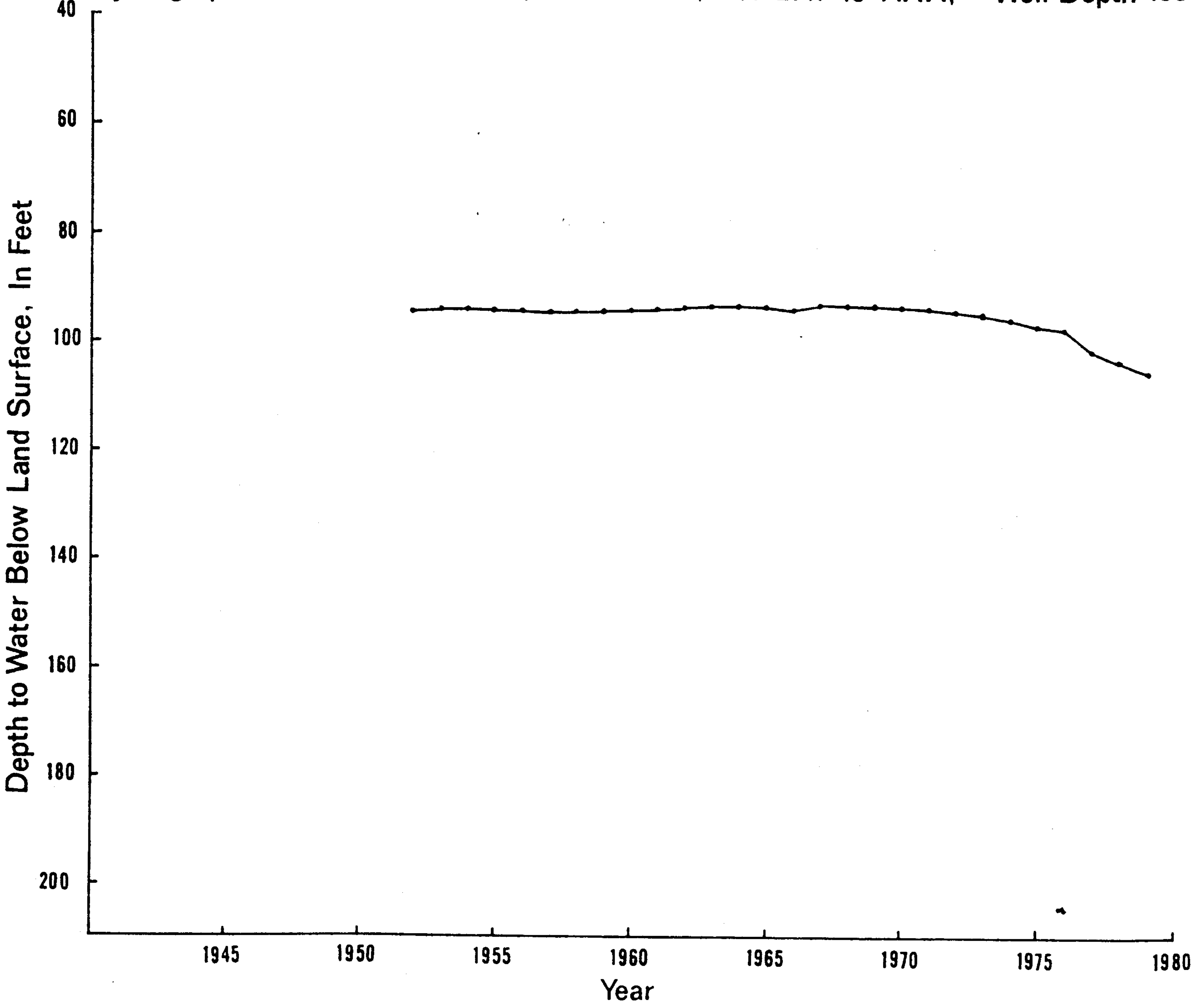
Hydrograph of Observation Well, Clark Co., 30 23w 06 AAA, Well Depth 160′



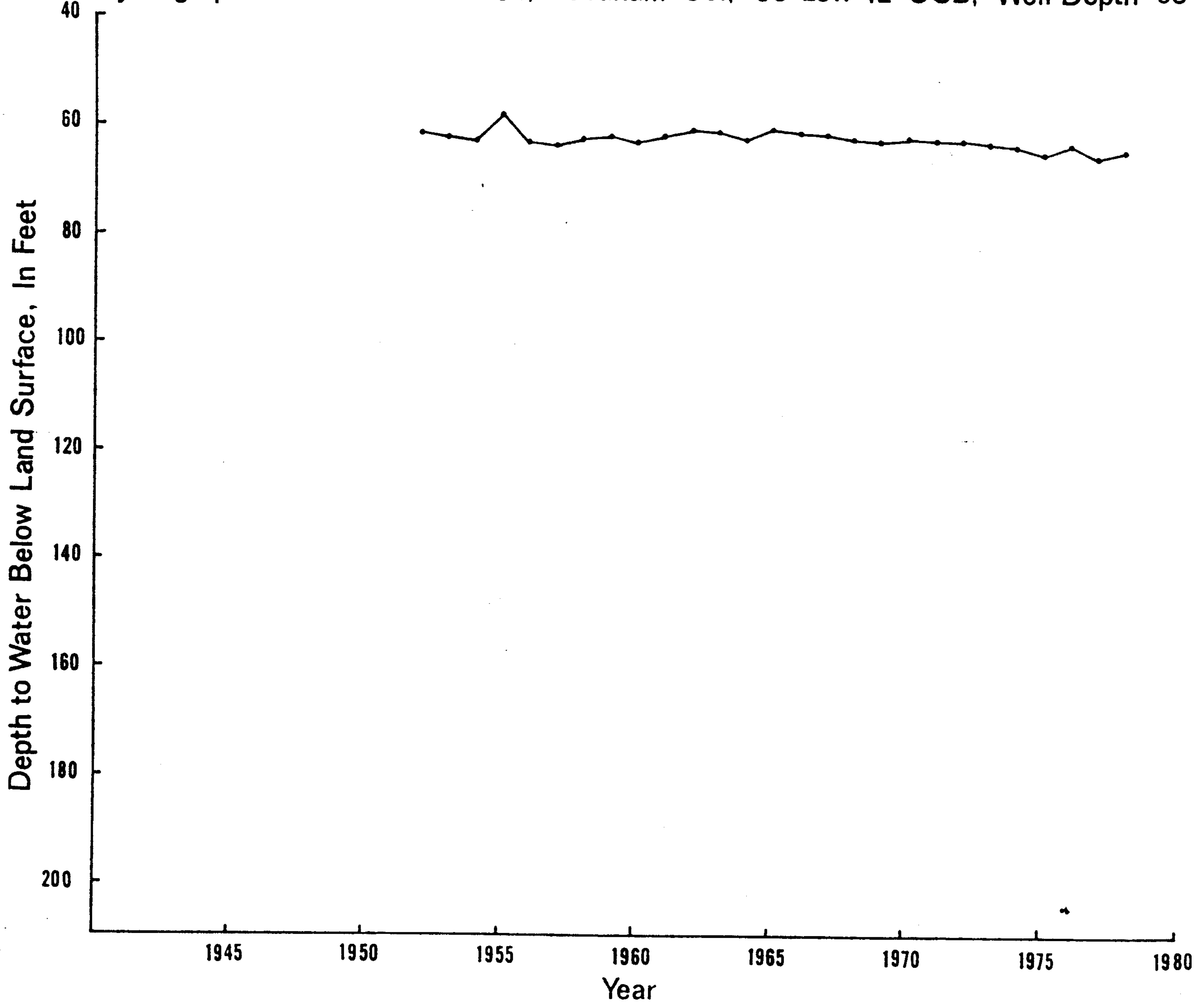
Hydrograph of Observation Well, Decatur Co., 05 30w 35 BCB, Well Depth 201′



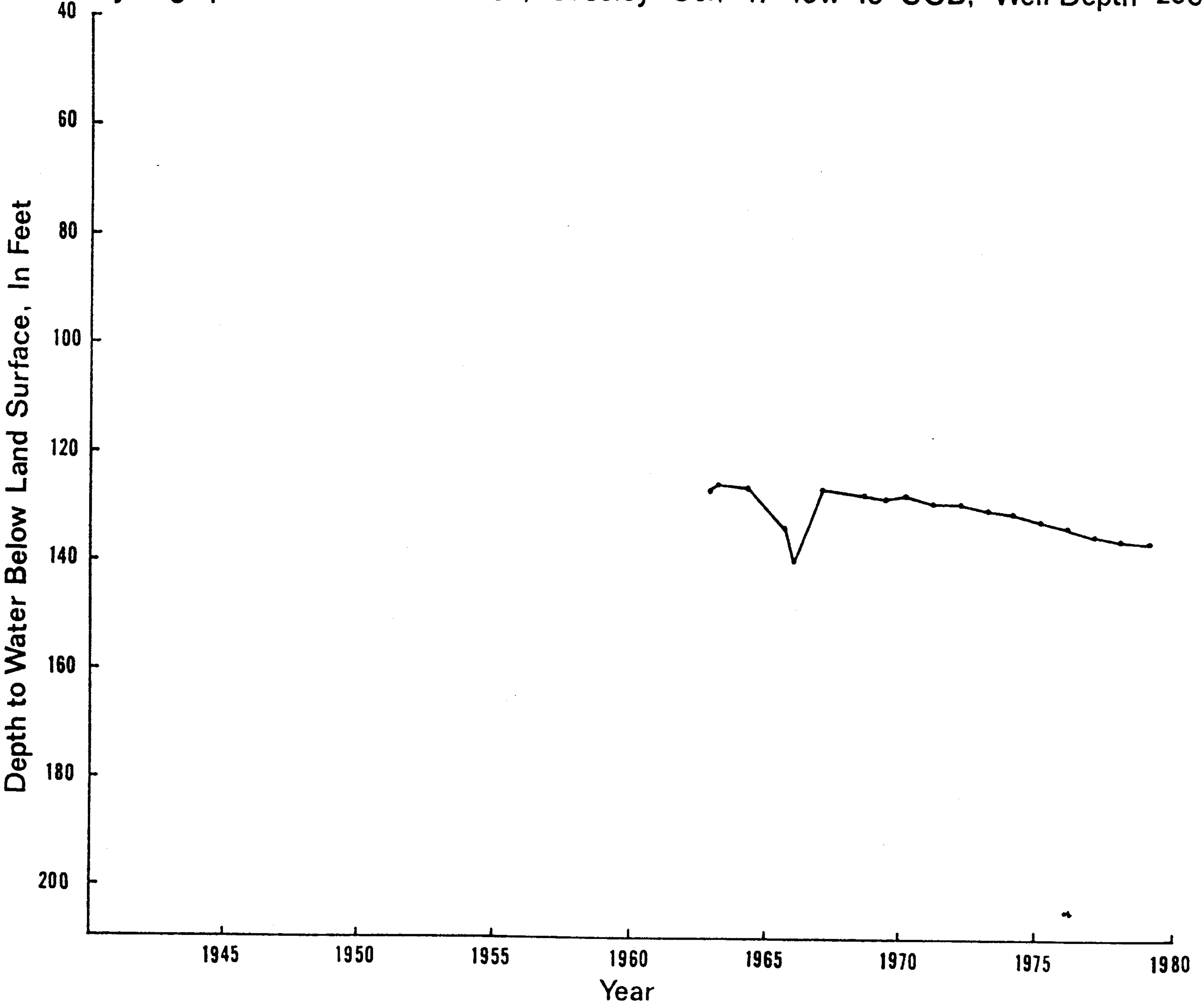
Hydrograph of Observation Well, Gove Co., 11 27w 16 AAA, Well Depth 108'



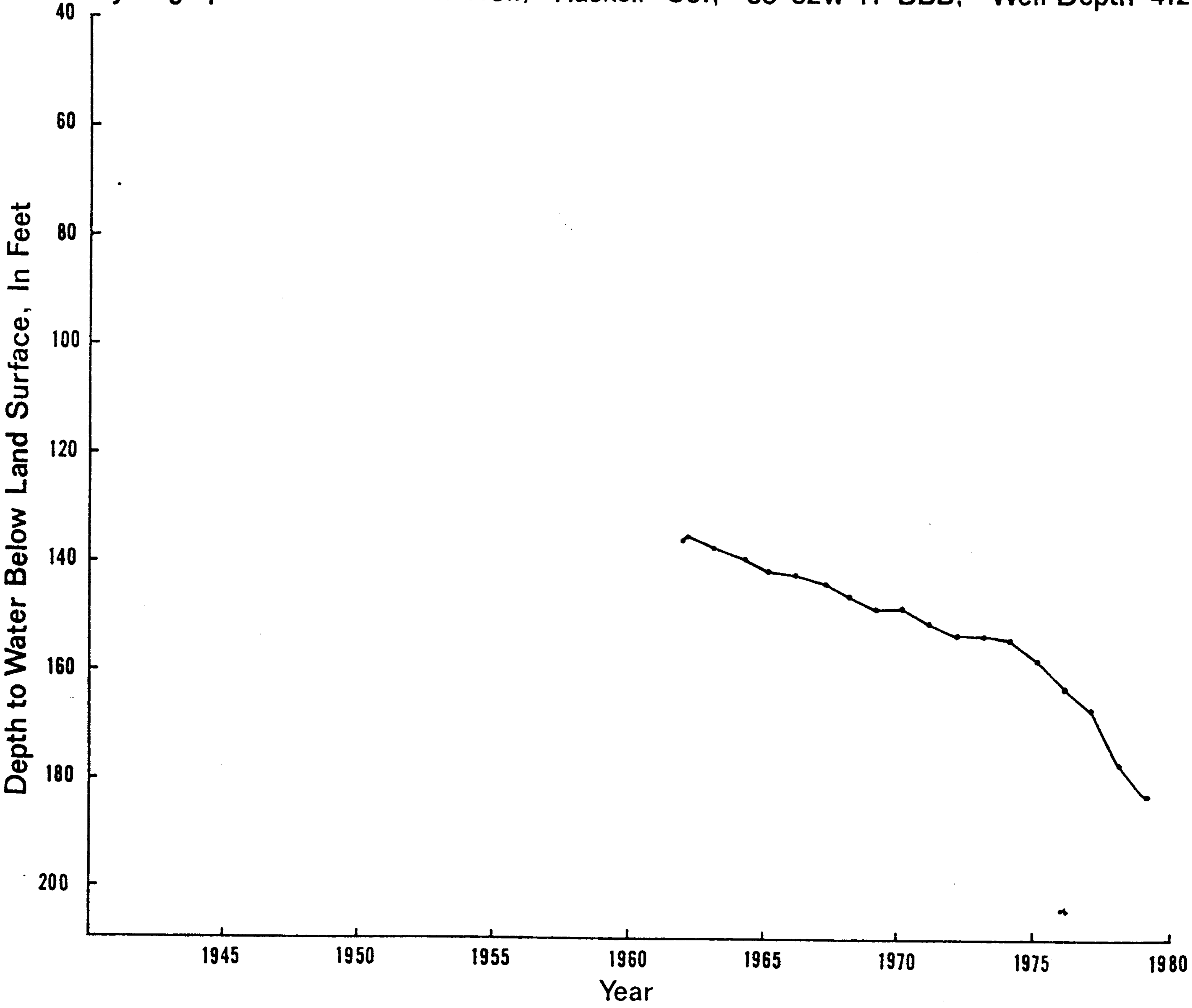
Hydrograph of Observation Well, Graham Co., 06 23w 12 CCB, Well Depth 65′

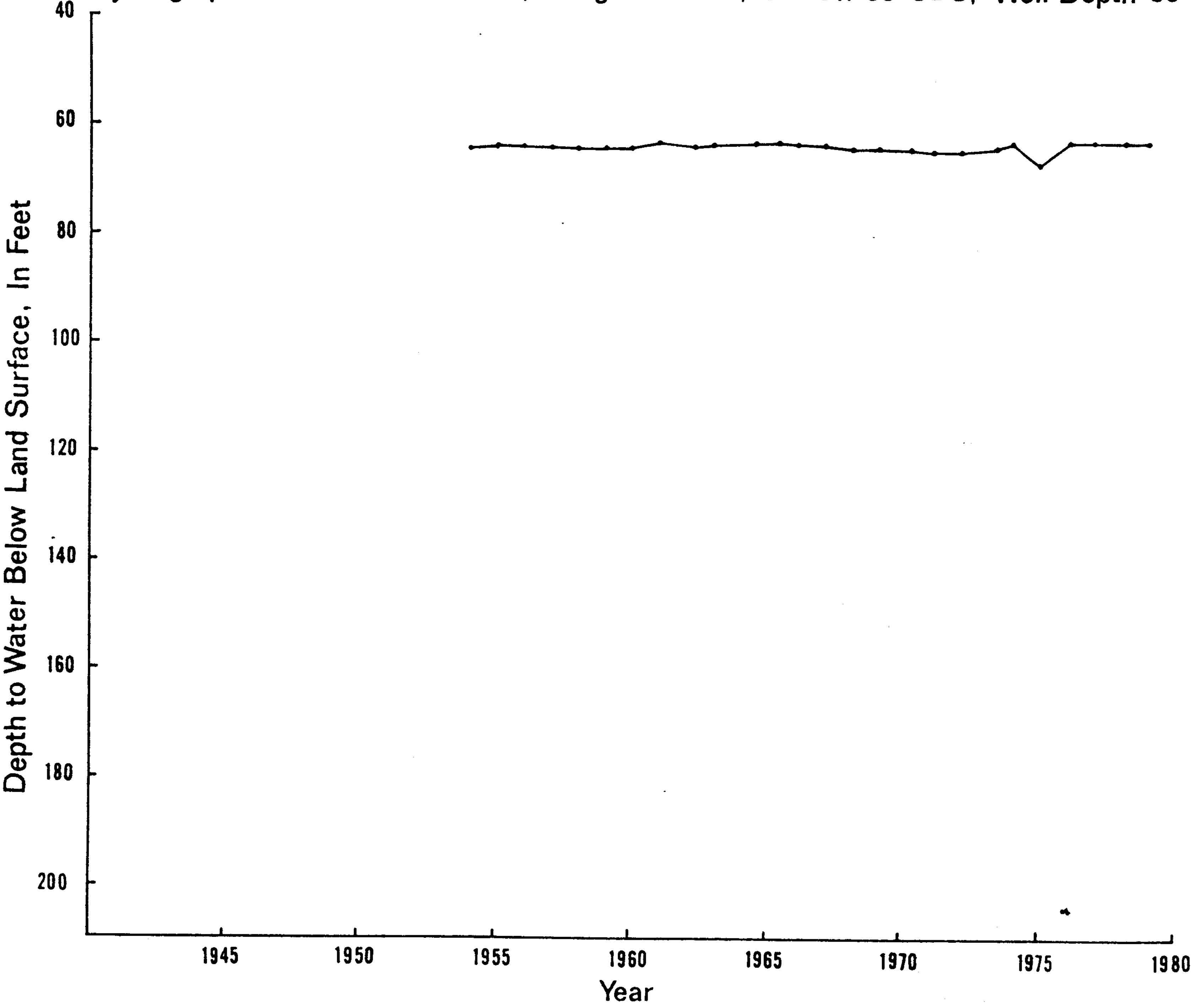


Hydrograph of Observation Well, Greeley Co., 17 40w 15 CCB, Well Depth 209′



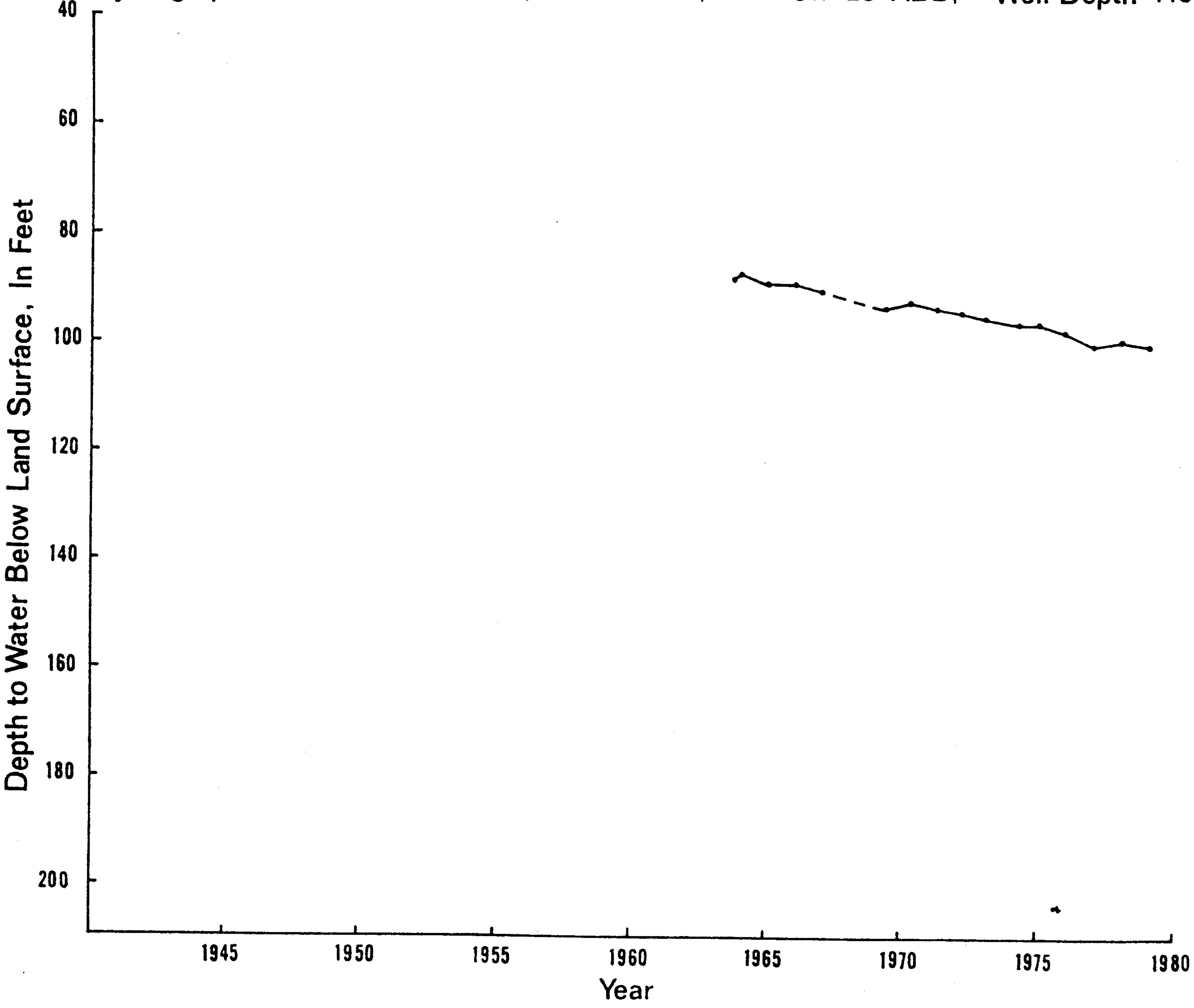
Hydrograph of Observation Well, Haskell Co., 30 32w 11 BBB, Well Depth 412'



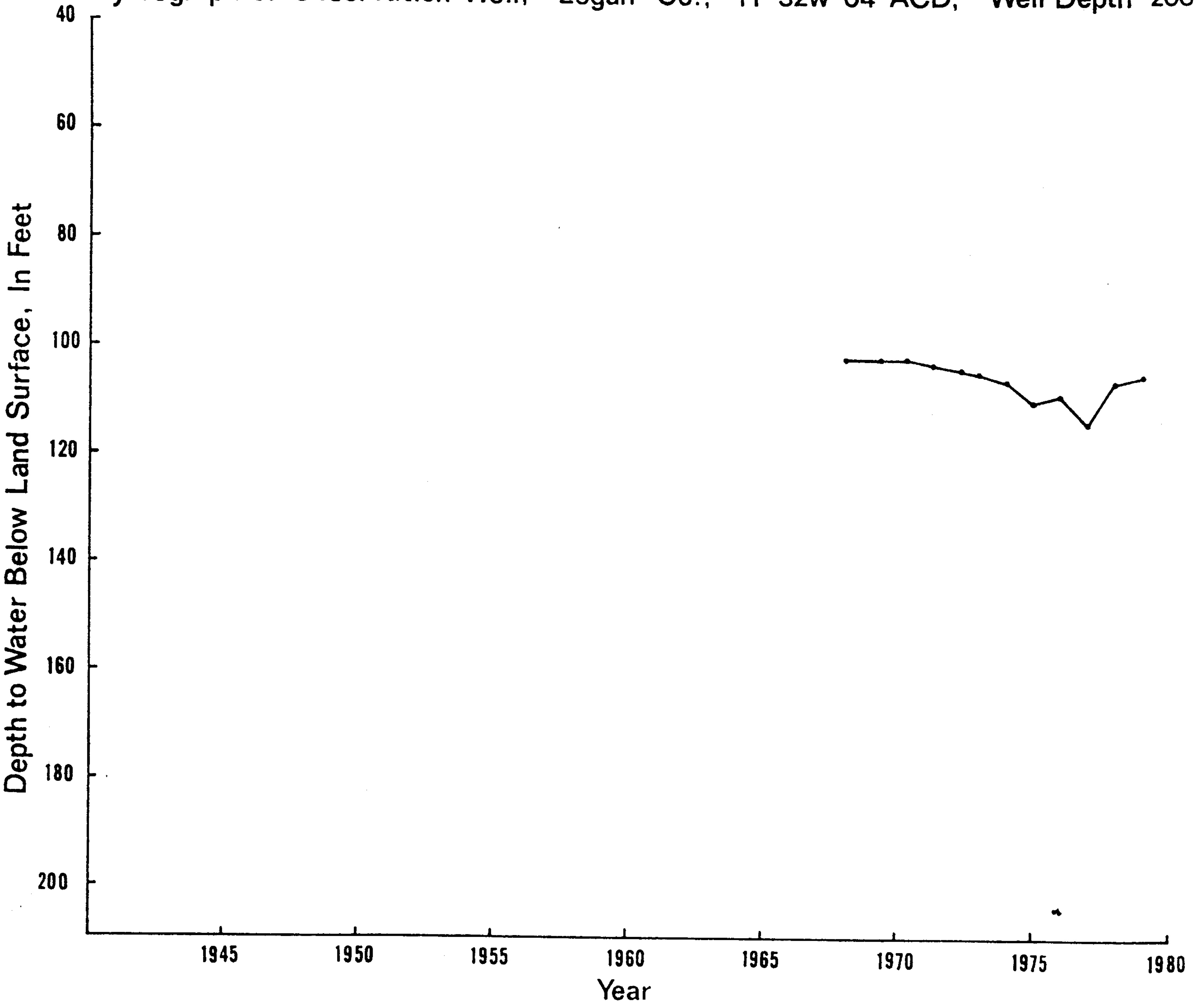


Hydrograph of Observation Well, Hodgeman Co., 24 26w 35 CBC, Well Depth 86′

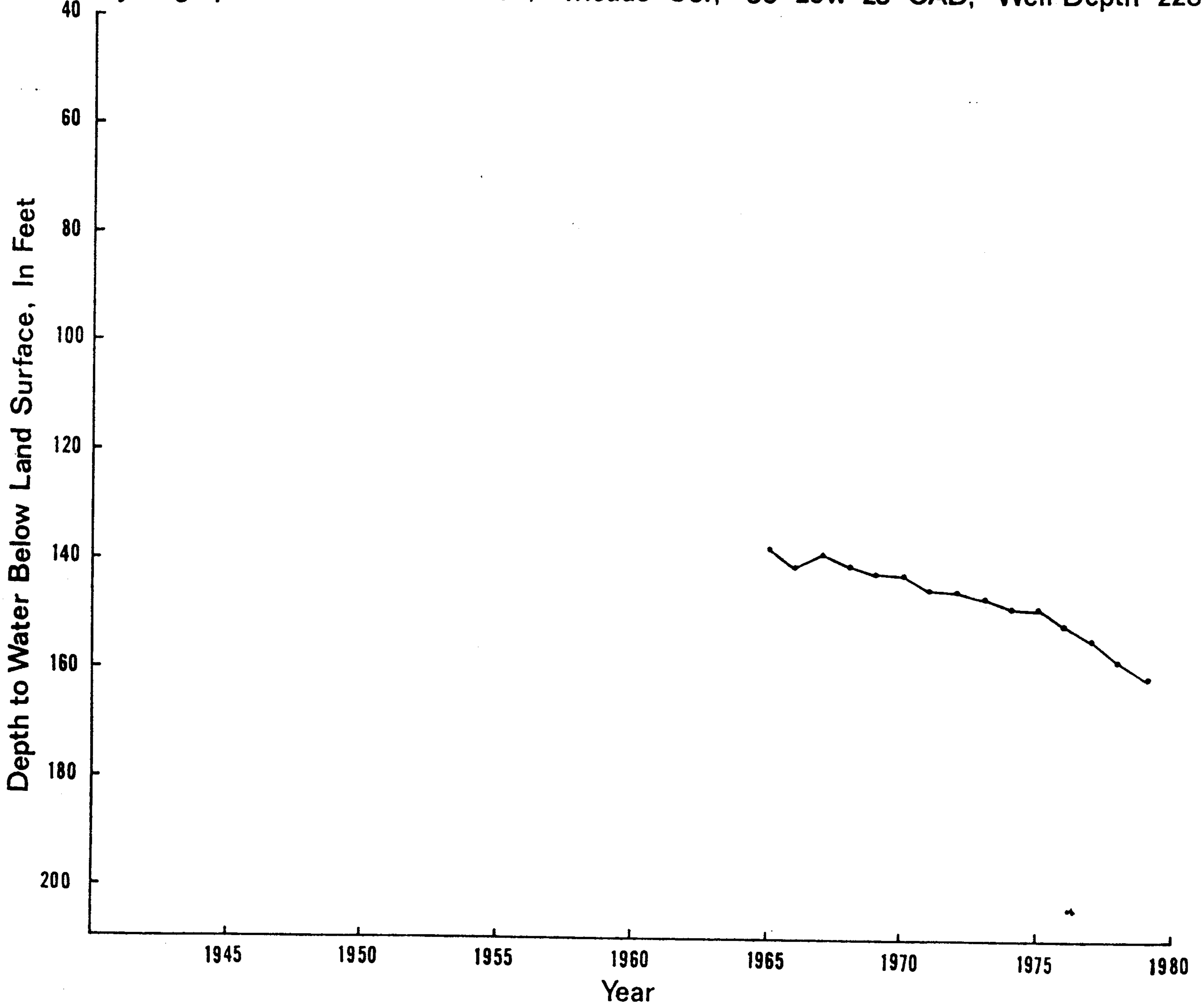
Hydrograph of Observation Well, Lane Co., 17 28w 26 ABB, Well Depth 140′



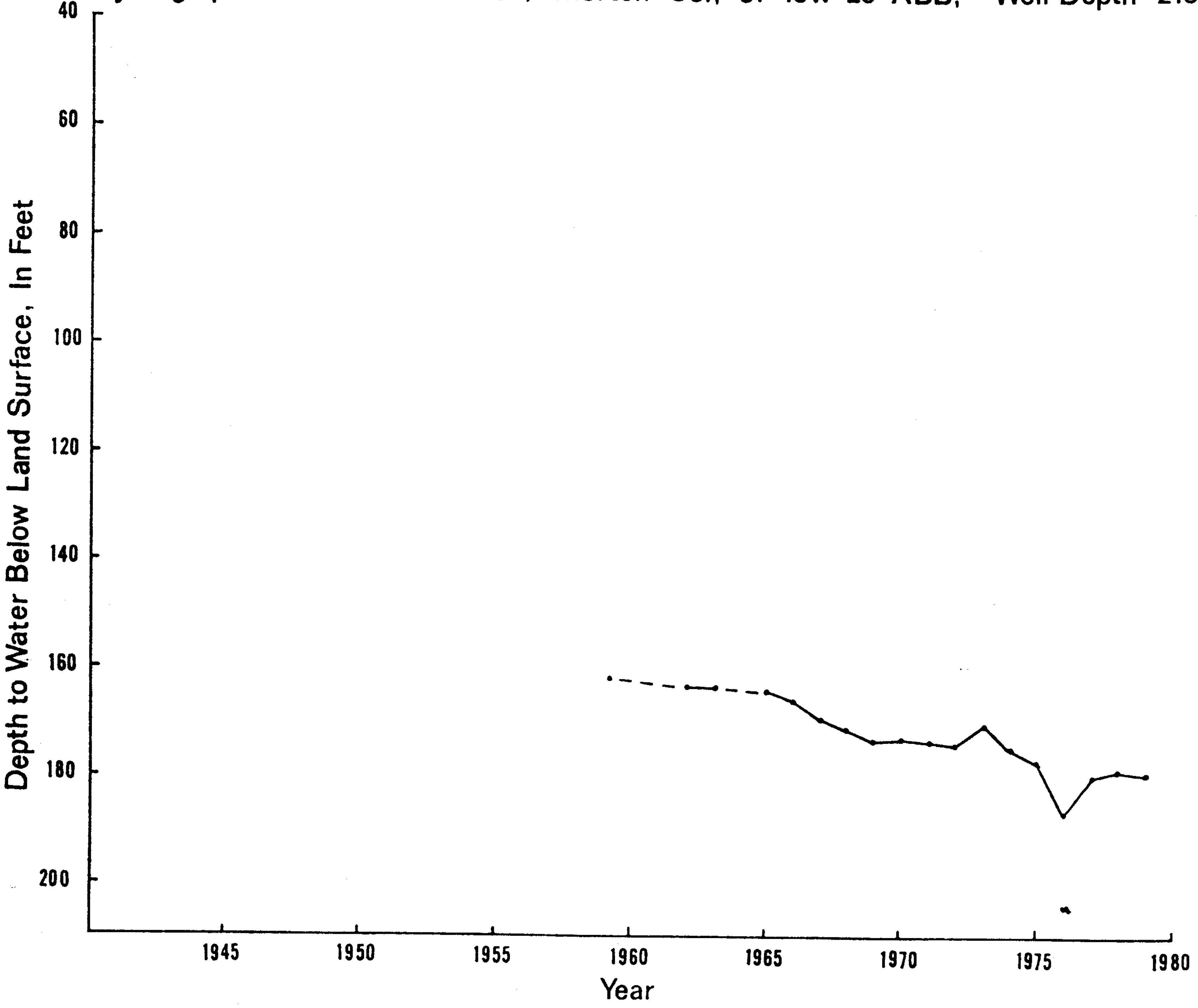
Hydrograph of Observation Well, Logan Co., 11 32w 04 ACD, Well Depth 208′



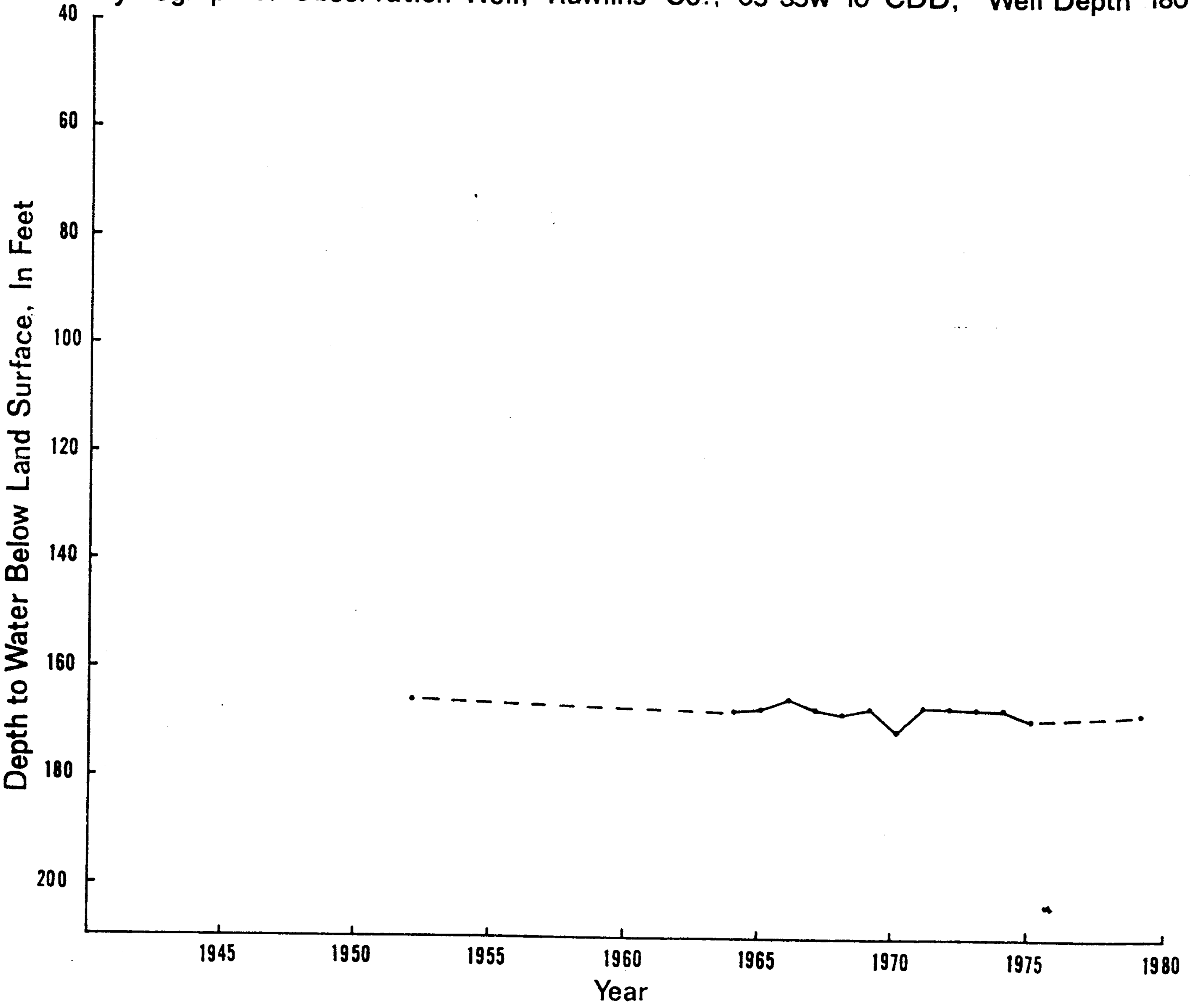
Hydrograph of Observation Well, Meade Co., 30 29w 23 CAD, Well Depth 228′

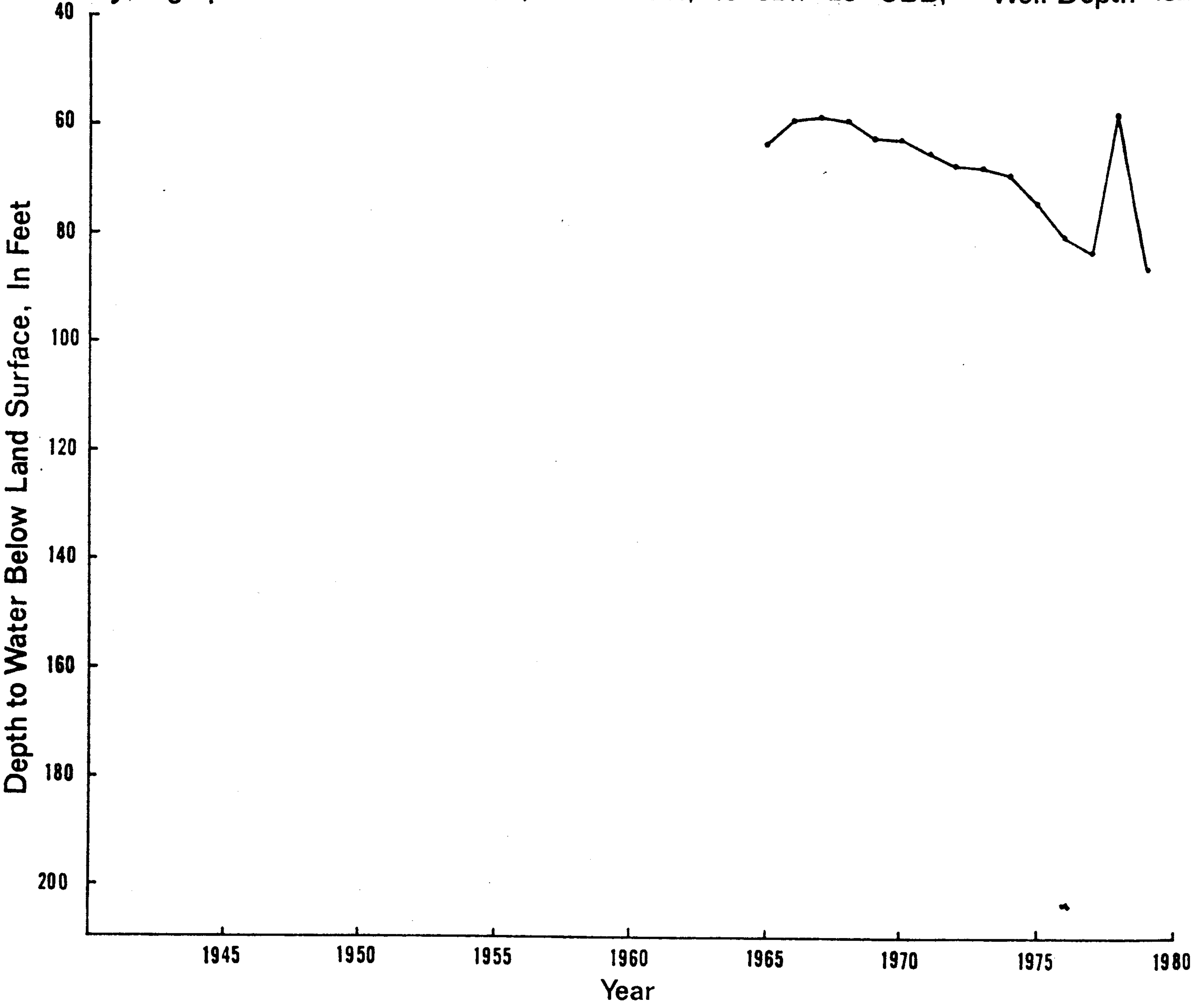


Hydrograph of Observation Well, Morton Co., 31 40w 29 ABB, Well Depth 215'



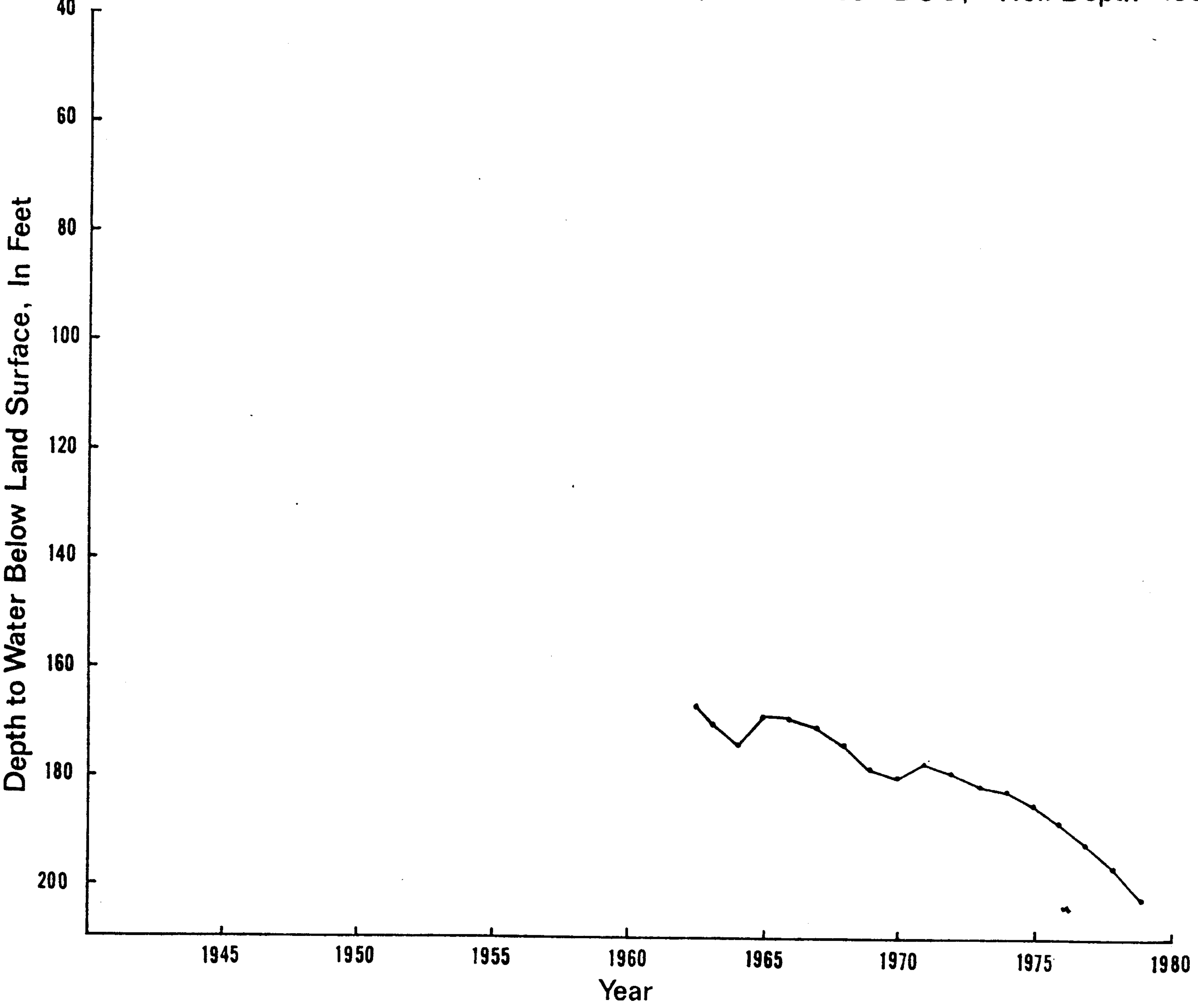
Hydrograph of Observation Well, Rawlins Co., 05 35w 10 CDD, Well Depth 180′



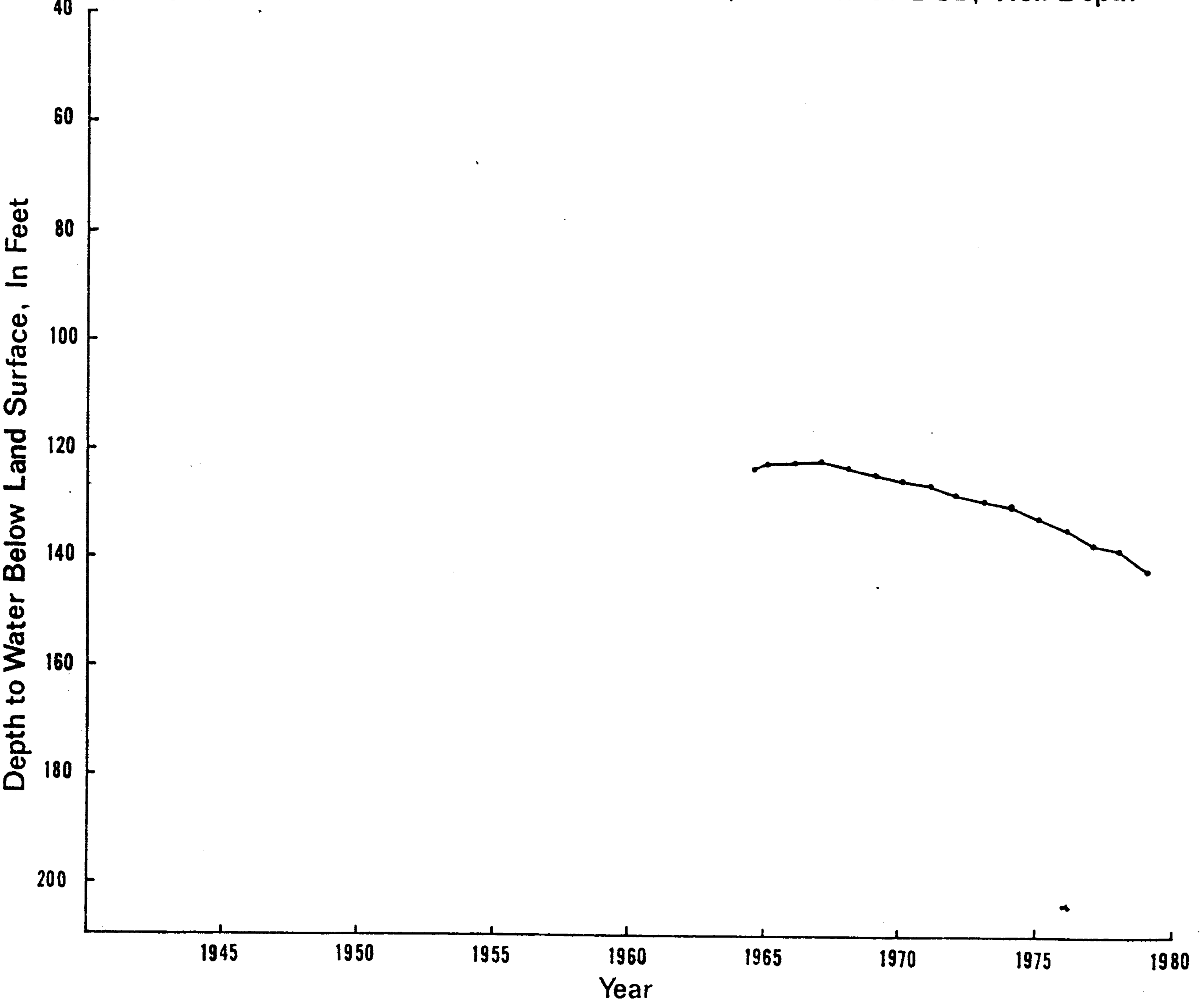


Hydrograph of Observation Well, Scott Co., 18 32w 20 CBB, Well Depth 132′

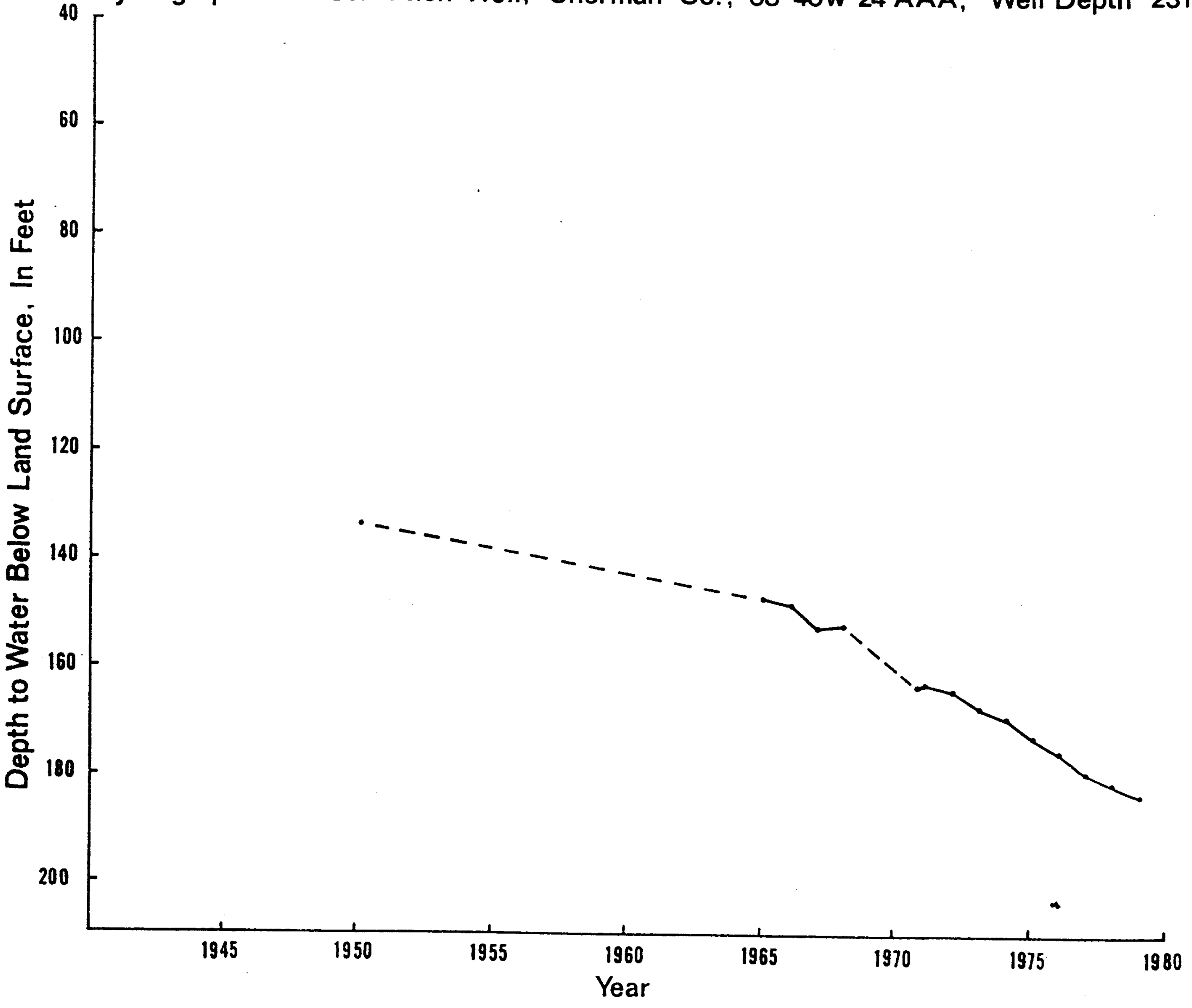
Hydrograph of Observation Well, Seward Co., 31 31w 08 BCC, Well Depth 400′



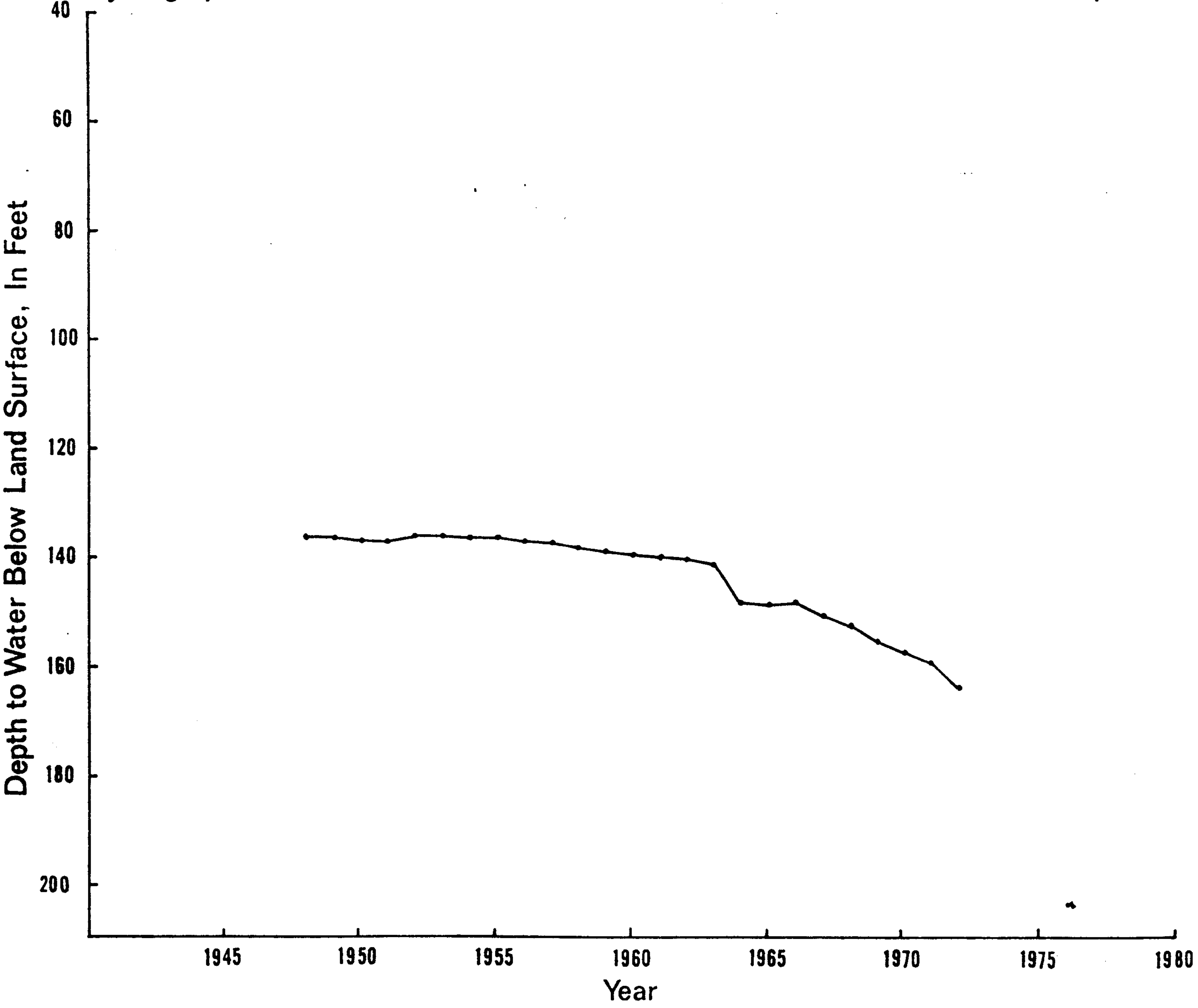
Hydrograph of Observation Well, Sheridan Co., 08 29w 01 DCB, Well Depth 240′



Hydrograph of Observation Well, Sherman Co., 08 40w 24 AAA, Well Depth 231′

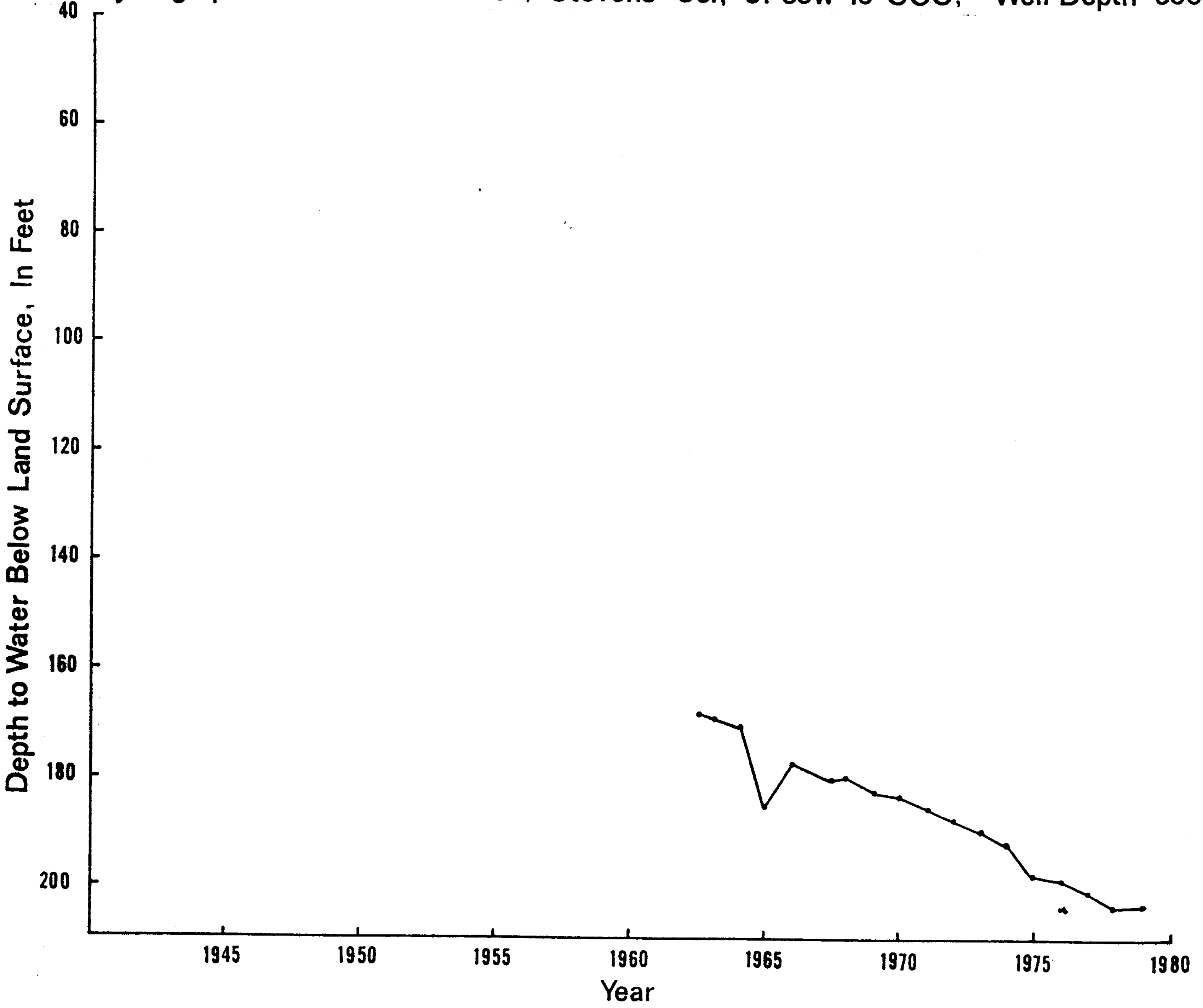


Hydrograph of Observation Well, Sherman Co., 08 40w 24 BAA, Well Depth 162'

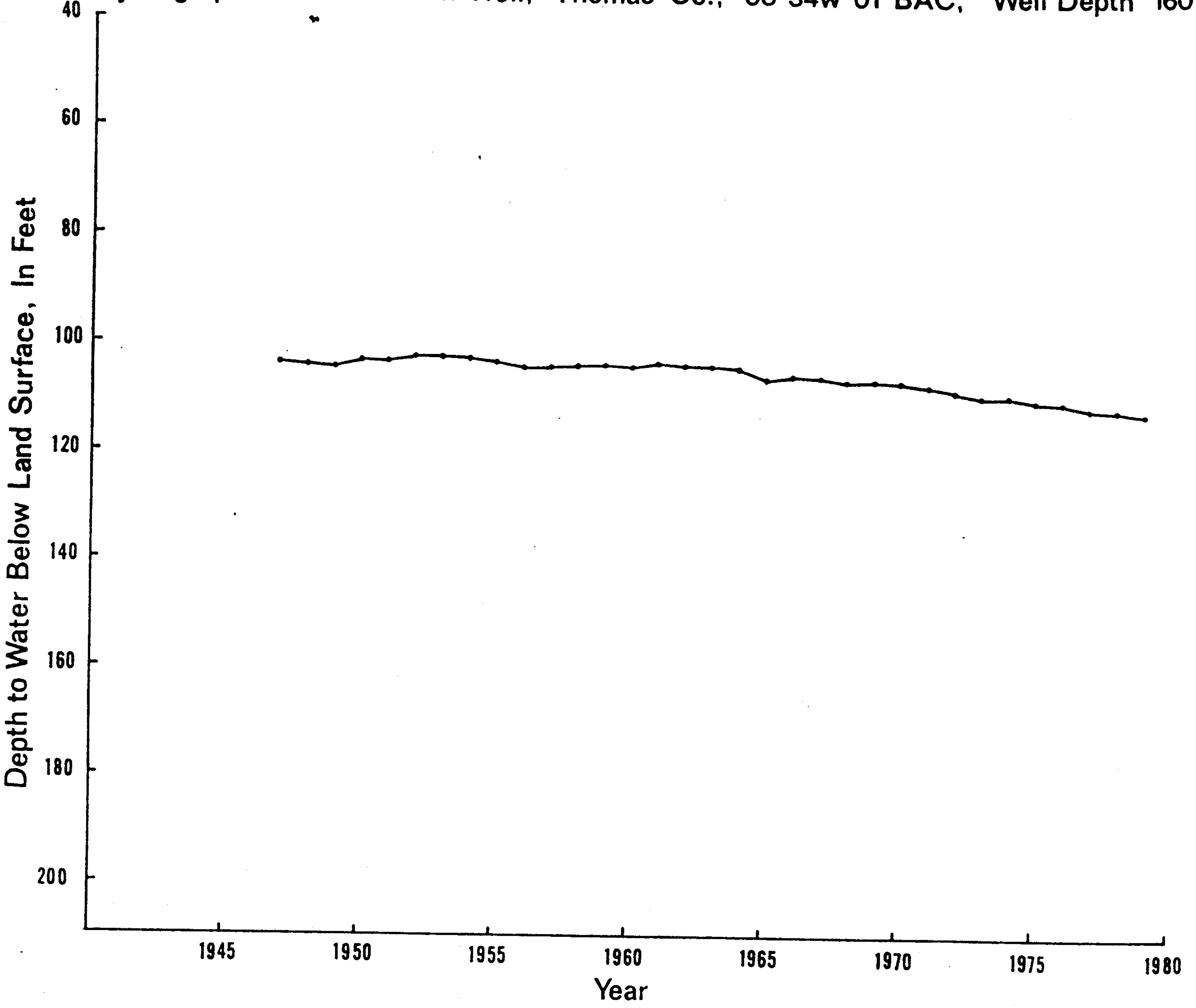


Hydrograph of Observation Well, Stanton Co., 28 39w 05 BBB, Well Depth 310′

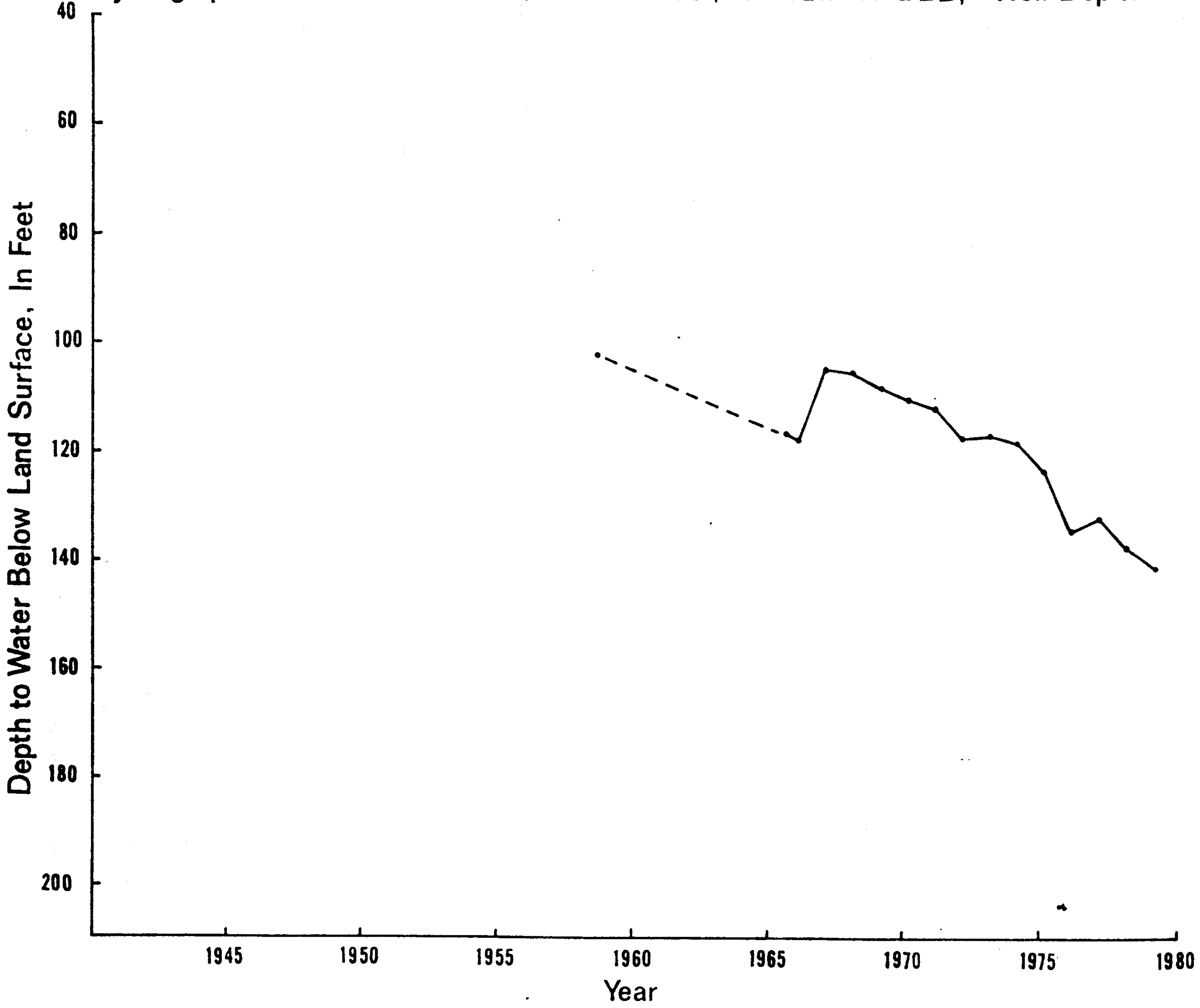
Hydrograph of Observation Well, Stevens Co., 31 35w 19 CCC, Well Depth 300′



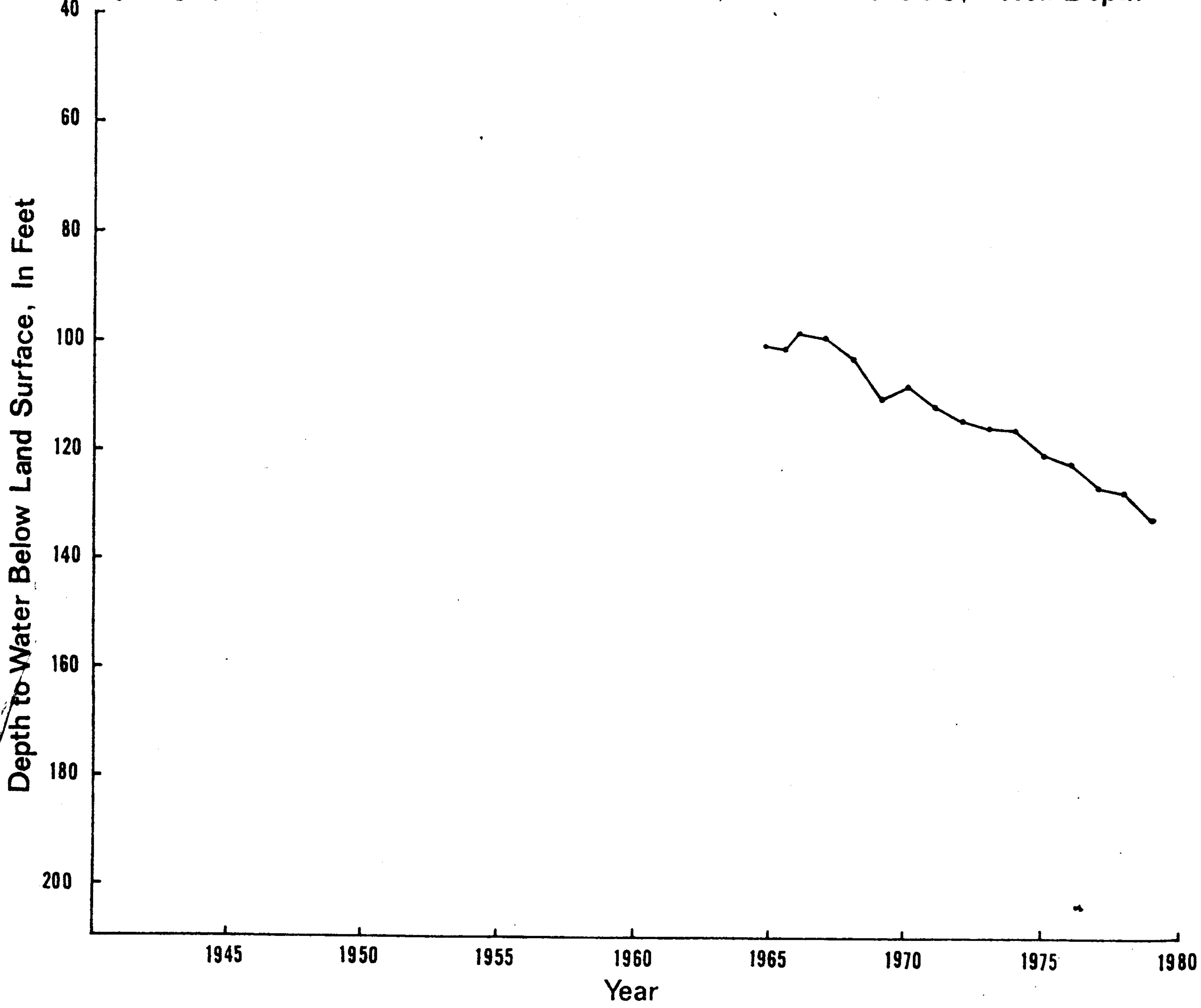
Hydrograph of Observation Well, Thomas Co., 08 34w 01 BAC, Well Depth 160'



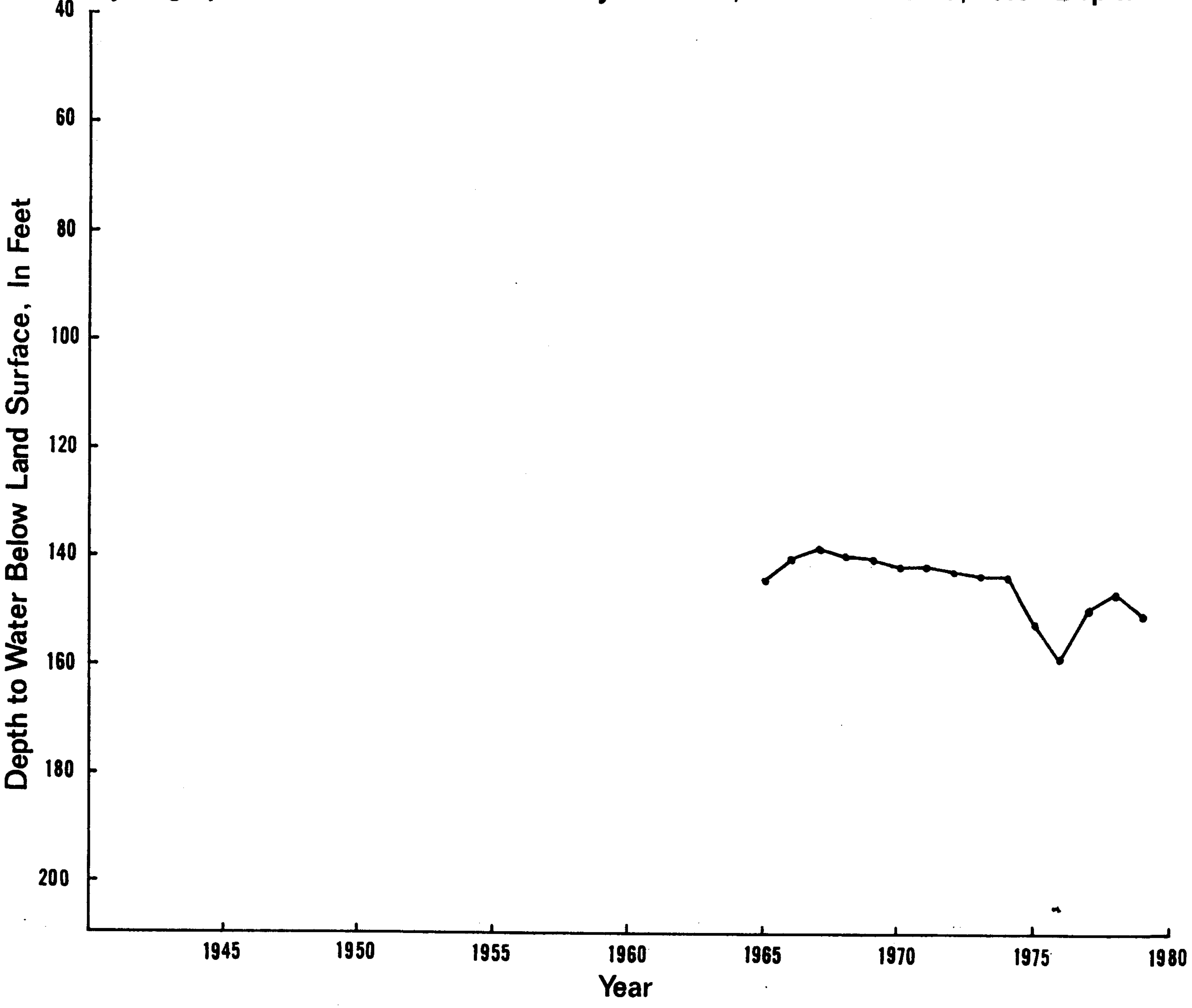
Hydrograph of Observation Well, Wallace Co., 14 42w 14 DBD, Well Depth 400′



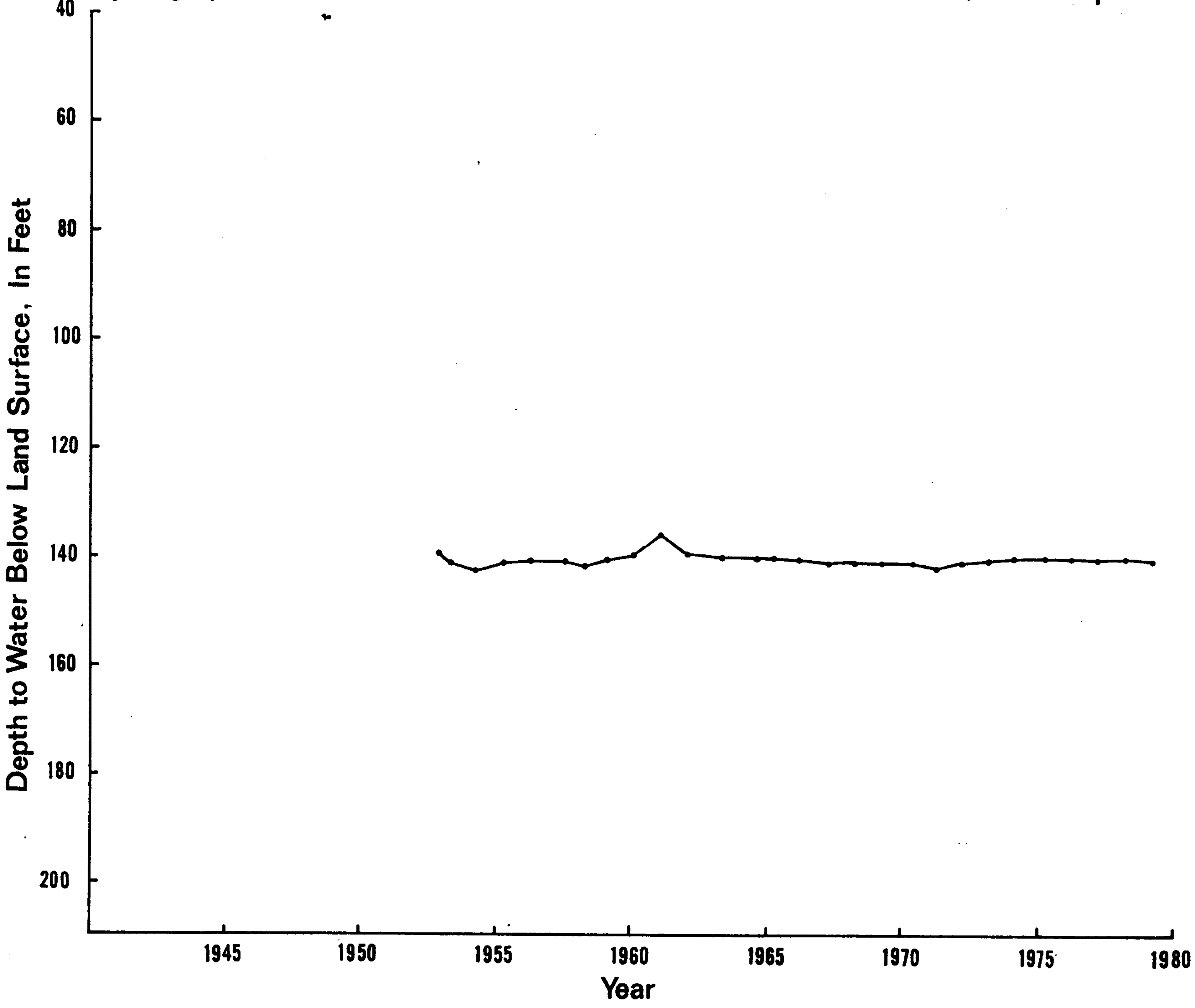
Hydrograph of Observation Well, Wichita Co., 17 37w 28 CCC, Well Depth 190′



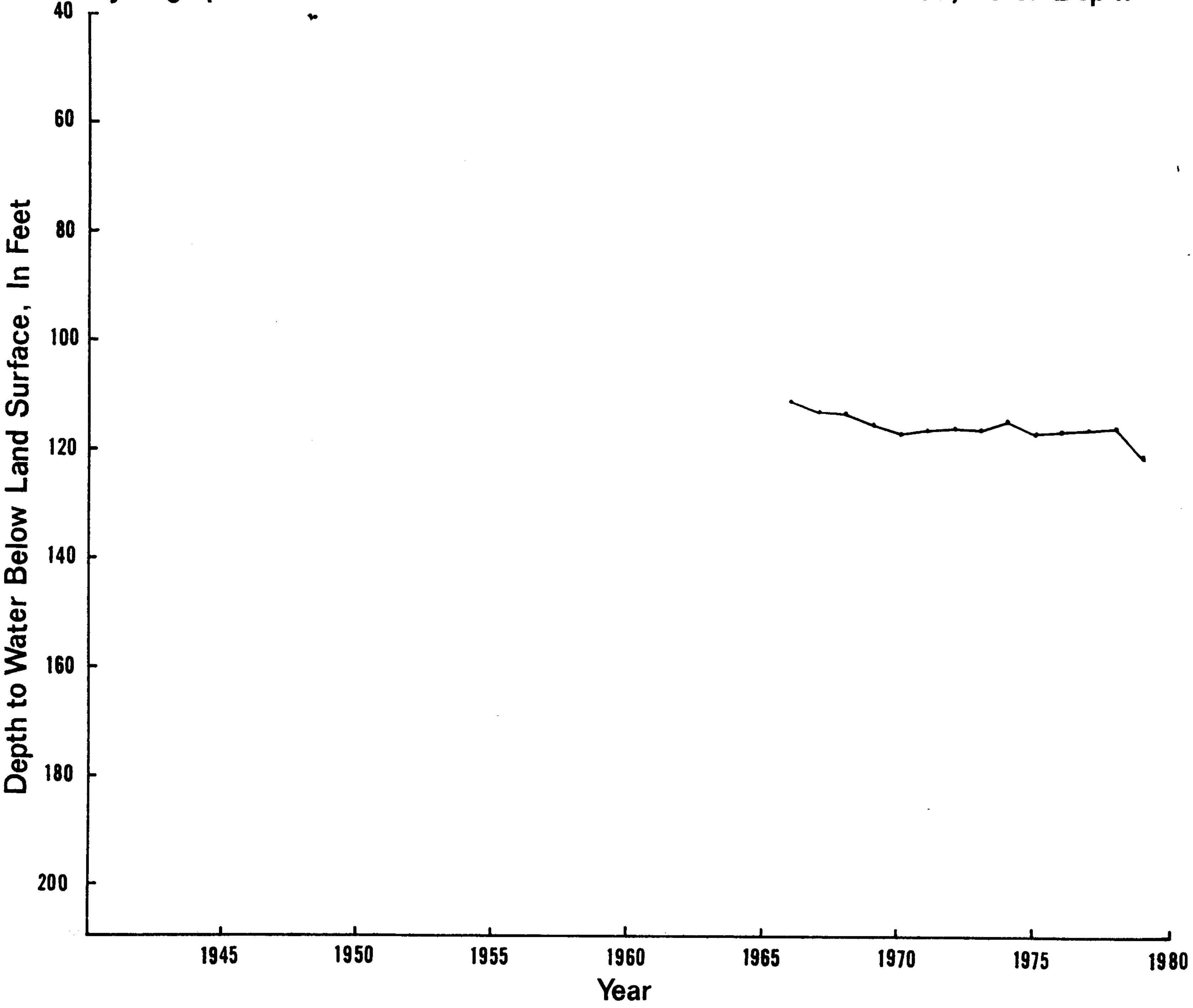
Hydrograph of Observation Well, Cheyenne Co., 05 39w 11 CBC, Well Depth 291′



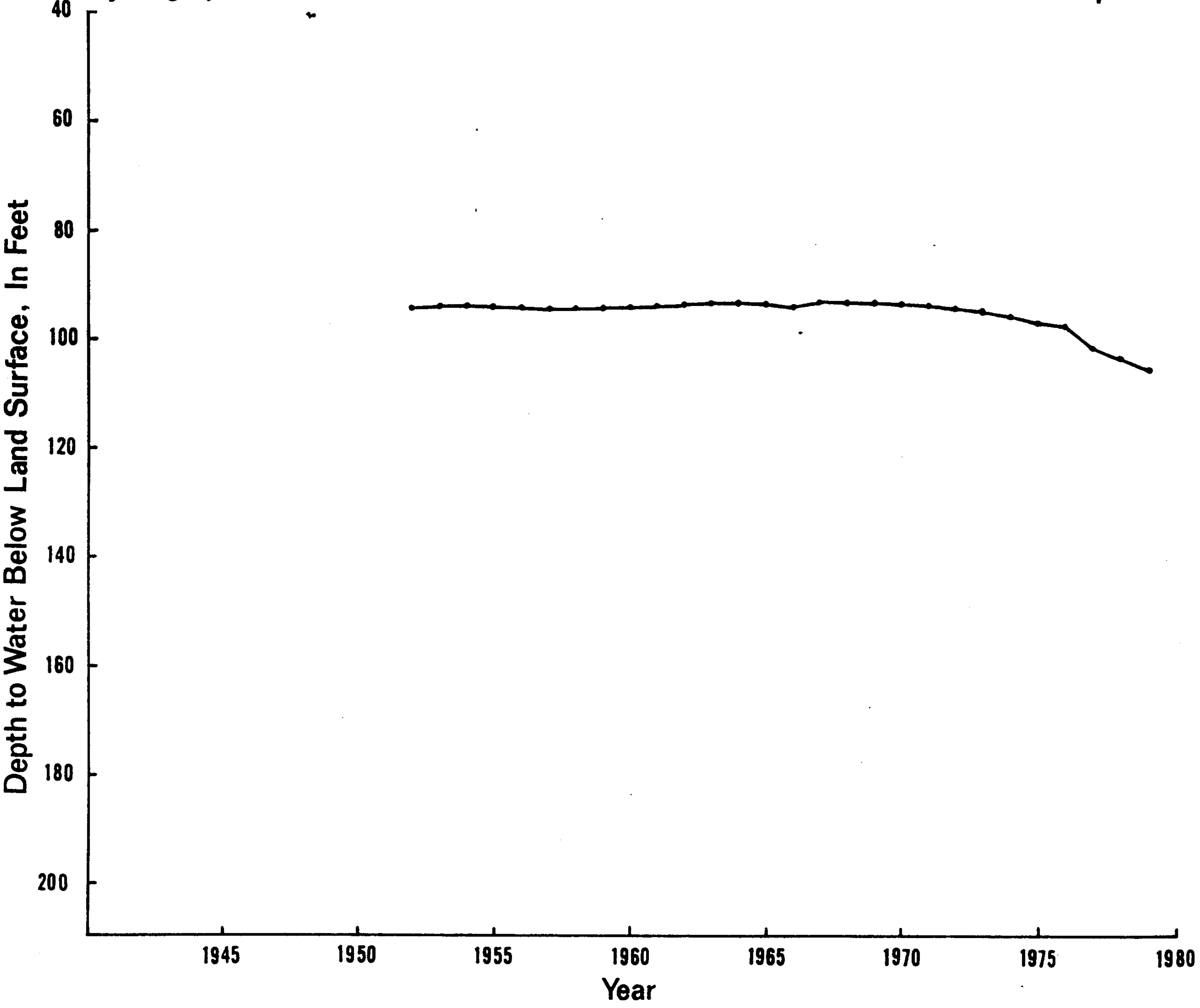
Hydrograph of Observation Well, Clark Co., 30 23w 06 AAA, Well Depth 160′



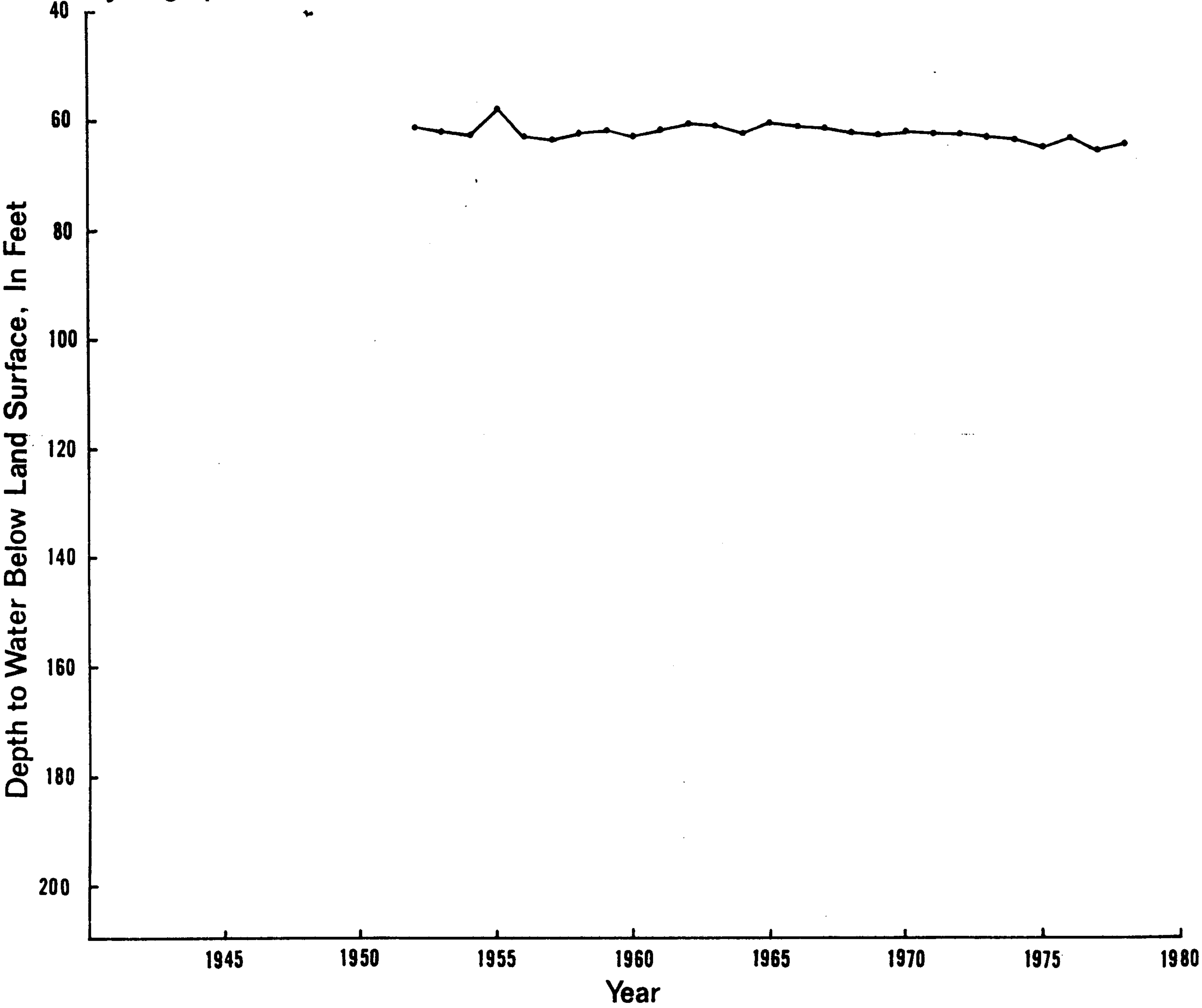
Hydrograph of Observation Well, Decatur Co., 05 30w 35 BCB, Well Depth 201′



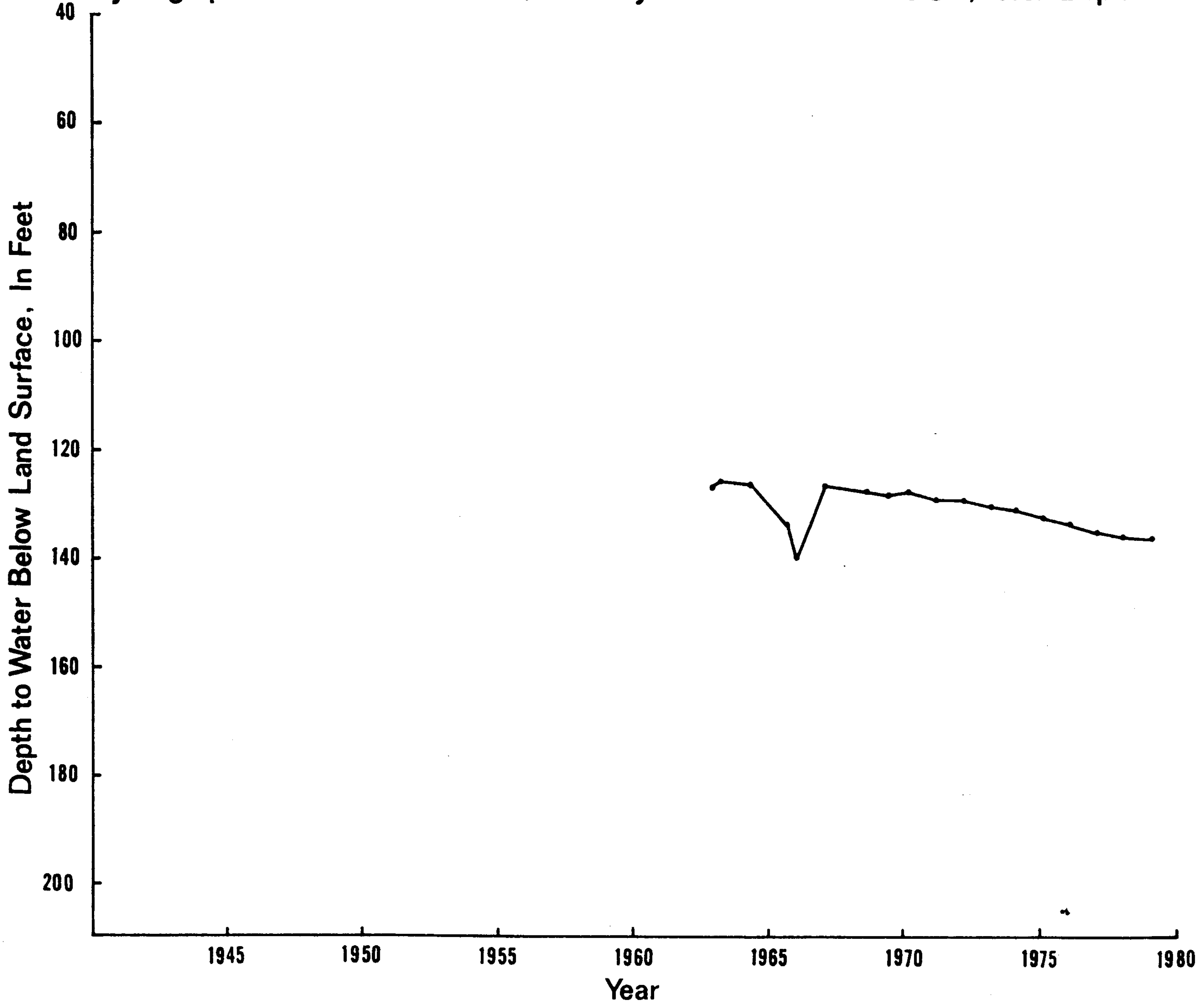
Hydrograph of Observation Well, Gove Co., 11 27w 16 AAA, Well Depth 108'

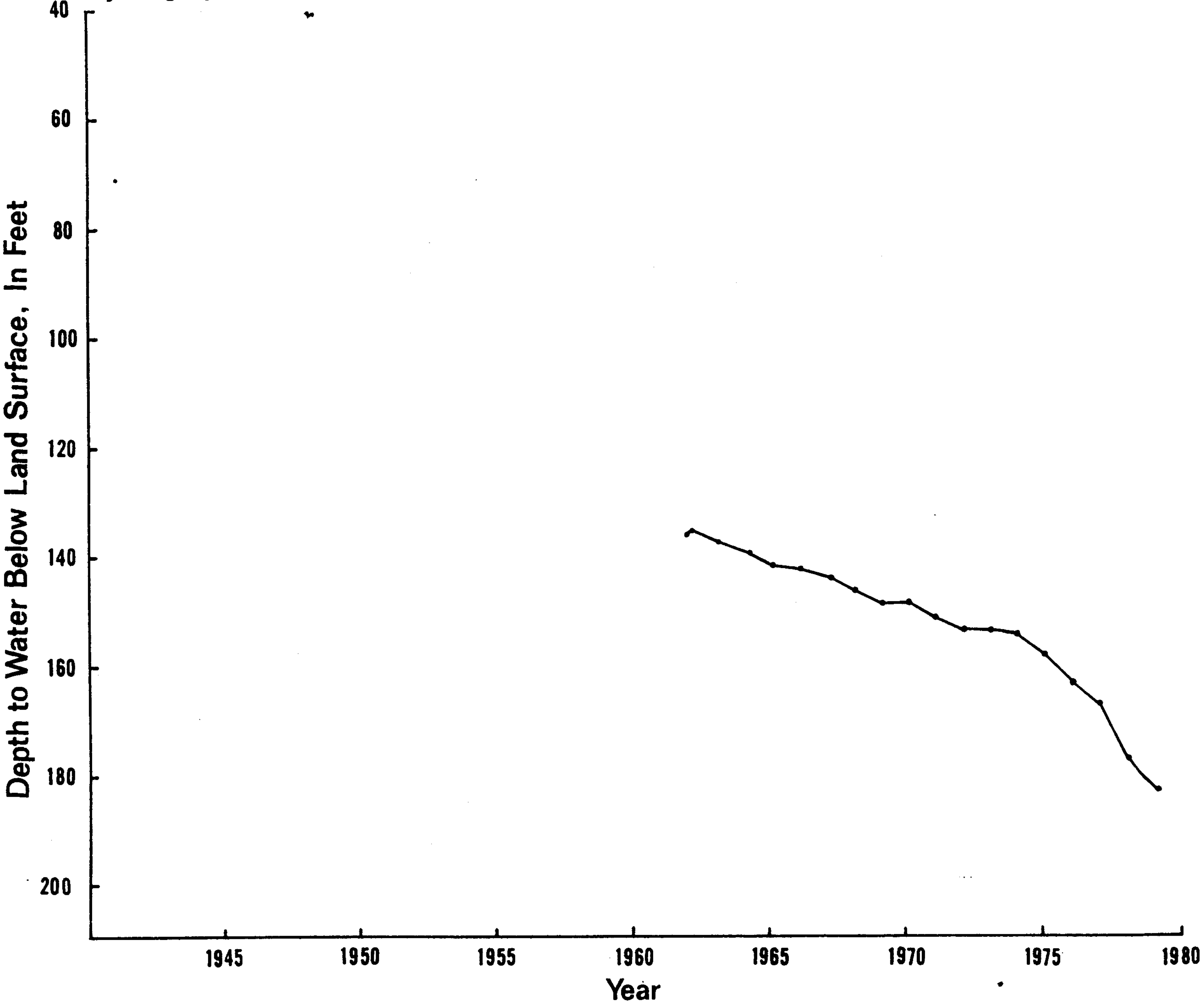


Hydrograph of Observation Well, Graham Co., 06 23w 12 CCB, Well Depth 65′



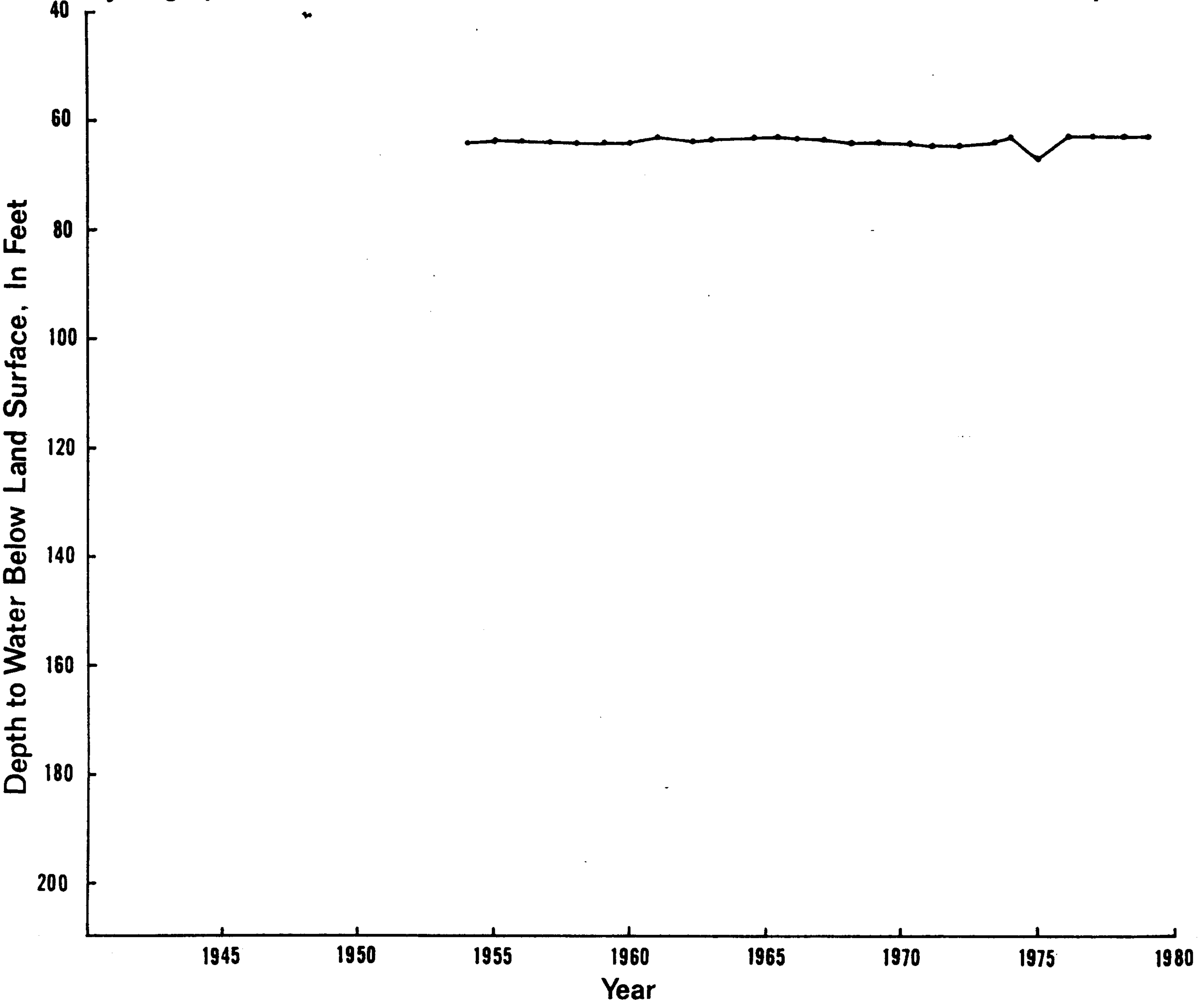
Hydrograph of Observation Well, Greeley Co., 17 40w 15 CCB, Well Depth 209′



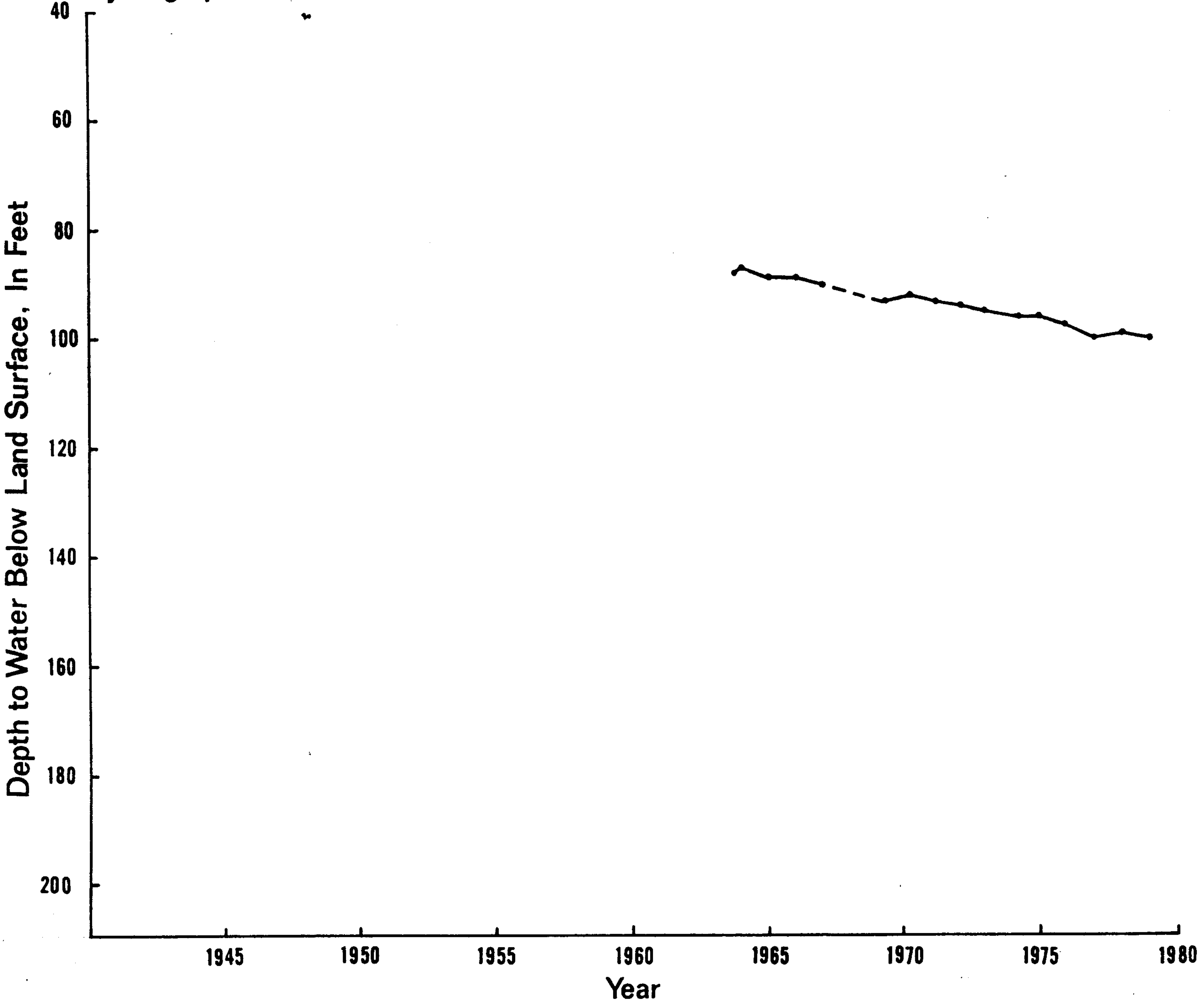


Hydrograph of Observation Well, Haskell Co., 30 32w 11 BBB, Well Depth 412'

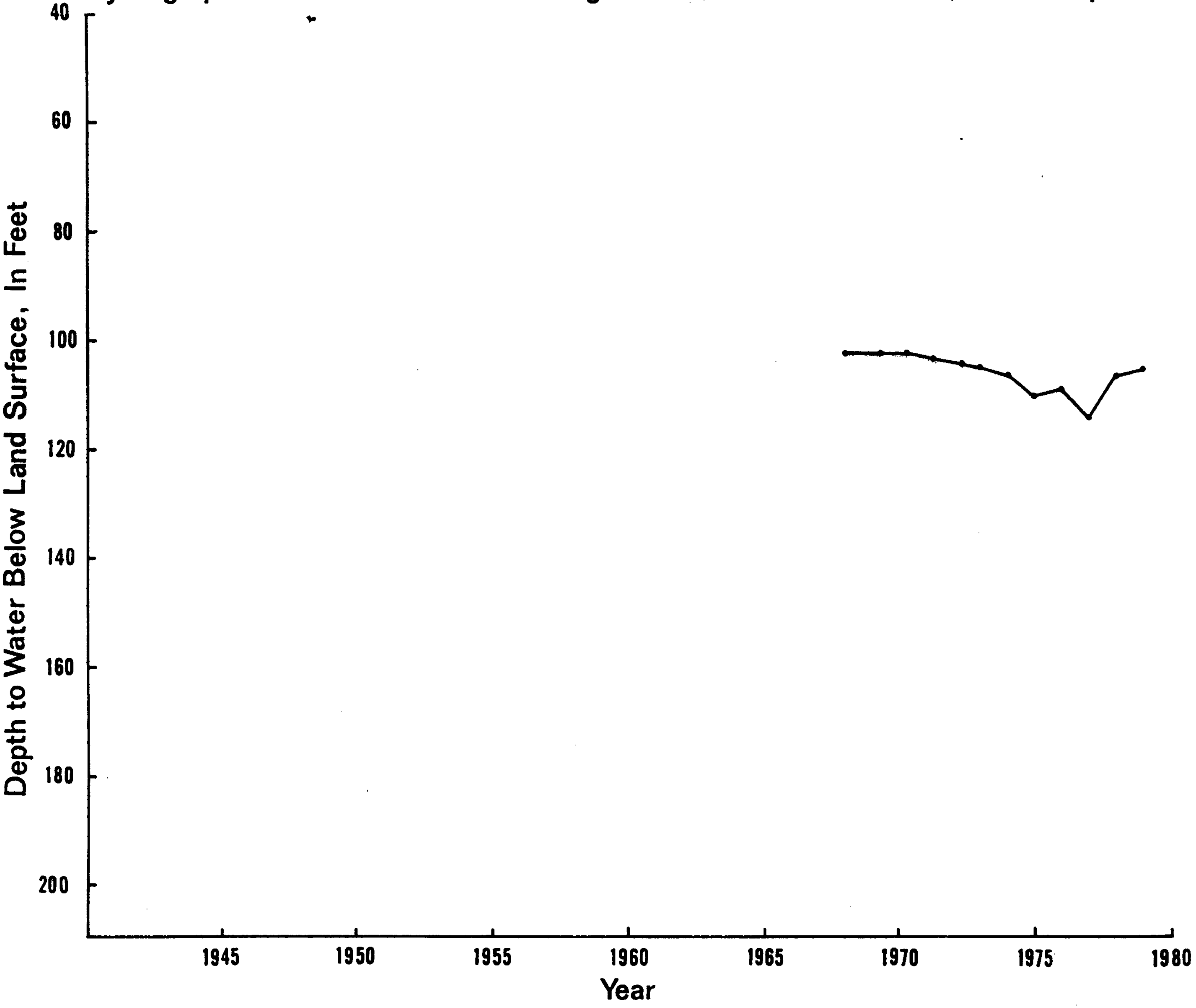
Hydrograph of Observation Well, Hodgeman Co., 24 26w 35 CBC, Well Depth 86′



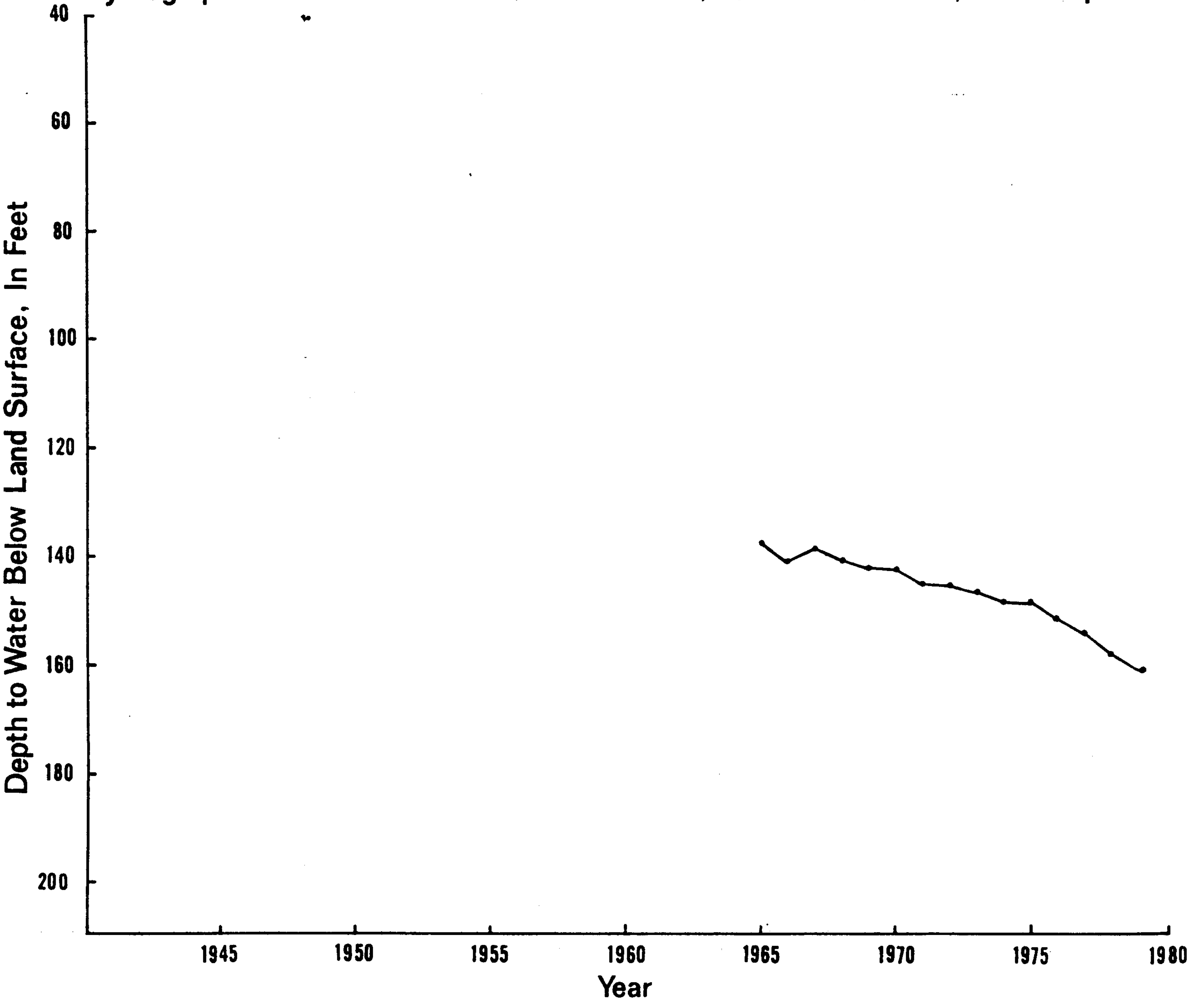
Hydrograph of Observation Well, Lane Co., 17 28w 26 ABB, Well Depth 140'



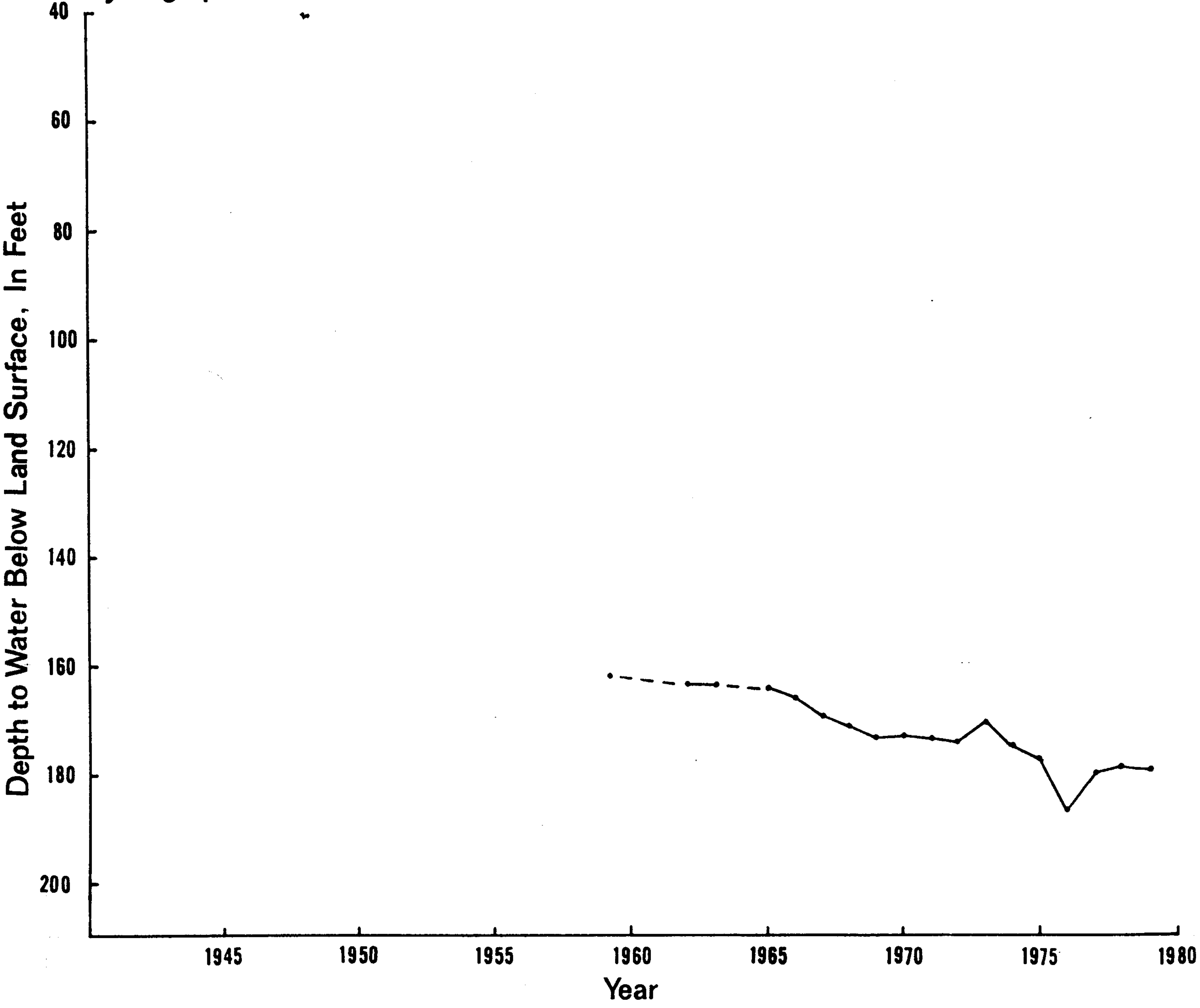
Hydrograph of Observation Well, Logan Co., 11 32w 04 ACD, Well Depth 208'



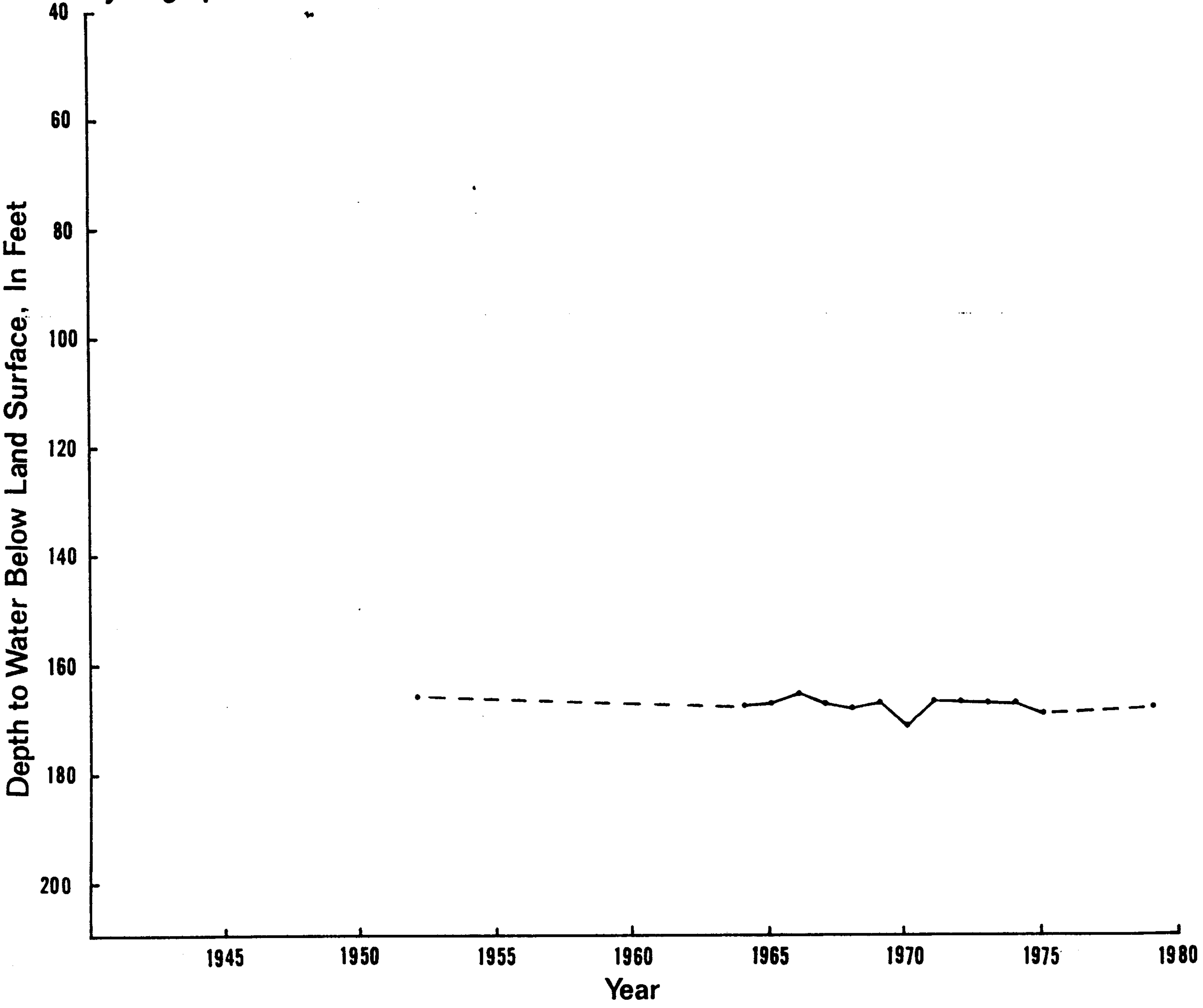
Hydrograph of Observation Well, Meade Co., 30 29w 23 CAD, Well Depth 228'



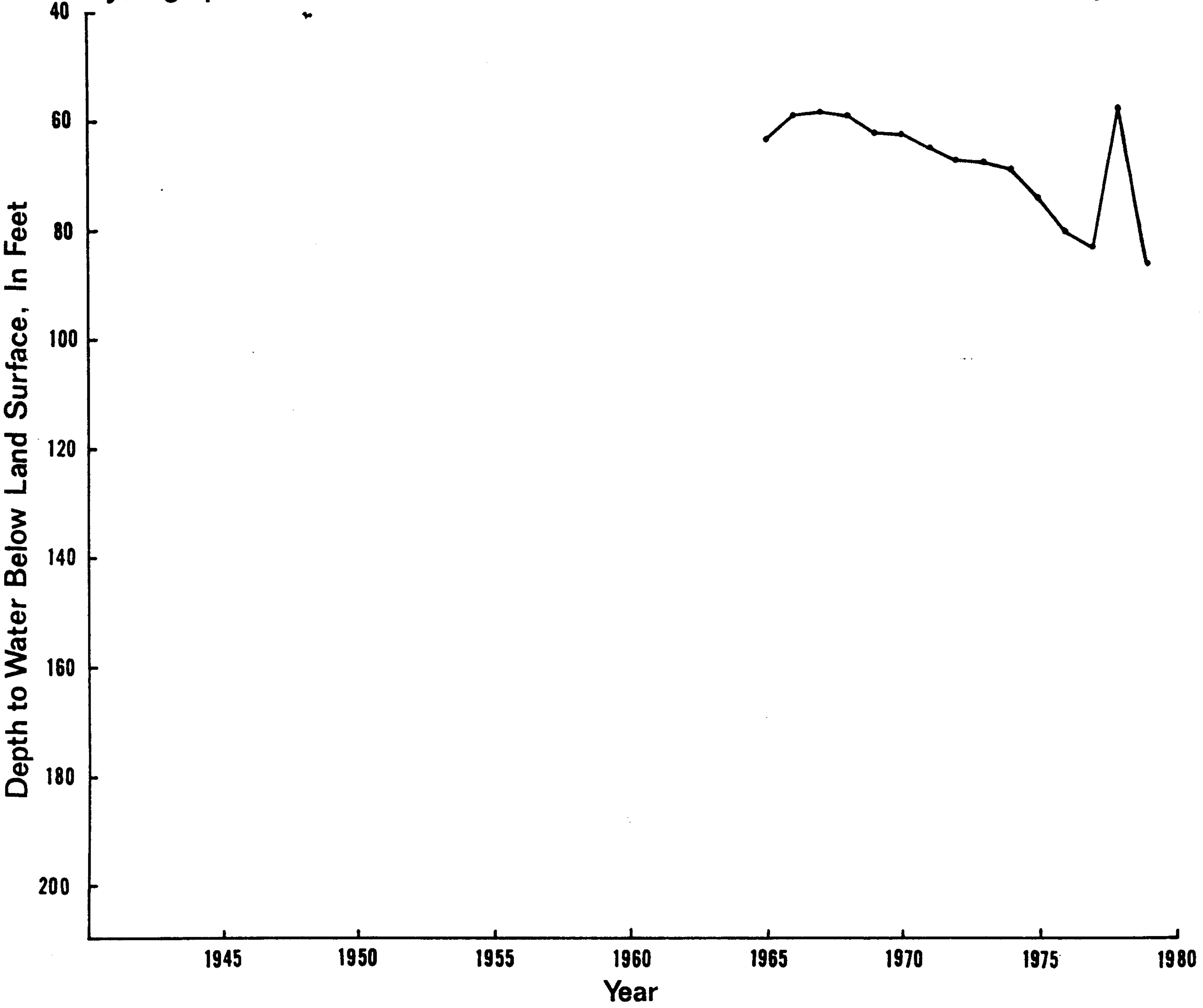
Hydrograph of Observation Well, Morton Co., 31 40w 29 ABB, Well Depth 215'



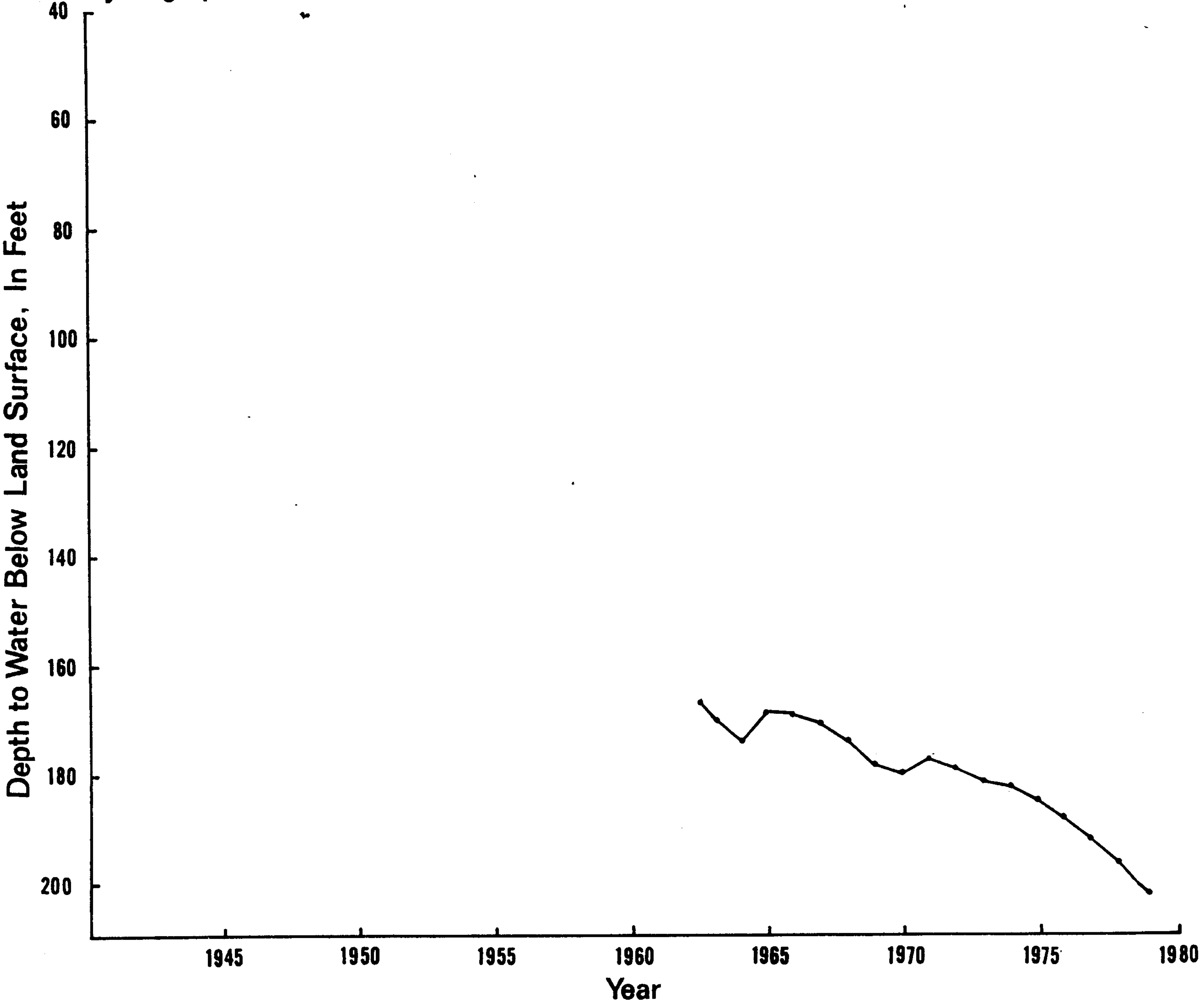
Hydrograph of Observation Well, Rawlins Co., 05 35w 10 CDD, Well Depth 180′



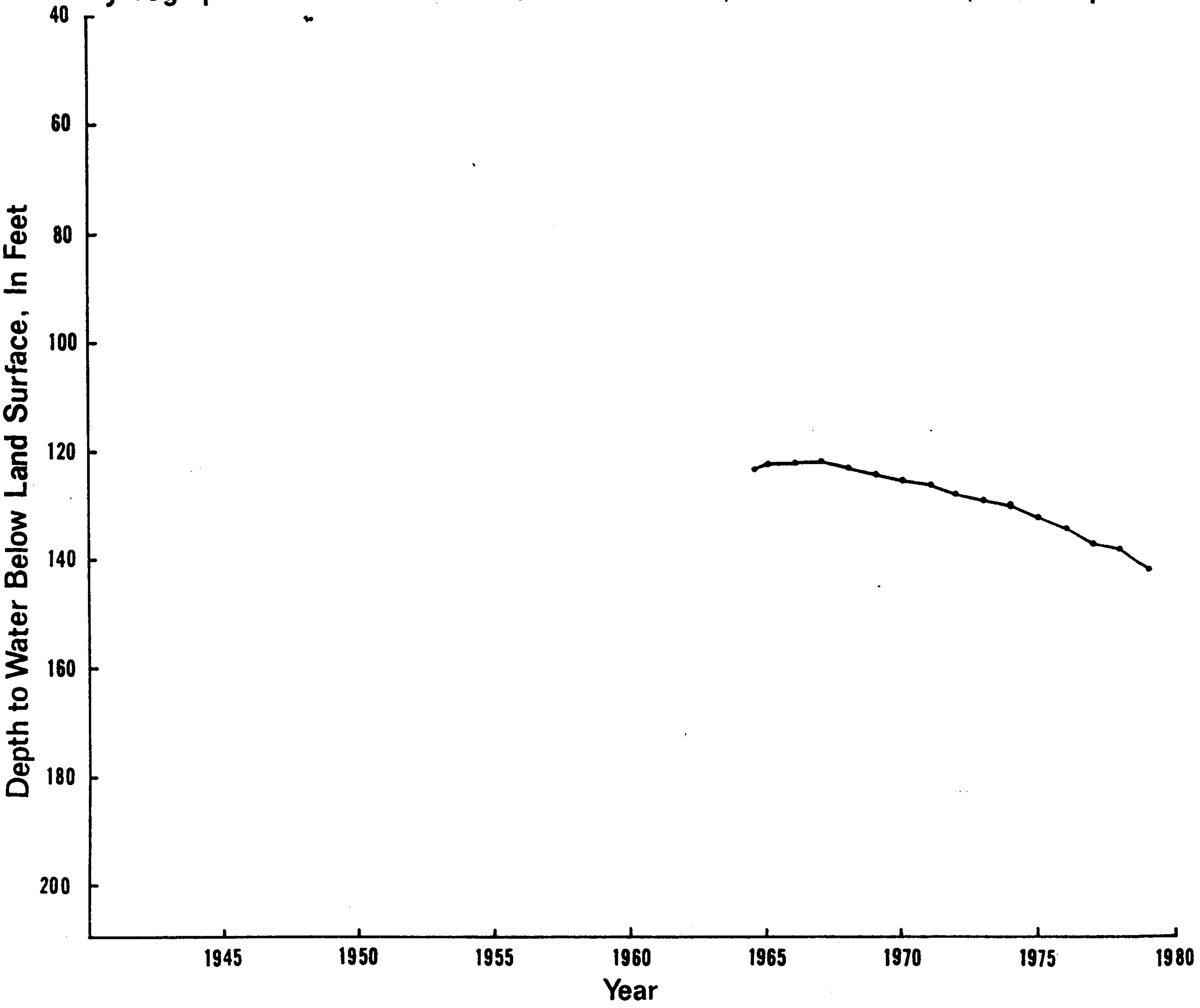
Hydrograph of Observation Well, Scott Co., 18 32w 20 CBB, Well Depth 132'



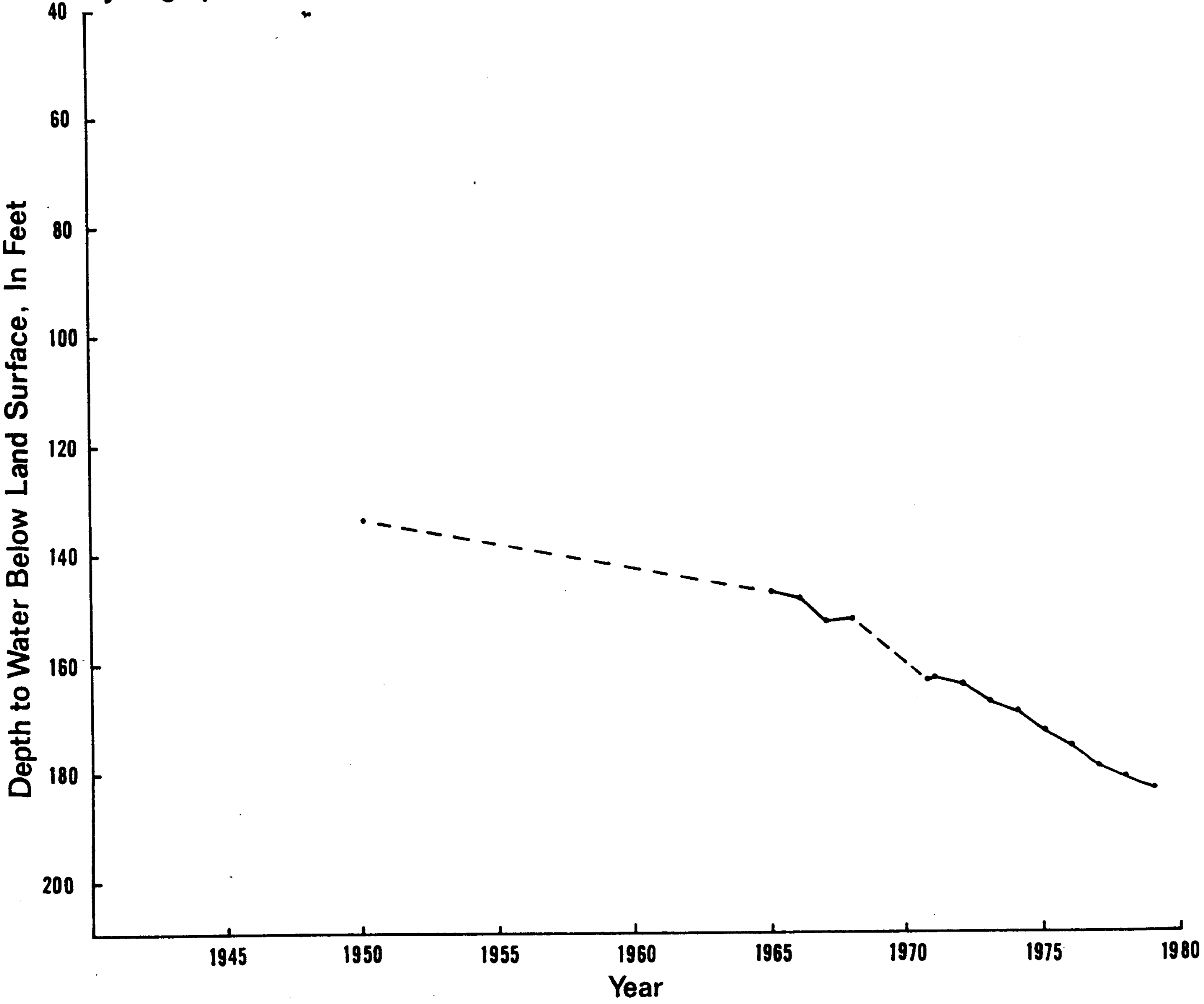
Hydrograph of Observation Well, Seward Co., 31 31w 08 BCC, Well Depth 400′



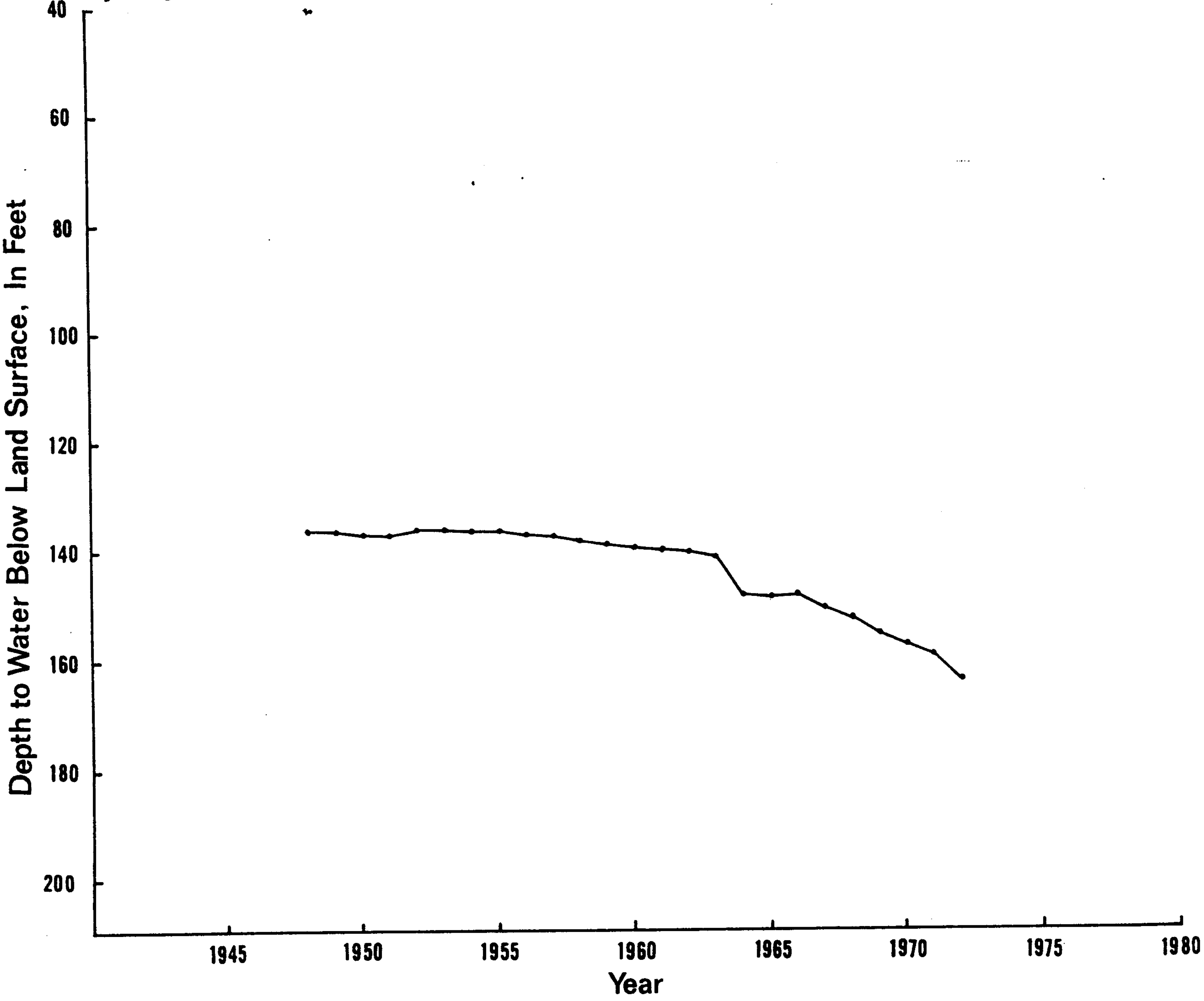
Hydrograph of Observation Well, Sheridan Co., 08 29w 01 DCB, Well Depth 240′

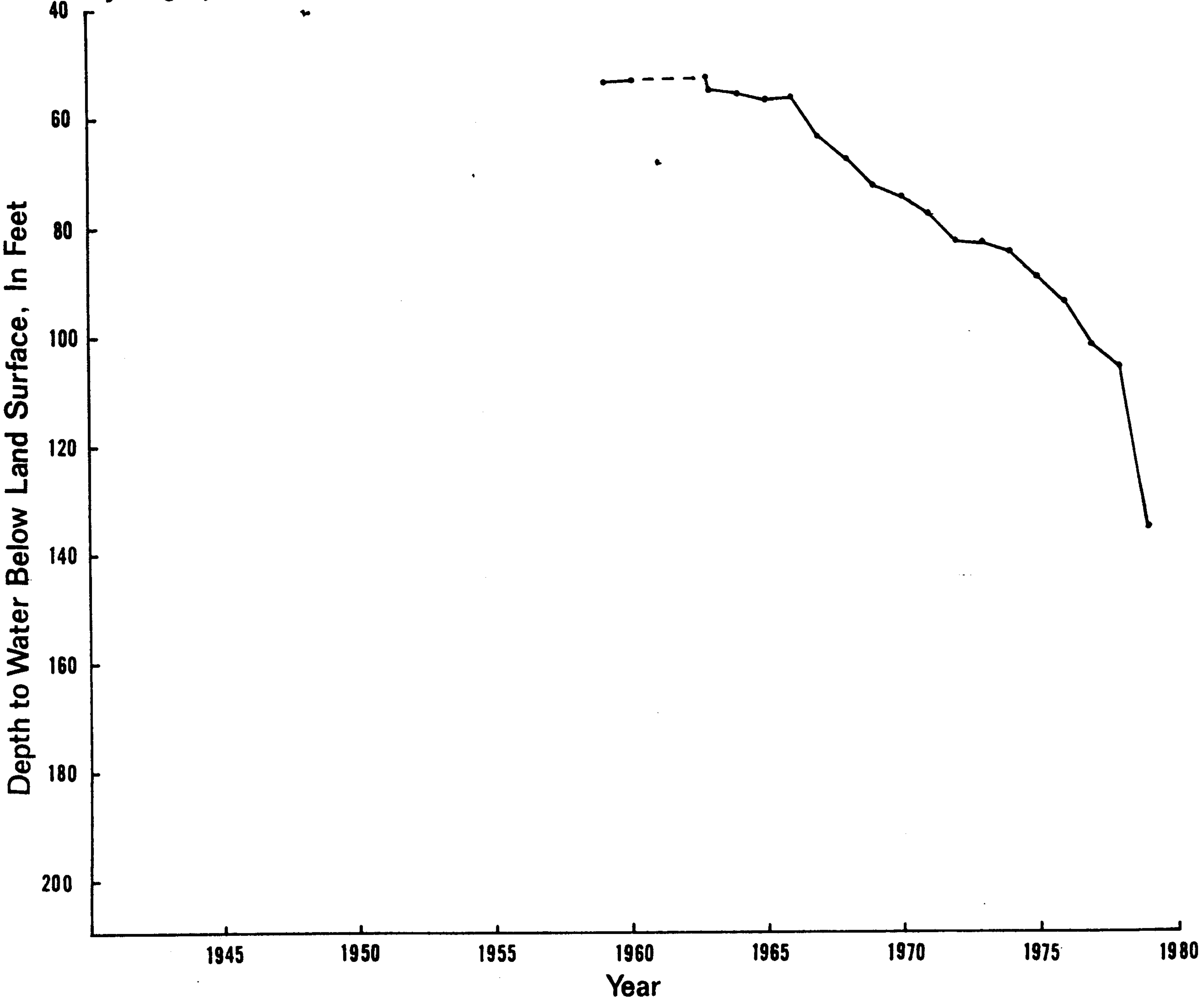


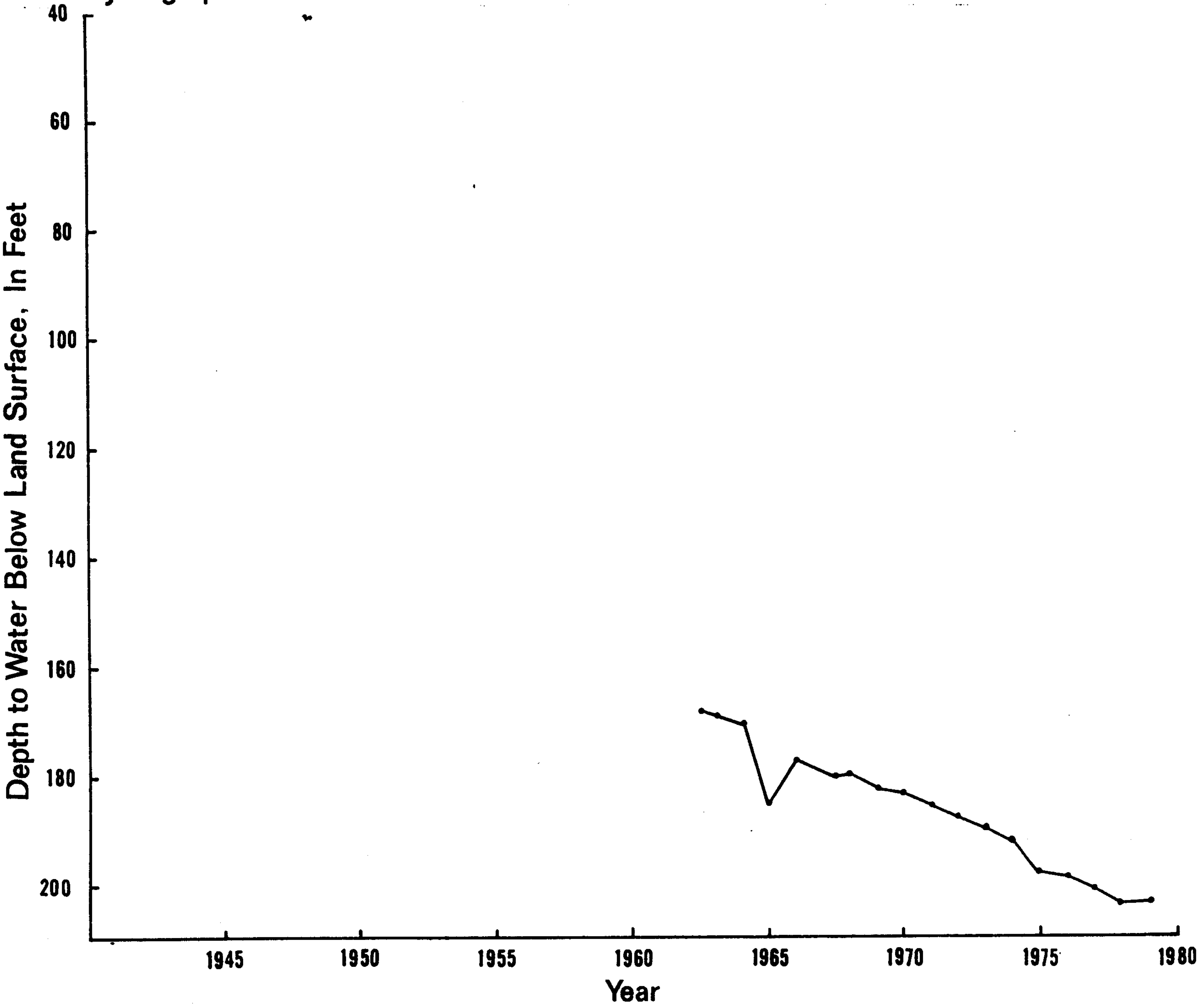
Hydrograph of Observation Well, Sherman Co., 08 40w 24 AAA, Well Depth 231′



Hydrograph of Observation Well, Sherman Co., 08 40w 24 BAA, Well Depth 162'

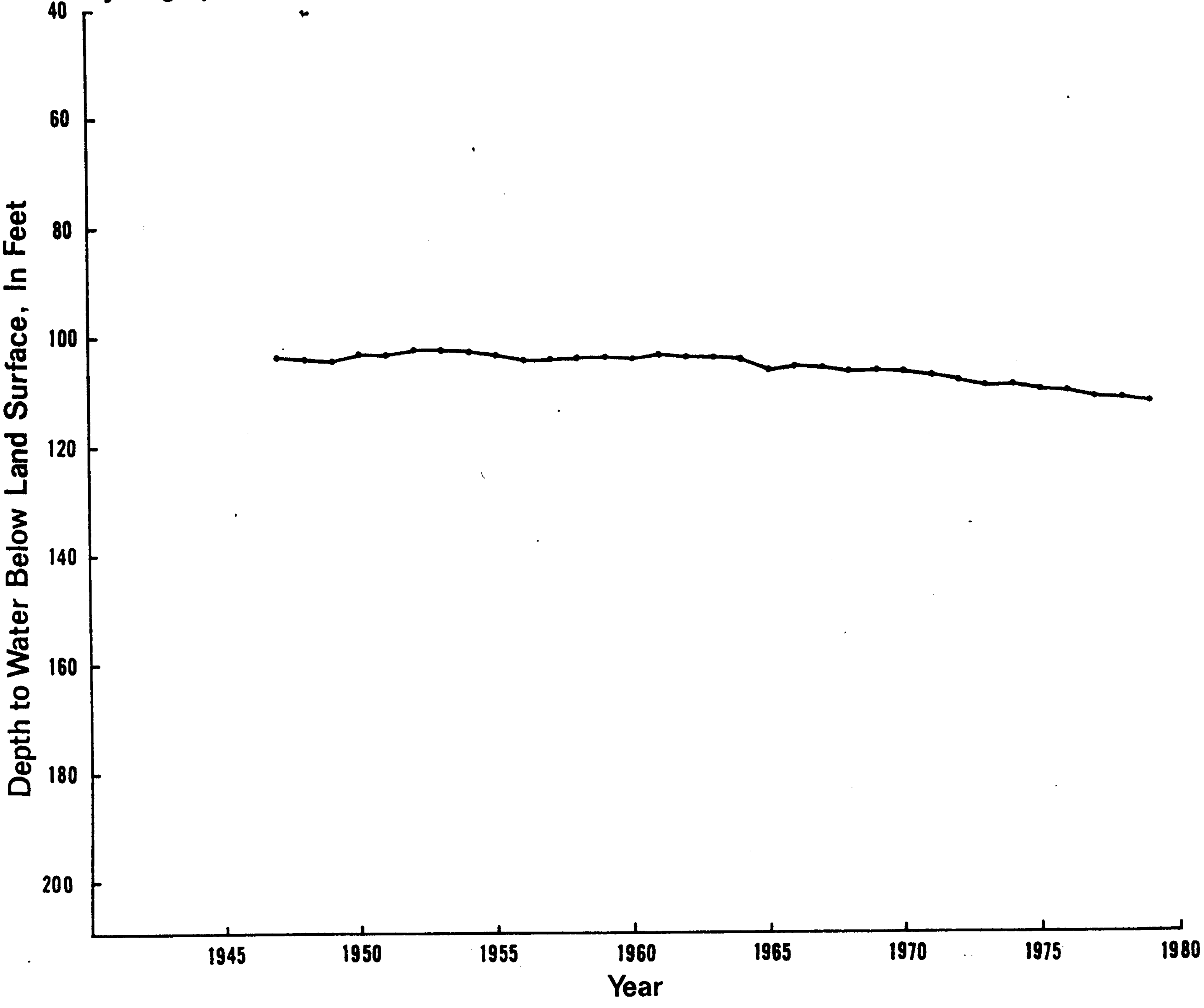



Hydrograph of Observation Well, Stanton Co., 28 39w 05 BBB, Well Depth 310'

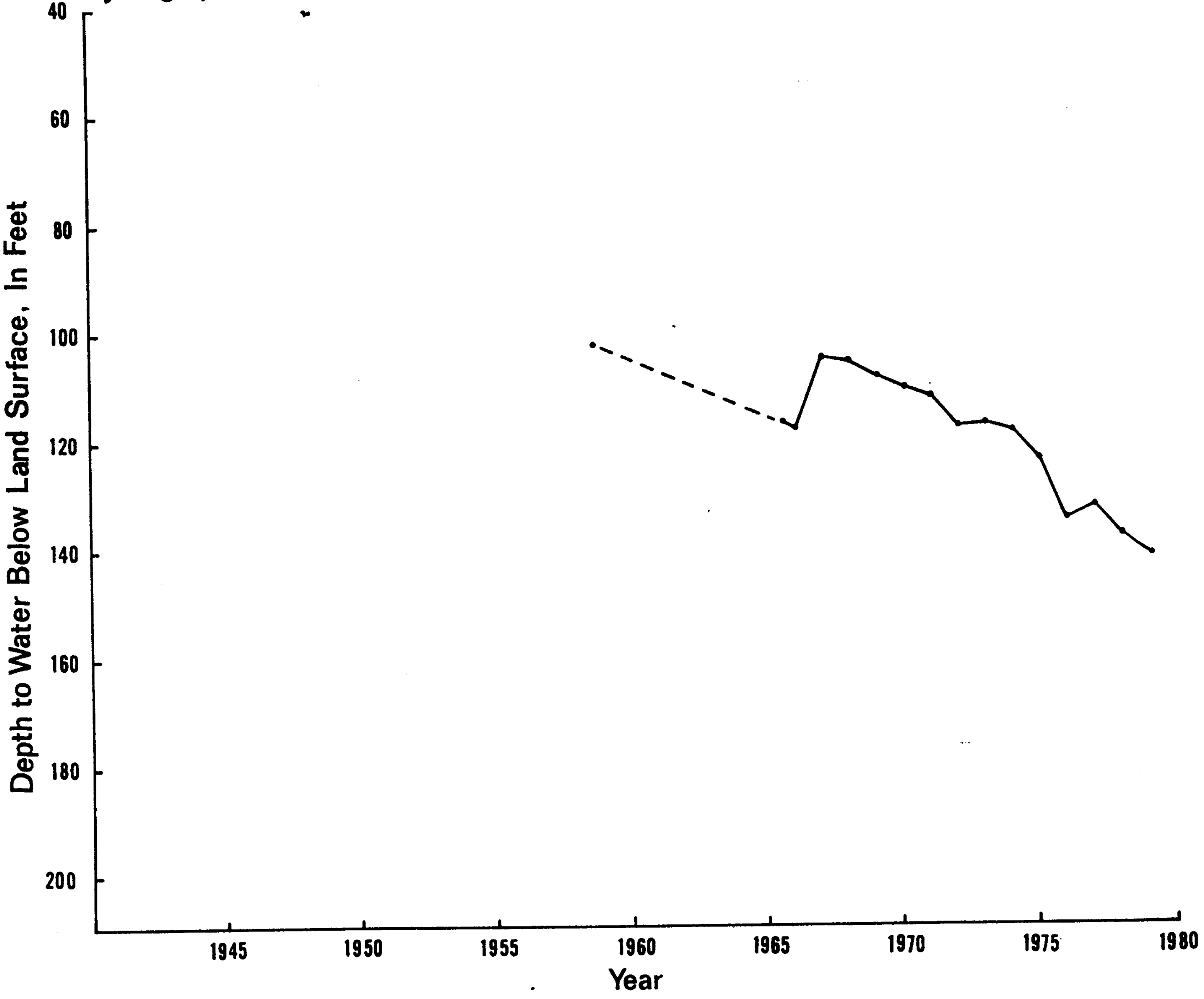


Hydrograph of Observation Well, Stevens Co., 31 35w 19 CCC, Well Depth 300′

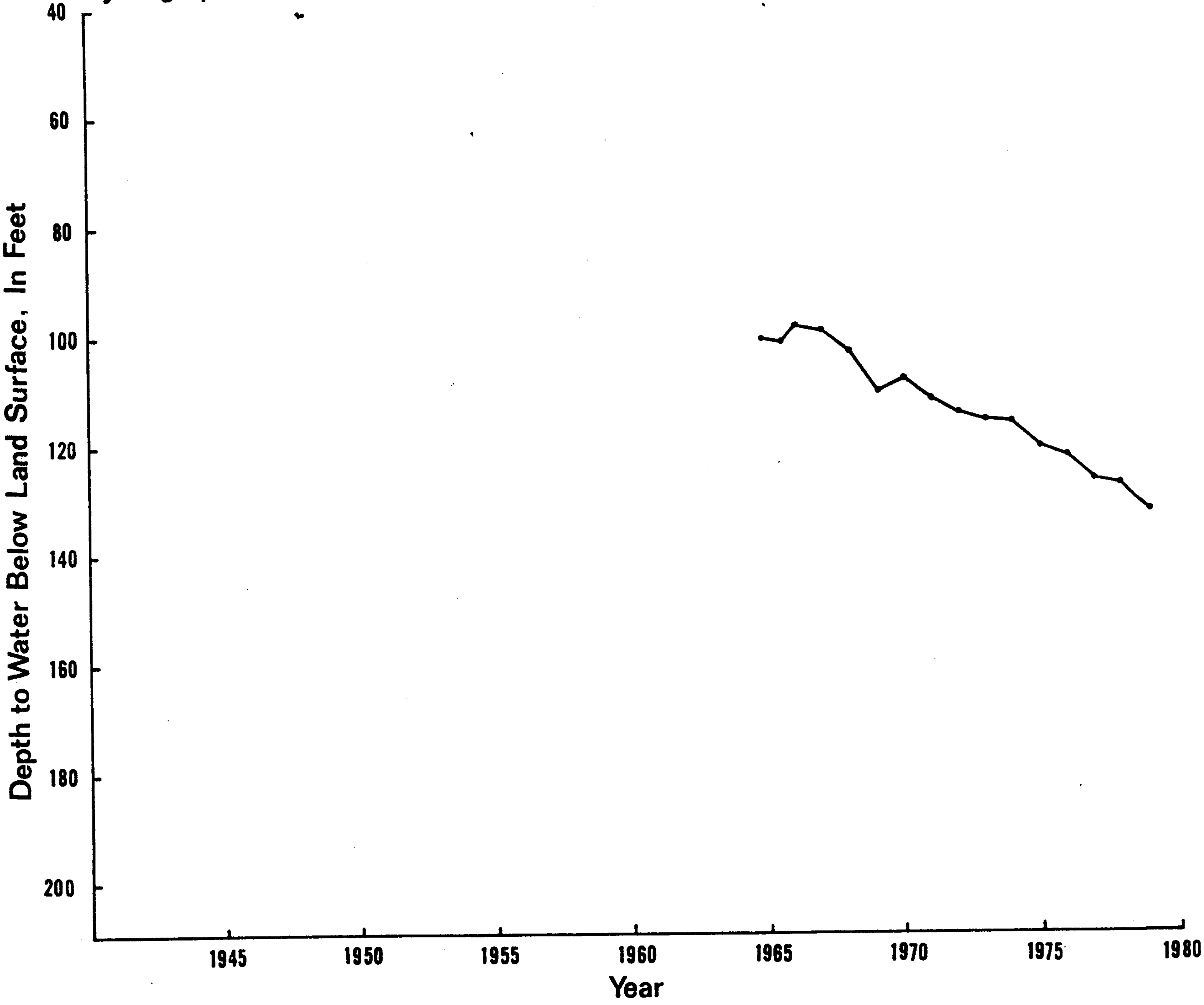
Hydrograph of Observation Well, Thomas Co., 08 34w 01 BAC, Well Depth 160′



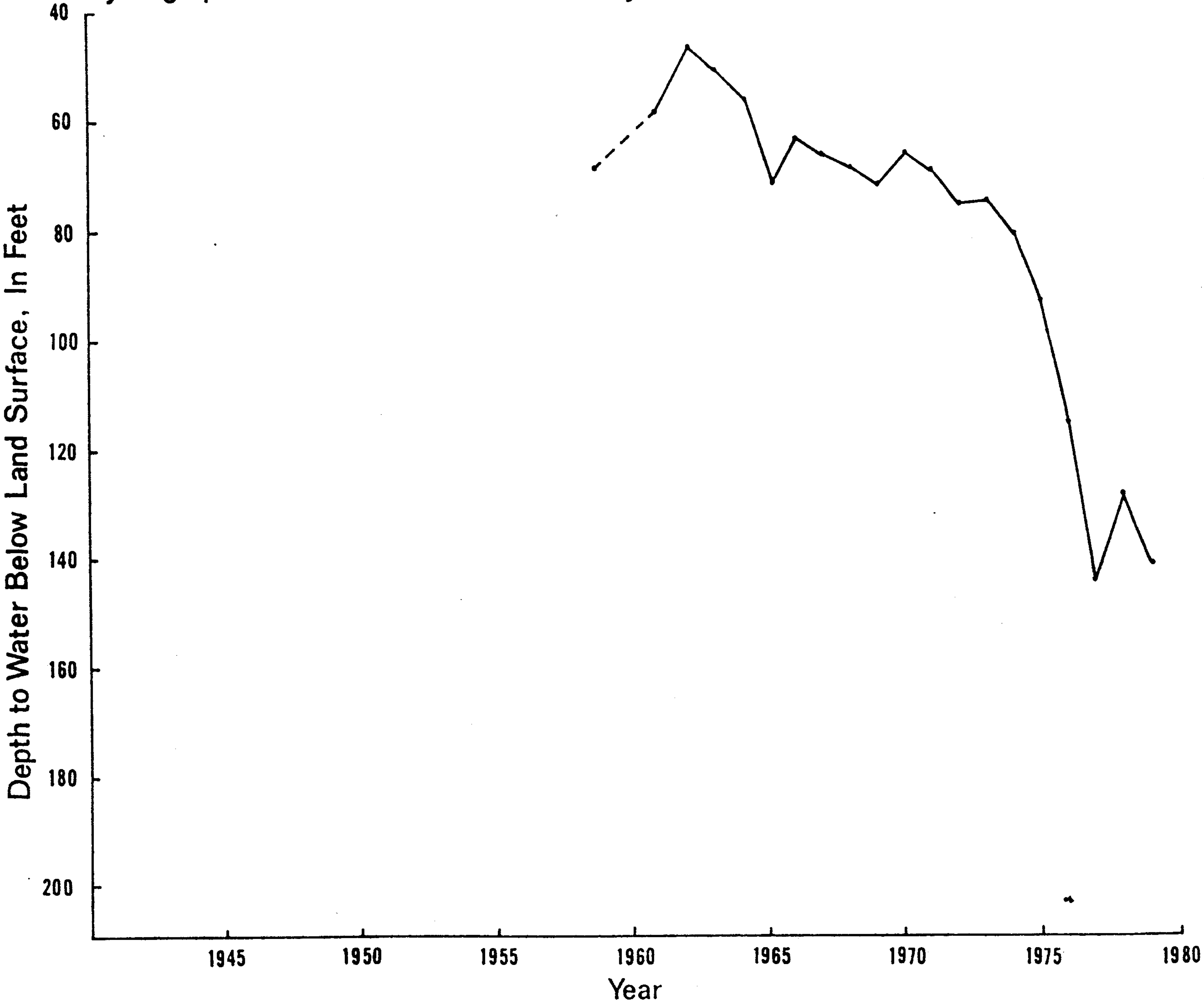
Hydrograph of Observation Well, Wallace Co., 14 42w 14 DBD, Well Depth 400'



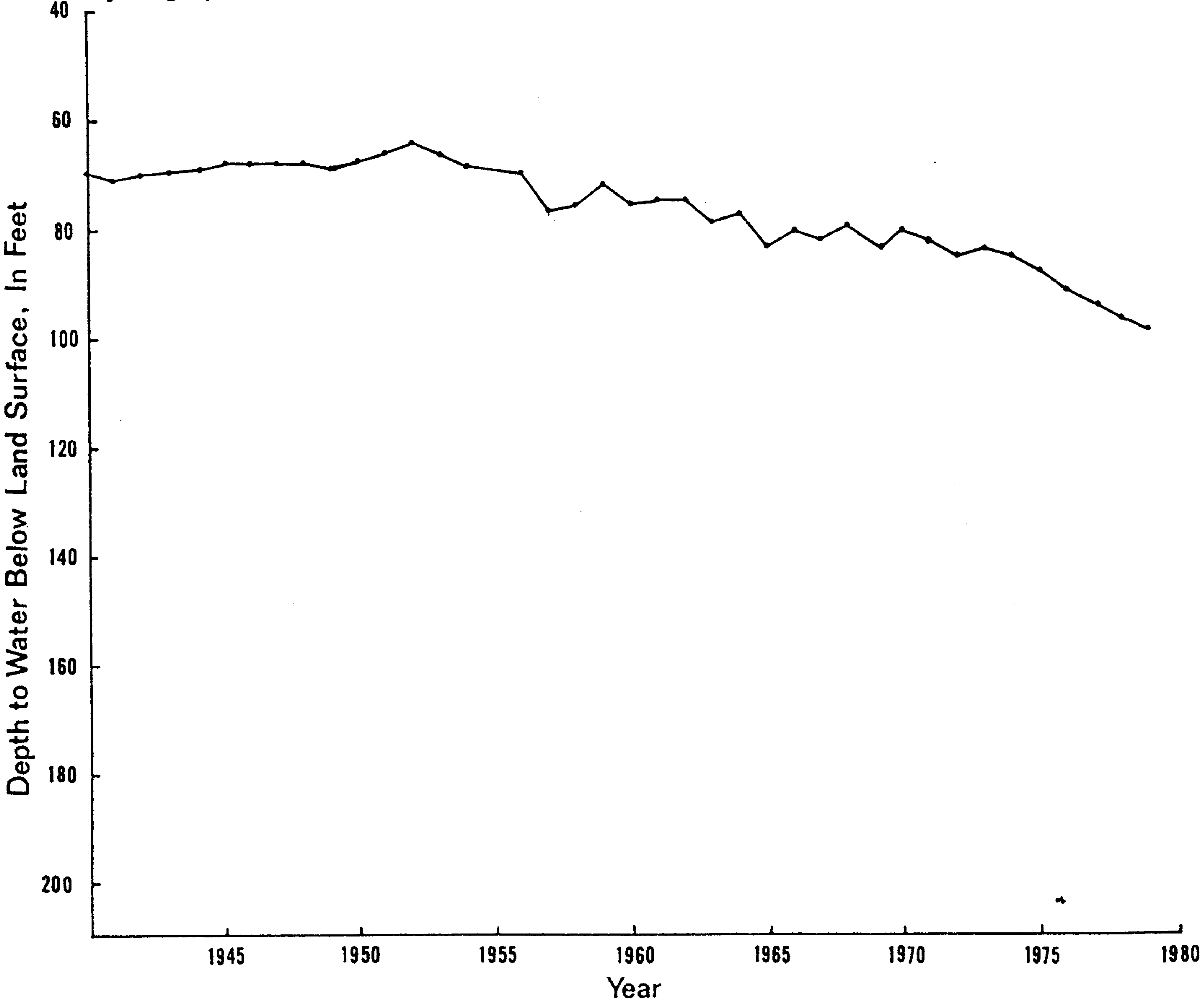
Hydrograph of Observation Well, Wichita Co., 17 37w 28 CCC, Well Depth 190′



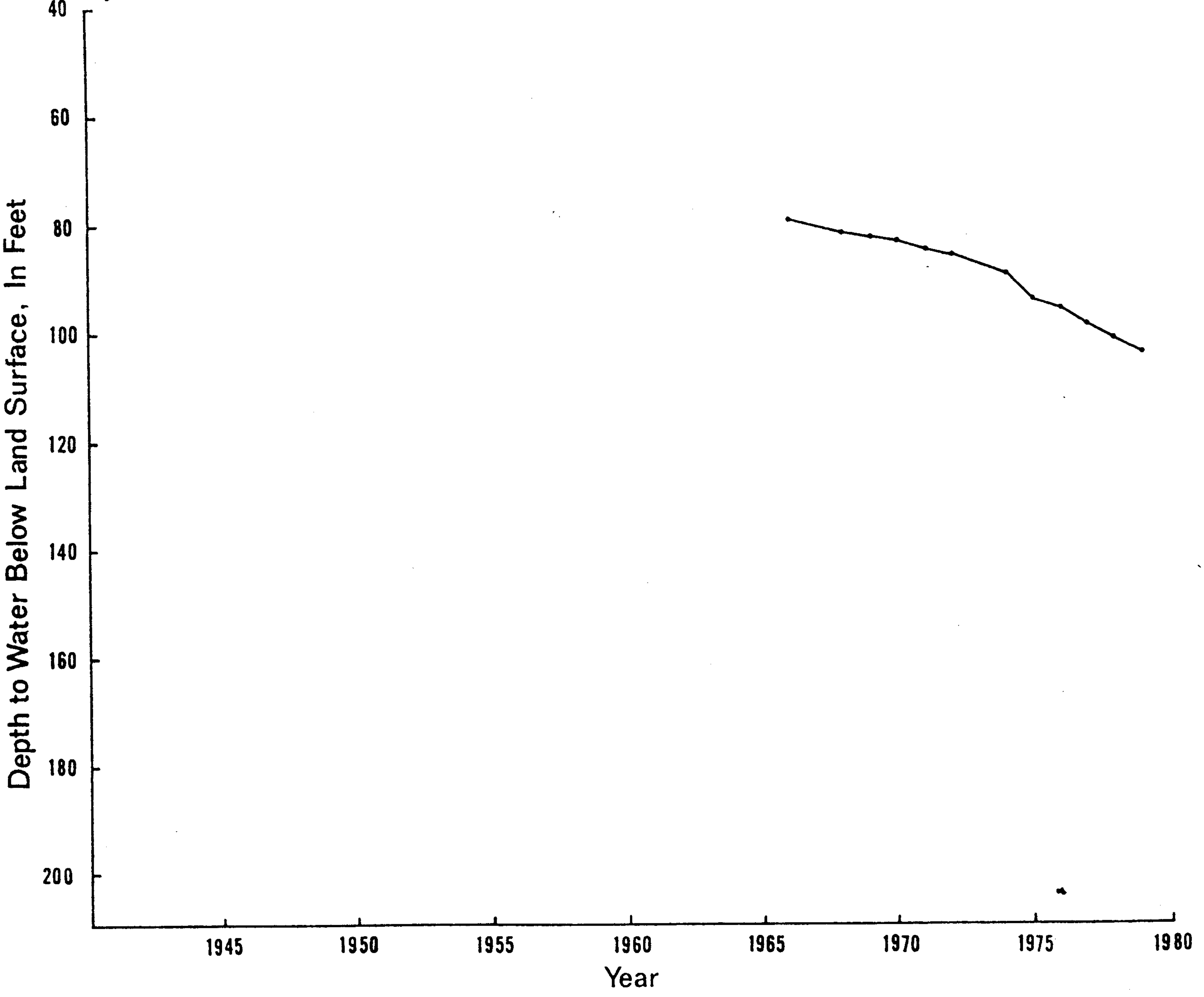
Hydrograph of Observation Well, Finney Co., 23 34w 14 BDC, Well Depth 313′



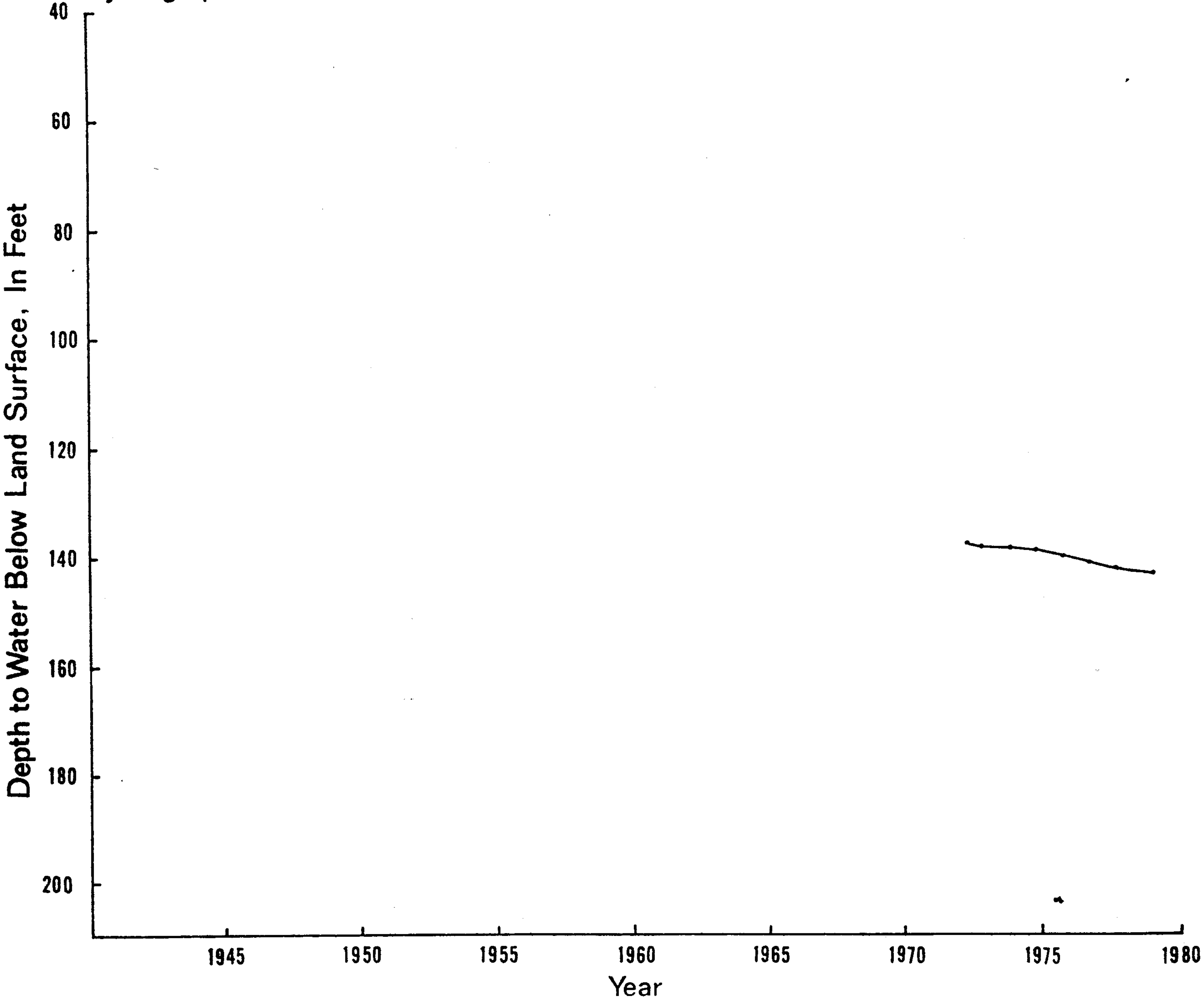
Hydrograph of Observation Well, Finney Co., 24 32w 03 DAC, Well Depth 185′



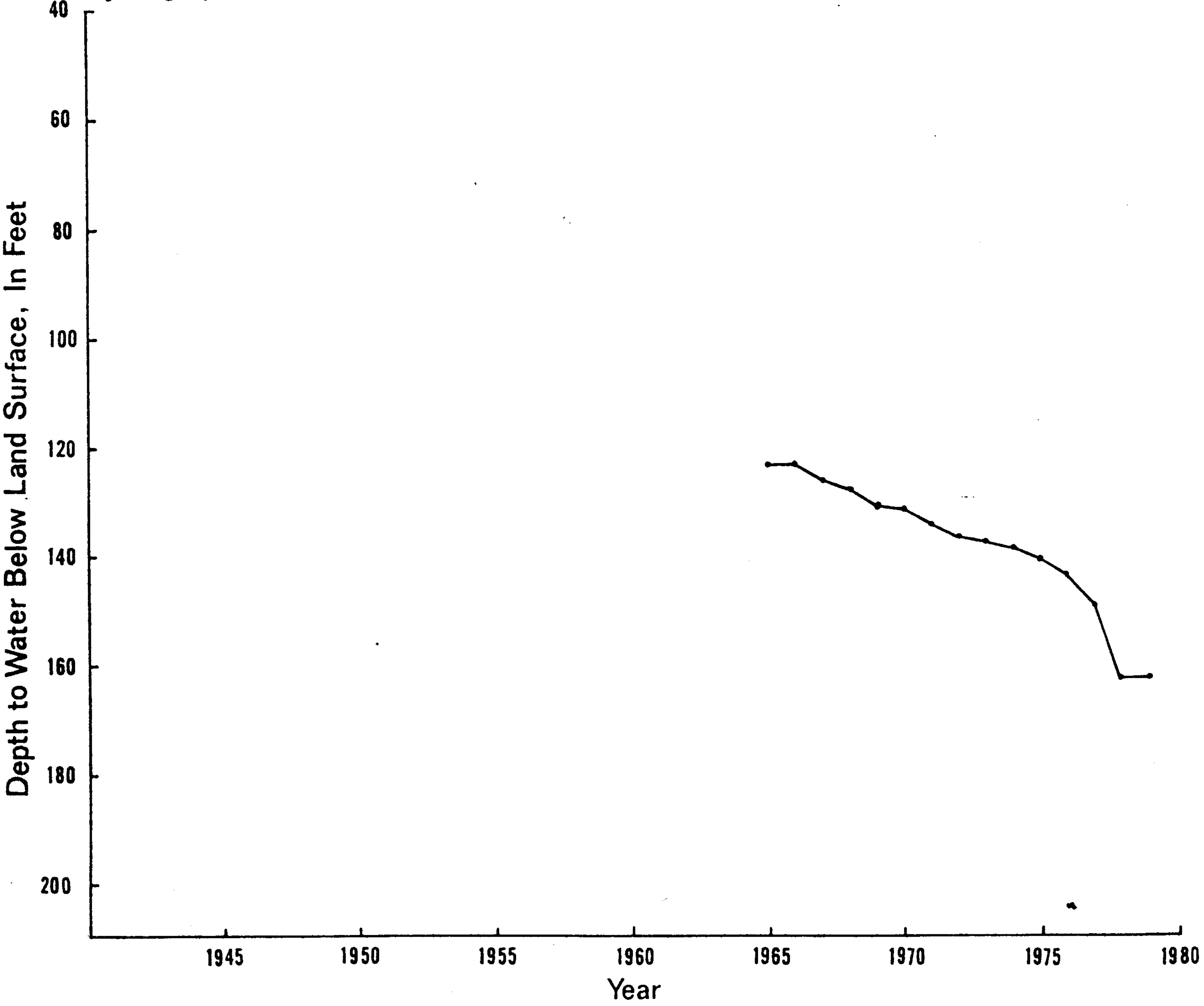
Hydrograph of Observation Well, Finney Co., 25 33w 21 CAC, Well Depth N.A.



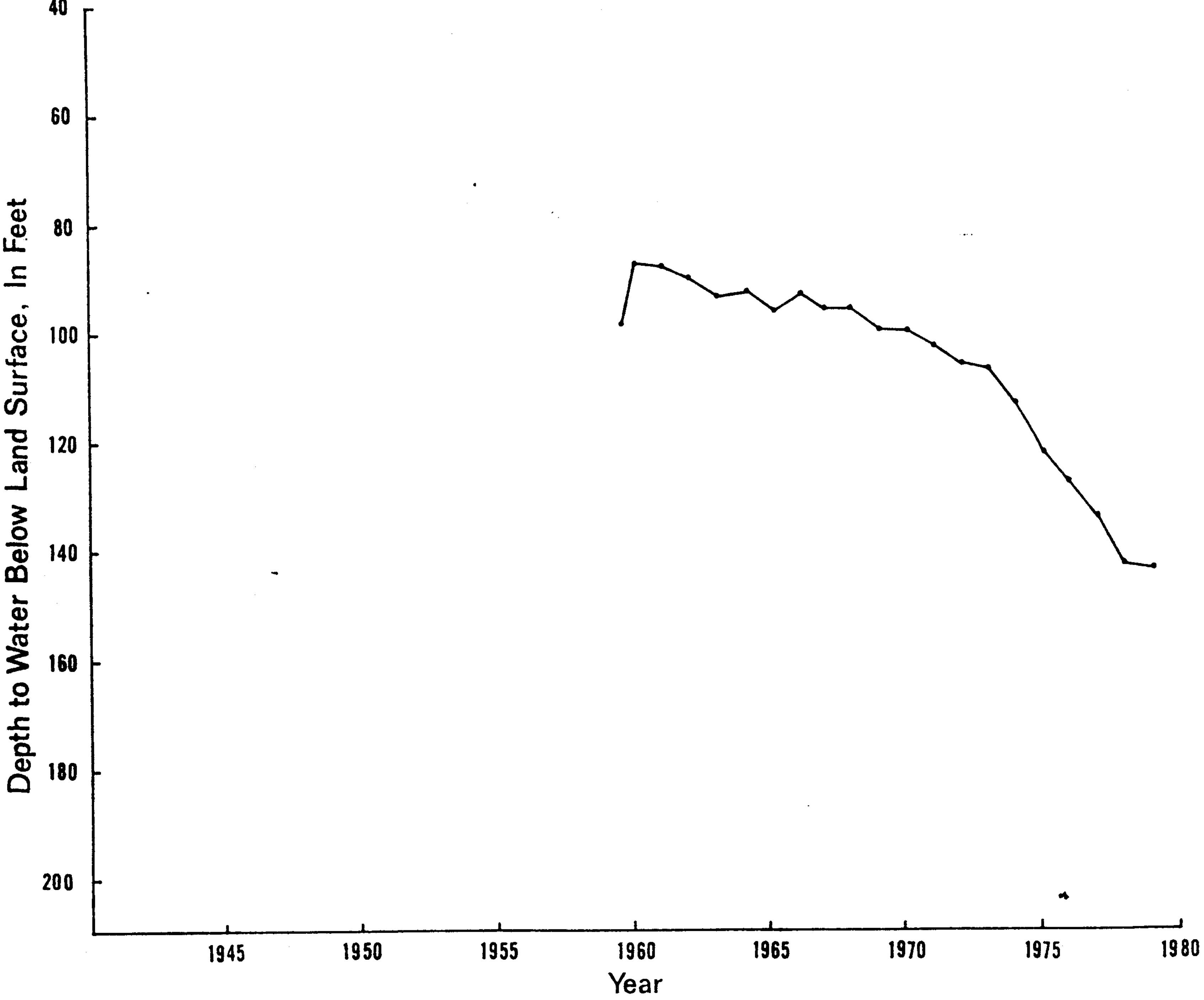
Hydrograph of Observation Well, Ford Co., 29 21w 06 ABB, Well Depth 189'



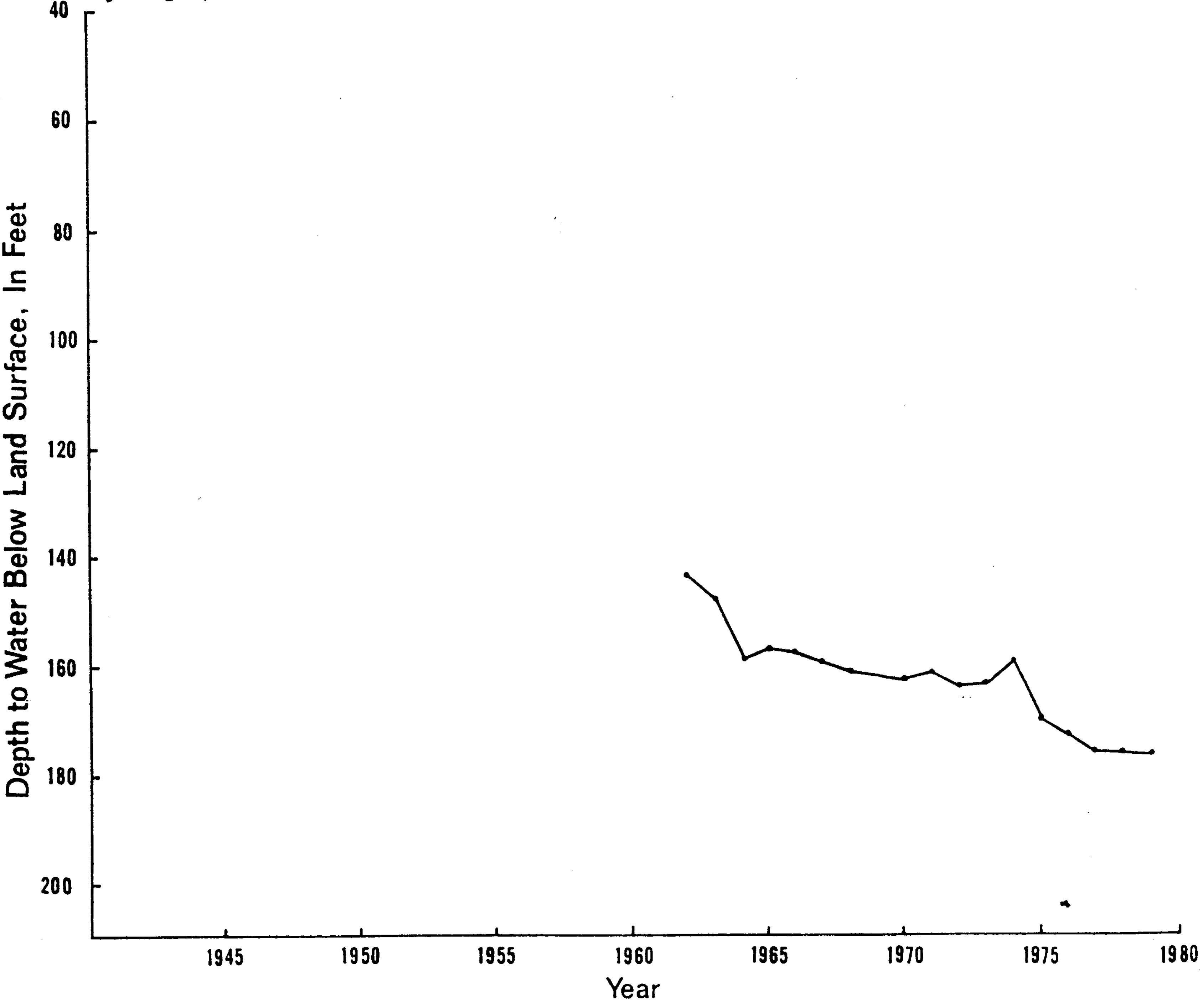
Hydrograph of Observation Well, Gray Co., 28 30w 06 BBA, Well Depth 285′



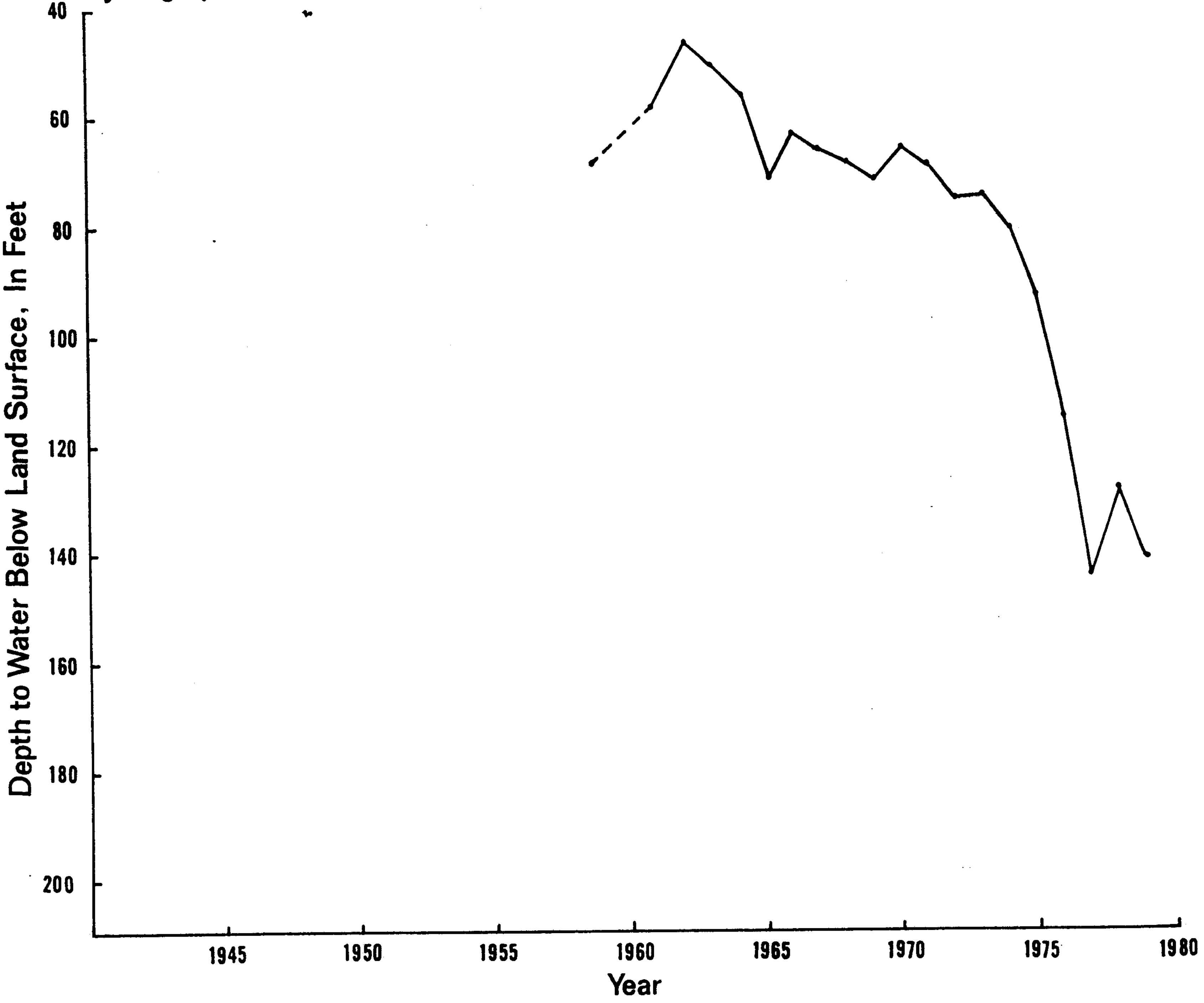
Hydrograph of Observation Well, Hamilton Co., 26 42w 22 CDB, Well Depth 265'



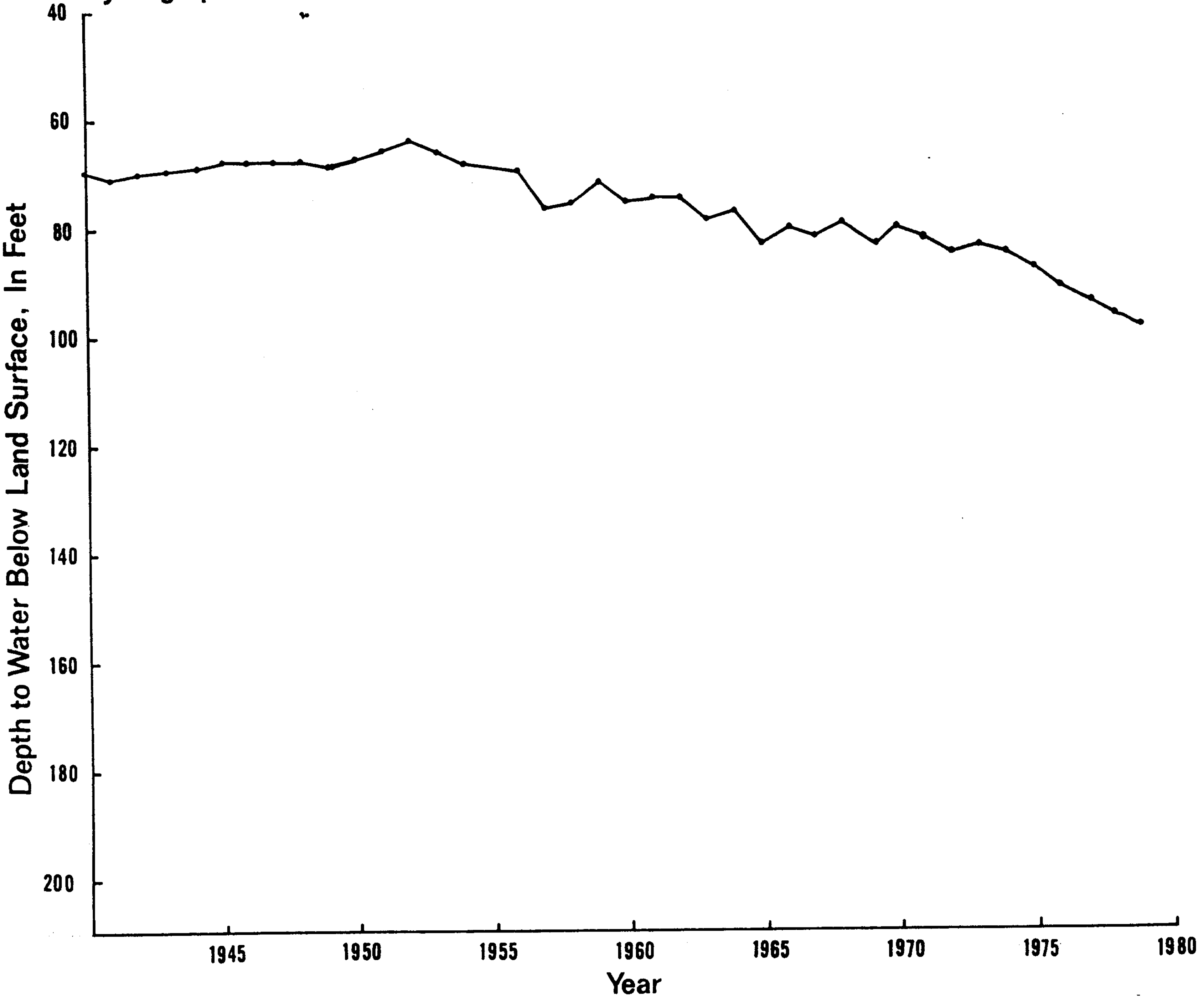
Hydrograph of Observation Well, Kearny Co., 23 36w 32 BBB, Well Depth 307'



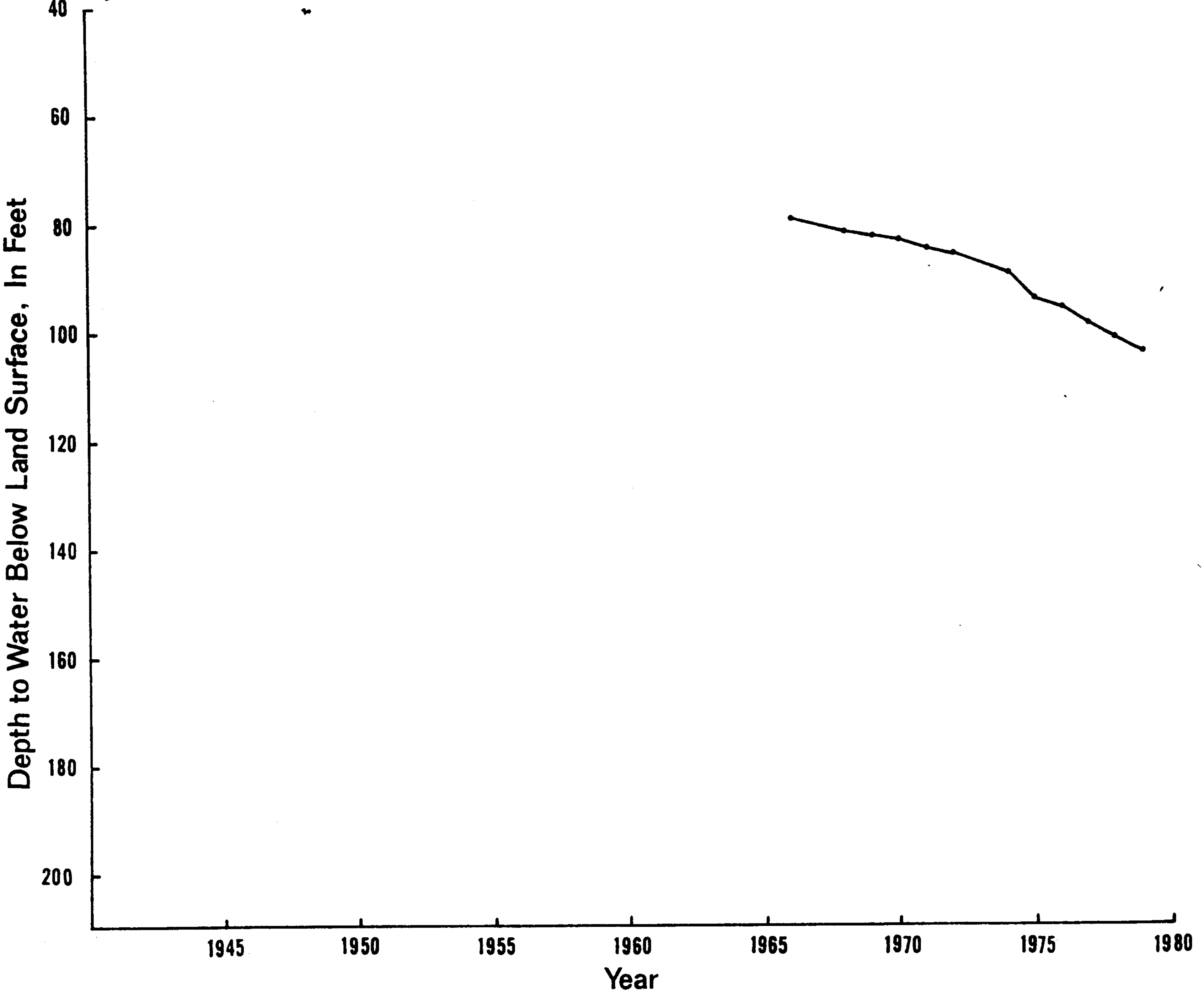
Hydrograph of Observation Well, Finney Co., 23 34w 14 BDC, Well Depth 313'



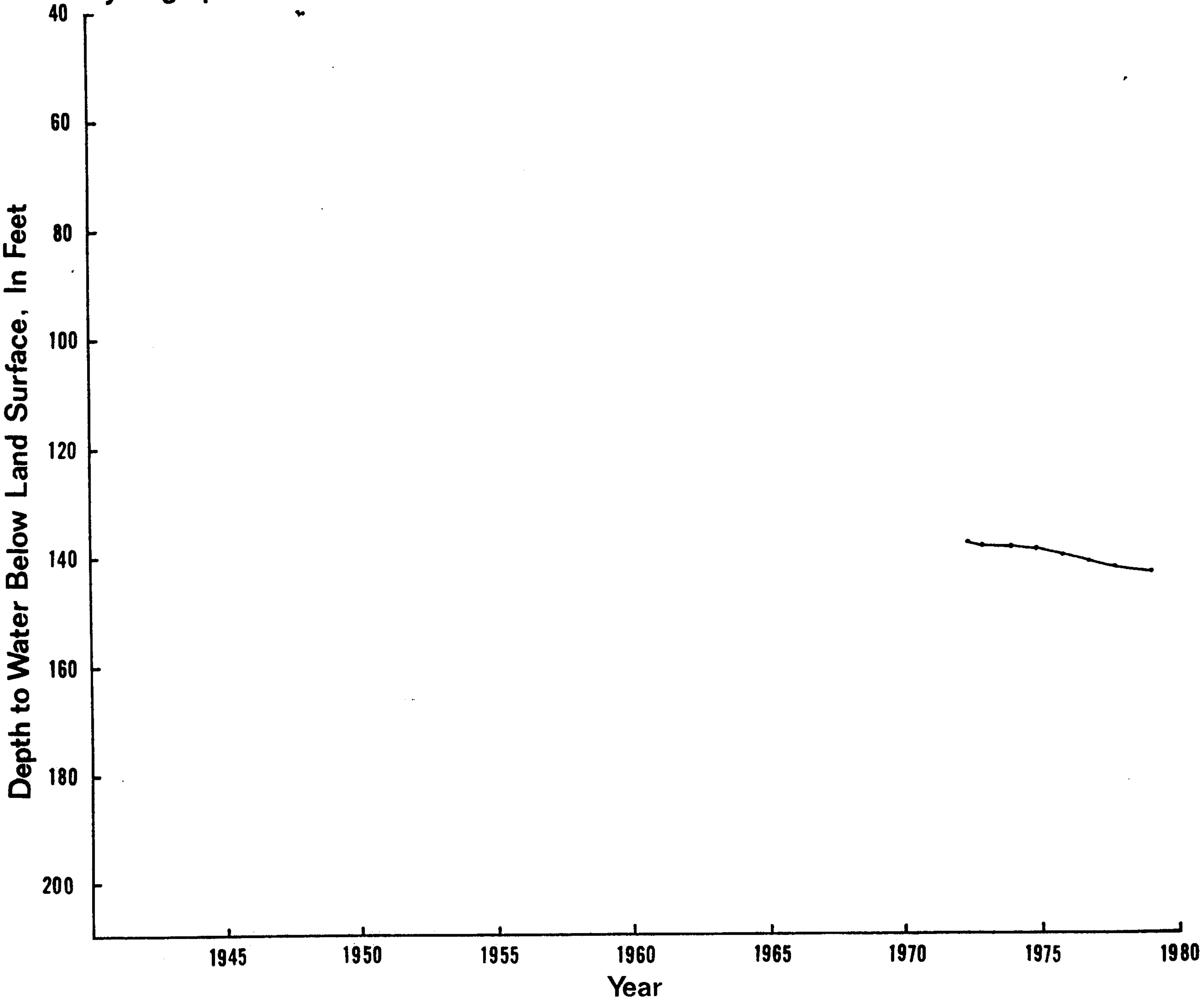
Hydrograph of Observation Well, Finney Co., 24 32w 03 DAC, Well Depth 185′



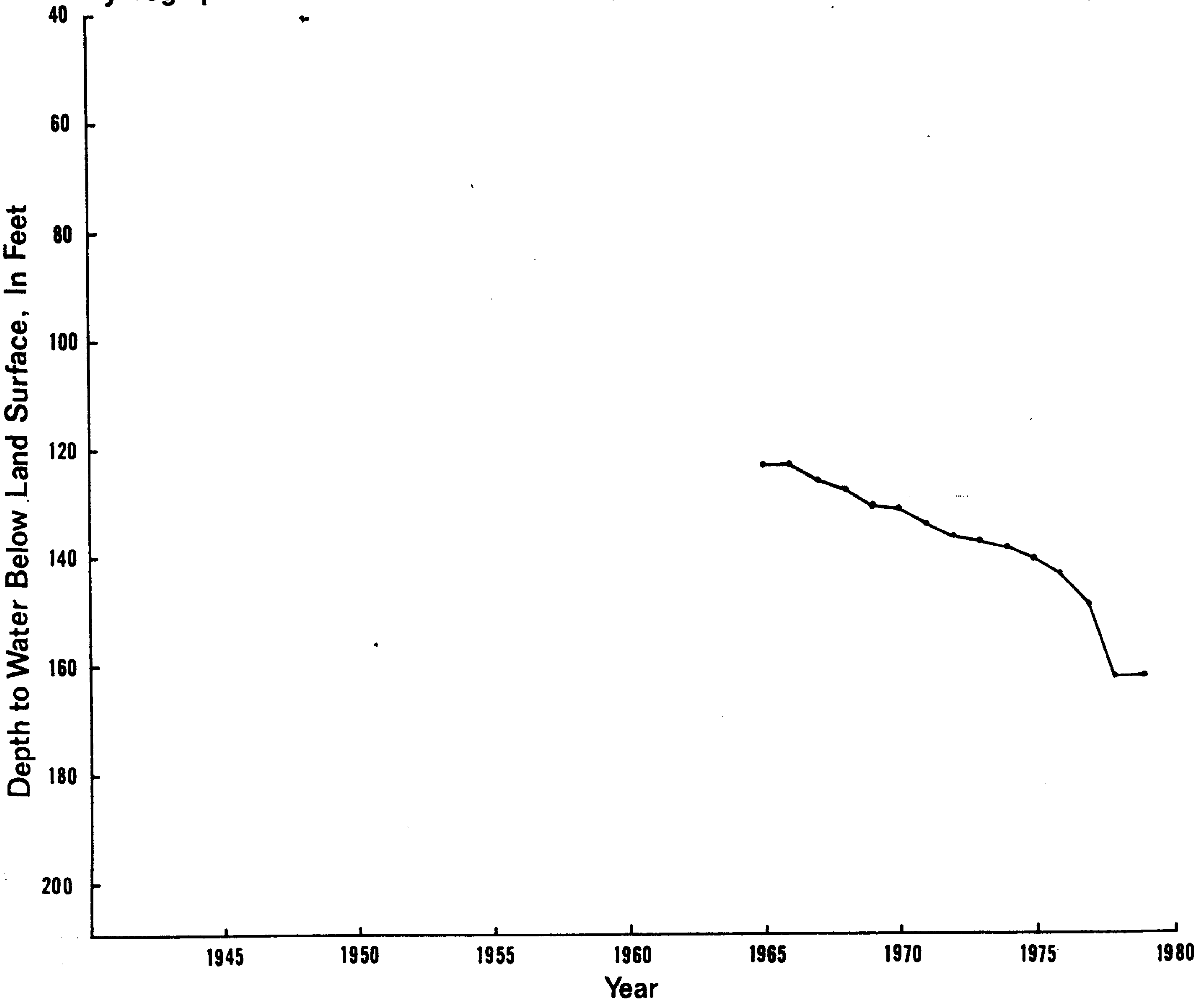
Hydrograph of Observation Well, Finney Co., 25 33w 21 CAC, Well Depth N.A.



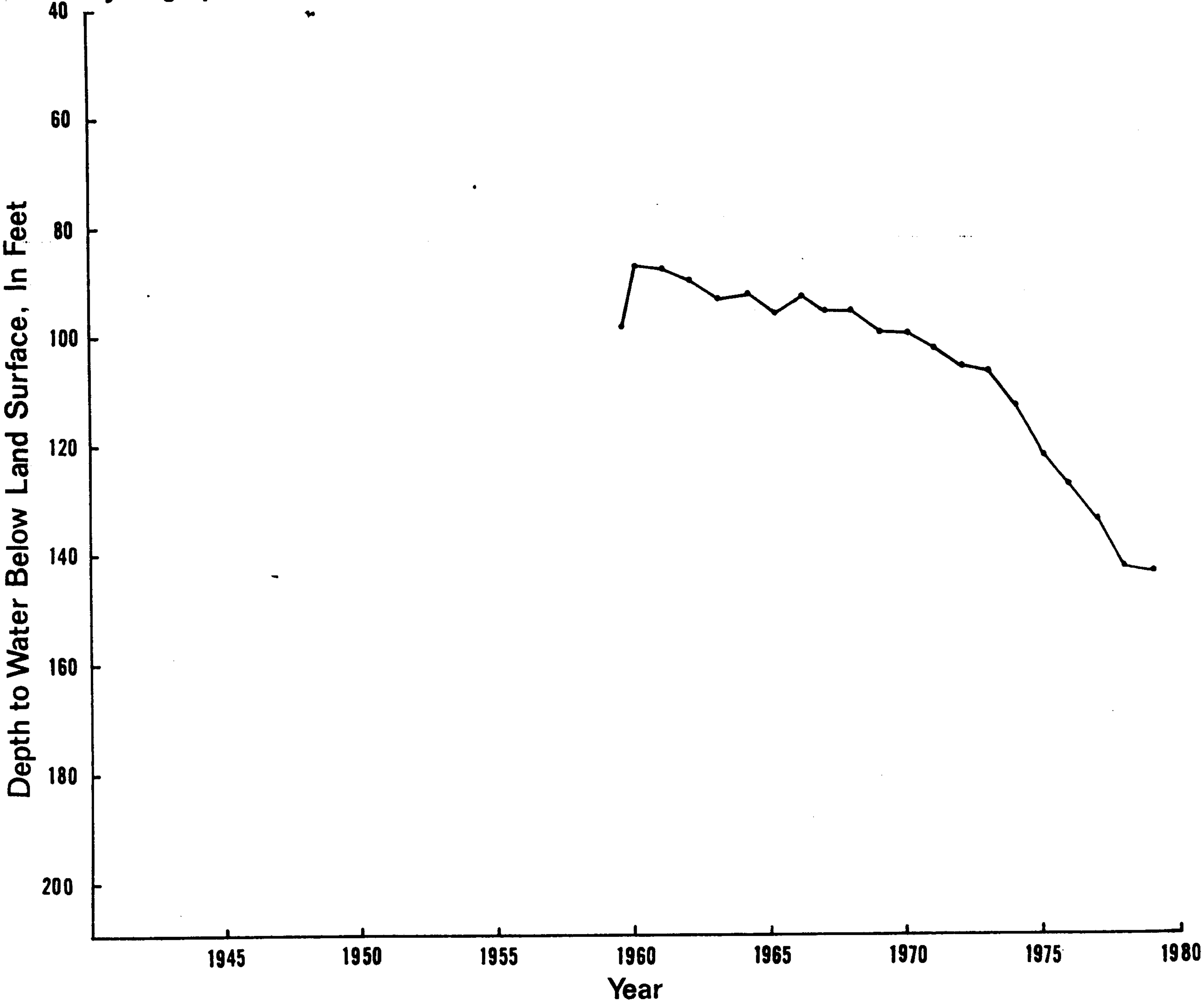
Hydrograph of Observation Well, Ford Co., 29 21w 06 ABB, Well Depth 189'



Hydrograph of Observation Well, Gray Co., 28 30w 06 BBA, Well Depth 285′



Hydrograph of Observation Well, Hamilton Co., 26 42w 22 CDB, Well Depth 265′



Hydrograph of Observation Well, Kearny Co., 23 36w 32 BBB, Well Depth 307'