HYDROGEOLOGY OF PARTS OF THE CENTRAL PLATTE AND LOWER LOUP NATURAL RESOURCES DISTRICTS, NEBRASKA

By J. M. Peckenpaugh and J. T. Dugan

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Multiply U.S. customary units	By	To obtain SI units
acre	0.0040	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.509	square kilometer
degree Fahrenheit (°F)	(°F -32)/1.8	degree Celsius

DEFINITION OF HYDROGEOLOGIC TERMS

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

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

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

Constant head - The condition used in ground-water modeling where water levels are not allowed to change unless the stream or aquifer goes dry.

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

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

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

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

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

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

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

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

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

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

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

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

DEFINITION OF HYDROGEOLOGIC TERMS

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

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

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

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

Seepage measurements - Streamflow measurements made during periods of low flows, when surface-water runoff is at a minimum.

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

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

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

Sustained cultivation - Dryland or irrigated cultivation that can be maintained for an extensive period of time.

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

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

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

Unsaturated zone - The zone between the land surface and the water table, including the capillary fringe.

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

HYDROGEOLOGY OF PARTS OF THE CENTRAL PLATTE AND LOWER LOUP NATURAL RESOURCES DISTRICTS, NEBRASKA

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ABSTRACT

Water-level declines of at least 15 feet have occurred in this heavily irrigated area of central Nebraska since the early 1930's, and potential for additional declines is high. To test the effects of additional irrigation development on water levels and streamflow in the area, computer programs were developed that represent the surface-water system, soil zone, and saturated zone of the hydrogeologic system. A two-dimensional, finite-difference ground-water flow model of the 3,374 square-mile study area was developed and calibrated using steady-state and transient conditions, and three management alternatives were examined. Results indicate that significant additional water-level declines will occur even if there is no additional ground-water development.

The first management alternative examined is diversion of an additional 125,000 acre-feet of water per year from the Platte River. This alternative would have a substantial effect on flows in the Platte River. During a water year in which flows are similar to those in 1957, months of zero streamflow at Grand Island and near Duncan would increase from the historical 2 and 3, respectively, to 7. Projected declines in ground-water levels based on this alternative and the 1976 level of ground-water development are small. After 5 years of such low flows, in 36 model nodes (997.4 acres per node) water levels would decline more than 5 feet, and the maximum decline would be 10.7 feet.

The second alternative examined is to allow no new ground-water development after 1980, but to apply irrigation water at five different rates ranging from a low of 80 percent of consumptive-irrigation requirements (CIR) to a high of 16.0 inches per year (about 125 to 150 percent of CIR) for the western part of the study area. With a medium application rate of 100 percent CIR, water-level declines of more than 20 feet are projected for 20 percent of the study area by the year 2000; maximum projected declines are between 60 and 79 feet. For the same application rate, maximum projected declines by the year 2020 are between 100 and 119 feet.

The third alternative is to allow potentially irrigable but unirrigated land to be developed at an annual rate of 2, 5, and 8 percent and to apply irrigation water at 80, 100, and 120 percent of CIR. Compared to water levels of August 31, 1976, maximum projected declines by the year 2000 for each of the development rates and for 100 percent of CIR are between 60 and 79 feet.

Thirty variations of the last two alternatives were evaluated, and maps showing results of 17 are included in this report. Also included are 10 maps delineating and describing the hydrogeologic characteristics of the aquifer.

Modeling results indicate that water levels will decline. The declines in shallow-water areas will increase the amount of evapotranspiration salvage, will cause more surface water to move into the aquifer, and will cause less ground water to move into the streams.

INTRODUCTION

During the past several decades, the availability of ground water for irrigation has enabled the farmers and ranchers in much of Nebraska to greatly increase productivity. This has been particularly true in this study area (fig. 1). Irrigation itself is not new to the area; both the Platte and the Loup Rivers, between which the study area lies in central Nebraska, have been used as sources of surface water for irrigation since the 1890's. However, limitations on the availability of surface water, the widespread availability of ground water and other factors spurred the use of and dependence on ground water for irrigation, so that now part of this area has the highest irrigation-well density of any comparable area of the State.

Ground-water supplies, while rechargeable in most instances, are not infinite, and in several areas of the State intensive withdrawals of ground water severely strain the capacity of the ground-water system so that water levels are declining. Although no severe problems of water-level decline have as yet been identified, progressive water-level declines are occurring in parts of the study area. Declines of at least 15 feet have been measured in parts of Dawson and Buffalo Counties.

The potential for additional water-level declines is high for several reasons. First, current ground-water pumpage for irrigation, which caused the present declines, will continue. Second, within the area, additional development that will accelerate current declines is likely. Finally, additional ground-water irrigation west of the study

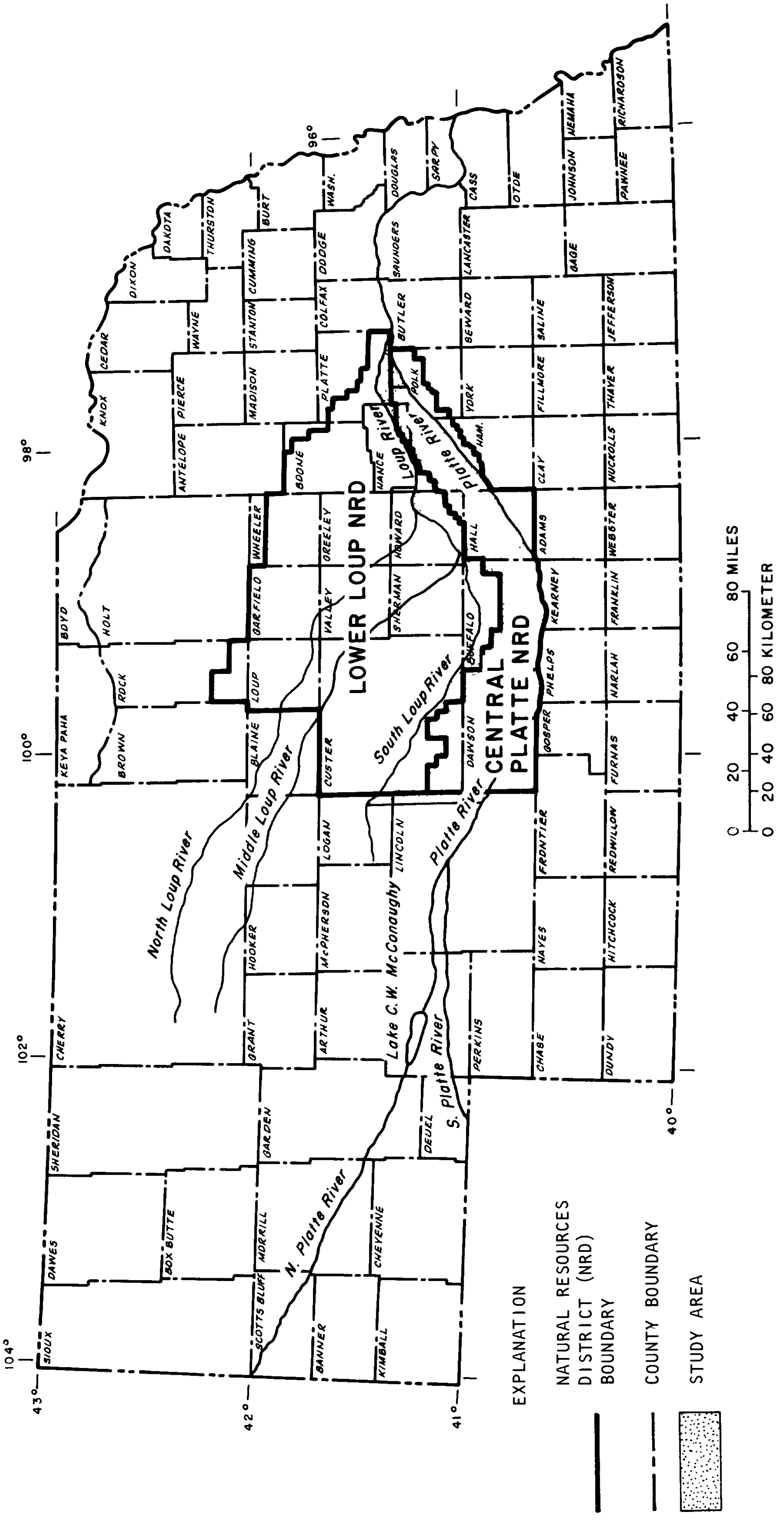


Figure 1.--Locations of the study area.

area and additional surface-water diversions from the Platte River may result in additional water-level declines, but only if these developments reduce the annual flows of the Platte River within the study area below a critical level. Fred Otradovsky of the U.S. Bureau of Reclamation, Grand Island, Nebr. (personal communication, 1983), believes a reduction of 50 percent in streamflow would cause less than a 1-foot drop in river stage. Such a drop in stage would produce additional but only small declines in ground-water levels.

The continuation of additional water-level declines is predictable; however, the location and magnitude of future declines are less predictable. Realizing this, the Central Platte and the Lower Loup Natural Resources Districts, in 1977, entered into an agreement with the U.S. Geological Survey to do a quantitative hydrogeologic study of the area. The results of this study are to serve as a basis for testing the effects of various management alternatives for additional irrigation development on water levels and streamflow in the study area and are the subject of this report.

Purpose and Scope

There are two principal purposes for this study. The first is to describe the hydrogeologic system of the study area. The second is to develop and demonstrate a capability for evaluating, quantitatively, the effects of different management alternatives on water levels and on streamflow in the study area.

In this study, the different components of the hydrologic system -- surface-water system, soil zone, unsaturated zone, and saturated zone -- were analyzed using mathematical programs whenever possible. These programs are linked to form a single model of the system so that the responses of the entire system to variations imposed on it can be simulated mathematically. The surface-water system is included in the model only to the extent necessary to determine the effects of surface water on recharge to the ground-water reservoir, or the converse.

Few new field data were obtained for this study. Hydrologic and geologic data obtained by previous investigators were reviewed and reinterpreted using numerical techniques. Also, large amounts of data on land use, climate, and water use were obtained from others. Such data are essential input in evaluating the effects of different management alternatives on the water resources of the study area.

Management alternatives for evaluation were selected in consultation with the Central Platte and the Lower Loup Natural Resources Districts. A total of 30 variations of alternatives were examined. Of these, results of the 17 most representative variations are shown in maps and tables of this report.

Previous Studies

Several previous investigations were made to determine the geology and hydrology of this area. Three cover nearly all of the present study area that lies within the Platte Valley -- the flood plains and terraces between the Platte and Loup Rivers -- and provide historic records, such as those of water levels, critical to this study. Reports on studies of smaller areas provide insight into special problems of local interest. Most of the previous studies were limited to terraces and flood plains of the Platte and Loup Rivers.

Lugn and Wenzel (1938), in an early study of south-central Nebraska, describe in detail the geology and hydrology of nearly all of the Platte Valley included in this study area. They discuss the origin, character, and thickness of the Pleistocene water-bearing materials in the Platte Valley, present logs of about 75 test holes, provide maps showing depth to water from the land surface and elevation of the water table during the summers of 1931 and 1932. They also discuss development of both surface- and ground-water irrigation up to 1932.

Wenzel (1940) investigated declining water levels beneath the city of Grand Island. He concluded that the cause was excessive pumping from wells too closely spaced and recommended that wells be installed outside the city so that pumping stress could be distributed over a larger area.

Several studies were made in the 1940's and 1950's as part of the program of the Department of the Interior for development of the Missouri River Basin. Waite and others (1949) supplemented existing hydrogeologic information on the Platte Valley from North Platte to Fremont, Nebr. Maps were presented that show net changes in water levels from 1930 to 1939 and from 1939 to 1946 and that show the elevation and configuration of the water table in March 1947.

Several areas investigated under the Missouri River Basin Program were being considered for project development by the U.S. Bureau of Reclamation. These areas cover a major part of the present study area. Keech (1952) describes the ground-water resources of the Wood River Unit from near Kearney to near Wood River, Nebr., a 233 square-mile area proposed for a balanced surface- and ground-water irrigation system.

Sniegocki (1955) describes the ground-water resources of the Prairie Creek Unit, a 650 square-mile area between the Loup and Platte Rivers extending from near Grand Island to Columbus. Schreurs (1956) describes the geology and ground-water resources of Buffalo County and parts of adjacent Dawson and Hall Counties, where consideration also was being given to development of a balanced surface- and ground-water irrigation system. Keech and Dreeszen (1964), in a report on the availability of ground water in Hall County, include a map showing the elevation and configuration of the water table in 1961. Their study, however, was not a part of the Missouri River Basin Program.

Several hydrogeologic studies have been conducted in the Loup River basin, but only one included any of the present study area. In that one, Hyland and Keech (1964) describe the ground-water resources of the Cedar Rapids Division in southeastern Howard and northwestern Merrick Counties.

More recently, hydrogeologic studies have been conducted for parts of the study area using ground-water flow models. Marlette and Lewis (1973) and Marlette and others (1974) discuss the development and results of a study using such a model for the Platte River valley of Dawson County. Also, Lappala and others (1979) used such a model in a study of the entire Platte River basin, which included all of the study area.

Bentall (1975a) describes the physiography, geology, soil, and agriculture of a large part of the study area. Bentall (1975b) also describes the hydrology of the study area and upstream reaches of the Platte River. In his reports, Bentall reviews previous studies and discusses the above items as they relate to a proposed surface-water diversion project in this area.

General Methodology

The general methodology for this study was first to subdivide the hydrogeologic system into four components -- surface-water system, soil zone, unsaturated zone, and saturated or ground-water zone. Computer programs were developed or obtained to represent each of the components except the unsaturated zone, for which this was not possible.

A ground-water flow model was developed to represent the hydrogeologic conditions in the area over time. Hydrogeologic data, necessary for the model, were obtained mainly from previous investigations. However, data on recharge and consumptive-irrigation requirements (CIR) were obtained either from existing files or were generated, in part, through use of computer programs. The model was then calibrated using the above data, and several management alternatives were simulated with the calibrated model.

The hydrogeologic data are those needed to describe the characteristics of the ground-water system. They include but are not limited to hydraulic conductivity, specific yield, base of the aquifer, and elevation of the water table. Recharge and CIR data, hereafter called "recharge-CIR data", are those necessary to generate data on deep percolation and discharge required for the ground-water flow model. Recharge-CIR data provide information on soils, climate, water requirements of plants, land use, irrigation-well distributions, acres irrigated per well, surface-water irrigation and seepage, and stream flow.

Acknowledgments

The authors appreciate the cooperation given by the Central Platte and Lower Loup Natural Resources Districts during this study. Also appreciated is the assistance of representatives of the U.S. Bureau of Reclamation and of the Nebraska Natural Resources Commission in obtaining data and programs. Special thanks are extended to Eric G. Lappala, the first project leader of this study, who worked with the cooperators in developing the study, developed numerous procedures, programs, and data used in the study, and provided technical guidance on many occasions.

PHYSICAL SETTING

The physiography, geology, climate, soils, natural vegetation, and land use of the study area are extremely important in influencing the surface-water and ground-water developments of the area. These features have also been instrumental in determining urban and rural development and the general economic systems of this area, which are strongly dependent upon agriculture, especially irrigated agriculture.

Location and Extent

The study area is shown in figure 1. It comprises all of the Central Platte Natural Resources District (NRD) north of the Platte River and all of the Lower Loup NRD south of the South Loup, Middle Loup, and Loup Rivers. The study area was extended 3 miles west of the western borders of Dawson and Custer Counties so that modeling errors near these borders could be minimized. The study area includes 3,374 square miles. Its maximum east-west distance is 155.7 miles and its maximum north-south distance is 59.3 miles.

Physiography

The study area lies within the High Plains section of the Great Plains Province. From central Hall County eastward, the study area does not fit the standard geologic description of the High Plains because the Tertiary materials are absent. A substantial Quaternary mantle is present in this area, and there is no surficial difference between areas where the Tertiary materials are present or absent.

Significant contrasts exist between the topography in the valleys and uplands of the study area. Three major topographic types are present: (1) uplands, (2) terraces, and (3) flood plains. Figure 2 delineates the location of these types. This figure was developed from soil maps of the area (Hayes and others, 1924, 1925, 1926, 1928; Veatch and Seabury, 1918; Paine and others, 1929).

The uplands are predominantly loess-mantled, highly dissected, and generally not suitable for sustained cultivation. However, relatively large tablelands are found in Custer County and small, flat interfluves occur in Dawson and Buffalo Counties. Both of these land forms support irrigated agriculture. Significant areas of the uplands and high terraces in southwestern Custer County, southeastern Howard County, and northern Merrick County are mantled with dune sand stabilized by grass. Most of this sandy material exists as a relatively thin veneer over loess (wind-blown silt) or as silty deposits that have drifted in from the Sand Hills or other nearby sources of sand.

The terraces and flood plains are the result of entrenchment of the Platte and Loup Rivers and their tributaries at elevations from 50 to 150 feet below the uplands and tablelands. The Platte River was superimposed on the existing Tertiary landscape, and Quaternary materials were deposited during periods of aggradation, while some of these materials and other units were eroded during periods of degradation. The terraces are primarily covered by a loess mantle with a sandy or gravelly substratum. The loess in some areas is reworked with sandy alluvium; whereas, in other areas it is eroded so that the terraces are covered by a silty and clayey alluvium.

The flood plains along the Platte River gradually blend into the terraces. Those along the north side of the river are more extensive than those on the south side. The flood plains in all but the downstream reaches of the Wood and South Loup Rivers are so narrow that they are not mappable at the scale used in figure 2. The flood plain of both streams widens toward the east, that of the Wood River as it merges with the flood plain of the Platte River and that of the South Loup River as it nears its confluence with the Middle Loup River. The flood plains

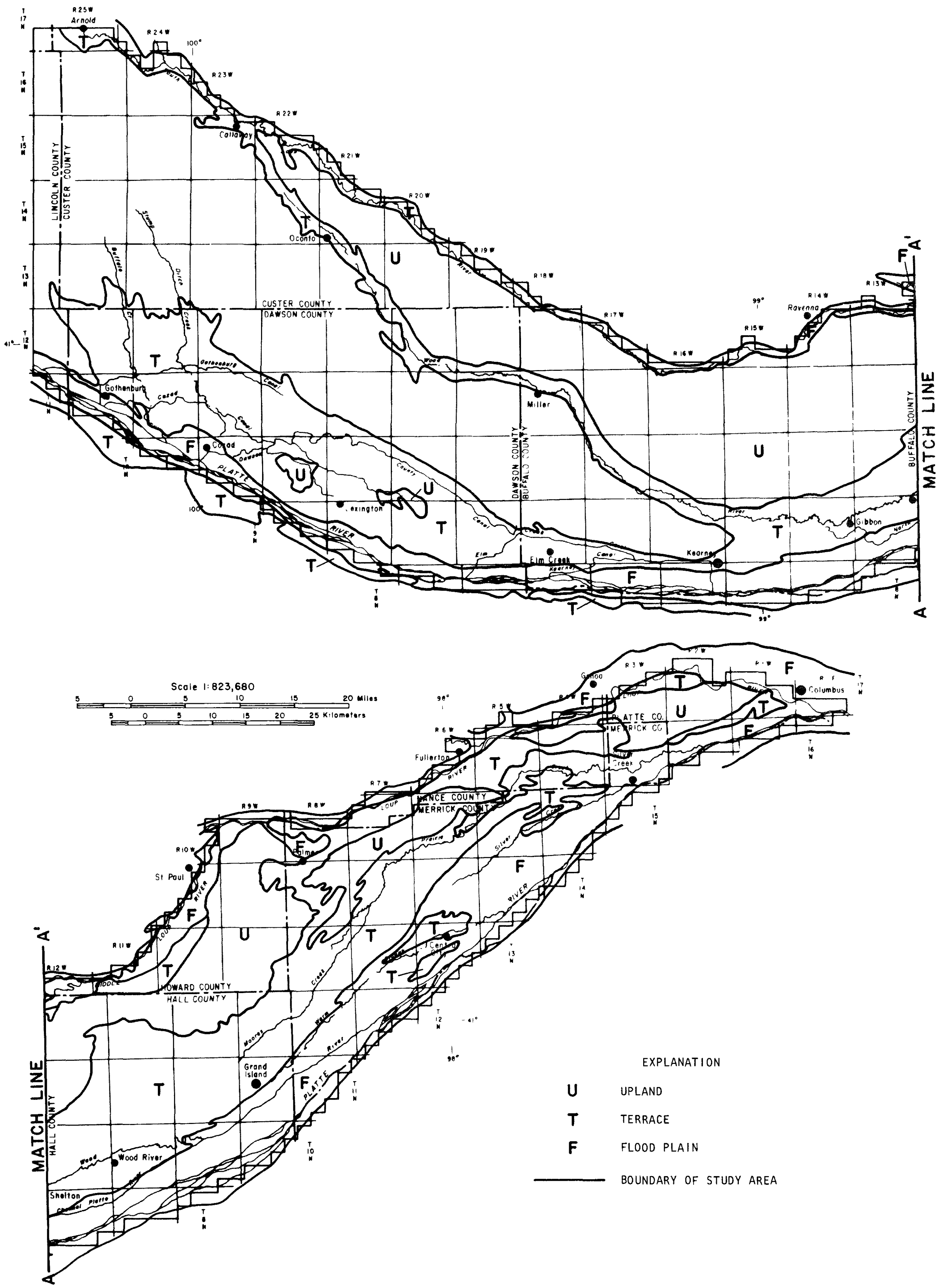


Figure 2.--Distribution of topographic types.

are usually covered by sandy, silty, and clayey materials that reflect the energy, or carrying capacity, of the moving water and their depositional history. However, some of the terraces and flood plains, near Shelton and west of Grand Island, are mantled with dune sands.

The width of the Platte Valley varies throughout the study area. It is about 12 miles wide east of Gothenburg, but narrows to about 6 miles near Elm Creek and to 3 miles west of Kearney. From there to western Merrick County it widens to a maximum of 17 miles. The terraces and flood plains of the Middle Loup and Loup Rivers, beginning in western Hall County, increase significantly in width from upstream reaches in which the valley is 1 to 4 miles wide. From Merrick County eastward to the confluence of the Loup and Platte Rivers, the Loup and Platte River valleys merge but are separated in two areas by uplands where dune sands have been deposited forming sandhills.

Land-surface elevation of the study area varies from 3,088 feet in the west to 1,405 feet in the east. From west to east, the Platte Valley declines from 2,400 feet to about 1,550 feet, which is an average slope of 7 feet per mile. West of Kearney the topography is rougher and has a steeper riverward slope than east of Kearney. From Merrick County eastward, the topography is nearly level, having slopes only slightly greater than those of the Platte River, except in northern Merrick County where rough sand dunes occur. Throughout most of the valley, the terraces merge gradually into the flood plains.

Geology

Quaternary deposits comprise the land surface in the study area and form the most significant portion of the saturated zone from the middle of Hall County eastward. These deposits are sands, gravels, silts, and clays of fluvial origin and silts and clays of eolian origin. The thickness of these deposits varies from about 20 feet in the Platte Valley of southwestern Buffalo County to about 350 feet in the upland of eastern Dawson County.

In the study area, several episodes of fluvial and eolian deposition were followed by periods of erosion and soil formation during Quaternary time. These events were related to the advancing and retreating (melting) of continental ice sheets in eastern Nebraska. These ice sheets blocked the valleys of eastward-flowing streams and diverted their flow southward and southeastward along the ice margins.

The diversion of these streams lowered their gradients and reduced their sediment-carrying capability. The streams aggraded their valleys and eventually constructed alluvial plains in front of the ice sheets. After melting of the ice sheets, the sediment load of these streams decreased. The level to which the streams could erode valleys into the alluvial plain lowered, and subsequent erosion produced a new landscape of valleys and uplands.

Within each depositional sequence, the lower part is generally coarse-textured sediments, sands and gravels, while the upper part is finer-textured sediments, silts and clays, which, in some cases, were largely removed during the erosional intervals. Thus, in many places the sand and gravel deposits of one sequence occur vertically adjacent to those of another sequence, or are separated only by thin layers of clay or silt.

The Quaternary deposits in the upland areas contain thicker intervals of silts and clays than in the flood plains and terraces, because the silts and clays in uplands were less subject to removal during erosional intervals. As a result, thick units of silts and clays, primarily loess, still remain beneath the uplands. However, only a few feet of loess remain beneath the flood plains and terraces because most of it has been removed by erosion or has been reworked into alluvium. The loess and loess-like alluvial deposits are the most extensive surface deposits in the study area.

Upper Quaternary dune sand covers parts of southwestern Custer County and extensive areas between the Platte and Loup River valleys in Hall, Merrick, Howard, Nance, and Platte Counties. These dune sands usually rest on loess. In several small areas, dune sand has been reworked from existing sand deposits to form areas of rough topography.

Alluvium, consisting primarily of reworked loess, mantles most terraces in the Platte Valley. Its deposition probably alternated with the deposition of silt and fine sand blown from the loess-mantled uplands. The thickness of the alluvium ranges from 50 feet, adjacent to the uplands, to zero feet at the margins of the terraces and flood plains. Alluvium extends up the Wood River valley and other stream valleys that drain the uplands.

The Tertiary Ogallala Formation lies immediately below the Quaternary deposits in the study area from the middle of Hall County westward. The Ogallala Formation, fluvial in origin, consists of semiconsolidated calcareous silt, sand, and sandstone with some interbedded marly zones, and with a basal gravel at some locations. The thickness of the Ogallala Formation ranges from zero feet at its eastern extent in Hall County to over 540 feet in Dawson and Custer Counties and is related to the topography of the underlying Cretaceous bedrock.

Cretaceous bedrock units, which are thick beds of shale with some thinner beds of shaley chalk and chalk are not considered hydrologically important to this study. These units directly underlie the Ogallala Formation and the Quaternary deposits where the Ogallala Formation is not present. The bedrock surface, which was produced by erosion, consists of valleys and intervalley ridges that are unrelated to the present land surface. The total relief of this buried surface is about twice the present land surface.

Climate

The climate of the study area, which has irregular precipitation, low to moderate humidity, hot summers, and severe winters, is typical of regions within large continents in the mid latitudes. The average temperature of the warmest month, July, ranges from 75° to 78° F across the study area, whereas, that of the coldest month, January, ranges from 22° to 26° F. Extreme temperatures range from -40° F to 117° F. The winters are slightly milder in the western part of the study area, and the summers are warmer and more humid in the eastern part. The growing season (period between killing frosts) averages from 150 days in the west to 160 days in the east.

Variability characterizes precipitation in the study area. Mean annual precipitation from 1931 to 1976 ranged from about 19.3 inches in the western part to about 24.8 inches in the extreme east. Annual precipitation frequently varies from the mean by 50 percent. Drought periods can last for several years. Noteworthy droughts since the last century occurred in the mid-1890's, 1930's, mid-1950's, and mid-1970's. The dry periods were accompanied by warmer-than-average temperatures, and increases in desiccating winds increased evapotranspiration losses and intensified drought conditions. Frequent short-term deficiencies of precipitation during the growing season often have serious effects on crop production. Although from 70 to 80 percent of the annual precipitation normally occurs during the growing season of April through September, it often is irregularly distributed. Precipitation generally is uniformly distributed over the study area from September through April because of its cyclonic or frontal origin. From May through August; however, most precipitation is the result of convective activity (thunderstorms); thus, it is distributed nonuniformly.

Potential evapotranspiration (PET) in the study area exceeds average annual precipitation. Although precipitation ordinarily exceeds PET from October through May, PET exceeds precipitation from June through September. Low humidity, periods of persistent winds, and a high incidence of sunshine contribute to high PET rates.

Soils

The soils of the study area are indicative of the climatic, geologic, and biotic factors that influence their development. The major soil characteristics resulted from the development of the soils on loess, or loess-like fluvial silts, in a semiarid to subhumid climate with a grassland regime. Development under such conditions produced dark, granular, relatively thin topsoils. Several of the soils possess an argillic horizon, which is an accumulation of clays in the upper subsoil resulting from downward movement of fine-grained materials (clays) during soil development.

The soils and topography of an area are strongly related. This is apparent from a comparison of the soils and topographic-types maps (fig. 3 and 2, respectively). On figure 3, the soils in the study area have been grouped according to hydrologic properties. The following discussion illustrates the relationships between soil groups and topography.

Dissected uplands are composed of soils possessing minimal development that are formed on loess. These soils comprise the Coly-Colby-Uly-Ulysses group (map symbol "F" on fig. 3).

Level uplands and high terraces exhibit much deeper soil development. They are formed on loess and reworked loess, with the major group being Holdrege-Hord-Hall-Kenesaw (map sumbol "E"). The substrata of some terrace soils may be sandy alluvium. These soils have moderate to low permeabilities and are well suited for irrigation.

Extensive areas of the uplands and terraces are mantled with highly permeable soils as a result of their formation in sandy alluvium or eolian sands. The Ortello-Blendon group (map symbol "D") and the Valentine-Thurman group (map symbol "G") are these types of soils.

Parts of the lower terraces that formed in loess and silty alluvium have a well-defined claypan and are slowly permeable and, in places, poorly drained. These soils form the Wood River - Silver Creek group (map symbol "H"). The Inavale-Loup-Alda-Platte group (map symbol "A") and the O'Neill-Sarpy group (map symbol "I") also occupy the lower terraces, but have been derived from sandy materials and are highly permeable and well drained.

Flood-plain soils include a variety of textural types ranging from silty or clayey to sandy, with the more sandy soils predominating. The Gibbon-Lamo group (map symbol "C") occupies clayey bottomlands; whereas, the Wann-Cass-Leshara group (map symbol "B") occupies sandy bottomlands. All of these soils are poorly drained as a result of seasonal high-water tables.

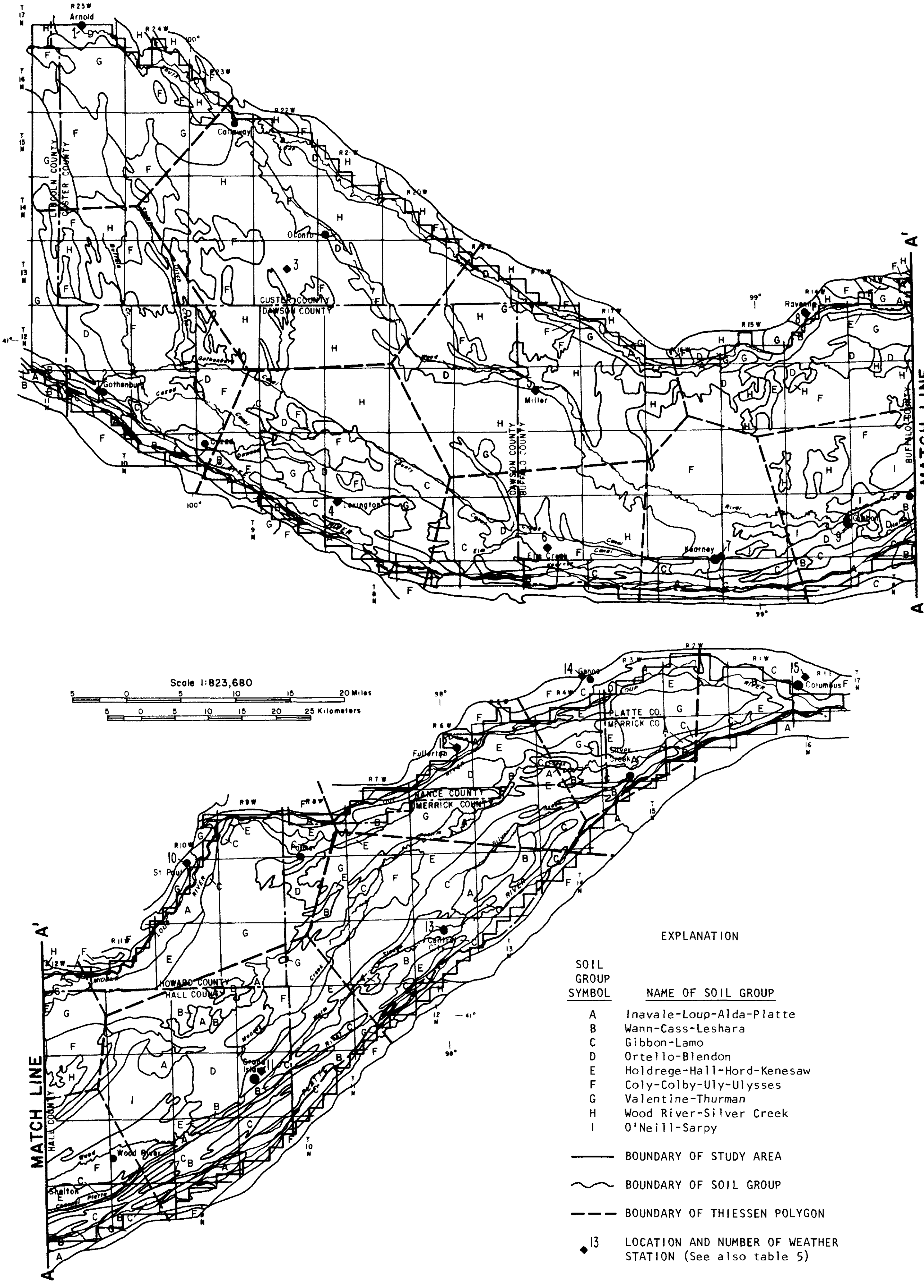


Figure 3.--Distribution of soil groups and Thiessen polygons used to distribute point climatic data.

The agricultural potential of most soils in the study area is high. Only the soils of the dissected uplands, which are thin and sloping, and of certain bottomlands, which are poorly drained because of frequent high-water table conditions or presence of a clay layer, have low agricultural potential.

Natural Vegetation

The natural vegetation of the study area has largely been replaced by cultivated crops. Only in the dissected uplands and along the streams, where conditions are not conducive to cultivation, do large tracts of natural vegetation remain.

The natural vegetation consists primarily of grasslands known as the mixed prairie. Weaver and Albertson (1956) divide the natural vegetation of the study area into three principal plant communities. Short grasses capable of thriving with low soil moisture predominate on the hilltops of the uplands. Tall and midgrasses of the true prairie occupy the bottoms, low terraces, and lower slopes of the hills where more moisture is available. Mixed short and taller grasses occupy the side slopes between hilltops and bottoms.

The mixed prairie gradually gives way to the true prairie to the east of Grand Island. Here the taller grasses become dominant as mean annual precipitation increases.

Most of the grasses, particularly the short varieties, have extensive root systems in relation to top growth. Roots often extend 4 to 7 feet downward with significant lateral expansion. Many of these grasses produce dense, tough sod that stabilizes the soil and limits runoff. Consumptive water requirements of the native grasses are nearly the same as those of legumes.

Along permanent streams, woodlands are present that contain both natural and introduced species. Many of these species, such as willows, are phreatophytes that have high consumptive water requirements.

Land Use

Agriculture is the predominant land use for at least 90 percent of the study area. Forty percent of the agricultural lands are unsuitable for cultivation and are left as rangeland. Most of the remaining agricultural lands are irrigated or are potentially irrigable. More than 600,000 acres in the study area are irrigated with ground water from more than 12,000 wells (Nebraska Department of Agriculture, annual report for 1976). About 44,000 acres in Dawson and Buffalo Counties are irrigated with surface water.

Land use within the study area, for selected years from 1931 through 1976, is listed in table 1. Information for this table was developed from county data on harvested crop acreages published by the Nebraska Department of Agriculture (annual reports, 1931-1976). Even though the information is for entire counties, it represents, adequately, land use in the study area.

Alfalfa acreage has not changed significantly during the period of study. Approximately 20 percent of the alfalfa in Dawson and Buffalo Counties receives supplemental irrigation water, and large acreages of alfalfa are subirrigated in the high-water table areas of the Platte River valley.

The acreage of small grains has declined significantly since the 1930's from about 20 percent to about 5 percent of the land area. Virtually no small grain is irrigated.

Acreages of irrigated row crops increased over time at the expense of dryland row crops and small grains. In Hall and Merrick Counties, irrigated row crops occupy about 50 percent of the land area. Total acreages of dryland and irrigated row crops increased since the 1930's for Platte, Hall, and Merrick Counties, but decreased, or remained about the same, for the other counties.

The principal row crop of both irrigated and dryland is corn; other row crops, in order of decreasing acreages are soybeans, grain sorghum, sugar beets, and potatoes. Most of these row crops, with grain sorghum being the principal exception, are irrigated.

Pasture and range acreages increased over time for most of the study area. Only in Merrick County have acreages of pasture and range decreased. During this period of 1931 to 1976, fluctuations in the acreages of pasture and range were numerous.

Table 1.--Land-use percentages for selected years

Year	Alfalfa: Irri-gated	Alfalfa: Non-irri-gated	Small grain	Row crops: Irri-gated	Row crops: Non-irri-gated	Pasture and range	Year	Alfalfa: Irri-gated	Alfalfa: Non-irri-gated	Small grain	Row crops: Irri-gated	Row crops: Non-irri-gated	Pasture and range
			Buffalo County							Custer County			
1931	0	7	17	1	35	40	1931	0	3	9	0	22	66
1935	0	8	18	1	30	43	1935	0	3	10	0	19	68
1940	0	2	10	1	21	66	1940	0	< .5	4	0	18	78
1945	0	3	17	1	34	45	1945	0	1	10	0	18	71
1950	< .5	6	18	8	21	47	1950	< .5	4	10	1	14	71
1955	1	9	10	10	18	52	1955	< .5	7	5	1	7	80
1960	1	7	10	17	15	50	1960	< .5	6	5	3	9	77
1965	1	7	5	13	9	65	1965	< .5	5	3	2	6	84
1970	2	6	5	20	7	60	1970	< .5	4	3	4	5	83
1976	2	5	5	29	6	53	1976	1	4	2	7	3	83
			Dawson County							Hall County			
1931	0	8	11	< .5	33	48	1931	0	8	26	< .5	35	31
1935	0	10	14	< .5	27	49	1935	0	10	27	< .5	28	35
1940	0	7	6	1	22	64	1940	0	3	18	1	21	57
1945	0	10	11	1	28	50	1945	0	4	23	< .5	35	38
1950	1	12	10	14	12	51	1950	< .5	5	23	17	16	39
1955	3	13	5	18	6	55	1955	< .5	8	16	22	16	38
1960	4	10	4	23	4	55	1960	2	4	10	36	2	46
1965	2	15	3	18	2	60	1965	1	6	6	32	6	49
1970	2	14	2	19	2	61	1970	1	4	4	36	5	50
1976	4	13	2	26	2	53	1976	1	4	3	50	5	37

Table 1.--Land-use percentages for selected years--Continued

Year	Alfalfa		Small grain	Row crops		Pasture and range	Year	Alfalfa		Small grain	Row crops		Pasture and range
	Irrigated	Nonirrigated		Irrigated	Nonirrigated			Irrigated	Nonirrigated		Irrigated	Nonirrigated	
	Howard County							Merrick County					
1931	0	7	20	0	28	45	1931	0	5	21	0	33	41
1935	0	7	18	0	25	50	1935	0	5	22	0	30	43
1940	0	1	13	< .5	22	64	1940	0	2	18	< .5	27	53
1945	0	4	21	0	25	50	1945	0	3	26	< .5	33	38
1950	< .5	7	19	1	22	51	1950	< .5	5	23	12	21	39
1955	< .5	10	14	1	19	56	1955	< .5	8	17	16	17	42
1960	< .5	6	11	5	19	59	1960	< .5	6	10	28	15	41
1965	< .5	7	6	10	12	65	1965	1	5	6	27	8	53
1970	< .5	6	4	16	7	67	1970	1	5	5	30	6	53
1976	1	5	3	16	9	66	1976	1	3	3	45	6	42
	Nance County							Platte County					
1931	0	7	19	0	37	37	1931	0	5	21	0	45	29
1935	0	7	22	0	34	37	1935	0	6	26	0	40	28
1940	0	2	16	0	30	52	1940	0	2	21	0	38	39
1945	0	3	20	0	32	45	1945	0	5	25	0	46	24
1950	< .5	6	21	< .5	29	44	1950	< .5	6	28	1	36	29
1955	< .5	8	16	1	27	48	1955	< .5	9	23	2	35	31
1960	< .5	6	13	3	29	49	1960	< .5	6	17	6	43	28
1965	< .5	7	8	5	21	59	1965	< .5	7	9	7	33	44
1970	< .5	6	8	7	18	61	1970	< .5	6	8	10	35	41
1976	< .5	5	6	14	22	53	1976	< .5	5	7	20	38	30

Short-term increases and decreases in some land-use categories usually represent either abnormal climatic conditions, significant variations in crop prices, or governmental policy changes. Long-term changes in some land-use categories reflect variations in ground-water irrigation development. The flood plain and terrace lands were irrigated for crop production earlier than the uplands. Thus land-use changes occurred first in the valleys and later in the uplands. The land-use changes also reflect the economics of producing and marketing different crops.

DESCRIPTION OF THE HYDROGEOLOGIC SYSTEM

For this study, the hydrogeologic system is divided into four components: Surface-water system, soil zone, unsaturated zone, and saturated or ground-water zone. Computer programs have been developed to represent and describe three of these components; however, there are neither appropriate data nor an adequate computer program to represent the unsaturated zone satisfactorily.

Surface-Water System

The surface-water system consists of streams and canals. This system and the ground-water zone are interrelated where the aquifer is connected hydraulically with streams and where canals provide passageways either for diversions or return flows to the streams.

Streams

Most of the major streams in the study area flow nearly parallel to the Platte or Loup Rivers. In areas having shallow water tables, several streams, particularly in Hall and Merrick Counties, frequently cease to flow during the irrigation season as ground-water pumpage lowers water levels. Other streams have no base flow and carry only surface runoff from precipitation.

Live reaches of the streams in the study area, that is, reaches interconnected with the saturated zone and in which there is perennial flow, are shown on figure 4. Each square, or node, on this model grid map represents an area of 6,525 by 6,525 feet, or 997.4 acres, and is identified by a row and column number. The nodes marked with "X" represent stream nodes and have live streams touching or flowing through them. For modeling purposes, the entire node is treated as a stream. Nodes corresponding to intermittent reaches are not marked with "X". Neither are the nodes corresponding to streams that are constantly flowing but not connected with the saturated zone.

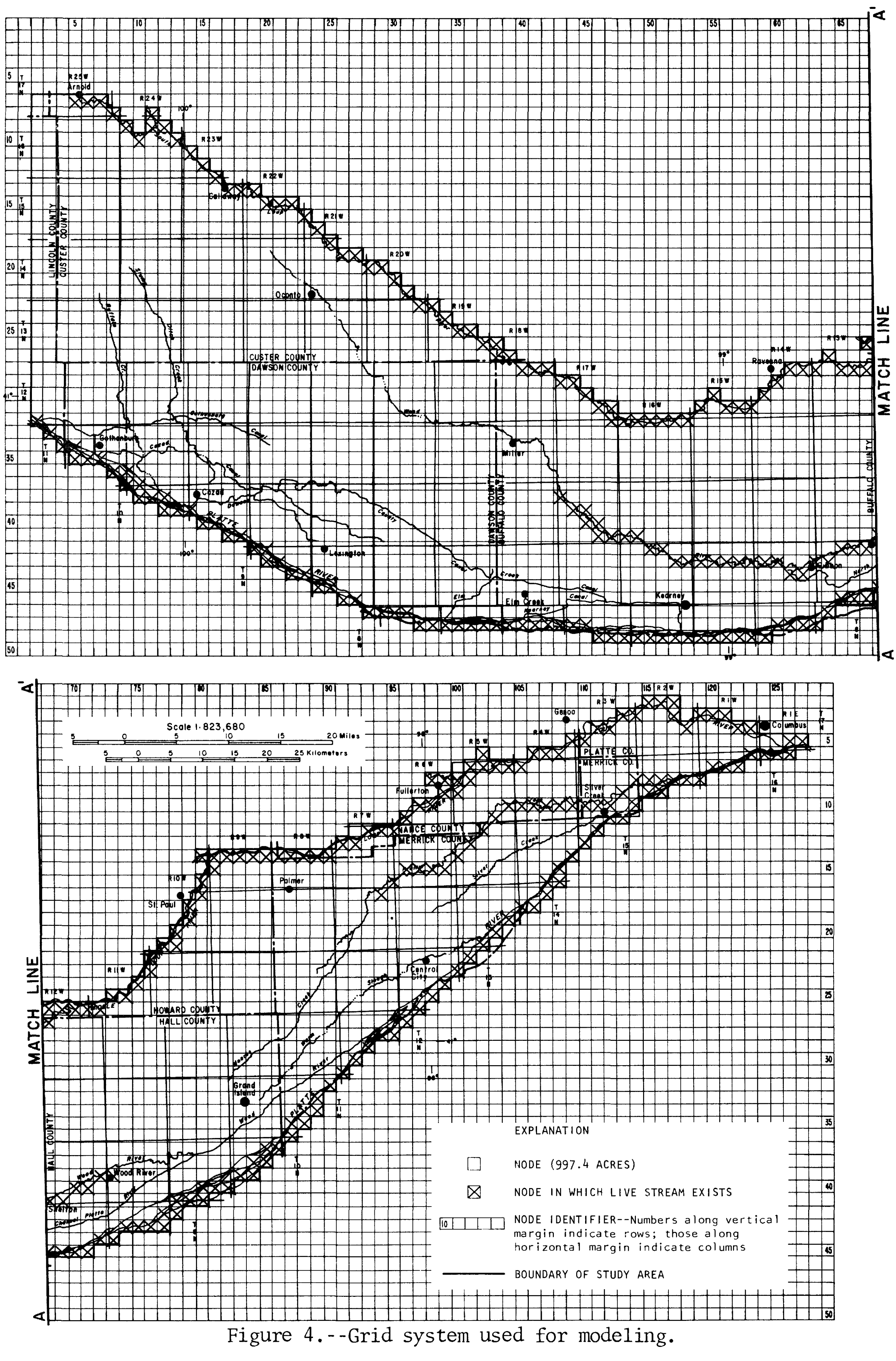


Figure 4.--Grid system used for modeling.

Stream reaches can either gain water from the ground-water system or lose water to it at different times during the year. Some reaches of the Platte River, for example, gain water from the ground-water system at certain times of year, but lose water to the ground-water system at other times. Streamflow in the Loup River system is relatively constant because it is derived almost entirely from ground-water discharge that is nearly constant throughout the year. Thus, in most of the Loup River system, the streams are gaining ones.

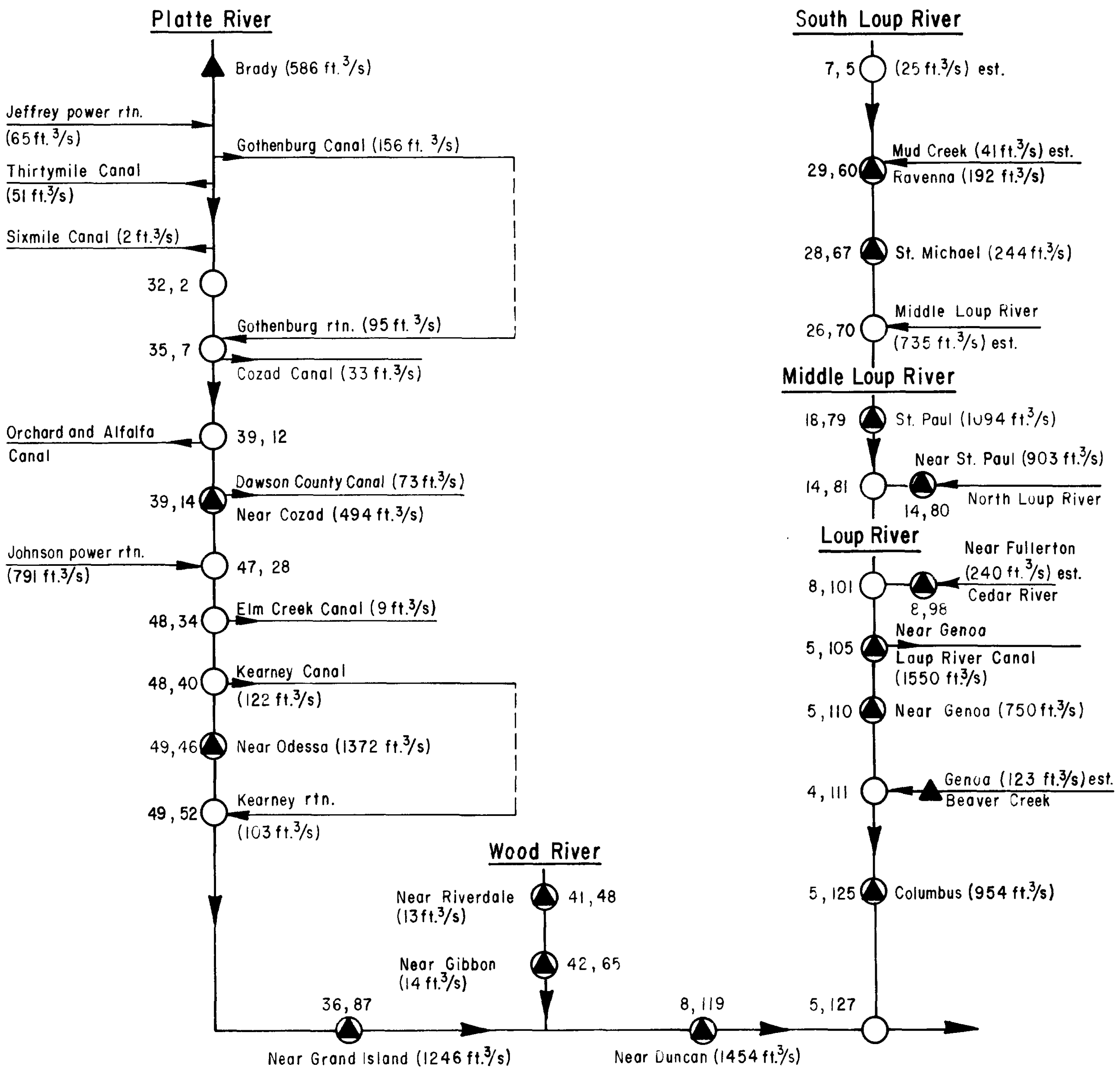
In the ground-water flow model for this study, average rates of streamflow were used whenever possible. However, the level of detail necessary in the model for handling the stream-aquifer relationship along the Platte River requires the use of streamflow rates for each 3-month irrigation pumping period (from June through August) and for each 9-month nonirrigation pumping period (from September through May).

Figure 5 is a schematic of the surface-water system showing the live streams, stream-gaging sites, canal diversions, and canal returns. The average annual flows at stream-gaging sites and of inflow from tributary streams are indicated. Also indicated are the average annual canal diversions and returns.

Base flows, calculated for stream-gaging sites at which flows are neither regulated by upstream reservoirs nor affected by canal diversions or return flows, are given in table 2. These flows were calculated by averaging streamflows in October, November, and December for the period of record. Streamflows caused by surface runoff from heavy precipitation were excluded in the calculations.

Seepage measurements were performed to supplement the base-flow data. Both base-flow data and seepage data indicate in what stream reaches and in what amounts water moves as seepage through the streambeds into the underlying saturated zone, or the converse. The results of seepage measurements for the Loup River system, Prairie Creek, Silver Creek, Wood River, and Warm Slough are listed in table A of "Additional Information."

Data on average streamflows, base flows, and seepage gains or losses help improve our understanding of the stream-aquifer relationships. For example, streamflows in the Wood River have declined since the 1930's, and the number and lengths of live reaches of this stream have also decreased. Analysis of flow, seepage, and ground-water pumpage data indicate that these changes are related to ground-water development near the Wood River. Decreases in streamflow also have occurred in Prairie and Silver Creeks because of ground-water development and drainage of high water-table areas. Effects of ground-water development on the Loup River system, however, appear to have been relatively minor.



EXPLANATION


INDICATES DIRECTION OF FLOW

32,2 
MODEL NODE--First number is row; second number is column location


STREAM-GAGING STATION

(1,372 ft^3/s) AVERAGE ANNUAL STREAMFLOW THROUGH SEPTEMBER 1976

Figure 5.--Schematic diagram of the surface-water system and average annual flows at selected sites.

Table 2.--Base flows for stream-gaging sites not affected by upstream regulation

[Stream node: first number is row; second number is column]

Station name and identification number	Stream node	Period of record	Base flow in cubic feet per second
Wood River near Riverdale - 06771000	(41, 48)	1947-1973	1.2
Wood River near Gibbon - 06771500	(42, 65)	1950-1976	.8
Wood River near Alda - 06772000	[1](38, 78)	1954-1978	.0
South Loup River at Ravenna - 06782500	(29, 60)	1941-1975	146.8
Mud Creek near Sweetwater - 06783500	[2](29, 60)	1947-1978	20.0
South Loup River at St. Michael - 06784000	[2](28, 67)	1944-1978	173.3
Middle Loup River at St. Paul - 06785000	[2](18, 79)	1929-1978	987.9
North Loup River near St. Paul - 06790500	[2](14, 80)	1929-1978	860.9
Beaver Creek at Genoa - 06794000	[2](4, 110)	1941-1978	75.8

[1]Not a stream node because streamflow is zero for most of the year.
[2]Stream gage is outside study area.

Effects of ground-water development in the study area on flows in the Platte River are masked by the regulation of flow from upstream reservoirs along the Platte River and its tributaries.

Canals

In the study area, four canals currently are used for irrigation. These canals, from west to east on figure 5, are the Gothenburg, Cozad, Dawson County, and Kearney Canals. All were in full operation prior to 1931, as was the Elm Creek Canal, abandoned in 1963. The Kearney Canal is used for hydroelectric-power generation. Until 1974, this was true also of the Gothenburg Canal. Figure 5 shows the main canals, but not the laterals or field-distribution systems.

Other canals either divert or return water to the south side of the Platte River and thus are outside the study area. These include Jeffrey Power Return and Johnson Power Return of the Tri-County Canal, Thirtymile Canal, Sixmile Canal, and Orchard and Alfalfa Canal. The Loup River Canal, also outside the study area, diverts water from the north side of the Loup River. Data on averages of water diverted or returned and on acres irrigated are given in table 3. As for streamflows previously discussed, annual canal flows were divided into a 3-month irrigation pumping period and a 9-month nonirrigation pumping period for use in the ground-water model. Flow volumes of the canals were evenly divided between these two pumping periods for each year from 1931 through 1976.

Soil Zone

The soil-zone component of the hydrogeologic system consists of the soils extending from the land surface through the plants' root systems. Of the water from precipitation and applied irrigation that infiltrates the soil zone, some is stored within the soil zone, some is withdrawn from the soil zone by evapotranspiration, some percolates to drains and is carried away as surface runoff, and some percolates to the underlying unsaturated zone or directly to the saturated zone, if no unsaturated zone exists.

Hydrologic Properties of the Soils

The soils in the study area have been delineated into nine soil groups (fig. 3) based on hydrologic properties of the soils. Each soil group was differentiated by soil texture, topographic position, slope, available water capacity, and average profile permeability of the soils. A listing of the hydrologic properties for the soil groups is provided in table 4. The source materials for information on these properties are available in published form from the Soil Conservation Service.

The available water capacity and the average profile permeability are important parameters in determining the amount of water stored in the soil and the amount that percolates downward to the saturated zone. Soils with higher permeabilities allow the water to move downward more rapidly than soils with lower permeabilities. Also, soils with high permeabilities have low available water capacity, which is the capacity of the soil to hold water for use by plants. The available water capacity is essentially the inverse of permeability. Thus, soils with high permeabilities and low available water capacities have a high potential for recharging the saturated zone, but soils with low permeabilities and high available water capacities, because they hold more water in the soil profile, have a low potential for recharging the saturated zone.

Infiltration of water and surface runoff are important in determining the amount of water stored in the soil profile and the amount recharged to the saturated zone. Soils with higher permeabilities normally have higher infiltration rates and lower surface runoff rates than soils with lower permeabilities. However, the intensity of rainfall, the amount of water in the soil profile, the vegetation cover, and whether the ground is frozen also influence infiltration rates.

Water Requirements of the Vegetation

Because different types of plants have different water requirements, it is necessary to distinguish between natural and cultivated vegetation and between the types of cultivated crops. Water requirements of land-use groups in table 1 in decreasing order are: irrigated alfalfa; dryland alfalfa (alfalfa and tame hay); irrigated row crops (corn, soybeans, grain sorghum, sugar beets, and potatoes); dryland row crops; pasture and range (fallow, urban lands, farmsteads, roads, woodlands, and predominantly pasture and range); and small grains (wheat, oats, barley, and rye).

Input to and Output from the Soil Zone

Precipitation and water applied in irrigation are inputs to the soil zone; whereas, evapotranspiration, surface runoff, and deep percolation are outputs from the soil zone.

Monthly precipitation data from 15 weather stations for the period January 1931 to December 1976 were compiled for this study. Missing monthly precipitation data were estimated from two or three surrounding weather stations using simple linear regression. Locations of these 15 weather stations are shown on figure 3, and the average annual precipitation for each station is listed in table 5.

Table 5.--Average annual precipitation for weather stations

Weather station	Identification number on figure 3	Node	Average annual precipitation from 1931-1976 (inches)
Arnold------------------	1	6, 5	20.76
Gothenburg--------------	2	34, 7	20.50
Oconto 6SW--------------	3	25, 21	19.34
Lexington --------------	4	42, 25	21.68
Miller------------------	5	34, 40	21.47
Elm Creek 1SSW----------	6	46, 40	21.67
Kearney-----------------	7	46, 54	23.28
Ravenna-----------------	8	28, 60	22.74
Gibbon------------------	9	43, 63	22.34
St. Paul----------------	10	17, 79	22.81
Grand Island WSO AP-----	11	32, 85	22.42
Fullerton---------------	12	8, 99	24.34
Central City------------	13	22, 98	23.73
Genoa 2W----------------	14	3, 108	24.30
Columbus 3NE------------	15	2, 126	24.81

Polygons (fig. 3) were constructed around each weather station using the Thiessen method (Linsley and others, 1958) to areally distribute the point measurements of precipitation. The area within each polygon is assumed to receive the same monthly precipitation as the weather station.

The study area contains both lands that are irrigated with surface water and with ground water. Those irrigated with surface water, the distribution of which has not changed appreciably since 1970, are all in Dawson and Buffalo Counties; those irrigated with ground water are dispersed throughout the study area. Figure 6 shows the distribution of the lands irrigated with surface water in 1970, and figure 7 shows the distribution of all lands irrigated in 1980, whether by surface water or ground water.

The amount of irrigation water applied depends on land use, varying with type of crop grown, as previously discussed. Where lands are irrigated with surface water, approximately 50 percent of the water diverted into canals is assumed to percolate from the canals to the saturated zone; the remaining 50 percent is applied to the crops (Fred J. Otradovsky, U.S. Bureau of Reclamation, personal commun., 1979).

The largest component of discharge from the soil zone is evapotranspiration (ET). The Jensen-Haise procedures for calculating potential evapotranspiration (PET), which are described by Jensen, Wright, and Pratt (1969) and Lappala (1978), were used for this study. The PET data were used with appropriate crop coefficients, which are monthly ratios of actual ET to PET, to obtain the ET values for the different crops. Additional details on the ET procedures will be given in the section on recharge-CIR.

The other components of discharge from the soil zone -- deep percolation (recharge) and surface runoff -- are discussed further in the section on recharge-CIR.

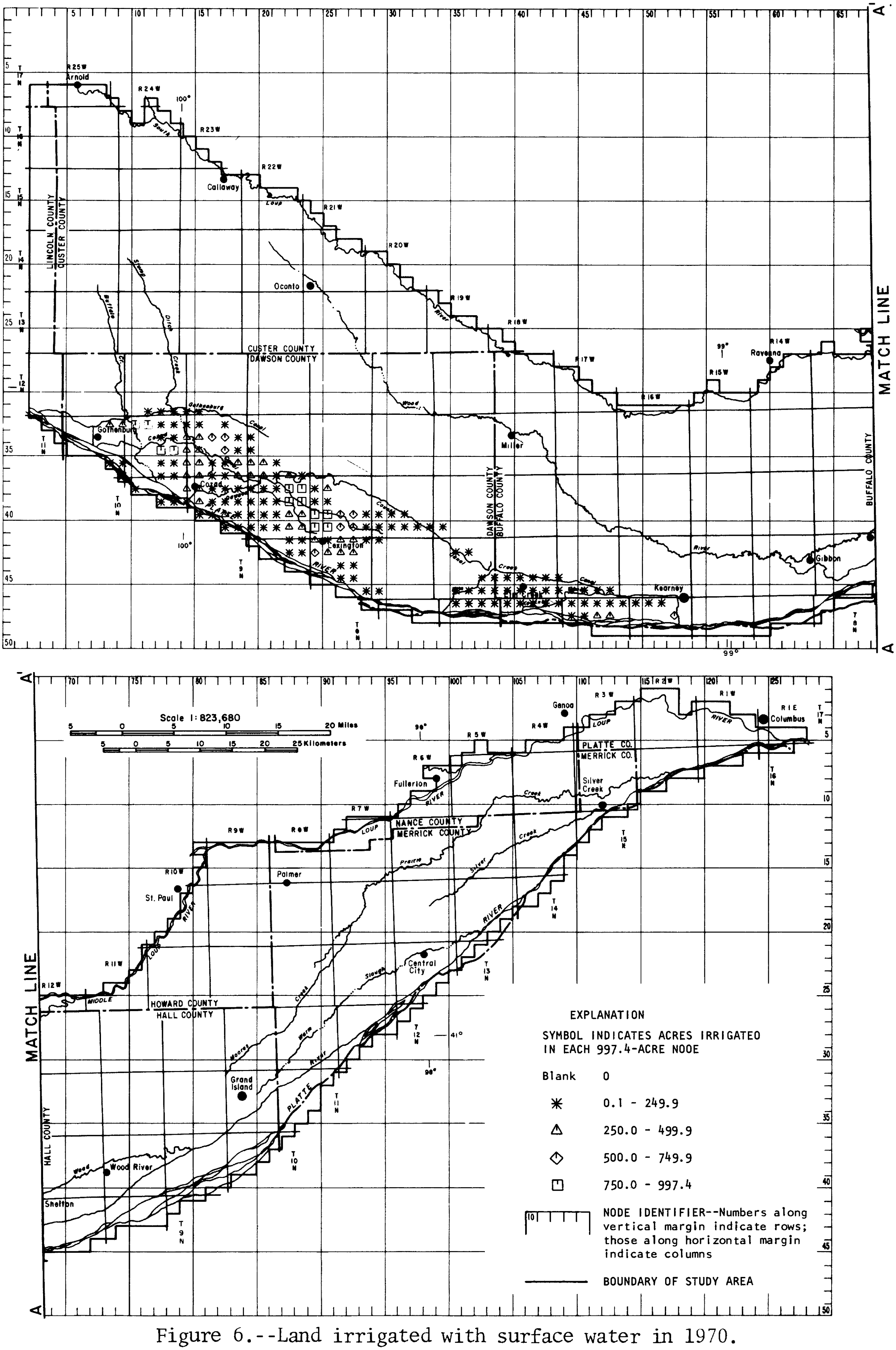


Figure 6.--Land irrigated with surface water in 1970.

Table 3.--Canal diversions, returns, and acreages

[Use of water: I, irrigation; P, power generation. Stream-node location blank if no specific return exists]

Canal	Use of water	Stream-node location		Average annual diversion		Average annual return (acre-ft)	Average acres irrigated
		Diversion	Return	Irrigation (acre-ft)	Power (acre-ft)		
Gothenburg-------------	I, P[1]	([2])	35, 7	33,370	80,000	68,580	7,940
Cozad------------------	I	35, 7	------	23,620	------	------	8,850
Dawson County----------	I	39, 14	------	52,820	------	------	20,830
Elm Creek[3]-------------	I	48, 34	------	6,850	------	------	3,000
Kearney----------------	I, P	48, 40	49, 52	13,240	74,990	74,990	3,420
Jeffrey Power Return----	P	([2])	([2])	------	------	46,840	-----
Thirtymile-------------	I	([2])	------	37,180	------	------	([2])
Sixmile----------------	I	([2])	------	1,370	------	------	([2])
Orchard and Alfalfa-----	I	39, 12	------	8,140	------	------	([2])
Johnson Power Return----	P	([2])	47, 28	------	------	573,400	-----
Loup River-------------	P	7, 105	([2])	------	1,123,000	------	-----

[1]Power generation discontinued in 1974.
[2]Outside study area.
[3]Abandoned in 1963.

Table 4.--Soil groups and their hydrologic properties

Map Symbol	Soil group	Topographic position	Texture	Range in slope (percent)	Available water capacity (inch per inch)	Average profile permeability (inch per hour)	Permeability of least permeable horizon (inch per hour)
A	Inavale-Loup-Alda-Platte.	Bottomland - low terraces.	Sand to loamy sand.	0 - 3	0.10	12.50	6.90
B	Wann-Cass-Leshara	Bottomlands	Sandy loam to loam.	0 - 3	.13	7.40	3.40
C	Gibbon-Lamo	Bottomlands	Silt loam to silty clay loam.	0 - 3	.21	4.70	.30
D	Ortello-Blendon	Uplands - terraces.	Sandy loam	0 - 10	.12	8.50	2.90
E	Holdrege-Hall-Hord-Kenesaw.	Level uplands, high terraces.	Silt loam to silty clay loam.	0 - 3	.20	1.20	1.07
F	Coly-Colby-Uly-Ulysses.	Dissected uplands.	Silt loam to silty clay loam.	0 - 30	.16	1.30	1.30
G	Valentine-Thurman.	Uplands, terraces.	Sand	2 - 30	.07	13.0	13.0
H	Wood River-Silver Creek.	Low terraces	Silt loam to silty clay loam.	0 - 3	.23	.95	.13
I	O'Neill-Sarpy	Low terraces	Sand	0 - 3	.10	11.50	4.50

Source: U.S. Soil Conservation Service, Soil Survey publications for selected counties.

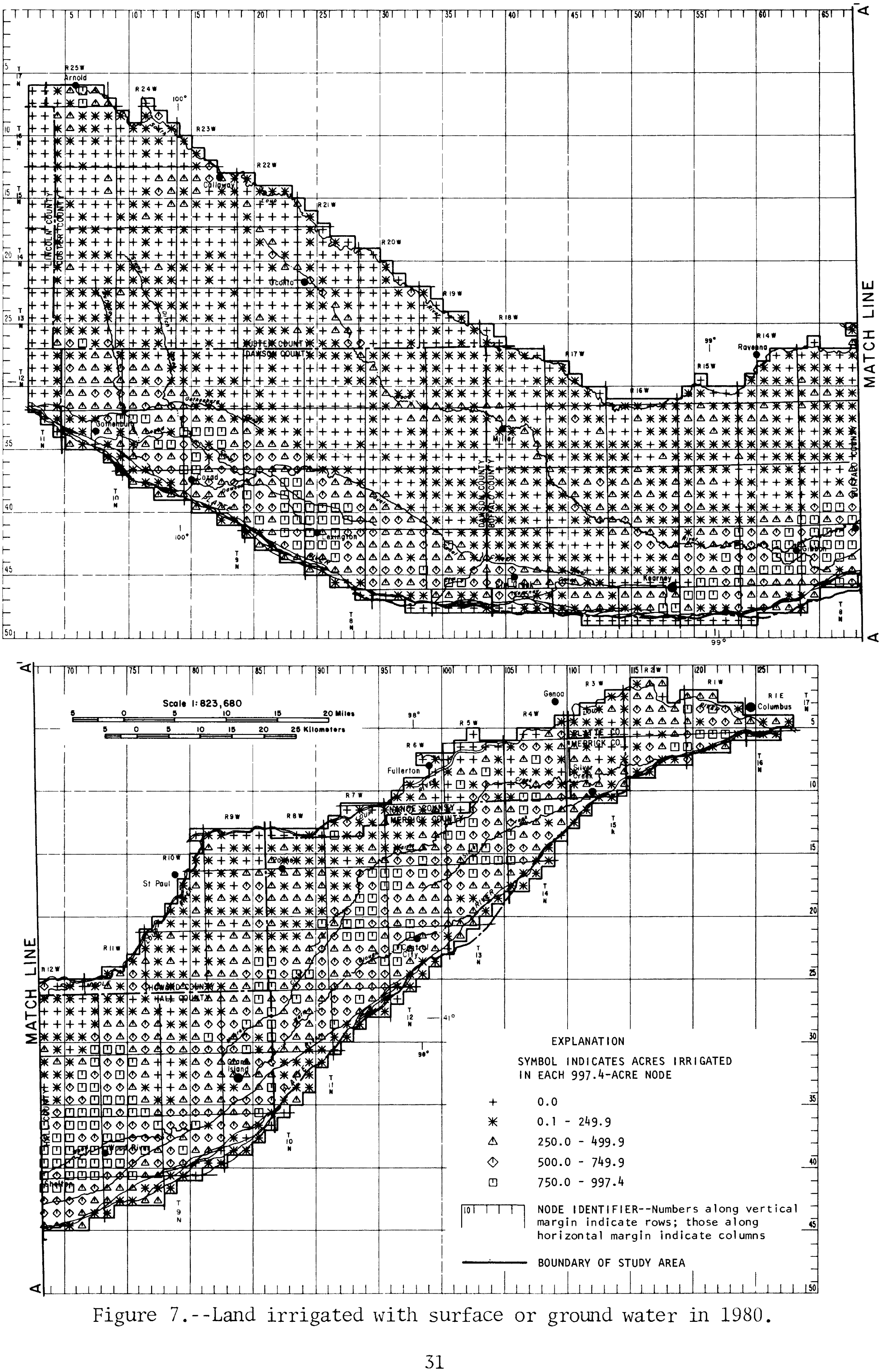


Figure 7.--Land irrigated with surface or ground water in 1980.

Unsaturated Zone

The unsaturated zone extends from the soil zone to the saturated zone, or ground-water zone. Water in the unsaturated zone may move downward, upward, or laterally, and it may be stored for limited periods. The physics of water movement within the unsaturated zone is complex and not completely understood. For this study the unsaturated zone is treated simplistically as a conduit through which water moves upward and downward with no storage. Major assumptions are that all water leaving the soil zone reaches the ground-water zone, that water moving up from the ground-water zone through the unsaturated zone reaches the soil zone, and that lateral movement of water within the unsaturated zone is negligible.

Saturated Zone

The saturated zone, also called the ground-water zone, hereafter will be referred to as the aquifer. It extends from the water table to the base of the lowest coarse-grained materials -- sand or gravel -- above the Cretaceous bedrock. The aquifer is composed of an upper part, which is primarily Quaternary materials, and a lower part, which is primarily the Ogallala Formation of Tertiary age, from eastern Hall County westward and fine-grained Quaternary materials from eastern Hall County eastward. For this study, the aquifer is divided into two parts because the materials have significantly different hydrogeologic properties. The Quaternary materials generally have higher hydraulic conductivities and storage capacities than the Ogallala Formation or the fine-grained Quaternary materials in the eastern part of the study area.

Boundaries of the Aquifer

The boundaries of the aquifer are important in delineating the occurrence of ground water in the study area. Water levels and changes in water levels over time define the upper surface of the aquifer; whereas, the configuration and elevation of the bases of two aquifer parts define the lower surfaces of the aquifer. The saturated thickness of the aquifer and the depths to water provide additional information on the boundaries of the aquifer.

Water Levels

The water table, which constitutes the upper boundary of the aquifer, fluctuates in response both to short-term and long-term variations, mainly in recharge but also in discharge. By comparing maps showing the configuration and elevation of the water table before and after large-scale irrigation development, it is possible to determine the effects of the development on the water table and to project probable future effects.

Figure 8 shows the configuration and elevation of the water table in the study area prior to the extensive ground-water development that began in the mid 1950's. The configuration shown for most of the Platte Valley was prepared from water-level data obtained during the summers of 1931 and 1932 by Lugn and Wenzel (1938). The configuration shown for the uplands, however, was developed from all water-level data available through 1978. These data were used because almost no water-level data were available for the uplands prior to the 1960's. No irrigation wells existed in the uplands in 1931 (fig. 9) and few existed prior to the 1950's. Most of the development of ground-water irrigation in the uplands followed the introduction in the late 1960's of center-pivot systems. Thus, the water-level data obtained are assumed to represent predevelopment water levels.

Although the water-table contours on figure 8 represent water-level conditions in the Platte Valley prior to large-scale ground-water development, surface-water development beginning in the 1890's had an impact on water levels in these counties prior to the 1930's. Lugn and Wenzel (1938) report that by 1931 irrigation with surface water had already caused water levels to rise, especially under terrace lands. Also, by 1931 about 600 irrigation wells were in operation in the Platte Valley from mid-Buffalo County through Hall County. As of 1931, there were no measurable water-level declines attributable to pumpage of ground water from these wells. Evidently, pumpage by these wells was offset by the interception of ground water that might otherwise have been lost to evapotranspiration.

Since 1931, the increase in the number of irrigation wells in the Platte Valley has been extraordinary. Figure 10 shows the distribution of irrigation wells registered with the Nebraska Department of Water Resources through December 31, 1976. Where well density is still low, water levels today probably do not differ greatly from those of predevelopment days. However, in many places, well density is so great that water levels today are bound to differ significantly from those predating development.

A second map showing configuration and elevation of the water table was required so that the ground-water flow model could be calibrated. The map prepared (fig. 11) is for the fall of 1976. Additional measurements of water levels were made to supplement those made in the fall of 1976 in the uplands of Buffalo County (fall 1977) and Custer County (spring 1978), and in southeastern Howard County (spring 1978).

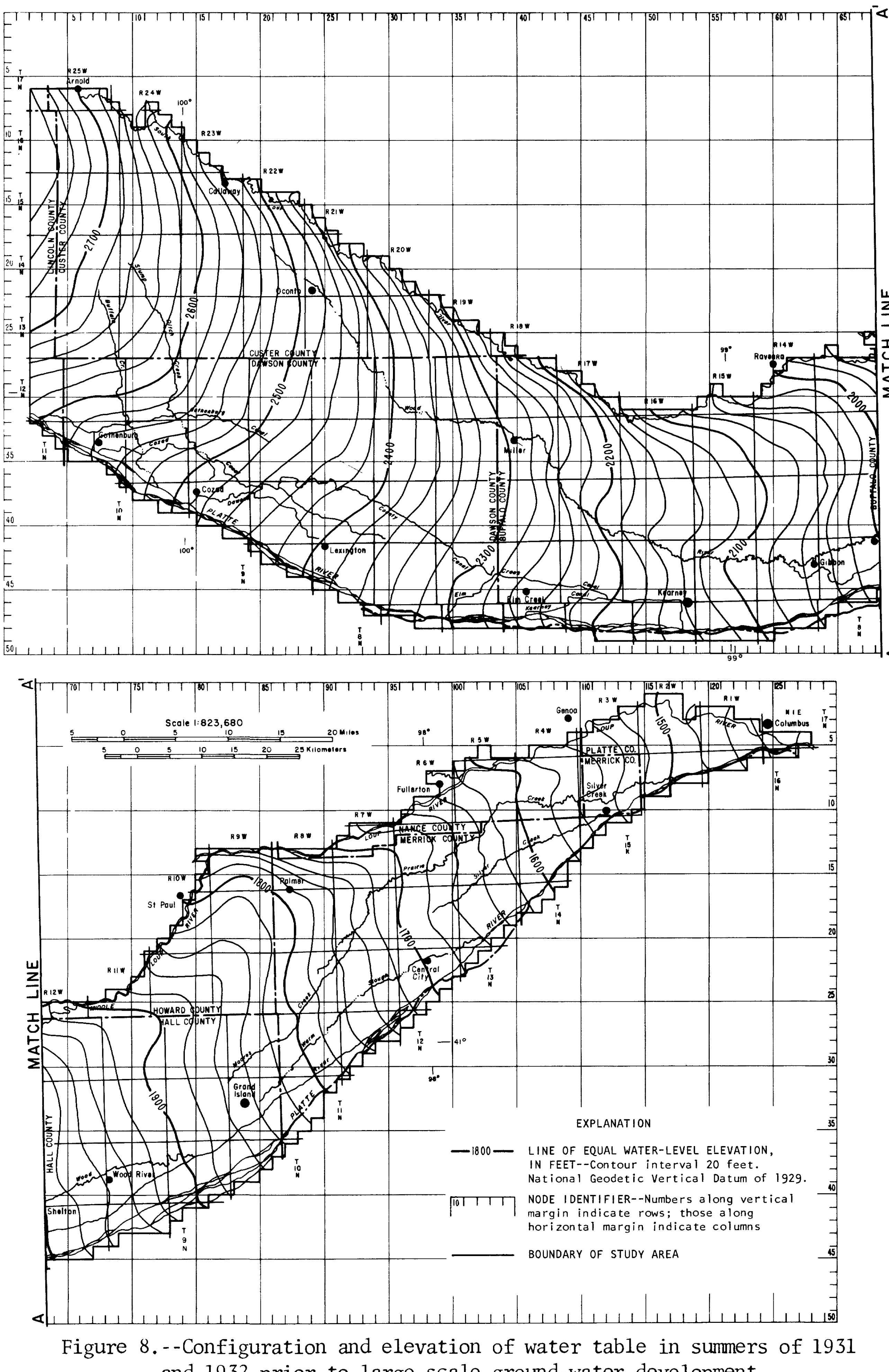


Figure 8.--Configuration and elevation of water table in summers of 1931 and 1932 prior to large-scale ground-water development.

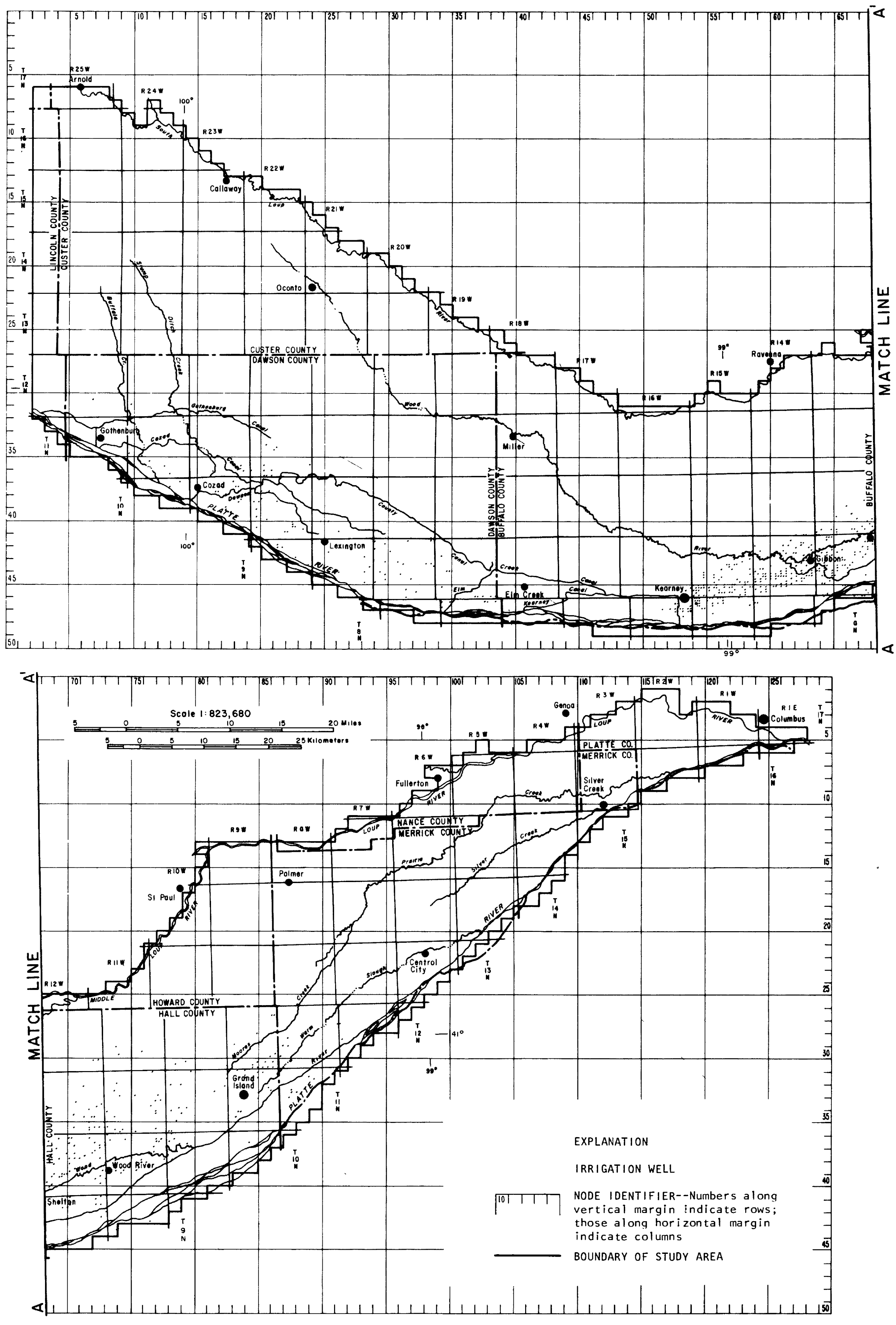


Figure 9.--Distribution of irrigation wells drilled through 1931.

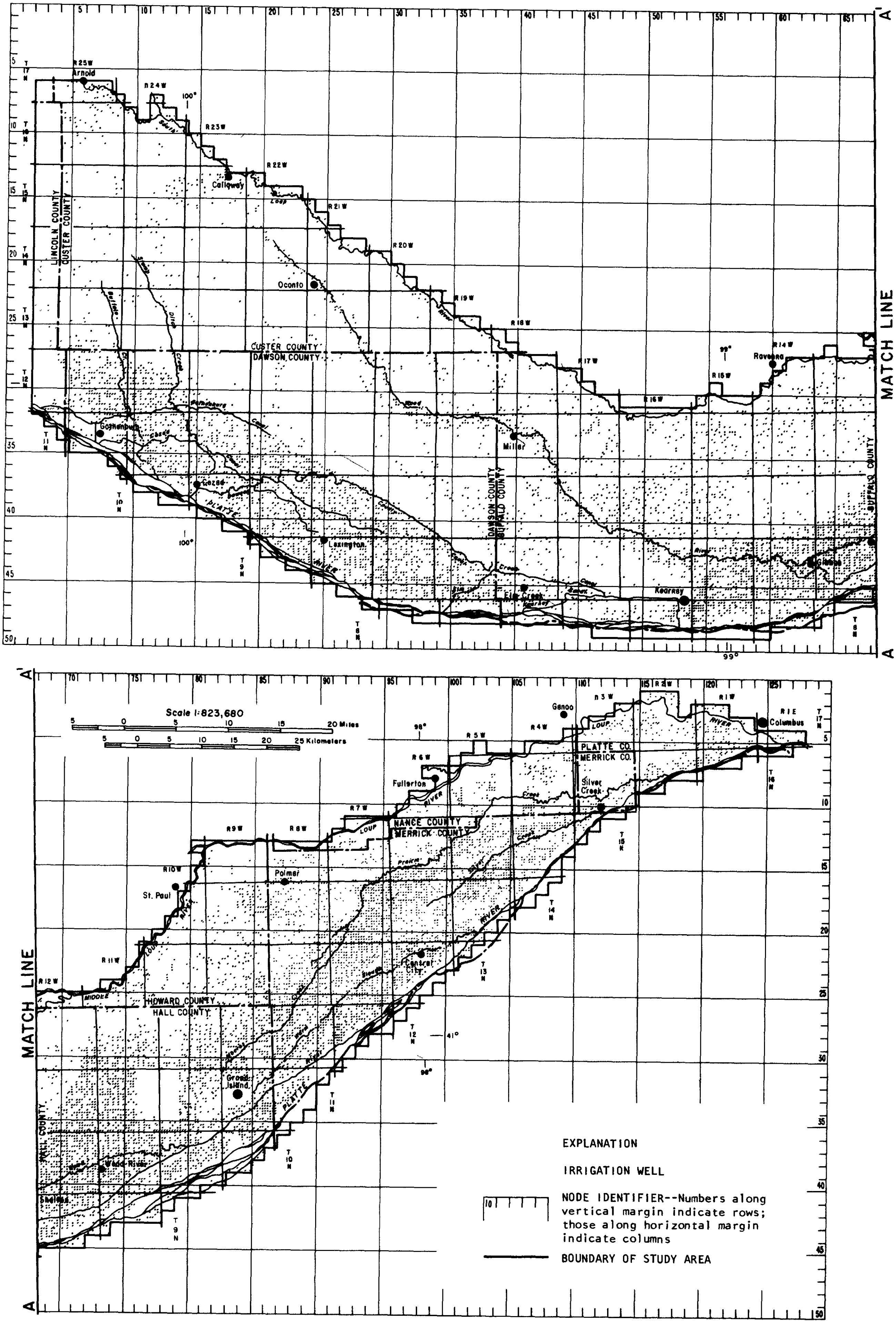


Figure 10.--Distribution of registered irrigation wells drilled through December 31, 1976.

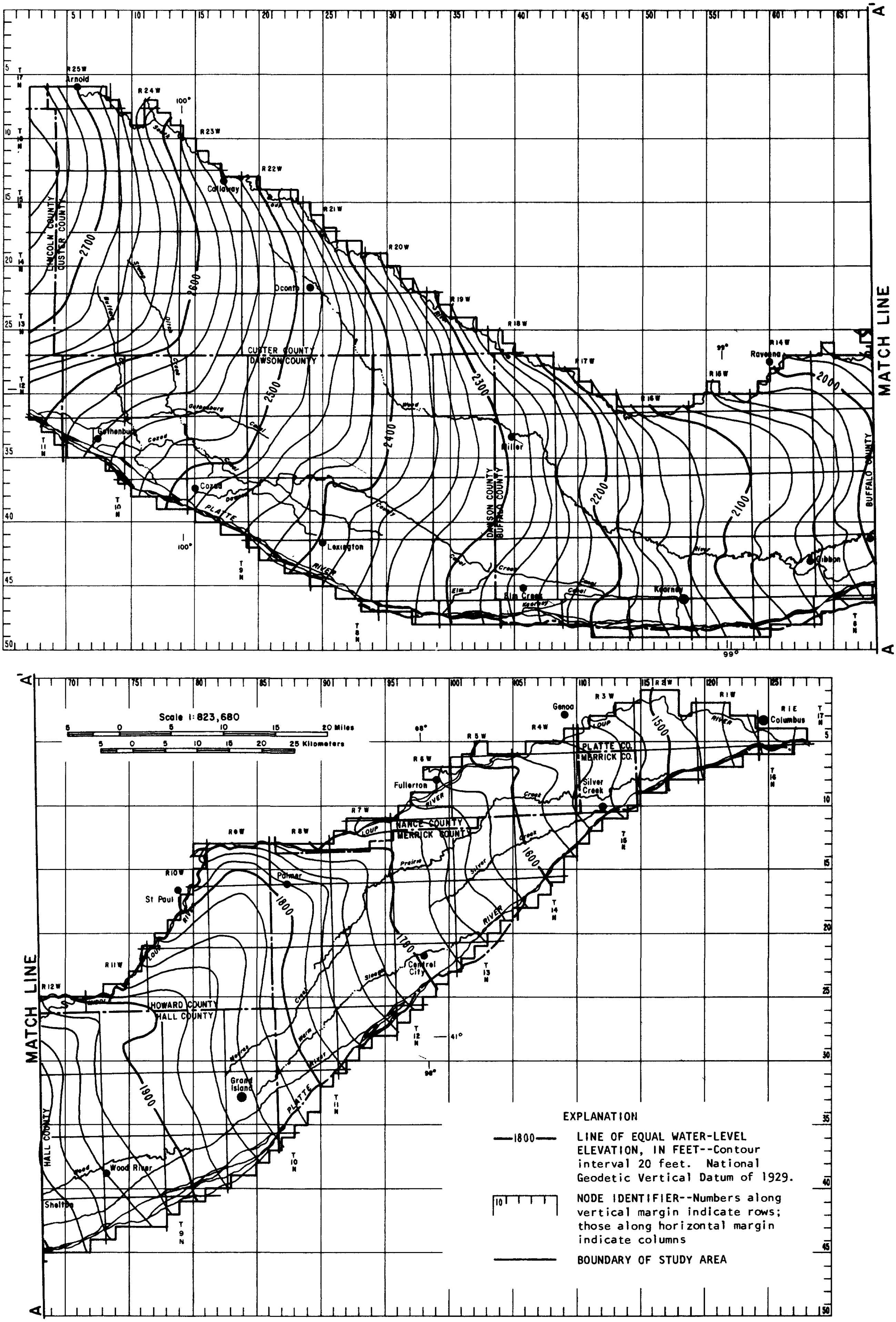


Figure 11.--Configuration and elevation of the water table, fall of 1976, prepared from measured water levels.

An examination of the water-level configuration maps of 1931 (fig. 8) and 1976 (fig. 11) shows both similarities and differences. Ground-water flow directions, which are perpendicular to water-table contour lines in an isotropic aquifer, are similar for most of the area. Major differences in the directions of ground-water flow are evident in southeastern Howard County. There are also a few minor changes in the direction of ground-water flow along some reaches of the Platte River, where formerly gaining segments of the stream are now losing segments. Inadequacies in the predevelopment water-level map may account for the differences in southeastern Howard County.

Differences between figures 8 and 11 indicate that noticeable changes occurred in the relationship between stream and aquifer along the Wood River. Locations of gaining and losing segments of the stream changed significantly from 1931 to 1976. Also, although not evident on the figures, in 1931, the Wood River was live or flowing about 3 miles further upstream than in 1976. Also, water levels declined noticeably since 1931. The most significant decline occurred in the Platte River valley of Dawson, Buffalo, and western Hall Counties. Water-level declines in the valley are illustrated by the upgradient positions of the 1976 water-level contour lines with respect to their positions in 1931.

Depth to Water

Depth to water is delineated on figure 12; depths in excess of 100 feet are not differentiated further. First, land-surface elevations were obtained for the center of each grid node using Geological Survey 7½-minute quadrangle topographic maps. These maps have a scale of 1:24,000 and contour intervals of 10 feet. Then, depth to water for each node was computed by subtracting the 1931 water level (fig. 8) from the land-surface elevation at the node.

An examination of figure 12 together with figure 2 (topographic types) indicates that shallow depths to water occur in the flood plains and terraces. Substantial increases in the elevation of water levels may occur shortly after major recharge events in the fall and spring of each year. The areas where the depth to water is 5 feet or less probably are more extensive following such events than is indicated on figure 12, especially during the spring. Likewise, in some areas where depths to water are shown to be between 6 and 10 feet below land surface, water levels may occasionally rise to within 5 feet of the land surface.

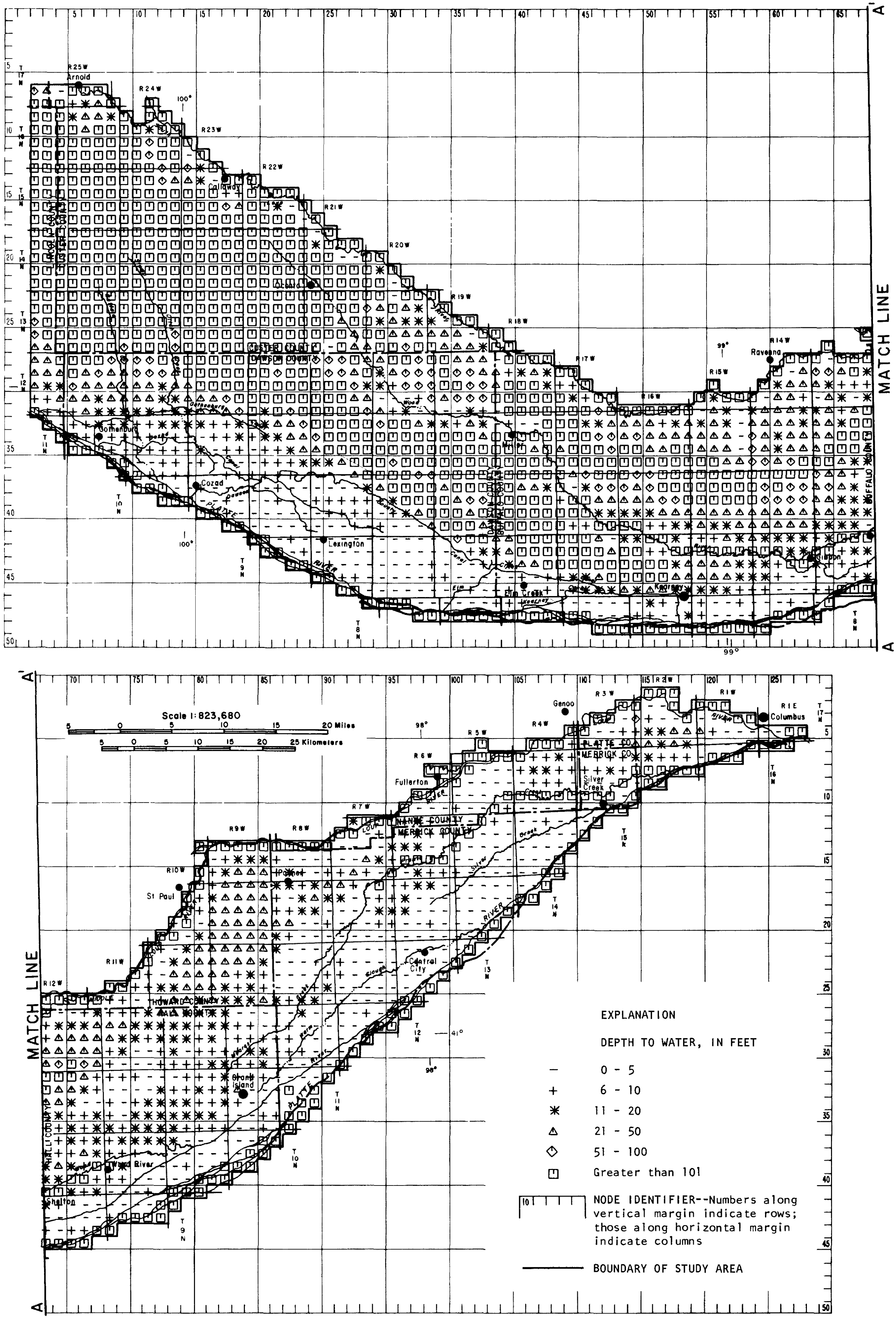


Figure 12.--Depth to water from land surface, summer 1931 and 1932.

Base of the Aquifer

As previously mentioned, the aquifer is divided into an upper and lower part, and the bases of the two parts are delineated on plate 1a and 1b, respectively. The base of the upper part slopes toward the east, with a decrease in elevation of about 1,400 feet -- from about 2,700 to 1,300 feet. The base of the lower part of the aquifer also slopes toward the east, but with a decrease in elevation of only about 950 feet. Elevations of this part vary from 2,250 feet in the west to 1,300 feet in the east.

Saturated Thickness

Plate 1c and 1d shows the variations in aquifer thickness with location of the upper and lower parts of the aquifer, respectively. The saturated thickness of the upper part ranges from zero feet in northern Buffalo County to 250 feet along the South Loup River in Custer County. The saturated thickness of the lower part of the aquifer ranges from less than 25 feet in the eastern part of the study area to more than 500 feet in the western part.

The areas of zero saturated thickness for the upper part of the aquifer in 1931, primarily in Buffalo County, occurred naturally and were not due to dewatering of the aquifer. At that time, no irrigation wells had yet been developed in the upper part of the aquifer; all subsequent development has been in the lower part.

Hydraulic Characteristics

The hydraulic characteristics of the aquifer indicate the availability and volume of ground water. For this study, hydraulic conductivity and specific yield are the parameters necessary to define the hydraulic properties of the aquifer.

Hydraulic Conductivity

The distribution of hydraulic conductivity, K, of the upper and lower parts of the aquifer is shown in plate 1e and 1f, respectively. Hydraulic conductivity of the upper part ranges from 1 to 300 feet per day, and that of the lower part from 1 to 79 feet per day. On plate 1e, a hydraulic conductivity of zero feet per day is indicated where the upper part of the aquifer was unsaturated. On plate 1f, however, a hydraulic conductivity of zero feet per day is indicated where the lower part of the aquifer is not present.

The hydraulic-conductivity maps were prepared starting with lithologic logs of test holes. For each lithologic unit described in the test-hole logs, a hydraulic-conductivity value was assigned according to the grain size of material comprising the unit and its degree of sorting and (or) silt content using table B given in "Additional Information." Each value, so assigned, was then multiplied by the thickness of the lithologic unit it represented. The sum of the products was divided by the saturated thickness of all the lithologic units to yield a weighted-average hydraulic conductivity for each of the two parts of the aquifer at each test-hole site. The weighted-average values were then plotted, and maps were developed showing lines of equal hydraulic conductivity. It is from these maps that the ranges in hydraulic conductivity shown for individual nodes in plate 1e and 1f eventually were obtained.

Hydraulic-conductivity values determined from aquifer tests (Lugn and Wenzel, 1938) and those derived from specific-capacity data for irrigation-wells were used to check and, in a few cases, modify the weighted-average values obtained as described in the previous paragraph. Aquifer-test data pertained only to the upper part of the aquifer; whereas, specific-capacity data pertained to the entire aquifer.

During the modeling process, the need for some modifications in the assigned weighted-average hydraulic-conductivity values became apparent. The modified values have been incorporated into plate 1e and 1f.

Hydraulic conductivity shown in plate 1e and 1f, if multiplied by the appropriate saturated thickness from plate 1c and 1d, can be used to compute the transmissivity of the aquifer at each node. The transmissivity is a good indicator of potential well yield at a given location. Areas where transmissivity is large are favorable for developing wells having high yields.

Specific Yield

The specific yield, Sy, or drainable porosity of the upper and lower parts of the aquifer is indicated in plate 1g and 1h, respectively. The range in Sy for the upper part of the aquifer is 0.16 to 0.26, and that for the lower part is 0.12 to 0.21.

Specific-yield values were developed, as were the hydraulic-conductivity values, from lithologic logs of test holes. For each lithologic unit, a specific-yield value was assigned depending on grain-size class or range, using table B given in "Additional Information." A weighted-average Sy for the saturated materials at each test hole was computed in the same manner described earlier for hydraulic conductivity. Values for individual test-hole sites were plotted, maps with lines of equal specific yield were prepared, and the specific-yield values shown on plate 1g and 1h for individual nodes were selected. The need for some changes in the original Sy values selected became evident during the modeling procedure; these changes have been incorporated into the illustrations.

Flow in the Aquifer

Ground water flows in the direction of decreasing hydraulic head, or approximately normal to the water-table contours (figs. 8 and 11). The regional ground-water flow pattern is modified near discharge and recharge areas. The flow paths converge toward areas of discharge and diverge from areas of recharge.

The velocity of ground-water movement through an aquifer is a function of the hydraulic conductivity and the gradient of hydraulic head, which is the potential energy of the water. The velocities are usually low and they are expressed as follows (Lappala, 1978):

$$\hat{q}_i = K\left(\frac{\partial h}{\partial x_i}\right) \tag{1}$$

where

$\hat{q}_i$ = the average unit area rate of volume flux, LT^{-1},

K = hydraulic conductivity, LT^{-1},

h = total hydraulic head, L,

x_i = a coordinate direction, L.

Rates of ground-water movement in the study area range from less than 10 feet per year to slightly more than 100 feet per year.

Underflow of ground water into the study area is along the western border of Dawson and Custer Counties and can be calculated as follows (Lappala, 1978):

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

where

Q = underflow across the study area boundary, L^3T^{-1},

i = an index on the interval used,

m = total number of increments,

$\hat{K}_i$ = average hydraulic conductivity over b_i and w_i, LT^{-1},

b_i = average aquifer thickness over interval i, L,

w_i = width of the increment i, L,

$(\frac{\partial h}{\partial n})_i$ = hydraulic gradient normal to the boundary, dimensionless.

The underflow into the study area was determined by the above equation to be 28,700 acre-feet in 1931 and 39,600 acre-feet in 1976.

The average volume of water in storage in the summers of 1931 and 1932 within the two parts of the aquifer were calculated by multiplying average saturated thickness by specific yield. The volume in storage in the upper part of the aquifer was 58,300,000 acre-feet, and that in the lower part was 62,500,000 acre-feet.

Outflows from the aquifer consist of discharge from domestic, municipal, industrial, and irrigation wells, ET losses from shallow water-table areas, and ground-water discharge to the surface-water system. ET losses and ground-water discharge to streams are handled within the ground-water flow model. The net recharge or discharge, which is entered into the flow model, will be discussed in the Recharge-CIR section. Underflow of ground water to areas outside the study area is negligible, and for modeling purposes, is assumed to be intercepted by the surface-water system.

PROCEDURES FOR ESTIMATING RECHARGE-CIR DATA

Hydrologic data seldom are in a form directly usable in a ground-water flow model. Ordinarily, "raw" data must be converted, combined with other data, or operated upon in some other manner before it can become usable. This section provides information on the procedures adopted to prepare data for use in the model and on simplifying assumptions made with regard to the data.

Soil-Zone Programs

The movement of water through and within the soil zone is represented by two computer programs: one is called the potential-evapotranspiration program (PET), and the other is called the soil-water program. These programs require input of climatic, soil, and crop data to calculate the CIR of the crops and the amount of water that will pass through the soil zone to become recharge to the aquifer.

The physical basis for, and operational procedures of the soil-zone programs were discussed by Lappala (1978). No changes were made in the PET program for this study, but two major changes were made in the soil-water program. The first change was the addition of a method to handle the nonuniform distribution of rainfall with respect to time. This involved adding a regression equation to the soil-water program (Fred J. Otradovsky, U.S. Bureau of Reclamation, written commun., 1979) in an attempt to account for the temporal errors that result from using monthly instead of daily precipitation data. The results of this change were increases in the values used for precipitation and deep percolation or recharge.

The second change in the soil-water program was the addition of a method to account for recharge that results because of seepage from road ditches, ponds, low areas, and intermittent drains. Originally, the rainfall-runoff curves in the soil-water program were developed from data collected on 4-acre watersheds and reflected only initial surface runoff. However, when larger areas are considered, much of the original surface runoff reaches road ditches, ponds, swales, etc., from which water percolates downward to become recharge to the aquifer. The fraction of the original surface runoff that is subsequently retained and percolates downward to become recharge is referred to as "seep" and is treated as additional deep percolation in the soil-water program (Fred J. Otradovsky, U.S. Bureau of Reclamation, written commun., 1979).

The PET program computes the monthly PET for the 15 weather stations in the study area. Inputs to the program are: (1) Monthly values for precipitation, air temperature, and percent possible sunshine; (2) the mean minimum and maximum air temperatures for the warmest month of the year (July); and (3) the mean daily solar radiation values on cloudless days for each month.

The locations of the weather stations are shown on figure 3. The areas for which records from a given station are assumed to apply are shown on the figure by Thiessen polygons. The station locations and polygons are shown on figure 3 because of the close relationship in the modeling process between climatic data and the soil properties.

Precipitation data were available for each weather station; however, air temperature data were not, and those for the Gothenburg, Kearney, and Central City stations were assigned to the other weather stations according to their location. If air temperature and precipitation data were missing, they were estimated by linear regression with data from nearby stations. Data on percent possible sunshine and mean daily solar radiation on cloudless days were available only for the National Weather Service station at North Platte, about 35 miles west of this study area.

Monthly output from the PET program and mean monthly precipitation and air temperature for each weather station were used as input to the soil-water program. Additional inputs to this program are: (1) Crop coefficients (fig. 13), which are the monthly ratios of actual to PET for row crops, alfalfa, small grain, and pasture and range; (2) infiltration-curve coefficients coupled with infiltration-curve numbers (fig. 14) that are dependent on the soils, lithology, topography, and crop types; and (3) water-holding capacity of the soil.

Figure 13 shows crop coefficients for different times of the year. These coefficients were modified from Lappala (1978). Modifications are the use of a coefficient of 1.0 for row crops during July, and a lowering of the coefficient for pasture and range from July through October when the grasses are dormant.

Figure 14 shows the relationship between monthly precipitation and monthly infiltration. The relationship differs markedly for different combinations of soil, vegetation, and topography, and therefore is expressed using four different curves. Selecting the appropriate curve is simple. For example, for sandy soils on flat topography, monthly infiltration is determined using curve 1. Table 6 gives the available water capacity, curve number, and seep values used for the nine soil groups in the study area.

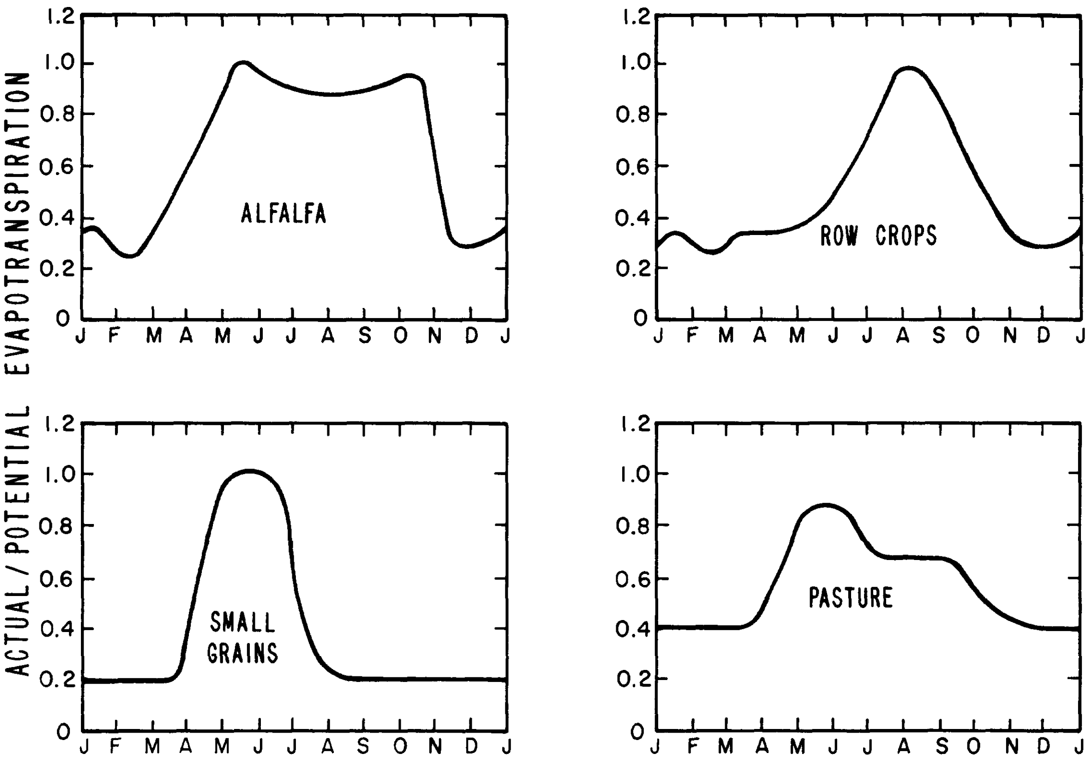


Figure 13.--Crop coefficients--the monthly ratio of actual to potential evapotranspiration--for four crop types. (Modified from Lappala, 1978).

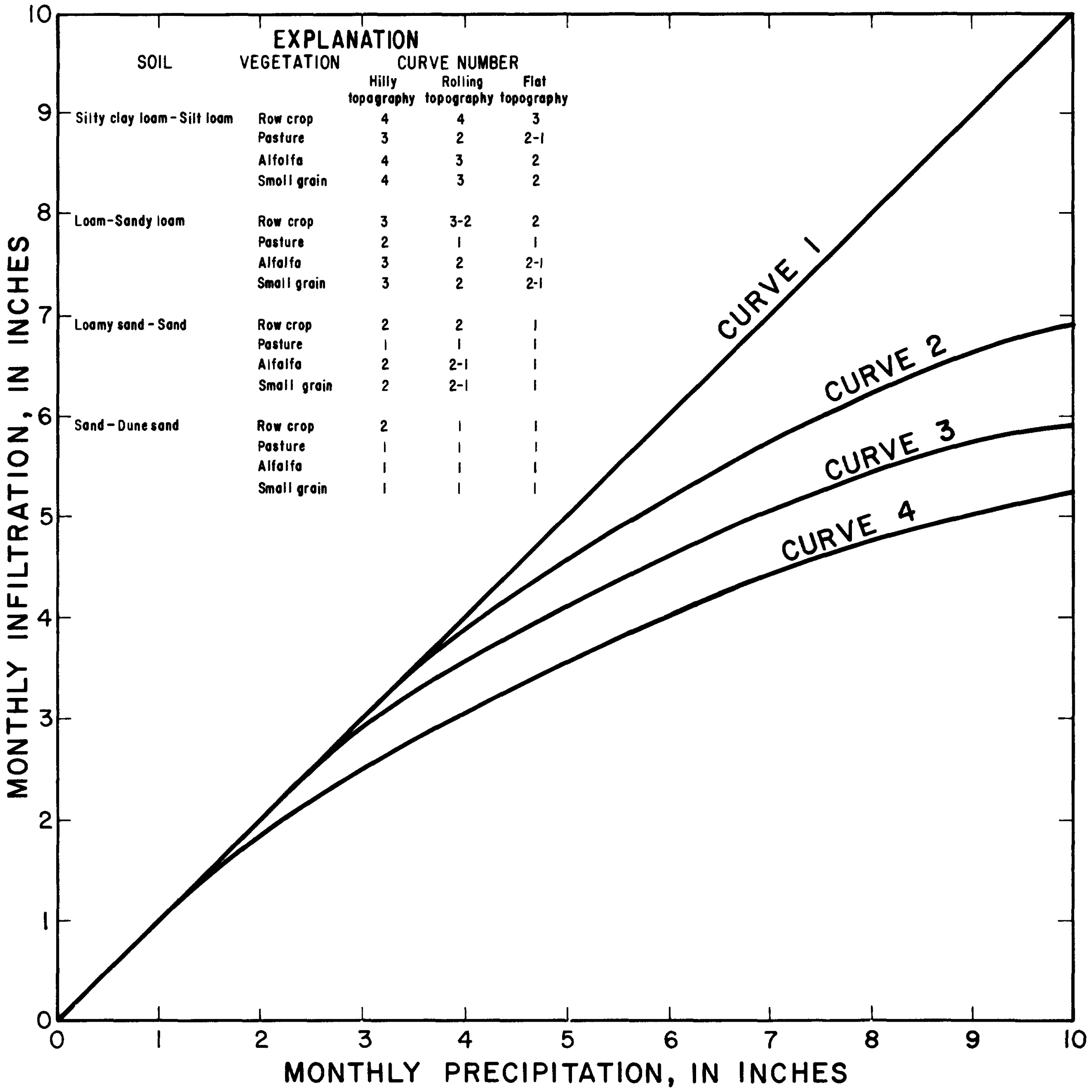


Figure 14.--Relationship of monthly precipitation to monthly infiltration for various combinations of crops, soils, and topography. (Modified from Lappala, 1978.)

Table 6.--Available water capacity, curve numbers, and seep values for the soil groups

Map symbol	Soil group	Available water capacity (inch per inch)	Curve number for				Seep[1]
			Row crop	Alfalfa	Small grain	Pasture	
A	Inavale-Loup-Alda-Platte	0.10	1	1	1	1	0.75
B	Wann-Cass-Leshara	.13	2	2	1	1	.50
C	Gibbon-Lamo	.21	2	2	2	1	.25
D	Ortello-Blendon	.12	2	2	1	1	.50
E	Holdrege-Hall-Hord-Kenesaw	.20	2	2	2	1	.25
F	Coly-Colby-Uly-Ulysses	.16	3	3	3	2	.10
G	Valentine-Thurman	.07	2	1	1	1	1.00
H	Wood River-Silver Creek	.23	2	2	2	1	.15
I	O'Neill-Sarpy	.10	1	1	1	1	.75

[1]Dimensionless; the fraction of the surface runoff generated in an area that percolates from ditches, drains, and swales in the area and eventually becomes recharge to the aquifer.

Output from the soil-water program includes data on the following items for each soil, crop, and weather station: (1) Infiltration, (2) ET, (3) surface runoff, (4) irrigated land deep percolation, (5) CIR, (6) irrigated land soil moisture, (7) dryland deep percolation, (8) dryland water shortage, and (9) dryland soil moisture. Deep percolation from dryland areas entirely from precipitation and seepage from ditches, drains, and swales; whereas, deep percolation from irrigation areas is from precipitation, excess irrigation, and seepage from ditches, drains, and swales. Output from the soil-water program for the soils that are found in the area enclosed by the Thiessen polygons, identified with the Gothenburg, Kearney, and Central City weather stations, is given in table C of "Additional Information." Ninety-two different combinations of weather stations and soils exist in the study area; table C presents a representative subset of these data.

Recharge-Discharge Programs

Computation of recharge to the ground-water system and of discharge from it requires data for a variety of parameters. Unfortunately, very few of these parameters are measurable directly; thus, procedures were developed by which their magnitudes could be estimated. These procedures comprise the recharge-discharge programs.

For this study the recharge-discharge programs consist of computer programs and the ET subroutine in the ground-water flow model. The Pumpage and Flowx programs, developed by the authors, compute the recharge-discharge values and streamflow data needed as input to the ground-water flow model. The Pumpage program uses recharge-CIR data from the soil-water program, together with data on additional parameters, to compute net recharge to the aquifer or discharge from the aquifer at each node for each pumping period. The Flowx program computes either the inflow to or the outflow from stream nodes using data from nodes just outside the study area but adjacent to the stream nodes. The ET subroutine by Trescott and others (1976) computes the discharges from shallow ground-water nodes for each time step within each pumping period.

Assumptions in the Procedures

Numerous assumptions are incorporated in the recharge-discharge program. Those believed to be most significant are discussed in the following paragraphs.

The first group of assumptions pertain to development of the Pumpage program. No measurements were available on the volumes of surface water diverted by canals that reach irrigated fields. After discussions with cooperators and personnel of the U.S. Bureau of Reclamation, the assumption was made that only 50 percent of the surface water diverted actually is applied in irrigation; the other 50 percent is assumed to be seepage loss that recharges the aquifer (Fred J. Otradovsky, U.S. Bureau of Reclamation, personal commun., 1979). Another assumption pertaining to surface water is that the acres irrigated with surface water have remained unchanged since 1970, both in location and extent.

The assumption that only 50 percent of the surface water diverted is actually applied in irrigation leads to still other assumptions. If the 50 percent applied is more than the CIR for a given node, the residual water is assumed to become recharge to the aquifer. If, on the other hand, the 50 percent applied is less than the CIR for the node, the deficit is assumed to be made up by pumping of ground water if an irrigation well exists in the node.

Data available on acreages of alfalfa do not distinguish between irrigated and nonirrigated acres. After discussions with cooperators, 20 percent of the alfalfa lands in the Platte River valley from Gothenburg to west of Kearney is assumed to be irrigated with ground water each year, and the remaining 80 percent is assumed to be subirrigated with shallow ground water.

The acres irrigated with ground water in each study are computed as the number of irrigation wells per node multiplied by the acres irrigated per well. The number of wells per node for each year was computed from the file of registered irrigation wells of the Nebraska Department of Water Resources, and the acres irrigated per well were computed for each county for 5-year intervals from data on registered irrigation wells given in "Nebraska Agricultural Statistics" (Nebraska Department of Agriculture, annual reports). The number of registered irrigation wells and acres irrigated per well for each county for 5-year intervals are given in table 7.

Procedures used to determine the acres irrigated with ground water have been substantiated by comparing computed results with results of field data collected by the Bureau of Reclamation for Buffalo, Hall, and Merrick Counties during 1946, 1970, and 1971. Results of this comparison are given in table 8. The greater number of wells and the lesser acres per well computed for this study from the Agricultural Statistics probably can be attributed to the inclusion of all registered irrigation wells drilled through the end of each year, even though not all such wells were used during the year.

Withdrawals of ground water for domestic, stock, industrial, and most municipal purposes are assumed to be insignificant with respect to regional water-level changes. Thus, ground-water usages for these purposes, except that for the cities of Grand Island and Kearney (table 9),

Table 7.--Registered irrigation wells and acres irrigated per well by county

Period	Number of wells	Acres irri-gated per well	Number of wells	Acres irri-gated per well	Number of wells	Acres irri-gated per well	Number of wells	Acres irri-gated per well
	Custer County		Dawson County		Buffalo County		Hall County	
1931-35	10	0.0	149	50.0	298	55.0	185	55.0
1936-40	17	0.0	294	50.0	307	60.0	255	55.0
1941-45	36	40.0	507	50.0	428	65.0	554	62.0
1946-50	84	40.0	763	50.0	618	70.0	855	60.0
1951-55	193	44.0	1,116	47.0	894	56.0	1,119	58.0
1956-60	467	67.0	1,931	53.0	1,507	55.0	2,182	61.0
1961-65	532	72.0	2,070	34.0	1,673	50.0	1,994	54.0
1966-70	711	82.0	2,222	32.0	1,958	52.0	2,294	51.0
1971-75	1,050	91.0	2,485	43.0	2,278	61.0	2,588	55.0
1976	1,325	104.0	2,763	47.0	2,641	62.0	2,927	57.0
	Merrick County		Howard County		Nance County		Platte County	
1931-35	49	30.0	1	0.0	0	0.0	7	50.0
1936-40	208	31.0	6	75.6	1	0.0	10	77.0
1941-45	415	36.0	14	50.0	5	40.0	49	50.0
1946-50	734	38.3	29	52.0	12	40.0	81	50.0
1951-55	1,052	38.0	72	39.0	24	43.0	126	42.0
1956-60	1,806	37.0	236	45.8	89	41.0	390	49.0
1961-65	2,042	35.0	277	50.0	136	46.0	462	59.0
1966-70	2,439	36.2	364	55.0	225	61.0	582	62.0
1971-75	2,910	38.0	461	65.0	353	68.0	818	72.0
1976	3,300	41.0	611	70.0	480	75.0	1,101	85.3

Table 8.--Comparison of registered irrigation-well statistics computed for this study with those of the U.S. Bureau of Reclamation

County and year	Computed for this study			Computed by U.S. Bureau of Reclamation		
	Acres irrigated	Number of wells	Acres per well	Acres irrigated	Number of wells	Acres per well
Buffalo:						
1946	39,200	548	71.5	41,700	503	82.9
1970	110,700	2,061	53.7	101,000	1,861	54.3
1971	123,300	2,128	57.9	116,000	1,947	59.5
Hall:						
1946	46,500	746	62.3	51,600	703	73.4
1970	117,000	2,383	49.1	117,000	2,241	52.1
1971	131,600	2,459	53.5	133,000	2,322	57.3
Merrick:						
1946	23,200	582	39.9	16,500	437	37.7

Table 9.--Municipal pumpage -- Grand Island and Kearney

Year	Grand Island	Kearney
	(acre-feet)	
1931	4,654	1,786
1935	6,057	1,839
1940	6,135	1,929
1945	9,079	2,176
1950	9,818	2,423
1955	14,902	2,633
1960	8,225	2,842
1965	[1]9,369	3,673
1970	[1]16,424	3,947
1971	[1]11,185	3,637
1975	[1]9,585	4,484

[1]Does not include pumpage from the Platte River well field, which was first used in 1965.

were not included in the recharge-discharge model. Of the withdrawals for Grand Island, only those from the well field within the city were included; those from the well field along the Platte River that fall within a stream node were not included because stream nodes are modeled as constant-head nodes.

To determine the volume of ground water pumped, the number of irrigated acres is multiplied by the CIR for a particular land use. An assumption is made that sufficient irrigation water will be applied to satisfy the CIR for that particular use. Thus, land use is the only unknown factor in this procedure for determining the pumpage.

Although information is available to indicate acres for each land-use category -- row crop, alfalfa, small grain, pasture and range -- by counties each year, comparable information on a farm-by-farm basis is not available. Therefore, assignment of acreages to different land-use categories for individual nodes for different periods clearly is impossible. The Conservation and Survey Division of the University of Nebraska developed land-use data for 1974 for the Central Platte Natural Resources District, and the U.S. Soil Conservation Service developed, but did not publish, a 1977 land-use map that covers the entire study area. Using information from these sources, acreages were assigned to each of the four land-use categories for each node. The acreages so assigned were not allowed to vary.

Additional lands brought under irrigation are assumed to have been used for growing dryland row crops and small grains. It is also assumed that all additional irrigated lands are irrigated row crops. Thus, as irrigated row-crop acreages increase, dryland row-crop and small-grain acreages decrease.

Calculations in the Flowx program also involve some assumptions. This program is used to quantify the movement of water between boundary streams and the aquifer immediately outside the study area.

The rate of water movement, in cubic feet per second, was calculated by using the summers of 1931 and 1932 water levels (fig. 8), the hydraulic conductivity for the entire aquifer at each node, the saturated thickness for the entire aquifer at each node, and the area of each node. The rate of water movement equals the product of the following: (1) hydraulic conductivity, (2) saturated thickness, (3) differences in hydraulic head between the stream node and the adjacent node outside the study area, and (4) the area of the node.

The output from the Flowx program -- the rate of water movement -- was input into the ground-water flow model and held constant for the entire calibration and predictive time intervals. An assumption was made that hydraulic-head changes from 1931-32 to 1976 did not significantly affect the rate of water movement. The rate of water movement was from +7.14 to -3.28 cubic feet per second, where positive values represent flow into streams from the ground-water system and negative values represent flow out of streams into the ground-water system.

The procedures that are used for computing evapotranspiration from the aquifer are based, in part, on assumptions. The physical processes that control ET losses from ground water are difficult to represent in a mathematical equation. For this study, the ET losses from ground water are assumed to be represented by the linear relationship,

$$q_{et_{(i,j,k)}} = ETr - \frac{ETr}{ETz}(G_{i,j} - h_{i,j,k}) \qquad (3)$$

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

$q_{et_{(i,j,k)}}$ is the ET from ground water for node (i,j) and time (k), in inches per year;

ETr is the maximum evapotranspiration rate from ground water, in inches per year;

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

$G_{i,j}$ is the elevation of the land surface, in feet; and

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

Use of the terms ETr and ETz is based on assumptions that the ET rate decreases linearly with depth, and that ET ceases at one depth regardless of type of soil or crop.

The ET values calculated by equation (3) represent ET losses or discharges from the aquifer. ETr and ETz were selected as 9 inches per year and 5 feet, respectively, after extensive experimentation with the values utilizing steady-state conditions in the ground-water flow model. When water levels at any node drop below ETz (5 feet), the ET losses are zero at that node.

ET salvage occurs when the water table is lowered by ground-water pumpage. The amount of ET salvaged equals the amount represented by the reduction in the water table down to ETz, which for this study is 5 feet. If the water table is maintained at a lowered level, ET salvage resulting from the original lowering of the water table becomes a continuing process. For this study, ET salvage is approximated as a linear function. It is zero when the water table is from 0 to 1 foot below land surface and increases linearly with depth to a maximum of 9 inches (ETr) at 5 feet below land surface. At depths to water greater than 5 feet, ET salvage remains at its maximum.

Input and Output

The input data differ for the various components of the recharge-discharge programs. Input data for the Pumpage program are as follows: Canal diversions (table 3); municipal ground-water pumpage for Grand Island and Kearney (table 9); number of wells per node; output from the soil-water program (table C of "Additional Information); land-use data; and acres irrigated per well (table 8). This program is run once for each pumping period and the output data are the net recharge or discharge for each node, which in turn become input data to the ground-water flow model.

The Flowx program uses as input water levels of the summers of 1931 and 1932, the average hydraulic conductivity, and the average saturated thickness of the aquifer. This program is run once for the entire simulation, and the output data, which are the flux values for the stream nodes, are read into the ground-water flow model for each pumping period.

The ET-loss procedures are performed within the model for each time step within the pumping period. Input data are the water levels, which may change after each time step; the land surface elevation; ETr; and ETz. Output data are ET flux values, which are handled as discharge from the aquifer.

The annual streamflows and canal diversions are computed and read into the ground-water flow model for each pumping period.

SIMULATION OF THE GROUND-WATER SYSTEM

The development of the ground-water flow model includes the selection of a type of model that can adequately represent the ground-water system, the generation of the necessary hydrogeologic and recharge-CIR data, and the calibration of the model and data against known changes in the water levels.

Description of the Ground-Water Flow Model

The type of model used in this study to simulate both the ground-water system and streamflow is the U.S. Geological Survey's two-dimensional, finite-difference model of ground-water flow developed by Trescott and others (1976). For this study, four modifications were made in the model. First, the model was modified to handle relationships between ground water and streamflow where streams are connected to the aquifer. Streamflow was handled by considering the stream network to be represented by a binary-tree structure. Surface water discharging into or from streams is processed by this accounting procedure. In addition, surface water that flows from the stream into the aquifer (inflow) or ground water that flows from the aquifer into the stream (outflow) are handled by this accounting procedure (Lappala, 1979). Second, it was modified by the addition of constant-gradient boundary nodes where water is added or removed from such nodes to maintain a constant water-table gradient (Lappala, 1979). Third, the procedures for storing hydrogeologic parameters were modified by Eric G. Lappala and Joe S. Downey (written correspondence, 1978) so that data for only the active nodes in the model are stored within the computer's central processing unit. Finally, the model was modified to permit the use of two values each for hydraulic conductivity, specific yield, and top and base of the aquifer for each node. This final modification, developed by Eric G. Lappala (written correspondence, 1978), allowed the use of hydrogeologic parameters required to describe both the upper and lower parts of the aquifer. This final modification was tested during this study by running the model as both one- and two-layer cases with the maximum possible pumpage; that is, with 100 percent of the study area irrigated with ground water. No stability or numerical problems occurred, indicating that the model was functioning properly with this modification.

The north, south, and east boundaries of this study area are streams (fig. 4). Nodes in which the streams are present are treated as constant-head nodes -- nodes in which water levels are not permitted to vary unless the streamflow in the node is zero. The west boundary lies approximately 3 miles west of the Central Platte NRD's boundary. Nodes along this boundary are constant-gradient nodes, in which gradient across them remains constant throughout time, but changes in saturated thickness of the aquifer are permitted. The extension of the study to the west was required to eliminate potential water-level problems at the NRD's boundary caused by the use of the constant-gradient nodes.

Assumptions in the Ground-Water Flow Model

Some assumptions necessary in developing and running the ground-water flow model pertain to the required input data; whereas, others pertain to the development and operation of the model. Assumptions pertaining to input data have already been discussed. Discussions that follow pertain to assumptions in the development and operation of the model.

1. The entire ground-water system can be represented as a non-homogeneous, isotropic, unconfined aquifer. There may be small areas in which the ground-water system responds like a confined aquifer; however, the regional response is that of an unconfined aquifer.

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

3. Irrigation wells penetrate, and are open to, the entire thickness of the upper and lower portions of the aquifer.

4. Pumping rates of irrigation wells are not affected by the saturated thickness of the aquifer. Thus, in model operation, the pumping rates are not adjusted as the aquifer is dewatered until the aquifer is completely dewatered and pumping ceases.

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

6. The boundary conditions -- constant-head nodes and constant-gradient nodes -- represent the aquifer at their locations.

Calibration of the Ground-Water Flow Model

Calibration of a model is the process of adjusting model input so that model output will be both realistic and valid. Commonly, calibration is accomplished by trial-and-error adjustment of input data until differences between model-output data and measured data are within acceptable limits. The calibration of the model usually involves operating the model under steady-state and transient conditions. Steady-state conditions are those in which the model results are independent of time and in which the elements of the hydrogeologic system are assumed to be in balance. Transient conditions are those in which the model results are dependent upon time and in which the elements of the hydrogeologic system are not required to be in balance.

For this study, the ground-water flow model was calibrated using the steady-state procedures to check the validity of data for hydraulic conductivity, recharge, water levels, and ET losses from ground water, and to determine the sensitivity of model results to changes in the various input data. Also, the model was calibrated using transient procedures occurring between 1931 and 1976. Model input values were adjusted until a reasonable fit occurred between the computed and measured 1976 water levels.

Steady-State Procedures

In operating the model using steady-state procedures, water levels from the summers of 1931 and 1932 (fig. 8) were used as the initial water levels, together with the weighted-average hydraulic conductivity and the elevations of the top and base of each part of the aquifer. With steady-state procedures, no storage of water is allowed in the model; thus, the specific-yield values were set at zero. Also, with steady-state conditions, model results are independent of time; therefore, the model was run for only one time step.

The ground-water model was run using steady-state procedures to check and, if necessary, to adjust some of the input data. Results from different runs in which selected input data were varied were compared; adjustments were then made in the original input data so as to produce model results that successfully simulated more closely the true response of the ground-water system.

The recharge data were modified, as necessary, by adjusting the soil, climate, crop, and seep values. For a few soils, the available water capacity (table 6) was adjusted to provide either more or less recharge. These adjustments were within a plausible range of available water capacities for the individual soils that comprise the soil group.

Due to the spatial variability of the climatic data, some adjustments were necessary so as either to raise or lower recharge. However, most were to lower recharge by 20-25 percent.

The only adjustment made in the crop data was to lower the coefficient (fig. 21) for pasture and range, because grasses become dormant during the summer. The effect was to lower the dryland and irrigated water requirements for pasture and range.

Adjustments in seep values (table 6) were made using information provided by Fred J. Otradovsky, U.S. Bureau of Reclamation (personal commun., 1979), who has developed procedures for testing input parameters to the soil-water program. These adjustments were made so that the seep values represented more accurately the seepage losses of the different soil groups. The effect of these changes were to increase recharge in some places, and to decrease it in others.

Steady-state procedures also were used to adjust the hydraulic conductivity for some of the nodes and the ET rate. The model was run using hydraulic conductivities ranging from 0.4 to 2.0 times the initial conductivities for both parts of the aquifer. The hydraulic conductivities selected were those that yielded water levels that most nearly matched those of the summers of 1931 and 1932. The average change in hydraulic conductivities was approximately 1.3 times the initial values. Similar techniques were used in selecting an ET rate; in this case, the model was run using ET rates ranging from 6 to 12 inches.

A major assumption in the procedures for adjusting input data so that computed and measured water levels were in agreement was that the summer 1931 and 1932 water levels were the most accurate input data. These water levels, therefore, were the last data to be adjusted. Water levels in the upland areas, which were not developed from the summer 1931 and 1932 measurements, were adjusted a number of times.

Transient Procedures

In running the model using the transient procedures, the water levels for the summers of 1931 and 1932 (fig. 8) were used as the initial water levels. The model was then run for the period January 1931 to September 1976 with the adjusted hydraulic conductivity, specific yield, elevations of the top and base of each part of the aquifer, and with other adjusted input data.

Normally, the initial water levels used in the model would have been smoothed by running the steady-state procedures to eliminate water-level irregularities that are caused by inadequacies in measurement, contouring, and coding. This was not done, however, because complete precipitation records for 1895 to 1931 are available for only 3 of the 15 weather stations in the study area. Therefore, recharge-discharge data necessary for generating the 1931-32 water levels are incomplete, and additional errors in the water levels would have occurred because of the inadequate climatic data. Thus steady-state procedures were used only to check and adjust some of the input values.

Output from the Flowx program, streamflows, and discharge from the Pumpage program were not modified while running the transient procedures. However, values for recharge (deep percolation) for parts of southwestern Custer County and southeastern Howard County were decreased by about 50 percent during the running of the transient procedures. Excessive simulated water-level rises were indicated for these areas when running the model for the calibration period of January 1931 to September 1976. Fine-grained materials beneath the surficial Valentine soils (fig. 3), which could not be directly included in the soil-water program, prevented complete deep percolation of water to the aquifer.

Hydraulic conductivity and specific-yield values were changed for a few nodes during running of the transient procedures. Plate 1e, 1f, 1g, and 1h indicate the final values used for these parameters.

Calibration of the ground-water model was considered complete when the computed 1976 water levels compared favorably with the measured 1976 water levels. Comparison of lines of equal water-level elevation prepared using computed water levels (fig. 15 with those measured water levels (fig. 11) shows good agreement, especially from Hall County eastward. West of Hall County the contour lines on the two figures are similar but show some divergence. The lines prepared from the computed water levels are more generalized and do not reflect the local effects of pumping and recharge as well as do the lines prepared from measured water levels.

Differences between computed water levels (fig. 15 and those derived from measurements in 1976 (fig. 11) are shown for each node on figure 16. For most nodes, the differences are less than 10 feet. Nodes for which differences are more than 10 feet are mostly in uplands where depths to water exceed 100 feet and where measured water-level data are sparse. The accuracy of water levels for individual nodes derived from measurements is plus or minus 5 feet, or one-half the contour interval of 10 feet used on work maps from which figure 11 was prepared.

A root-mean-square (RMS) analysis was performed on the 1976 computed and measured water levels as a check on the calibration of the model. This analysis involved the following: (1) Subtracting the computed from the measured 1976 water levels for each node, (2) squaring the differences,

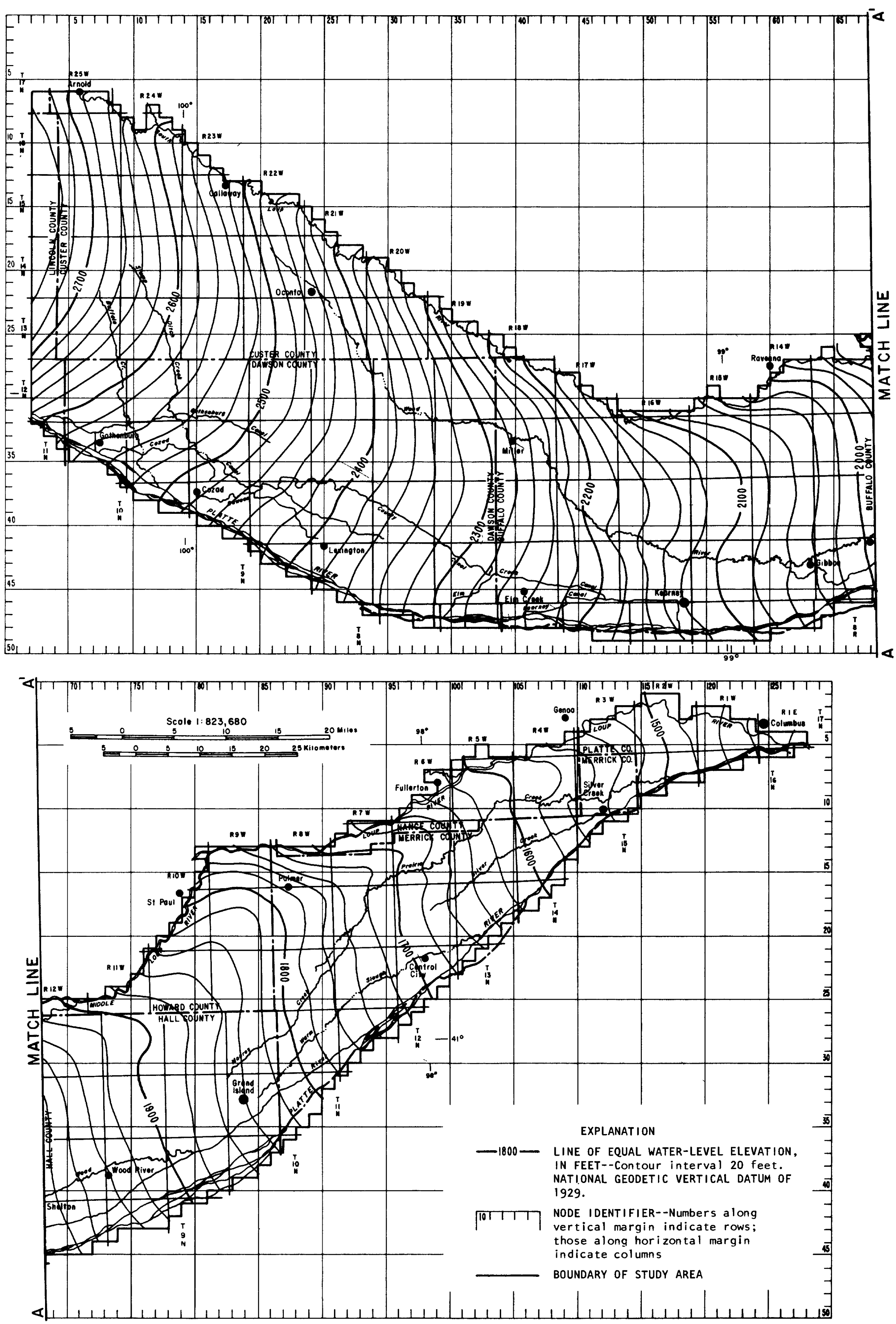


Figure 15.--Configuration and elevation of the water table, August 31, 1976, prepared from computed water levels.

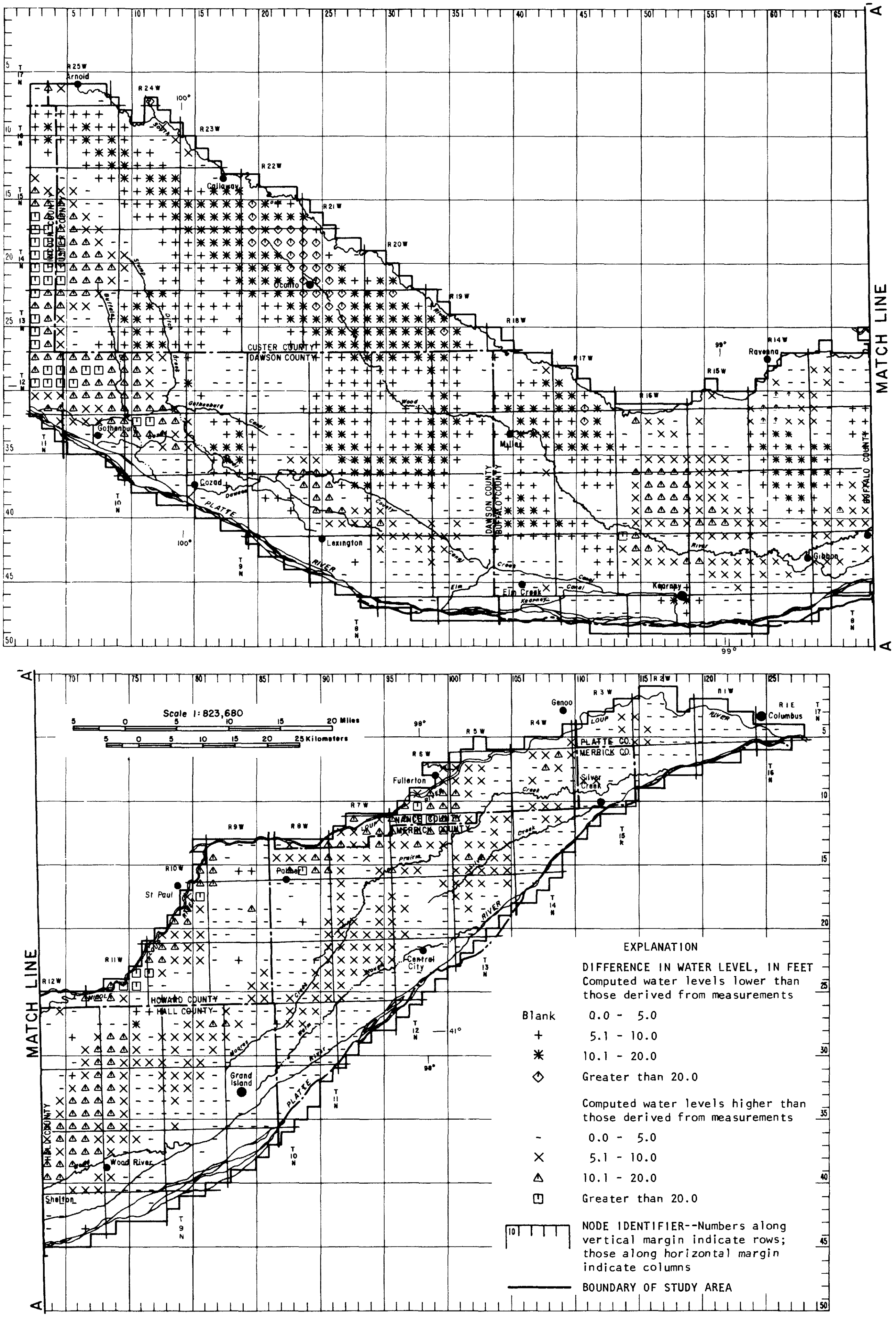


Figure 16.--Differences for individual nodes between computed water levels and those derived from measurements, 1976.

(3) adding all the squared differences for all the nodes, and (4) dividing this sum by the number of nodes and taking the square root of the result. The results of the RMS analysis, excluding the constant-head nodes, for all flood plain, terrace, and upland nodes, for flood plain and terrace nodes, and for upland nodes were 8.84, 7.76, and 9.66 feet, respectively. The lower RMS values (7.76) occur in the flood plain and terrace areas where both the 1931-32 and 1976 water-level data are more plentiful. Such RMS values, which are less than a water-level contour interval of 10 feet, indicate that water levels generated by the model are acceptable for this study.

Model-computed streamflows are compared to measured streamflows -- those computed from measurements and gaging records -- in table 10. The model-computed flows were generated using data on precipitation and on surface water (averaged for the nonirrigation pumping period of September through May) flowing into the study area. The model-computed flows represent streamflow for May 31; whereas, the measured flows are mean daily flows for the month of May.

It is unrealistic to expect that the computed flows for May 31 would match individual daily flows published for May 31. This is because individual daily flows are dependent upon the time relationship between precipitation, surface runoff, and surface-water discharges, and thus are highly variable. However, one might expect them to match the mean daily flows for May in which the time component is not as critical. This they do reasonably well.

Model-computed and measured streamflows for the irrigation pumping period of June through August compare less favorably than do the flows for the nonirrigation pumping period. This is due principally to the extreme variability in measured streamflows during this period, which is caused by variable precipitation and snowmelt along the upper reaches of the Platte River.

A check of the computational performance of the model was made by examining the balance of fluxes (flows) into and out of the aquifer. Table 11 indicates the rates of the different types of flux that were generated by the model for the irrigation pumping periods during 1931, 1950, 1960, 1970, and 1976. The sums of the rates in the last column are all extremely small, indicating that the model was not encountering stability or other numerical problems and that the model was properly processing and tabulating flux values. The negative storage values (ground water added to storage) and the large recharge values for 1950 and 1960 represent time periods during which precipitation was much higher than average.

Table 10.--Comparison of measured streamflows, in cubic feet per second, to those computed by the model

[Measured flow: Mean daily flow from published records. Computed flow: Model-generated flow for May 31]

Stream node	Gaging station reference site	May 1950		May 1956		May 1960	
		Measured flow	Computed flow	Measured flow	Computed flow	Measured flow	Computed flow
	South Loup River						
29, 60	At Ravenna	260	263	138	244	([1])	256
28, 67	At St. Michael	338	270	186	250	536	263
	Middle Loup River						
18, 79	At St. Paul	1,501	1,022	1,075	1,000	1,764	1,015
	North Loup River						
14, 80	Near St. Paul	1,223	903	930	903	1,481	903
	Loup River						
5, 110	Near Genoa	551	634	174	610	1,268	627
5, 125	At Columbus	906	775	332	748	1,990	770
	Wood River						
41, 48	Near Riverdale	16	19	1	10	21	27
42, 65	Near Gibbon	26	25	0	16	36	34
	Platte River						
39, 14	Near Cozad	289	147	24	76	336	188
48, 34	----------------	1,261	991	171	489	1,011	860
49, 46	Near Odessa	1,418	913	120	392	889	809
36, 87	Near Grand Island	1,646	980	169	471	1,400	859
8, 119	Near Duncan	1,885	990	288	474	2,244	872

Table 10.--Comparison of measured streamflows, in cubic feet per second, to those computed by the model--Continued

Stream node	Gaging station reference site	May 1965		May 1970		May 1976	
		Measured flow	Computed flow	Measured flow	Computed flow	Measured flow	Computed flow
	South Loup River						
29, 60	At Ravenna	([1])	252	143	248	([1])	241
28, 67	At St. Michael	547	258	201	256	217	250
	Middle Loup River						
18, 79	At St. Paul	1,532	1,009	708	1,008	888	1,003
	North Loup River						
14, 80	Near St. Paul	1,141	903	811	903	949	903
	Loup River						
5, 110	Near Genoa	1,148	621	49	621	259	618
5, 125	At Columbus	2,028	764	202	763	575	765
	Wood River						
41, 48	Near Riverdale	86	27	3	12	([1])	16
42, 65	Near Gibbon	129	31	2	18	.10	19
	Platte River						
39, 14	Near Cozad	149	419	548	572	130	244
48, 34	-----------------	896	1,116	1,921	1,668	936	971
49, 46	Near Odessa	1,065	1,022	1,720	1,554	845	857
36, 87	Near Grand Island	1,241	1,093	1,841	1,656	1,080	956
8, 119	Near Duncan	1,550	1,105	1,994	1,669	1,348	979

[1]No value reported.

Table 11.--Rates of water movement during irrigation pumping periods for selected years

[Rates, in cubic feet per second]

Period	Storage[1]	Constant gradient[2]	Recharge[3]	Pumping[4]	Evapotranspiration[5]	Constant head[6]		Sum
						Inflow	Outflow	
June-August 1931	566.28	40.06	34.62	-266.69	-133.17	78.00	-318.71	0.38
June-August 1950	-260.80	47.66	832.93	-181.84	-197.23	72.79	-313.12	.39
June-August 1960	-220.17	50.07	716.03	-92.04	-207.57	65.35	-313.26	-1.59
June-August 1970	1,090.04	52.64	78.34	-879.11	-138.30	85.29	-288.21	.69
June-August 1976	1,072.79	55.03	207.32	-925.29	-193.99	81.50	-296.52	.83

[1]Positive values indicate ground water removed from storage; negative values indicate ground water added to storage.

[2]Rate of underflow into western edge of study area along constant gradient nodes.

[3]Recharge to aquifer. Does not include recharge from excess surface water on surface-water irrigated lands.

[4]Total withdrawal during irrigation season from pumping of irrigation and municipal wells.

[5]Rate at which water is lost to evapotranspiration where water levels are within 5 feet of land surface.

[6]Rate of inflow or outflow through constant-head (stream) nodes. Inflow is water moving from stream to aquifer; outflow is water moving from aquifer to stream.

The cumulative water balance resulting from model computations for the entire calibration period, which ended on August 31, 1976, is given in table 12. The percent difference between inflow and outflow was less than 1 percent, which again indicates that the model encountered no problems in processing the fluxes.

Table 12.--Cumulative water balance resulting from computations for the calibration period 1931-1976

Inflow, in millions of cubic feet		
From storage	46,822	
From constant gradient flux[1]	68,866	
From recharge[2]	583,872	
From constant head, inflow[3]	107,291	
Total gains		806,851
Outflow, in millions of cubic feet		
To evapotranspiration[4]	239,878	
To constant head, outflow[3]	440,655	
To pumpage	126,258	
Total losses		806,791
Difference between gains and losses		60
Percent difference		0.01

[1]Underflow into western edge of study area across the constant-gradient nodes.
[2]Does not include recharge from excess surface water on surface-water irrigated lands.
[3]Inflow or outflow through the constant-head (stream nodes). Inflow is water moving from stream to aquifer; outflow is water moving from aquifer to stream.
[4]Rate by which water is lost to evapotranspiration where water levels are within 5 feet of land surface.

Sensitivity Analysis

The effects of data uncertainties on simulation results can be assessed, to a certain degree, by performing sensitivity analyses on the various types of input data for both steady-state and transient conditions. The sensitivity of the model was examined by adjusting hydraulic conductivity, specific yield, and recharge within their expected ranges and observing the resulting changes in computed water levels.

Results of sensitivity analyses indicated that water levels were more responsive to adjustments in recharge than to adjustments in hydraulic conductivity or in specific yield by a factor of at least 2. Also, the magnitude of changes in water levels in response to adjustments in discharge and in ET losses are similar to the magnitude of changes in response to adjustments in recharge.

Potential Uses and Limitations of the Calibrated Model

A variety of management alternatives or predictive schemes can be examined utilizing the calibrated model. However, careful construction and application of the predictive schemes must be followed or erroneous results will be produced. Also, there are limitations on what the model can predict with reasonable accuracy even if good techniques are employed.

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

Alternatives in rates of applying irrigation water might be based on existing technology, future technology, or expected changes in farm practices. An examination of literature on existing technology reveals that the irrigation-application rates vary significantly with type of cultivation, of weed-control programs, and of irrigation-scheduling procedures. Future technology may reduce rates at which irrigation water must be applied through development of more drought-resistant varieties of plants and through the use of more water-efficient farming practices. Changes in farming practices might include the growing of crops that require less water or deliberately using less irrigation water than is required to achieve maximum yield.

Numerous alternatives relating to surface-water use are possible for the study area. Present surface-water irrigated acreage in Dawson and Buffalo Counties might be altered so that more or less ground water for irrigation may be required. Irrigation projects using surface water have been proposed for Buffalo and Hall Counties that might provide recharge to the ground-water system and reduce ground-water pumping by converting some ground-water irrigated lands to surface-water irrigation.

Variations in the flows of the boundary streams are possible in the future because of additional diversions either within the study area or upstream, or because of additional ground-water irrigation in upstream areas, or both. The probable effects of these variations on the hydrology of the study area can be examined in the ground-water flow model by varying flows in the boundary streams.

The model should not be used to examine management alternatives that it was not designed to handle. For example, this model was not designed to handle relationships between streamflows and bank storage in the ground-water system during floods. Nor was it designed to handle alternatives relating to economics, government policies, and numerous other items.

MANAGEMENT ALTERNATIVES EXAMINED

Selecting management alternatives to be examined with a ground-water flow model is often difficult because water-resources development is uncertain. A technique commonly used is to identify a type of development likely to take place and to describe the effects on the hydrology of the area for both an assumed lowest and assumed highest probable rate of development. At least tentative management decisions can be made using results of interpolation between the effects of the assumed lowest and highest probable rates of development.

Also, the number of alternatives that can be examined is limited by practicable considerations of cost and time. It is important, therefore, that the alternatives selected for examination be realistic and meet the perceived needs of planning agencies. To assure this, the alternatives were selected in close consultation with personnel of both cooperating agencies.

The management alternatives examined pertain to three major areas of concern. These are as follows: (1) The effects on ground-water levels and on streamflows that might result from diverting annually within the study area an additional large volume of water from the Platte River; (2) the effects on water levels and on streamflow if no new ground-water irrigation development takes place from 1980 through

2020, but if five different irrigation-application rates are used; and (3) the effects on water levels and on streamflow if the annual rate of irrigation development of irrigable but unirrigated land is 2, 5, or 8 percent and if the irrigation-application rates are less than, equal to, or greater than CIR.

Additional Diversion of Water from the Platte River

The first management alternative examined is the diversion of an additional 125,000 acre-feet of water per year from the Platte River. This alternative is based on a plan to divert as much as 125,000 acre-feet per year for a proposed irrigation project outside the Platte River Basin. Water for the proposed irrigation project would be diverted from the Central Nebraska Public Power and Irrigation District's Tri-County Canal. Without this diversion, this water would be returned to the Platte River at stream node 47,28 -- the Johnson Power Return on figures 4 and 5. The maximum rate of diversion is set at 450 cubic feet per second, and at no time would it be allowed to exceed 75 percent of the flow of the Platte River. Diversions are to be permitted between September 1 and January 15, with additional diversions permitted after April 1, if necessary to obtain 125,000 acre-feet. However, for modeling purposes, all diversions are made between September 1 and January 15.

The first step in analyzing this management alternative was to run the ground-water model using steady-state procedures. The 1976 water-level configuration map (fig. 11) was used as the initial water levels. The net recharge or discharge values used were the average values for the 1931 to 1976 climatic period with 1976 irrigation-well distribution and land use. Output from running the steady-state procedures were "smoothed" 1976 water levels. Irregularities in the measured 1976 water levels and errors and irregularities in hydraulic conductivity and recharge-discharge values were lessened by developing the "smoothed" water levels.

The final step was to run the ground-water flow model with transient procedures. In this step, the "smoothed" 1976 water levels were used as the initial water levels. The 1957 water-year streamflow and climatic data and the 1976 irrigation-well distribution and land-use data were used to generate net recharge or discharge values for each node for a 1-year period. This was repeated five times using the same data to generate 5 years of data.

The rationale for the previous procedures is as follows: First, this alternative has been examined earlier using a ground-water flow model developed for the Platte River Basin, Nebraska Level B Study (Lappala and others, 1979). The purpose of this current examination is to update the earlier results to 1976 ground-water conditions. Second, this current examination of the alternative was performed before the present ground-water flow model was completely calibrated. Therefore, steady-state procedures were used to develop the "smoothed" 1976 water levels used as input for the transient procedures instead of model-computed 1976 water levels. Third, 1976 data on irrigation-well distribution and land use were used to generate recharge-discharge data because they correspond in time to the 1976 water levels. Fourth, climatic data for the 1931-76 period were used in order to include a wide variety of climatic conditions. Finally, streamflow values used for stations along the Platte River were those of the 1957 water year, because they are typical of those one might expect during a prolonged period of low flow. This is indicated by the fact that the 1957 annual flow at Grand Island was 483,000 acre-feet, which is close to the 479,000 acre-feet average for the 1953-57 period -- the period of lowest prolonged streamflow on record since closure of the dam on Lake McConaughy.

The output from two model runs using transient procedures are two sets of data, one indicating what the water levels would be with the diversion, and the other indicating what the water levels would be without the diversion. The differences between these sets of water levels for March 31, after 5 years of simulation are shown on figure 17 It should be noted that the differences are those that developed following a prolonged 5-year period of low flow. They clearly would be less following shorter prolonged periods of low flow, or periods of normal or high flows. It should also be noted that a diversion of 125,000 acre-feet of water represents 26 percent of the annual flow at Grand Island for the 1957 water year. However, this diversion would represent only 12 percent to less than 5 percent of the annual flow for normal- or high-flow years, respectively.

An evaluation of figure 17 indicates that the declines in water levels greater than 5 feet would occur in 36 nodes, and that declines greater than 10 feet would occur in 3 nodes. The maximum decline would be 10.7 feet in node 33,87. The pattern of declines was well established within the first 2 years of the 5-year period; during the remaining 3 years, both the amount of decline and the areal extent of the decline increased.

The slight decline in water level just south of Elm Creek, near stream node 48,40, at the Kearney Canal diversion site would be the result of the decrease in return flows from the Johnson Power Return at stream node 47,28.

The effects of pumpage in the Grand Island well field, which is on an island in the Platte River near stream node 39,84, were not evaluated. Inclusion of this well field would most likely produce increased water-level declines in this area because of the additional water pumped from the aquifer.

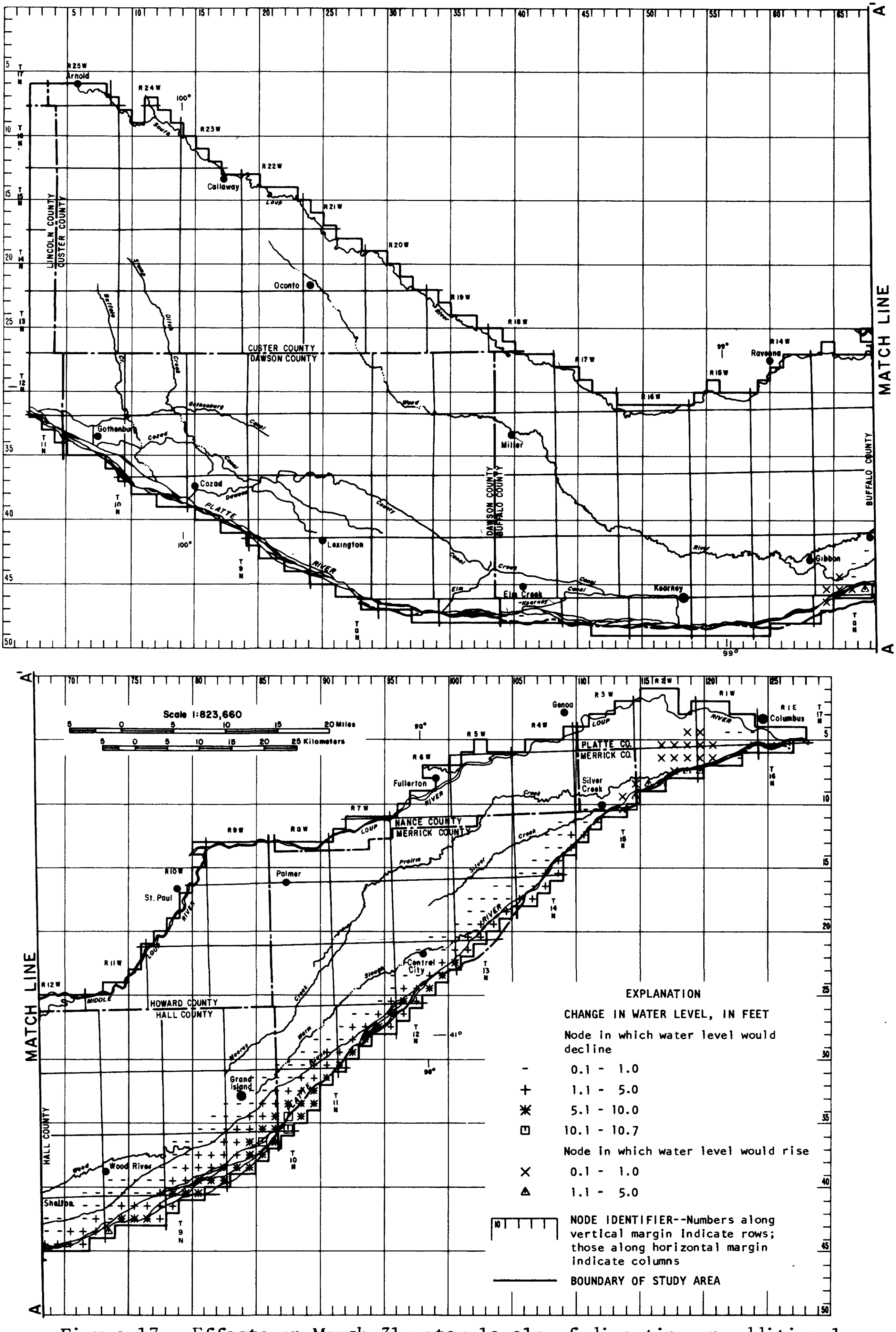


Figure 17.--Effects on March 31 water levels of diverting an additional 125,000 acre-feet of water from the Platte River for 5 years.

Recharge from the Loup River affects the area from columns 113 through 126 when the Platte River is dry. Evidently, when the Platte River is dry, water flows from the Loup River through the aquifer toward the dry channel of the Platte River.

The effects that the additional diversion would have on flow in the Platte River are shown in table 13. The measured flows are the mean daily flows reported for each of the months in the U.S. Geological Survey annual water-data report for 1957. The computed flows by the ground-water model and by other procedures (State of Nebraska, 1978) are those that would have occurred in 1957 had there been diversion of an additional 125,000 acre-feet that year. Whereas, without the diversion, the Platte River was dry at Grand Island in September and October and near Duncan in December. Had there been the diversion, it would have been dry the entire period of September through March.

The declines in water levels and streamflows projected as a result of additional diversion are for a period following 5 years of low streamflow in which the Platte River was dry for as much as 6 months annually. The declines projected would have been less had they been applied to a period of normal streamflow.

No New Ground-Water Irrigation Development After 1980

Before this set of management alternatives could be examined, the calibrated ground-water flow model had to be extended from September 1, 1976, to August 31, 1980. Data on irrigated acres from 1977 to 1980 were generated by the same procedures used in generating data on irrigated acres from 1931 to 1976. Climatic and streamflow data for the 1951 through 1954 period were used in the recharge-discharge model to represent the 1977 through 1980 period. The use of the existing 1951-54 data instead of the 1977-80 data allowed a considerable savings in time and effort in running this and the final management alternative. The use of this shortcut does not impair the predictive results, since the objective of the predictive schemes was not 1980 water levels but water levels in the 1990's through 2020.

To examine this management alternative, it was necessary to know the acres irrigated in 1980 (fig. 7). In addition, the acres suitable for irrigation (fig. 18) and acres suitable but not irrigated as of 1980 (table 14) were developed for each node. The acres suitable for irrigation were determined by examining both the hydrologic properties of the soils and the hydrogeologic limitations of the aquifer. Urban areas were excluded, but no areas were excluded because of hydrogeologic limitations of the aquifer.

Table 13.--Effect of diversion of an additional 125,000 acre-feet on streamflows in the Platte River had the diversion occurred during the 1957 water year

[Measured streamflows are actual flows without diversion. Computed streamflows are flows that would have occurred with diversion.]

Month and year	Average flow, in cubic feet per second								
	Platte River at Overton[1]			Platte River at Grand Island[2]			Platte River near Duncan[3]		
	Meas-ured	Computed by others[4]	Computed by model	Meas-ured	Computed by others[4]	Computed by model	Meas-ured	Computed by others[4]	Computed by model
September 1956	55	14	13	0	0	0	0	0	0
October 1956	404	111	110	0	0	0	0	0	0
November 1956	641	192	191	139	0	0	0	0	0
December 1956	573	203	202	267	0	0	128	0	0
January 1957	607	157	156	200	0	0	154	0	0
February 1957	723	360	359	683	0	0	564	0	0
March 1957	665	665	664	769	0	0	820	0	0
April 1957	802	677	676	958	827	630	979	587	629
May 1957	2,479	2,479	2,478	2,444	2,444	2,400	2,293	2,293	2,367
June 1957	1,636	1,636	1,635	2,233	2,233	1,530	2,453	2,453	1,495
July 1957	339	339	338	307	307	233	409	409	200
August 1957	157	157	156	6	6	67	4	4	32

[1]Stream node 48, 34
[2]Stream node 36, 87
[3]Stream node 8, 119
[4]From State of Nebraska, 1978

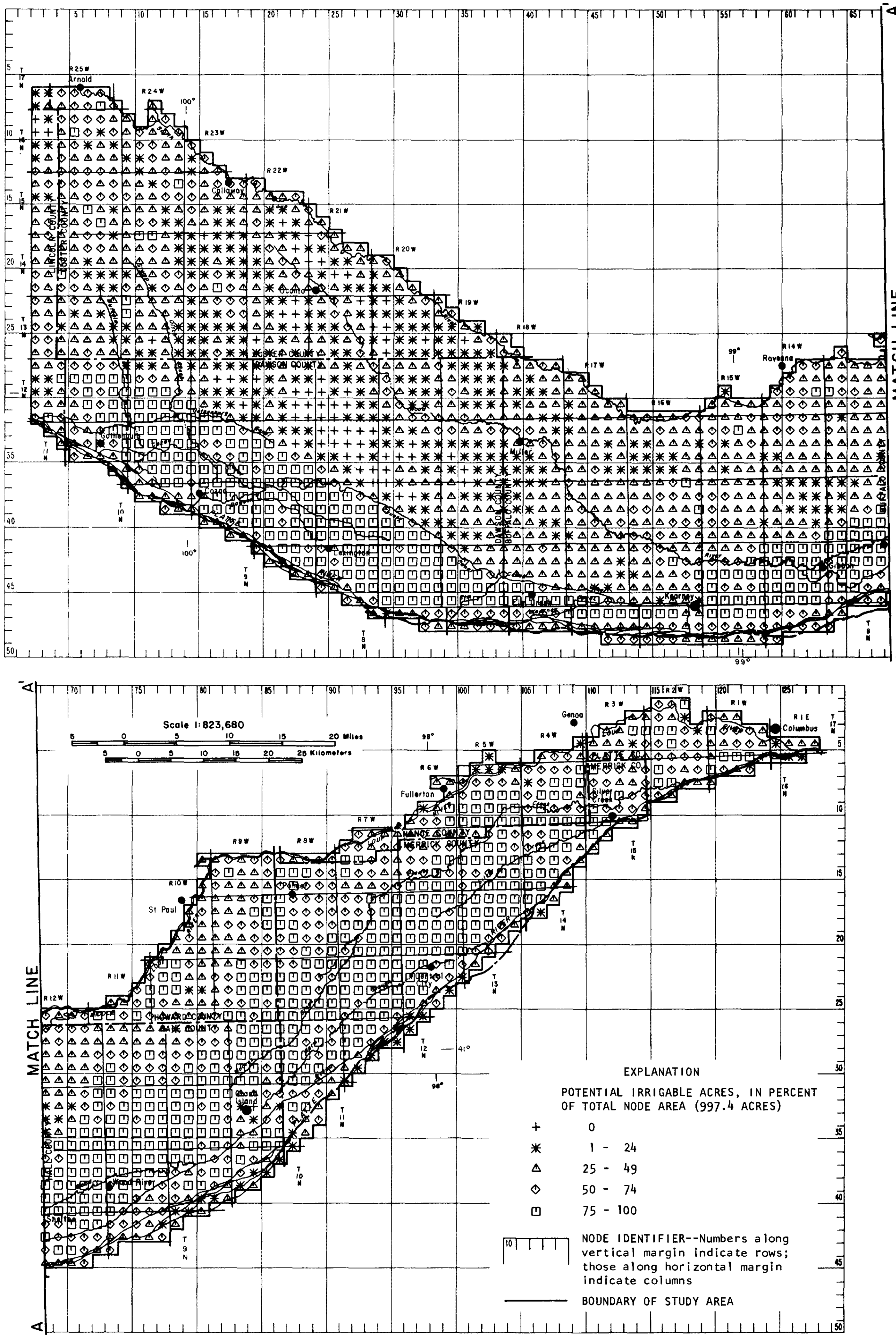


Figure 18.--Land suitable for irrigation.

Table 14.--Irrigation status in 1980 of land, in acres, within study area

County	Land suitable for irrigation	Land irrigated	Land suitable for irrigation but not irrigated
Custer	160,000	50,000	110,000
Dawson	300,000	160,000	140,000
Buffalo	280,000	150,000	130,000
Hall	200,000	140,000	60,000
Merrick	240,000	140,000	100,000
Howard	77,000	30,000	47,000
Nance	65,000	26,000	39,000
Platte	58,000	33,000	25,000

The 1980 level of ground-water irrigation development is considered to be the zero or the no-additional-development management alternative. The following procedures and conditions applied in the examination of this alternative:

(1) The 1951 to 1970 climatic and streamflow data were used to obtain 1 through 20 years and 21 through 40 years of predictive data to be used, in turn, as input for the 40-year predictive period. Data for this period were selected because this period occurred after the Tri-County Canal system and Lake McConaughy became operational in the early 1940's. Also, it contained wet, normal, and dry periods, and thus appeared to have been a representative period. The average annual precipitation for all the weather stations for the period was 0.65 inches more than for the 1931-76 period -- a period that included the very dry 1930's.

(2) Five different irrigation-application rates recommended by cooperators, in order of increasing magnitude, were considered: (a) 80 percent of CIR; (b) low rates of 8.8 inches per year in Buffalo County eastward and 10.2 inches per year in Dawson and Custer Counties; (c) CIR; (d) medium rates of 11.0 inches per year in Buffalo County eastward and 12.75 inches per year in Dawson and Custer Counties; and (e) high rates of 13.75 inches per year in Buffalo County eastward and 16.0 inches per year in Dawson and Custer Counties. CIR differs with soil group and crop. Specifically, how it differs in this study area can be seen in table C of "Additional Information."

Following the procedures and conditions mentioned, a modified Pumpage program was used to generate recharge and discharge data for the predictive period. The ground-water flow model then was run to simulate the 40-year predictive period, and output results indicate projected water levels for each of the application rates. Literally hundreds of combinations of time spans and application rates might have been examined. For this report, however, results of examination of only a few such combinations have been chosen for presentation and are given in plate 2a, 2b, 2c, and 2d.

Plate 2a and 2b bracket the range of application rates and show what is likely to happen to water levels by the year 2000 at a low rate of irrigation application (80 percent of CIR) and a high rate. Plate 2c indicates what is likely to happen at a medium rate (CIR) of irrigation application. Similar illustrations could have been presented for the remaining two application rates indicated in (b) and (d) above; they would have shown intermediate water-level declines relative to those on the plate presented.

The projected water-level declines shown in the plate are relative to water levels of August 31, 1976. Water levels of 1976 were used as the base for comparison rather than those for 1980 because they are calibrated water levels and, thus, are more accurately defined. The time span involved is about 24 years.

The declines in water level that might be expected by May 31, 2020, which marks the end of a predictive time span of 44 years, are indicated on plate 2d. The further we project into the future, the greater the uncertainty. Thus, no attempt is made to "bracket" a range in application rates, as was done for the shorter predictive period. Instead, the CIR application rate, which is the rate that will satisfy the consumptive-irrigation requirements of the crops, is used for the longer predictive period.

Comparison of plate 2a, 2b, and 2c clearly shows that both the areas and magnitudes of water-level declines will differ significantly depending on which irrigation-application rate is used. If an application rate of 80 percent of CIR is used (fig. 2a), declines of more than 20 feet below 1976 levels can be expected in several areas comprising about 10 percent of the study area. The maximum decline to be expected will be between 40 and 59 feet in an area north of the city of Wood River.

If an application rate exceeding CIR (fig. 2b) is used, declines of more than 20 feet below 1976 levels can be expected in nearly half the study area; declines of more than 40 feet will be common. The maximum decline will be between 120 and 139 feet in the area north of the city of Wood River.

If an application rate equal to CIR is used (fig. 2c), declines of more than 20 feet below 1976 levels can be expected in about 20 percent of the study area; declines of more than 40 feet can be expected in two areas. The maximum decline expected will be between 60 and 79 feet, again in the area north of the city of Wood River.

Plate 2d shows projected water-level declines by 2020, assuming an application rate equal to CIR. This plate can be compared logically only with plate 2c, with which it shares a common application rate. Areas and magnitudes of water-level decline on plate 2d are greater than those on plate 2c simply because the predictive period involved is longer.

Water-level declines that may be expected if the higher application rates are used will be so great that parts of the aquifer from Hall County eastward will be completely dewatered. The number of nodes that will be dewatered by the year 2020 for the CIR and the high irrigation-application rates are 11 and 99, respectively.

Balance in the rates of flux into and out of the aquifer for the CIR application rate is indicated in table 15. A comparison of this table with table 11 indicates that much less water would be lost to ET from the shallow water-table areas under this alternative than has been lost historically. This is to be expected, because ET from the shallow water-table areas ceases when the depth to water exceeds 5 feet, and with the greater water-level declines, the areas within 5 feet of the land surface become smaller.

The projected effects that the different irrigation-application rates would have on streamflow in the years 2000 and 2020 are presented in table 16. The model-computed streamflow for May 31, 1970, represents the 20th year of the 1951 to 1970 climate and streamflow data that were used to generate the predictive recharge-discharge data for the model. Depletions shown, therefore, are the amounts by which the flows in 2000 and 2020 will fail to match those in 1970.

Most of the stream nodes for which depletions are given are at stream-gaging locations. The first stream node listed for the Platte River is node 32,2 on the western edge of the study area; so, as indicated by the zeros in table 16, there will be no depletions at this stream node if this management alternative is followed. Likewise, no depletions will occur at stream nodes 14,80 along the North Loup River and 8,98 along the Cedar River. At each of the remaining stream nodes, the expected depletions increased with the irrigation-application rate. Also, in nearly all cases, depletions will be higher in 2020 than in 2000. The exception will be for the Wood River near Gibbon and near Chapman, where the model indicates that there would be little or no flow on May 31 in either year as projected depletions equal computed flows.

Table 15.--Rates of water movement for the alternative that assumes no new ground-water irrigation development after 1980 and an application rate equal to consumptive-irrigation requirements

[Rates, in cubic feet per second]

Period	Storage[1]	Constant gradient[2]	Recharge[3]	Pumping[4]	Evapotranspiration[5]	Constant head[6]		Sum
						Inflow	Outflow	
June-August 1990	1,783.71	65.89	206.35	-2,020.27	-18.52	159.82	-176.23	0.75
June-August 2000	4,007.80	70.08	39.19	-4,120.71	-11.77	164.33	-156.96	-8.05
June-August 2010	1,714.79	75.78	206.35	-2,027.95	-11.56	187.53	-143.98	.97
June-August 2019	1,187.68	78.12	100.03	-1,364.40	-13.89	164.04	-150.60	.97
September-May 2020	-394.29	78.09	358.76	-19.88	-16.19	152.91	-160.15	.75

[1]Positive values indicate ground water removed from storage; negative values indicate ground water added to storage.

[2]Rate of underflow into western edge of study area along constant gradient nodes.

[3]Recharge to aquifer. Does not include recharge from excess surface water on surface-water irrigated lands.

[4]Total withdrawal during irrigation season from pumping of irrigation and municipal wells.

[5]Rate at which water is lost to evapotranspiration where water levels are within 5 feet of land surface.

[6]Rate of inflow or outflow through constant-head (stream) nodes. Inflow is water moving from stream to aquifer; outflow is water moving from aquifer to stream.

Table 16.--Projected streamflow depletions for the years 2000 and 2020 compared to computed streamflow of 1970 for three rates of ground-water irrigation application assuming no new ground-water development after 1980

[Streamflow and depletions, in cubic feet per second]

Stream node	Gaging station reference site	Model computed stream-flow, May 31, 1970	Depletions					
			Applying 80 percent of CIR		Applying CIR		Applying at a high rate[1]	
			May 31, 2000	May 31, 2020	May 31, 2000	May 31, 2020	May 31, 2000	May 31, 2020
	South Loup River							
29, 60	At Ravenna	248	33	41	38	49	49	64
28, 67	At St. Michael	256	35	45	41	53	53	71
	Middle Loup River							
18, 79	At St. Paul	1,008	41	53	47	63	64	87
	North Loup River							
14, 80	Near St. Paul	903	0	0	0	0	0	0
	Cedar River							
8, 98	Near Fullerton	240	0	0	0	0	0	0
	Loup River							
5, 110	Near Genoa	621	47	61	55	74	78	106
5, 125	At Columbus	763	51	65	60	78	90	119
	Wood River							
41, 48	Near Riverdale	12	7	9	8	10	11	12
42, 65	Near Gibbon	18	17	17	17	17	18	18
39, 70	Near Chapman	16	16	16	16	16	16	16
	Platte River							
32, 2	----------------	560	0	0	0	0	0	0
39, 14	Near Cozad	572	6	8	9	12	13	17
48, 34	----------------	1,668	16	19	23	30	36	48
49, 46	Near Odessa	1,554	19	24	29	38	47	62
36, 87	Near Grand Island	1,656	49	61	66	87	121	153
8, 119	Near Duncan	1,669	67	77	93	123	176	219
5, 127	-----------------	2,433	119	152	154	202	267	342

[1]High rate is 13.75 inches in Buffalo County and eastward and 16.0 inches in Dawson and Custer Counties.

The depletions projected in table 16 apply only to May 31. However, they are typical of the magnitude of the depletions that can be expected for any day during the nonirrigation period of September through May.

Irrigation Development at Selected Rates from 1981 to 2020

To assume no new irrigation development after 1980, as was done in the previous section, is instructive but somewhat unrealistic. New lands will undoubtedly be brought under irrigation using ground water, but the rate at which this will occur is uncertain. Recognizing this uncertainty, both cooperators agreed that we should bracket what they believed to be a high development rate and a low development rate, and that we should consider, in addition, one intermediate rate. Thus, a decision was reached to examine the effects on ground-water levels of development rates that would annually convert to irrigation 2, 5, or 8 percent of the acres irrigable but unirrigated at the end of each predictive year. The period simulated was from 1981 to 2020.

The effects on ground-water levels will depend significantly on the rate at which irrigation water will be applied. Irrigation application rates of 80 percent of CIR, CIR, and 120 percent of CIR were examined. Results are presented for all three application rates in 2000 and the CIR application rate in 2020.

Climatic and streamflow data for the period 1951 to 1970 were used to represent equivalent data for the periods 1981 to 2000 and 2001 to 2020.

New acres assumed to be developed for irrigation each year were selected by counties using a random-procedures program provided by Richard A. Kern, Nebraska Natural Resources Commission (personal commun., 1981). This program selected nodes and tested whether they contained the minimum acres required for development -- at least 10 acres of irrigable but unirrigated lands in terraces and flood plains, or at least 100 acres in uplands. If a randomly-selected node did not contain the minimum required acres, the node was not used and another was randomly selected. The selection and testing process continued until the required percentage of acres was selected for each county. This procedure was repeated for each year of the predictive period or until all irrigable plots of adequate size in the county had been placed under irrigation.

Table 17 contains information on the projected irrigated acres and projected irrigable but not irrigated acres for 1990, 2000, 2010, and 2019 (the last irrigation pumping period used in the predictive period)

Table 17.--Projected irrigated acreages for selected years for 2, 5, or 8 percent annual ground-water irrigation development rates

County	Suitable for irrigation (acres)	Rates of development (Percent)	1990		2000		2010		2019	
			Suitable for irrigation but not irrigated (acres)	Projected for irrigation (acres)	Suitable for irrigation but not irrigated (acres)	Projected for irrigation (acres)	Suitable for irrigation but not irrigated (acres)	Projected for irrigation (acres)	Suitable for irrigation but not irrigated (acres)	Projected for irrigation (acres)
Custer	160,000	2	92,000	68,000	75,000	85,000	62,000	98,000	52,000	108,000
		5	68,000	92,000	41,000	119,000	26,000	134,000	17,000	143,000
		8	50,000	110,000	23,000	137,000	11,000	149,000	6,000	154,000
Dawson	300,000	2	114,000	186,000	93,000	207,000	76,000	224,000	64,000	236,000
		5	84,000	216,000	50,000	250,000	30,000	270,000	19,000	281,000
		8	61,000	239,000	26,000	274,000	11,000	289,000	5,000	295,000
Buffalo	280,000	2	106,000	174,000	87,000	193,000	71,000	209,000	59,000	221,000
		5	78,000	202,000	47,000	233,000	28,000	252,000	18,000	262,000
		8	56,000	224,000	25,000	255,000	11,000	269,000	5,000	275,000
Hall	200,000	2	49,000	151,000	40,000	160,000	33,000	167,000	28,000	172,000
		5	36,000	164,000	22,000	178,000	14,000	186,000	9,000	191,000
		8	27,000	173,000	12,000	188,000	6,000	194,000	3,000	197,000
Merrick	240,000	2	82,000	158,000	68,000	172,000	56,000	184,000	47,000	193,000
		5	61,000	179,000	35,000	202,000	24,000	216,000	16,000	224,000
		8	45,000	195,000	21,000	219,000	11,000	229,000	7,000	233,000
Howard	77,000	2	38,000	39,000	31,000	46,000	26,000	51,000	21,000	56,000
		5	28,000	49,000	17,000	60,000	10,000	67,000	6,000	71,000
		8	20,000	57,000	9,000	68,000	4,000	73,000	2,000	75,000
Nance	65,000	2	32,000	33,000	26,000	39,000	22,000	43,000	18,000	47,000
		5	24,000	41,000	15,000	50,000	9,000	56,000	6,000	59,000
		8	17,000	48,000	8,000	57,000	4,000	61,000	3,000	62,000
Platte	58,000	2	20,000	38,000	16,000	42,000	13,000	45,000	11,000	47,000
		5	15,000	43,000	8,000	50,000	5,000	53,000	3,000	55,000
		8	10,000	48,000	4,000	54,000	1,000	57,000	0	58,000

for annual ground-water irrigation development rates of 2, 5, and 8 percent. An examination of this table shows significant differences in the projected irrigable acres, especially between the 2 and 8 percent development rates.

Data obtained as just described were used in a modified version of the Pumpage program discussed in an earlier section. Outputs from the Pumpage program were recharge and discharge data that were used in the calibrated ground-water model. Output from the ground-water model was then used to construct plate 3a to 3h.

Plate 3a and 3b show areas and magnitudes of water-level declines to be expected by the year 2000 if the rate of irrigation development is 2 percent. Both the area and the magnitude of the declines increases with the rate of application.

Plate 3c and 3d show areas and magnitude of water-level declines to be expected by 2000 if the rate of irrigation development is 5 percent, and plate 3e and 3f show areas and magnitude of water-level declines to be expected by 2000 if the rate of irrigation development is 8 percent. The same pattern of increased area and increased severity of decline are evident in these illustrations as was mentioned for plate 3a and 3b.

Maximum water-level decline, regardless of which plate is consulted, will occur north of the city of Wood River. As for the previous management alternative, declines are projected from August 31, 1976, instead of 1980. By the year 2000, the maximum decline below the August 31, 1976, water levels, for each development rate with an application rate of 120 percent of CIR, will be between 80 and 99 feet. Also, by 2000 declines of 60 to 79 feet will develop northwest of Cozad and northeast of Grand Island if water is applied at 120 percent of CIR.

Water-level declines that may be expected by 2020, if rates of irrigation development are 2 percent and 8 percent, respectively, are shown in plate 3g and 3h. For each rate of development, only the CIR application rate was presented. Because of the tentative nature of a 40-year projection and the need for economizing space in this report, illustrations are not included for the 5-percent development rate nor for application rates of 80 and 120 percent of CIR.

In plate 3g water-level declines of 100 to 119 feet are projected for the year 2020 north of the city of Wood River and along the western boundary of Merrick County. Such declines are more extensive and up to 40 feet greater than declines projected through the year 2000 for the same development and application rates (plate 3b).

As plate 3h indicates, a development rate of 8 percent through the year 2020 will result in much more extensive water-level declines than any of the management alternatives previously described. These declines are up to 60 feet greater than those representing the same development and application rates for the year 2000. Also, declines of 80 to 99 feet will occur in a small area northwest of Cozad. Maximum water-level declines by the year 2020 will be 120 to 139 feet north of the city of Wood River and northeast of Grand Island.

The rates of flux generated by the ground-water model, assuming an application rate equal to CIR and annual irrigation-development rates of 2, 5, and 8 percent, are listed in table 18. The rates are for the 1990, 2000, 2010, and 2019 irrigation pumping periods and for the 2020 nonirrigation pumping period. A comparison of data in this table to data in table 14 indicates the projected effects of additional ground-water irrigation development. The amount of pumping will have increased by, in some cases, as much as a factor of two.

Fluctuations in pumping, recharge, storage, and the other parameters listed in table 18 can be explained, in part, by variations in the climatic data used as input for the 40-year interval. Thus, it is useful to compare rates of flux for years for which the same climatic and streamflow data were used. These are, in one case, the years 1960 (from table 11), 1990, and 2010 and, in another case, the years 1970 (from table 11), 2000, and 2020. Such comparisons indicate that with additional development the volume of pumpage and water removed from the aquifer (storage) increase, that flow from the stream to the ground-water system (inflow) likewise increases, and that recharge from infiltration through the soil zone to the aquifer decreases. Also, the amount of water loss to ET decreases as development increases. The net effect is a decrease in the volume of ground water stored in the aquifer and a lowering of water levels.

The water-level declines will become larger as the application rates and the irrigation-development rates increase, and parts of the aquifer east of the Buffalo-Hall County line will be dewatered. The number of nodes that will be dewatered by the year 2020 with 2, 5, and 8 percent irrigation-development rates and with an application rate equal to CIR will be 15, 25, and 28, respectively.

The projected effects of different rates of irrigation development and of different rates of application on streamflow are shown in table 19. The depletions are compared to computed streamflow of May 1970 for reasons discussed previously in the section "No New Ground-Water Irrigation Development after 1980." Data in this table indicate that increased streamflow depletions accompany increased development and application rates.

Table 18.--Rates of water movement for ground-water irrigation development rates of 2, 5, and 8 percent and a rate of application equal to consumptive-irrigation requirements

[Rates, in cubic feet per second]

Period	Storage[1]	Constant gradient[2]	Recharge[3]	Pumping[4]	Evapotranspiration[5]	Constant head[6]		Sum
						Inflow	Outflow	
			2 percent development rate					
June-August 1990	2,254.95	64.36	136.86	-2,433.87	-15.16	160.39	-166.26	1.26
June-August 2000	5,135.36	68.00	27.10	-5,268.77	-6.85	172.64	-134.96	-7.45
June-August 2010	1,963.21	71.18	31.54	-2,102.47	-8.03	173.84	-128.71	.55
June-August 2019	2,047.90	72.81	48.67	-2,226.09	-7.36	180.16	-116.15	-.07
September-May 2020	-492.37	73.35	394.91	-5.04	-9.49	166.03	-128.47	-1.09
			5 percent development rate					
June-August 1990	2,785.46	64.14	103.08	-2,951.24	-11.36	163.81	-154.23	-.34
June-August 2000	6,108.74	67.58	24.87	-6,299.33	-4.62	191.31	-114.71	-26.17
June-August 2010	2,436.60	69.24	23.89	-2,622.47	-5.08	203.25	-104.10	1.33
June-August 2019	2,457.27	69.81	41.28	-2,691.32	-4.62	220.81	-92.05	1.18
September-May 2020	-569.11	70.40	413.72	-5.03	-6.26	200.31	-105.05	-1.02
			8 percent development rate					
June-August 1990	3,107.44	65.12	71.63	-3,263.91	-9.06	171.78	-145.81	-2.81
June-August 2000	6,572.92	69.17	24.70	-6,793.91	-3.25	209.83	-101.57	-22.11
June-August 2010	2,568.49	70.05	22.82	-2,790.80	-3.87	226.79	-93.36	.11
June-August 2019	2,552.44	69.74	39.90	-2,820.13	-3.78	245.54	-83.24	.48
September-May 2020	-603.64	70.17	419.07	-5.03	-5.01	220.10	-96.66	-.99

[1]Positive values indicate ground water removed from storage; negative values indicate ground water added to storage.

[2]Rate of underflow into western edge of study area along constant gradient nodes.

[3]Recharge to aquifer. Does not include recharge from excess surface water on surface-water irrigated lands.

[4]Total withdrawal during irrigation season from pumping of irrigation and municipal wells.

[5]Rate at which water is lost to evapotranspiration where water levels are within 5 feet of land surface.

[6]Rate of inflow or outflow through constant-head (stream) nodes. Inflow is water moving from stream to aquifer; outflow is water moving from aquifer to stream.

Table 19.--Projected streamflow depletions for the years 2000 and 2020 compared to computed streamflow of 1970 if annual rate of ground-water irrigation development is 2, 5, or 8 percent

[Streamflow and depletions, in cubic feet per second]

Stream node	Gaging station reference site	Computed streamflow, May 31, 1970	Rate of development (Percent)	Depletions: Applying 80 percent of CIR, May 31, 2000	Depletions: Applying 80 percent of CIR, May 31, 2020	Depletions: Applying CIR, May 31, 2000	Depletions: Applying CIR, May 31, 2020	Depletions: Applying 120 percent of CIR, May 31, 2000	Depletions: Applying 120 percent of CIR, May 31, 2020
	South Loup River								
29, 60	At Ravenna	248	2	41	59	48	71	55	83
			5	48	72	57	87	66	102
			8	54	79	64	95	77	112
28, 67	At St. Michael	256	2	44	64	52	77	59	90
			5	51	79	61	95	71	112
			8	58	85	69	104	81	122
	Middle Loup River								
18, 79	At St. Paul	1,008	2	50	75	60	90	69	106
			5	59	92	71	112	82	131
			8	67	100	80	122	94	143
	North Loup River								
14, 80	Near St. Paul	903	2	0	0	0	0	0	0
			5	0	0	0	0	0	0
			8	0	0	0	0	0	0
	Cedar River								
8, 98	Near Fullerton	240	2	0	0	0	0	0	0
			5	0	0	0	0	0	0
			8	0	0	0	0	0	0
	Loup River								
5, 110	Near Genoa	621	2	59	88	70	107	82	126
			5	70	110	84	134	98	158
			8	79	120	96	147	113	172
5, 125	At Columbus	763	2	64	94	76	115	89	136
			5	76	117	92	144	108	169
			8	86	127	105	157	133	184
	Wood River								
41, 48	Near Riverdale	12	2	8	9	9	10	10	11
			5	9	10	10	11	10	12
			8	9	10	10	11	11	12
42, 65	Near Gibbon	18	2	18	17	17	17	17	17
			5	18	18	18	17	18	17
			8	17	17	18	17	18	18
39, 70	Near Chapman	16	2	16	16	16	16	16	16
			5	16	16	16	16	16	16
			8	16	16	16	16	16	16

Table 19.--Projected streamflow depletions for the years 2000 and 2020 compared to computed streamflow of 1970 if annual rate of ground-water irrigation development is 2, 5, or 8 percent--Continued

Stream node	Gaging station reference site	Computed streamflow, May 31, 1970	Rate of development (Percent)	Depletions: Applying 80 percent of CIR, May 31, 2000	Depletions: Applying 80 percent of CIR, May 31, 2020	Depletions: Applying CIR, May 31, 2000	Depletions: Applying CIR, May 31, 2020	Depletions: Applying 120 percent of CIR, May 31, 2000	Depletions: Applying 120 percent of CIR, May 31, 2020
	Platte River								
32, 2	--------------	560	2	0	0	0	0	0	0
			5	0	0	0	0	0	0
			8	0	0	0	0	0	0
39, 14	Near Cozad	572	2	9	12	12	18	16	23
			5	12	19	17	26	21	33
			8	14	22	19	30	24	38
48, 34	--------------	1,668	2	20	25	30	39	40	53
			5	26	36	38	53	39	69
			8	30	42	42	60	54	77
49, 46	Near Odessa	1,554	2	35	31	36	47	48	61
			5	31	43	45	63	58	82
			8	35	50	49	71	63	92
36, 87	Near Grand Island	1,656	2	51	66	70	94	91	122
			5	59	82	80	115	103	147
			8	64	91	89	127	111	160
8, 119	Near Duncan	1,669	2	71	92	95	130	125	167
			5	80	114	110	158	141	200
			8	88	126	122	174	152	217
5, 127	--------------	2,433	2	135	187	174	246	215	305
			5	158	232	203	303	250	371
			8	175	253	227	331	277	403

SUMMARY OF CONCLUSIONS

Maps and tables presented in this report indicate that water levels will decline in the future throughout much of the study area even without additional development beyond the 1980 level unless reductions are made in the volume of ground water used. These reductions might be attained either through cutbacks in the acreages irrigated or through cutbacks in the amount of ground water applied per acre. A variety of methods can be employed to accomplish these reductions; some have been previously discussed.

Declines ranging from 0 to about 139 feet will occur in Hall County and in Merrick County before 2020, depending on the assumed rate of ground-water development (up to 8 percent per year). Similarly, declines ranging from 0 to about 79 feet will occur before 2020 from Buffalo County westward. Declines of up to about 99 feet will occur by the year 2020 a few miles northeast of Gothenburg for the development rate of 8 percent per year.

Water-level declines occur in areas where aquifer discharge exceeds aquifer recharge. As areas where the depth to water exceeds 5 feet increase, the volume of ET salvage will reach a maximum, and ET losses from the ground water will decrease and approach a minimum. Also, additional ground water will be removed from storage in order to satisfy pumpage requirements. Finally, as water levels decline, more surface water will move into the aquifer and less ground water will move into the streams.

The pumpage, storage (water removed from storage), and inflow (water moving from the stream to the aquifer) rates will increase with additional ground-water development; however, the rates of recharge, ET losses from ground water, and outflow (water moving from the aquifer to the stream) will decrease.

The relationship between the aquifer and the surface-water system is important in determining future water levels in the study area. The simulations indicate that the movement of water from the streams to the aquifer will increase with time and that the rate of increase will be proportional to the rate of new irrigation development. Also, decreases in streamflow probably will occur because of additional surface-water diversions, additional ground-water development west of the study area, and changing farming practices west of the study area. These decreases in streamflow may affect water levels if the streamflow reductions are large enough to significantly lower the stream stages.

SELECTED REFERENCES

Bentall, Ray, 1975a, Physiography, geology, soils, and agriculture, Nebraska Mid-State Division: University of Nebraska, Conservation and Survey Division, 76 p.

_______ 1975b, Hydrology, Nebraska Mid-State Division and Associated Areas: University of Nebraska, Conservation and Survey Division, 256 p.

Hayes, F. A., and others, 1924, Soil Survey of Howard County, Nebraska: U.S. Department of Agriculture, Bureau of Soils and the University of Nebraska, State Soil Survey, 39 p.

_______ 1925, Soil Survey of Dawson County, Nebraska: U.S. Department of Agriculture, Bureau of Soils and the University of Nebraska, State Soil Survey, 45 p.

_______ 1925, Soil Survey of Nance County, Nebraska: U.S. Department of Agriculture, Bureau of Soils and the University of Nebraska, State Soil Survey, 45 p.

_______ 1926, Soil Survey of Custer County, Nebraska: U.S. Department of Agriculture, Bureau of Chemistry and Soils and the University of Nebraska, State Soil Survey, 54 p.

_______ 1926, Soil Survey of Merrick County, Nebraska: U.S. Department of Agriculture, Bureau of Soils and the University of Nebraska, State Soil Survey, 46 p.

_______ 1928, Soil Survey of Buffalo County, Nebraska: U.S. Department of Agriculture, Bureau of Chemistry and Soils and the University of Nebraska, State Soil Survey, 56 p.

Hyland, J. B., and Keech, C. F., 1964, Ground water in Cedar Rapids Division of lower Platte River Basin, Nebraska: U.S. Geological Survey Water-Supply Paper 1779-H, p. H1-H12.

Jensen, M. E., Wright, J. C., and Pratt, B. J., 1969, Estimating soil moisture depletion from climate, crop, and soil data: American Society of Agricultural Engineers, Paper 69-941.

Johnson, A. I., 1967, Specific Yield--Compilation of specific yield for various materials: U.S. Geological Survey Water-Supply Paper 1662-D, 74 p.

Keech, C. F., 1952, Ground-water resources of the Wood River unit of the lower Platte River Basin, Nebraska: U.S. Geological Survey Circular 139, 96 p.

Keech, C. F., and Dreeszen, V. H., 1964, Availability of ground water in Hall County, Nebraska: U.S. Geological Survey Hydrologic Investigations Atlas HA-131, 1 sheet.

Lappala, E. G., 1978, Quantitative hydrogeology of the Upper Republican Natural Resources District, southwest Nebraska: U.S. Geological Survey Water-Resources Investigations 78-38, 200 p.

Lappala, E. G., Emery, P. A., and Otradovsky, F. J., 1979, Simulated changes in ground-water levels and streamflow resulting from future development (1970 to 2020) in the Platte River Basin: U.S. Geological Survey Water-Resources Investigations 79-26, 82 p.

Linsley, Jr., R. K., Kohler, M. A., and Paulhus, J. H., 1958, Hydrology for Engineers: New York, McGraw-Hill Book Company, 340 p.

Lugn, A. L., and Wenzel, L. K., 1938, Geology and ground-water resources of south-central Nebraska with special reference to the Platte River valley between Chapman and Gothenburg: U.S. Geological Survey Water-Supply Paper 779, 242 p.

Marlette, R. R., and Lewis, G. L., 1973, Progress Report - Digital simulation of conjunctive-use irrigation in Dawson County, Nebraska: University of Nebraska unpublished report on a research project, 26 p.

Marlette, R. R., Lewis, G. L., and Keasling, R. L., 1974, Digital simulation of conjunctive-use irrigation in Dawson County, Nebraska: Presentation at the fall meeting of American Geophysical Union, 28 p.

National Oceanic and Atmospheric Administration, Nebraska climatological data: NOAA annual and summary reports.

Nebraska Department of Agriculture, annual reports (1931-1976), Nebraska agricultural statistics: Nebraska Crop and Livestock Reporting Service.

Nebraska Department of Water Resources, (Annual) Reports of diversions and returns, Platte River from near Brady to Columbus, Nebraska: Unpublished records.

_______ (Annual) Registered irrigation well records: Unpublished records.

Paine, L. S., and others, 1929, Soil Survey, Platte County, Nebraska: U.S. Department of Agriculture, Bureau of Chemistry and Soils and University of Nebraska, State Soil Survey, p. 1423-1469.

Schreurs, R. L., 1956, Geology and ground-water resources of Buffalo County and adjacent areas, Nebraska, <u>with a section on</u> Chemical quality of ground water by F. H. Rainwater: U.S. Geological Survey Water-Supply Paper 1358, 175 p.

Seevers, P. M. (Project coordinator), 1978, Land-use data in the Central Platte Natural Resources District, Nebraska, Summer 1974: University of Nebraska, Conservation and Survey Division, map, 2 sheets.

Sniegocki, R. T., 1955, Ground-water resources of the Prairie Creek unit of the lower Platte River basin, Nebraska, <u>with a section on</u> Chemical quality of the ground water, by F. H. Rainwater: U.S. Geological Survey Water-Supply Paper 1327, 133 p.

State of Nebraska, 1978, In matter of Applications 15146 and 15148 for permits to divert water from Platte River watershed to Little Blue River watershed for irrigation and storage, filed by Little Blue Natural Resources District: Nebraska Department of Water Resources, Hearing opened April 17, 1978, Exhibit 22, vol. 1.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, 116 p.

U.S. Geological Survey, annual report, Water resources data for Nebraska, Part 1: U.S. Geological Survey annual reports.

U.S. Soil Conservation Service, unpublished 1977 county land-use maps.

Veatch, J. O., and Seabury, V. H., 1918, Soil Survey of Hall County, Nebraska: U.S. Department of Agriculture, Bureau of Soils and the University of Nebraska, State Soil Survey, 41 p.

Waite, H. A., and others, 1949, Progress report on the geology and ground-water hydrology of the lower Platte River valley, Nebraska, with a section on the Chemical quality of the ground water, by H. A. Swenson: U.S. Geological Survey Circular 20, 211 p.

Weaver, J. E., and Albertson, F. W., 1956, Grasslands of the Great Plains: Johnsen Publishing Company, 395 p.

Wenzel, L. K., 1940, Local overdevelopment of ground-water supplies, with special reference to conditions at Grand Island, Nebraska: U.S. Geological Survey Water-Supply Paper 836-E, p. 233-280.

ADDITIONAL INFORMATION

The following tables provide data pertaining to the report area, or to methodology used in the report that may be useful but not essential for an understanding of the report.

Table A gives results of discharge measurements made during seepage surveys of streams in the report area. These results have been used in the calibration of the model and in interpreting ground-water/surface-water relationships.

Table B indicates the methods used in estimating hydraulic conductivity and specific yield from descriptions of materials comprising a lithologic unit. Specific yield is estimated from grain-size class or range alone. Hydraulic conductivity, however, is estimated from grain-size class or range and either the estimated degree of sorting or the estimated silt content. Judgment is exercised in determining which of the values to use, or whether to use some intermediate value.

Table C is presented to show the type of output data generated by the soil-water program for the 15 weather stations in the report area. Data are given in the table for only three of the weather stations -- Gothenburg, Kearney, and Central City. Data for the Gothenburg station typically represents weather conditions in the western part of the report area; those from the Kearney station, weather conditions in the central part; and those from the Central City station, weather conditions in the eastern part.

Table A.--Seepage measurements for parts of the Loup River system, Prairie Creek, Silver Creek, Wood River, and Warm Slough

Stream	Node	Observation of zero flow or measured discharge, in cubic feet per second
		September 21, 1978
South Loup River	6, 4	11
	7, 5	20
Sand Creek[1]	8, 6	0
	7, 6	.26
Devils Gulch[1]	6, 7	0
South Loup River[2]	7, 8	35
	9, 11	43
Powell Canyon[1]	7, 11	0
	9, 11	0
South Loup River	10, 13	52
	12, 15	60
Sand Creek[1]	14, 16	0
	14, 17	.03
	14, 17	.36
Cottonwood Creek[1]	14, 18	0
South Loup River	14, 18	61
	15, 20	68
	15, 22	71
Spring Creek[1]	14, 22	0
	14, 21	.29
Yellow Dog Canyon[1]	13, 22	0
	14, 22	.02
Tributary to South Loup River	16, 22	.01
South Loup River	17, 24	81
Tributary to South Loup River	19, 24	0
	19, 25	.31
South Loup River	19, 26	87
Ash Creek[1]	17, 27	0
	20, 28	0
South Loup River	20, 29	90
Tributary to South Loup River	20, 30	0
South Loup River	21, 30	100
Burr Oak Creek[1]	22, 30	.03
South Loup River	23, 32	87
Deer Creek[1]	23, 34	0
Warm Swamp[1]	25, 31	0
	34, 33	.02

Table A.--Seepage measurements for parts of the Loup River system, Prairie Creek, Silver Creek, Wood River, and Warm Slough--Continued

Stream	Node	Observation of zero flow or measured discharge, in cubic feet per second
		September 21, 1978
South Loup River	25, 35	88
Box Elder Creek[1]	24, 35	0
Tributary to South Loup River	25, 35	0
South Loup River	26, 37	94
	27, 40	98
Otter Creek[1]	28, 40	0
Elk Creek[1]	27, 42	0
South Loup River	28, 42	90
	29, 44	94
Death Creek[1]	31, 44	0
South Loup River	31, 47	87
		September 20, 1978
Swenson Creek[1]	31, 47	0
Deer Creek[1]	32, 47	0
	32, 47	0
South Loup River	32, 49	96
Rusco Creek[1]	32, 50	0
South Loup River	32, 52	90
Dry Creek[1]	31, 53	0
Sand Creek[1]	31, 57	0
South Loup River	31, 57	86
Cedar Creek[1]	33, 57	0
	31, 57	.17
South Loup River	29, 60	90
Tributary to South Loup River	27, 55	15
	27, 56	13
	28, 57	14
Dry Creek[1]	27, 58	0
Tributary to South Loup River	28, 59	16
Beaver Creek[1]	28, 61	0
South Loup River	27, 63	103
	28, 67	99
Sweet Creek[1]	29, 67	0
	27, 68	0
Middle Loup River	26, 68	427
	26, 72	516

Table A.--Seepage measurements for parts of the Loup River system, Prairie Creek, Silver Creek, Wood River, and Warm Slough--Continued

Stream	Node	Observation of zero flow or measured discharge, in cubic feet per second
		September 20, 1978
South Loup River	26, 68	94
Loup River	23, 75	529
Oak Creek[3]	22, 75	34
Turkey Creek[3]	20, 74	7.2
	20, 76	11
Loup River	18, 79	469
Lake Creek[3]	19, 79	0
	17, 80	.04
	17, 80	0
Tributary to Lake Creek	17, 80	.01
		September 19, 1978
North Loup River	14, 79	823
Loup River	14, 82	1,290
Spring Creek[3]	13, 82	4.3
Loup River	14, 87	1,280
Cottonwood Creek[3]	14, 88	0
Elk Creek[3]	15, 88	0
Loup River	13, 90	1,230
Tributary to Loup River	14, 90	.02
Horse Creek[3]	11, 92	.07
Tributary to Loup River	11, 93	0
	11, 94	0
	13, 94	0
Loup River	12, 95	1,320
	10, 98	1,160
Cedar River	8, 99	171
Loup River	8,101	1,320
Plum Creek[3]	7,102	.62
Council Creek[3]	6,104	0
Loup River	7,105	1,280
		November 11, 1978
Silver Creek	18, 99	0
	16,101	0
	14,103	0
	13,105	0
	13,106	0

Table A.--Seepage measurements for parts of the Loup River system, Prairie Creek, Silver Creek, Wood River, and Warm Slough--Continued

Stream	Node	Observation of zero flow or measured discharge, in cubic feet per second
		November 11, 1978
Tributary to Silver Creek-----------------	15,105	0
	14,106	0
	13,108	0
Silver Creek-----------------------------	12,108	0
	12,110	0
	11,111	.02
Tributary to Silver Creek-----------------	11,111	0
Silver Creek-----------------------------	11,111	.18
		November 14, 1978
Prairie Slough---------------------------	17, 93	0
Prairie Creek----------------------------	16, 95	.02
	15, 97	.61
	15, 98	0
	14, 99	.11
	13,100	.38
	13,101	.95
	12,102	.85
	11,103	.35
	10,104	2.6
	10,106	0
	10,108	0
	10,110	.64
	10,112	.33
	9,113	.73
	8,115	2.6
Wood River-------------------------------	41, 48	0
Tributary to Wood River------------------	41, 49	0
Wood River-------------------------------	41, 48	0
	42, 51	0
Wood River tributary---------------------	42, 51	0
Wood River-------------------------------	43, 52	0
Wood River tributary---------------------	43, 52	0
	43, 58	0
Wood River-------------------------------	43, 54	0
	43, 56	0
Wood River tributary---------------------	43, 56	0
	43, 56	0

Table A.--Seepage measurements for parts of the Loup River system, Prairie Creek, Silver Creek, Wood River, and Warm Slough--Continued

Stream	Node	Observation of zero flow or measured discharge, in cubic feet per second
		November 14, 1978
Wood River	43, 57	0
	43, 57	.01
Wood River tributary	43, 57	0
Wood River	43, 59	.05
	43, 60	0
	43, 61	0
Wood River tributary	43, 62	0
Wood River	43, 62	0
	43, 63	1.5
	42, 65	1.0
	42, 66	.20
	42, 67	.22
	41, 69	.04
	40, 70	.40
	39, 72	.43
	38, 73	.48
	38, 75	.19
	38, 77	0
	38, 78	0
	37, 79	.17
	37, 81	.09
	36, 83	0
	35, 85	0
	33, 86	0
Wood River tributary	33, 85	.33
Wood River	32, 88	11
	30, 90	9.3
	29, 92	9.6
Warm Slough	22, 99	0
	21,100	0
	20,102	0

[1]South Loup River tributary.
[2]Outside study area.
[3]Loup River tributary.

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

Grain-size class or range from sample description	Hydraulic conductivity, in feet per day[1]						Specific yield[2]
	Estimated from degree of sorting			Estimated from silt content			
	Poor	Moderate	Well	Slight	Moderate	High	
Fine-grained materials:							
Clay----------------------------	----	-------	----	1.0	---	----	1.0
Silt, slightly clayey-----------	----	-------	----	10.0	---	----	10.0
Silt, moderately clayey---------	----	-------	----	8.0	---	----	8.0
Silt, very clayey---------------	----	-------	----	4.0	---	----	3.0
Silt; loess; sandy silt---------	----	-------	----	15.0	---	----	15.0
Sands and gravels[3]:							
Very fine sand------------------	13	20	27	23	19	13	20.0
Very fine to fine sand----------	27	27	----	24	20	13	20.2
Very fine to medium sand--------	36	41- 47	----	32	27	21	20.4
Very fine to coarse sand--------	48	-------	----	40	31	24	20.5
Very fine to very coarse sand---	59	-------	----	51	40	29	20.6
Very fine sand to fine gravel---	76	-------	----	67	52	38	20.7
Very fine sand to medium gravel-	99	-------	----	80	66	49	20.8
Very fine sand to coarse gravel-	128	-------	----	107	86	64	20.9
Fine sand-----------------------	27	40	53	33	27	20	21.0
Fine to medium sand-------------	53	67	----	48	39	30	21.5
Fine to coarse sand-------------	57	67- 72	----	53	43	32	22.0
Fine to very coarse sand--------	70	-------	----	60	47	35	23.0
Fine sand to fine gravel--------	88	-------	----	74	59	44	24.0
Fine sand to medium gravel------	114	-------	----	94	75	57	25.0
Fine sand to coarse gravel------	145	-------	----	107	87	72	25.5
Medium sand---------------------	67	80	94	64	51	40	26.0
Medium to coarse sand-----------	74	94	----	72	57	42	26.1
Medium to very coarse sand------	84	98-111	----	71	61	49	26.3
Medium sand to fine gravel------	103	-------	----	84	68	52	26.5
Medium sand to medium gravel----	131	-------	----	114	82	66	26.7
Medium sand to coarse gravel----	164	-------	----	134	108	82	26.9
Coarse sand---------------------	80	107	134	94	74	53	27.0
Coarse to very coarse sand------	94	134	----	94	75	57	26.9
Coarse sand to fine gravel------	116	136-156	----	107	88	68	26.7
Coarse sand to medium gravel----	147	-------	----	114	94	74	26.5
Coarse sand to coarse gravel----	184	-------	----	134	100	92	26.0
Very coarse sand----------------	107	147	187	114	94	74	25.9
Very coarse sand to fine gravel-	134	214	----	120	104	87	25.5
Very coarse sand to medium gravel-----------------------	1,270	199-227	----	147	123	99	25.3
Very coarse sand to coarse gravel-----------------------	207	-------	----	160	132	104	25.1
Fine gravel---------------------	160	214	267	227	140	107	25.0
Fine to medium gravel-----------	201	334	----	201	167	134	24.0
Fine to coarse gravel-----------	245	289-334	----	234	189	144	23.5
Medium gravel-------------------	241	321	401	241	201	160	23.0
Medium to coarse gravel---------	294	468	----	294	243	191	22.5
Coarse gravel-------------------	334	468	602	334	284	234	22.0

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

Table C - Output from soil-water program using data for Gothenburg, Kearney, and Central City weather stations
[I, infiltration; ET, evapotranspiration; RO, surface runoff; DPI, deep percolation (recharge from irrigated lands; CIR, consumptive irrigation requirements; SMI, soil moisture of irrigated lands; DPD, deep percolation (recharge) from drylands; STD, water shortage of dryland; SMD, soil moisture of drylands]

Map symbol	Soil group	Land use	Soil-water program output, in inches								
			I	ET	RO	DPI	CIR	SMI	DPD	STD	SMD
						Gothenburg					
A	Inavale-Loup-Alda-Platte	Row crop	20.50	31.03	0.0	3.37	12.50	3.97	3.04	13.56	2.13
		Alfalfa	20.50	38.55	0.0	.56	14.72	3.72	.37	18.39	.63
		Small grain	20.50	23.59	0.0	5.00	6.00	2.24	3.78	6.90	1.29
		Pasture	20.50	31.36	0.0	2.14	10.23	1.88	1.76	12.61	.39
B	Wann-Cass-Leshara	Row crop	19.98	31.03	.52	2.61	12.60	5.11	2.18	13.22	2.65
		Alfalfa	19.98	38.55	.52	.59	15.99	4.70	.53	19.07	.54
		Small grain	20.50	23.59	0.0	4.53	6.09	3.19	3.11	6.24	1.81
		Pasture	20.50	31.36	0.0	1.75	10.29	2.62	1.30	12.14	.68
C	Gibbon-Lamo	Row crop	19.72	31.03	.78	1.36	12.32	8.07	.80	12.08	3.55
		Alfalfa	19.72	38.55	.78	.26	17.46	8.02	.26	19.03	.55
		Small grain	19.72	23.59	.78	3.10	6.35	5.96	1.44	5.34	2.68
		Pasture	20.50	31.36	0.0	1.09	10.58	4.63	.51	11.34	1.26
D	Ortello-Blendon	Row crop	19.98	31.03	.52	2.77	12.65	4.73	2.38	13.42	2.48
		Alfalfa	19.98	38.55	.52	.62	15.77	4.32	.55	19.09	.53
		Small grain	20.50	23.59	0.0	4.68	6.07	2.86	3.33	6.45	1.64
		Pasture	20.50	31.36	0.0	1.86	10.26	2.37	1.44	12.28	.58
E	Holdrege-Hall-Hord-Kenesaw	Row crop	19.72	31.03	.78	1.36	12.32	8.07	.80	12.08	3.55
		Alfalfa	19.72	38.55	.78	.26	17.46	8.02	.26	19.03	.55
		Small grain	19.72	23.59	.78	3.10	6.35	5.96	1.44	5.34	2.68
		Pasture	20.50	31.36	0.0	1.09	10.58	4.63	.51	11.34	1.26
F	Coly-Colby-Uly-Ulysses	Row crop	18.77	31.03	1.73	1.39	12.89	6.15	.97	13.21	2.93
		Alfalfa	18.77	38.55	1.73	.19	17.34	5.64	.19	19.92	.36
		Small grain	18.77	23.59	1.73	3.19	6.85	3.92	1.65	6.49	1.73
		Pasture	19.56	31.36	.94	1.06	10.90	3.23	.57	12.35	.74
G	Valentine-Thurman	Row crop	19.46	31.03	1.04	4.35	13.07	2.60	4.16	14.69	1.34
		Alfalfa	20.50	38.55	0.0	1.01	14.26	2.46	.80	18.83	.35
		Small grain	20.50	23.59	0.0	5.55	5.83	1.40	4.64	7.75	.79
		Pasture	20.50	31.36	0.0	2.77	10.16	1.20	2.45	13.30	.15
						Kearney					
A and I	Inavale-Loup-Alda-Platte; O'Neill-Sarpy	Row crop	23.28	29.01	0.0	5.92	10.87	4.50	5.32	11.03	2.66
		Alfalfa	23.28	35.96	0.0	1.77	12.41	4.76	1.23	13.88	1.70
		Small grain	23.28	21.93	0.0	7.76	5.13	2.61	6.48	5.11	1.70
		Pasture	23.28	29.18	0.0	4.47	8.90	2.32	3.83	9.71	.90
B	Wann-Cass-Leshara	Row crop	22.45	29.01	.83	4.75	10.79	5.86	4.05	10.58	3.34
		Alfalfa	22.45	35.96	.83	1.37	13.37	6.01	.13	14.43	1.64
		Small grain	23.28	21.93	0.0	7.28	5.03	3.74	5.79	4.42	2.55
		Pasture	23.28	29.18	----	3.89	8.76	3.28	3.10	8.98	1.40
C	Gibbon-Lamo	Row crop	22.03	29.01	1.25	3.08	9.94	9.46	1.88	8.81	4.95
		Alfalfa	22.03	35.96	1.25	.58	13.94	10.22	.41	14.27	1.77
		Small grain	22.03	21.93	1.25	5.33	4.93	6.86	3.39	3.25	4.48
		Pasture	23.28	29.18	.00	2.88	8.32	6.12	1.82	7.68	2.75
D	Ortello-Blendon	Row crop	22.45	29.01	.83	4.96	10.93	5.39	4.32	10.85	3.09
		Alfalfa	22.45	35.96	.83	1.46	13.28	5.50	1.02	14.49	1.59
		Small grain	23.28	21.93	.00	7.44	5.07	3.36	6.02	4.65	2.25
		Pasture	23.28	29.18	.00	4.06	8.80	2.96	3.32	9.20	1.24

Table C - Output from soil-water program using data for Gothenburg, Kearney, and Central City weather stations--Continued

Map symbol	Soil group	Land use	Soil-water program output, in inches								
			I	ET	RO	DPI	CIR	SMI	DPD	STD	SMD
					Kearney--Continued						
E	Holdrege-Hall-Hord-Kenesaw	Row crop	22.03	29.01	1.25	3.08	9.94	9.46	1.88	8.81	4.95
		Alfalfa	22.03	35.96	1.25	.58	13.94	10.22	.41	14.27	1.77
		Small grain	22.03	21.93	1.25	5.33	4.93	6.86	3.39	3.25	4.48
		Pasture	23.28	29.18	.00	2.88	8.32	6.12	1.82	7.68	2.75
F	Coly-Colby-Uly-Ulysses	Row crop	20.75	29.01	2.53	2.92	10.85	7.16	2.11	10.33	3.90
		Alfalfa	20.75	35.96	2.53	.51	14.60	7.10	.29	15.44	1.34
		Small grain	20.75	21.93	2.53	5.09	5.63	4.56	3.25	4.40	2.76
		Pasture	21.79	29.18	1.49	2.43	9.07	4.15	1.54	8.91	1.69
H	Wood River-Silver Creek	Row crop	21.87	29.01	1.41	2.69	9.75	10.34	1.38	8.47	5.32
		Alfalfa	21.87	35.96	1.41	.36	13.98	11.38	.25	14.26	1.78
		Small grain	21.87	21.93	1.41	4.94	4.76	7.77	2.98	3.00	5.00
		Pasture	23.28	29.18	.00	2.70	8.20	6.84	1.59	7.45	3.06
					Central City						
A	Inavale-Loup-Alda-Platte	Row crop	23.73	29.01	.00	5.79	10.36	4.56	5.11	10.37	2.71
		Alfalfa	23.73	36.10	.00	1.71	12.12	4.66	1.13	13.47	1.52
		Small grain	23.73	22.12	.00	8.00	5.10	2.54	6.64	5.01	1.67
		Pasture	23.73	29.30	.00	4.40	8.64	2.22	3.61	9.17	.79
B	Wann-Cass-Leshara	Row crop	22.97	29.01	.76	4.77	10.31	5.94	3.91	9.91	3.43
		Alfalfa	22.97	36.10	.76	1.34	12.99	6.08	.93	14.01	1.56
		Small grain	23.73	22.12	.00	7.52	5.09	3.61	5.87	4.24	2.37
		Pasture	23.73	29.30	.00	3.85	8.47	3.23	2.91	8.46	1.28
C	Gibbon-Lamo	Row crop	22.59	29.01	1.14	3.18	9.46	9.53	1.80	8.15	4.96
		Alfalfa	22.59	36.10	1.14	.58	13.45	10.41	.39	13.81	1.76
		Small grain	22.59	22.12	1.14	5.66	4.91	6.85	3.48	2.96	4.26
		Pasture	23.73	29.30	.00	2.87	7.99	6.08	1.64	7.18	2.65
D	Ortello-Blendon	Row crop	22.97	29.01	.76	4.98	10.44	5.47	3.42	10.19	3.18
		Alfalfa	22.97	36.10	.76	1.43	12.92	5.56	1.01	14.09	1.48
		Small grain	23.73	22.12	.00	7.68	5.10	3.23	6.11	4.48	2.12
		Pasture	23.73	29.30	.00	4.03	8.53	2.88	3.13	8.68	1.12
E	Holdrege-Hall-Hord-Kenesaw	Row crop	22.59	29.01	1.14	3.18	9.46	9.53	1.80	8.15	4.96
		Alfalfa	22.59	36.10	1.14	.58	13.45	10.41	.39	13.81	1.76
		Small grain	22.59	22.12	1.14	5.66	4.91	6.85	3.48	2.96	4.26
		Pasture	23.73	29.30	.00	2.87	7.99	6.08	1.64	7.18	2.65
F	Coly-Colby-										
F	Coly-Colby-Uly-Ulysses	Row crop	21.34	29.01	2.39	3.03	10.39	7.21	2.07	9.71	3.94
		Alfalfa	21.34	36.10	2.39	.50	14.18	7.24	.31	15.02	1.29
		Small grain	21.34	22.12	2.39	5.48	5.69	4.49	3.51	4.27	2.65
		Pasture	22.37	29.30	1.36	2.55	8.75	4.14	1.59	8.50	1.55
G	Valentine-Thurman	Row crop	23.73	29.01	.00	6.90	11.17	3.00	6.48	11.75	1.73
		Alfalfa	23.73	36.10	.00	2.48	12.15	2.97	2.01	14.36	.86
		Small grain	23.73	22.12	.00	8.57	5.08	1.56	7.53	5.91	.97
		Pasture	23.73	29.30	.00	5.12	8.75	1.36	4.54	10.10	.35

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