# SIMULATED CHANGES IN GROUND-WATER LEVELS AND STREAMFLOW RESULTING FROM FUTURE DEVELOPMENT (1970 to 2020) IN THE PLATTE RIVER BASIN, NEBRASKA

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 79-26

(Open-File Report)

Prepared in cooperation with

Missouri River Basin Commission
Nebraska Department of Water Resources
Conservation and Survey Division, University
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Department of Agricultural Engineering,
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U.S. Bureau of Reclamation
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U.S. Environmental Protection Agency

1979

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director

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U.S. Geological Survey
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100 Centennial Mall, North
Lincoln, Nebraska 68508

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## SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) METRIC UNITS

The International System (SI) is a consistent system of metric units adopted by the Eleventh General Conference of Weights and Measures in 1960. Selected factors for converting Inch-pound units used in this report to SI metric units are given below.

| Multiply Inch-pound units | By | To obtain SI units |
|---|---|---|
| acre | 0.0040 | square kilometer ($km^2$) |
| acre-foot (acre-ft) | 1,233 | cubic meter ($m^3$) |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year ($m^3/yr$) |
| foot (ft) | .3048 | meter (m) |
| foot per day (ft/d) | .3048 | meter per day (m/d) |
| foot per year (ft/yr) | .3048 | meter per year (m/yr) |
| cubic foot per second ($ft^3/s$) | 28.3162 | liter per second (L/s) |
| inch (in) | 25.4 | millimeter (mm) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| mile (mi) | 1.609 | kilometer (km) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| degree Fahrenheit (°F) | 5/9 (F -32) | degree Celsius (°C) |

# SIMULATED CHANGES IN GROUND-WATER LEVELS AND STREAMFLOW RESULTING FROM FUTURE DEVELOPMENT (1970 to 2020) IN THE PLATTE RIVER BASIN, NEBRASKA

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## ABSTRACT

Future changes in ground-water levels and streamflow caused by a limited set of water-resources development conditions were simulated with digital models of stream-aquifer systems within the Platte River Basin, Nebraska. Simulated water-resources use in the basin included private development of ground water for irrigation, Federal development of surface-water systems for irrigation, and development of ground water to supply municipal demands of Lincoln and Omaha.

Simulated future conditions indicate that significant permanent declines in ground-water levels and streamflows may occur as a result of private development of ground water for irrigation. The largest simulated declines in ground-water levels were more than 80 feet by the year 2020 in upland areas in the Elkhorn and Middle Platte subbasins under conditions of rapid development of all irrigable lands. Simulated depletion of perennial streamflows by ground-water withdrawals indicated that future surface-water supplies may be limited in parts of the basin. Simulated depletions to major streams exceeded 60 percent of average perennial flow in the Elkhorn subbasin under conditions of rapid private development of ground water for irrigation.

Simulations that evaluated the effects of combined private ground-water development with proposed Federal development of surface water for irrigation showed that in the project areas, ground-water level declines were reduced compared to "without project" conditions. In some project areas, simulated ground-water levels rose with the application of surface water in excess of consumptive-use requirements and soil-moisture storage capacities. The ground-water level rises would lead to water-logged conditions in parts of the Middle Platte subbasin.

The accuracy of the models developed in this study would be improved most by collection of additional data on ground-water withdrawals and storage properties at the aquifer.

## INTRODUCTION

Water-resources development in the Platte River Basin in Nebraska far exceeds that of any other area of comparable size in the Missouri River Basin. Extensive development of both ground- and surface-water resources has taken place, and more is contemplated. Some problems associated with development have occurred, and others are anticipated. Near the completion of the Type I Comprehensive Framework Study of the Missouri River Basin (Missouri River Basin Commission, 1975), it became apparent that the Platte River Basin in Nebraska would require a more detailed study before evaluations of future projects or programs could be initiated. As a result, a "Level B Study" of the Platte River Basin in Nebraska was begun.

The Level B Study was a Federal and State interagency effort to formulate a comprehensive plan for the conservation, development, and management of the water and related land resources of the Platte River Basin of Nebraska. The technical information for the study was provided by 14 task forces. This report describes the work of the Stream-Aquifer Hydrology Task Force, which was headed by the U.S. Geological Survey.

## PURPOSE AND SCOPE

The objective of the Stream-Aquifer Hydrology Task Force was to provide a quantitative description of the response of stream-aquifer systems resulting from a limited set of basinwide water-resources development plans. Quantification was achieved through the use of digital models. The degree of quantification was limited by the requirements for basinwide consistency in results and utilization of the existing (1970) data base describing the geohydrologic framework of the basin. This report describes the development and use of these models. Stream-aquifer relations are of concern because many stream appropriators and others fear that pumping from wells will deplete low streamflow significantly. Where good hydraulic connection exists between a stream and an aquifer, pumping from wells adjacent to or very near the stream induces recharge from the stream and depletes streamflow. Pumping from wells that are farther from the streams may intercept ground water that otherwise would seep into streams.

There has been considerable speculation regarding the source of water pumped from wells in the basin. This speculation has arisen because there has been little widespread sustained depletion of ground water despite large withdrawals from the aquifers. Consequently, although no sustained change in streamflow has been observed, some believe that streams which are in hydraulic connection with the aquifer are the source of water pumped for irrigation. Others believe that most of the water pumped for irrigation is salvaged from evapotranspiration. The stream-aquifer models developed by this task force were designed to evaluate the effect of increased development of ground water and surface water and the salvage of evapotranspiration on water levels and streamflow.

## TASK FORCE ORGANIZATION AND OPERATION

The Stream-Aquifer Hydrology Task Force was composed of representatives from the U.S. Geological Survey; Conservation and Survey Division and Department of Agricultural Engineering, University of Nebraska; Nebraska Department of Water Resources; U.S. Bureau of Reclamation; U.S. Soil Conservation Service; U.S. Army Corps of Engineers; and Environmental Protection Agency. Task Force membership is listed below; names of original participants are in parentheses.

| | |
|---|---|
| Geological Survey | Eric Lappala, Leader<br>(Philip A. Emery) |
| Nebraska Department of Water Resources | Marion Ball |
| Conservation and Survey Division, University of Nebraska-Lincoln | (Peter W. Huntoon) |
| Bureau of Reclamation | Fred Otradovsky |
| Soil Conservation Service | Robert O. Kluth<br>(Norman Hadenfeldt) |
| Corps of Engineers | Al Harrison |
| Environmental Protection Agency | Ed Novak |
| Department of Agricultural Engineering, University of Nebraska-Lincoln | Deane Manbeck |

Paul Harley, Department of the Interior Representative on the Planning Board, provided coordination between the Task Force and the Board.

The following persons served as citizen advisors to the Task Force:

| | |
|---|---|
| Rudolph Kokes, Ord, Nebr. | Forest Hanson, Mead, Nebr. |
| Earl Penry, Atkinson, Nebr. | Paul Jenkins, Gothenburg, Nebr. |
| Fred Salmon, Jr., Wakefield, Nebr. | Mark Bolin, Gibbon, Nebr. |

The Conservation and Survey Division of the University of Nebraska and the Bureau of Reclamation at Grand Island made major contributions. Contributions by agencies represented on the Task Force follow.

Conservation and Survey Division

1. Compiled and plotted the following data on preliminary maps--scale 1:250,000:

   a. Configuration and altitude of base of aquifer.
   b. Aquifer properties.
   c. Depth to water table.
   d. Configuration and altitude of water table in 1970.

2. Provided assistance regarding application of data to the model.

3. Drafted illustrations for final report.

U.S. Bureau of Reclamation (USBR)

1. Supplied basic hydrologic data, including irrigated acreage and ground-water withdrawals.

2. Updated existing USBR hydrologic studies.

3. Participated in the design, calibration, and use of the digital models.

Corps of Engineers

1. Provided data used to estimate base flow of streams.

2. Provided consultation services.

The Soil Conservation Service supplied information regarding land and water use.

Other major phases of the investigation, including development and use of the digital models, were accomplished by the U.S. Geological Survey in collaboration with other agencies and task forces.

## HYDROLOGIC SETTING

The Level B study area comprises the Platte River Basin within Nebraska (fig. 1), an area of 40,800 $mi^2$. It extends the full length of the State, a distance of nearly 470 mi, and its greatest width is about 153 mi. The altitude of the Platte River ranges from 4,025 ft at the Wyoming-Nebraska line to 940 ft at the mouth. The highest point in the basin, 5,424 ft, is at the southwest corner of the Nebraska panhandle.

The Platte River Basin is subdivided into four subbasins: the Elkhorn, Loup, Upper Platte, and Lower Platte. For stream-aquifer analyses discussed in this report, the Upper Platte subbasin is divided into two reaches: the Twin Platte reach extends upstream from North Platte to the Wyoming and Colorado State lines and the Middle Platte reach extends from North Platte to Columbus.

Boundaries used for the five stream-aquifer models are shown in figure 2. Modeled boundaries do not always correspond to subbasin boundaries. Where possible, model boundaries were chosen to coincide with ground-water divides or streams.

### Physiography and Drainage

The basin comprises a variety of terrains (fig. 3). Tablelands and sandhills constitute the largest part of the basin. The remainder is loess hills and plains, drift hills, and valley lands.

The Sand Hills region is hydrologically important because the sandy soils readily absorb precipitation and virtually no overland runoff occurs. Furthermore, the thickness of saturated materials beneath the Sand Hills region is greater than in any other part of the basin. As withdrawals by pumping there are small, most of the absorbed water

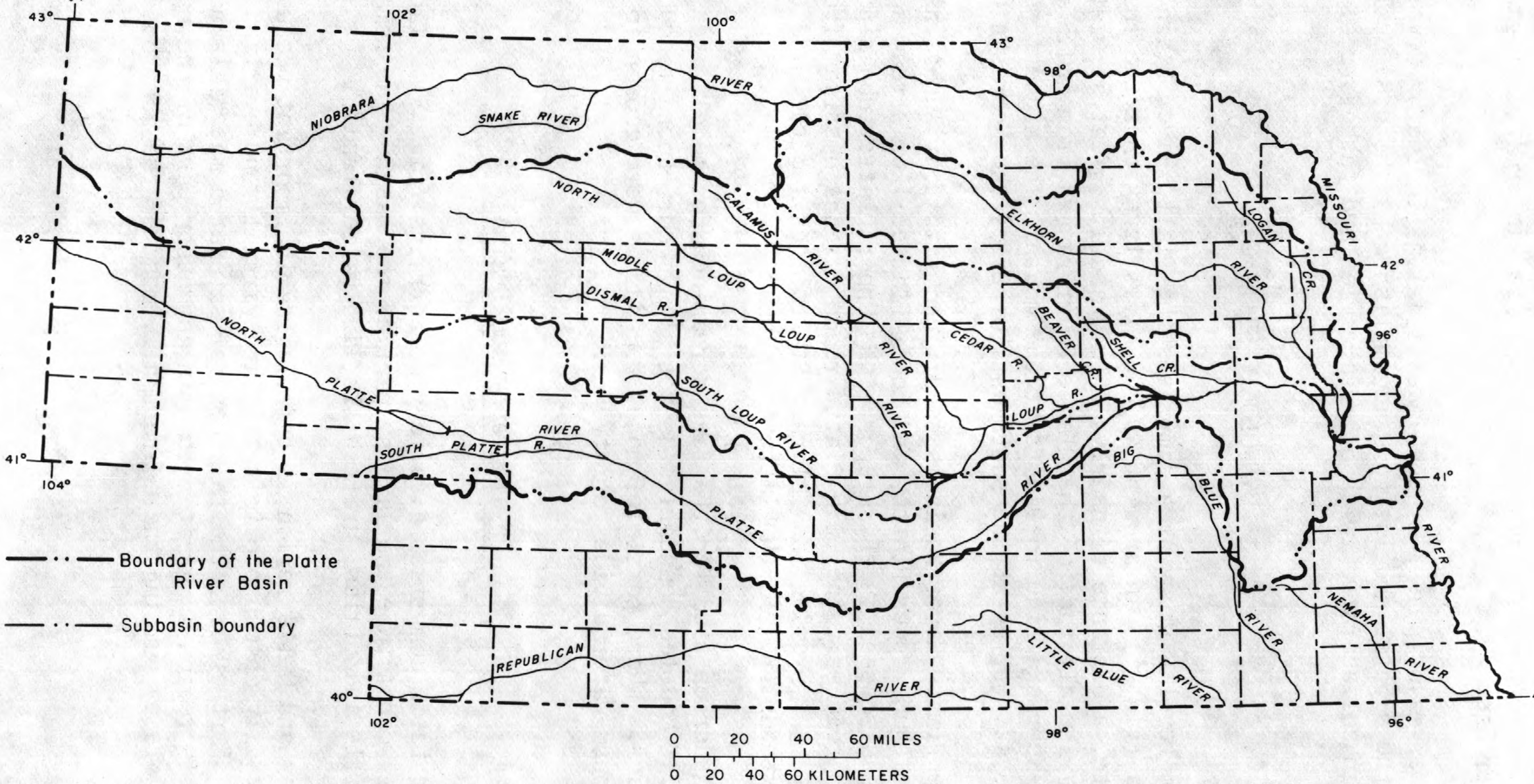



Figure 1.--Location of the Platte River basin, Nebraska.

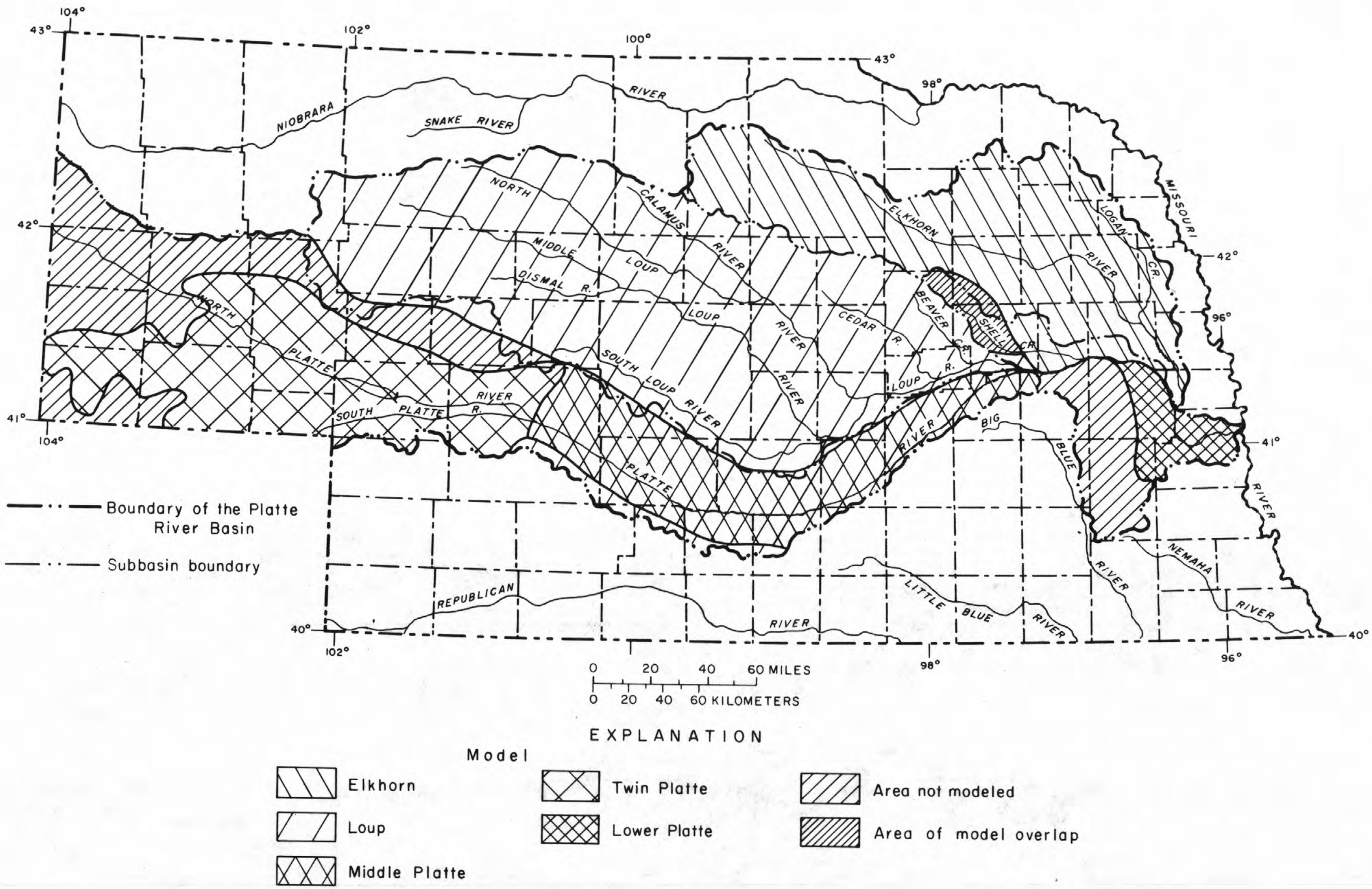



Figure 2.--Subbasins simulated by stream-aquifer models.

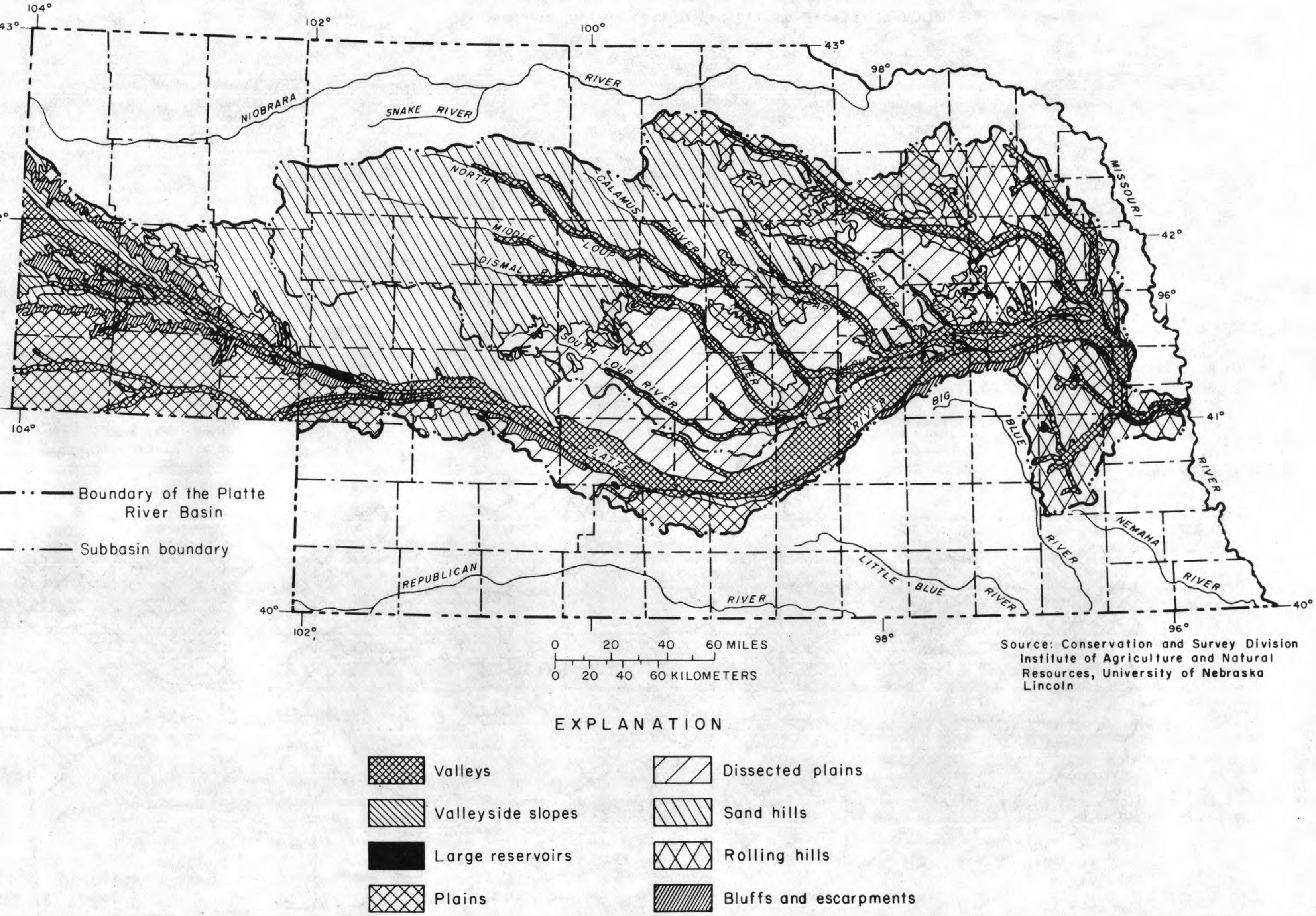



Figure 3.--Physiographic regions of the Platte River basin study area.

eventually moves to areas where it is discharged either by evapotranspiration or by seepage to streams. Streams originating in the Sand Hills region are noted for their steady flow and are an important source of water for irrigation and electric-power generation.

Streamflow in the basin is derived from three sources: Surface-water inflow from Wyoming and Colorado, precipitation on the basin, and ground-water seepage. Each source is variable in quantity, and this variability constitutes a principal problem in managing the water resources of the basin.

Construction and operation of reservoirs in the Wyoming part of the North Platte River drainage basin to meet seasonal variations in water demand have done much to regulate the inflow of surface water to Nebraska. Surface-water inflow from Colorado to the South Platte River is generally least when the demand for water in Nebraska is greatest; therefore, usefulness of this inflow is limited.

Precipitation is highly variable both geographically and seasonally. Normal annual precipitation ranges from 15 inches at the western end of the basin to 31 inches at the eastern end, or about 50 million acre-ft/yr basinwide. Unless snowmelt or spring rains produce overland runoff, virtually all precipitation evaporates, is consumed by vegetation, or is added to ground-water storage. It is estimated that in 1970 only about 1 percent of the precipitation produced overland runoff from the basin. Somewhat greater values would occur in years when large discharges resulted from rain falling on rapidly melting snow cover.

The amount of rainfall that is temporarily added to ground-water storage from year to year is estimated to average at least 7 percent. This percentage differs greatly geographically. For example, as much or more than 25 percent of the precipitation in the Sand Hills Region may be added to storage, but only a fraction of 1 percent of the precipitation percolates to the ground-water reservoirs in the western tablelands. A fairly large percentage of the precipitation on some valley lands percolates to ground-water storage. Evapotranspiration probably ranges from less than 75 to more than 99 percent of the average annual precipitation. The total quantity of water consumed by evapotranspiration is greater than total precipitation in some years because some of the water thus consumed is from holdover storage in surface reservoirs, soil moisture, or ground water.

## Geology

Rocks exposed at the surface in the Platte River Basin range in age from Pennsylvanian to Quaternary. However, this study confines itself to rocks of Tertiary and Quaternary age. The Tertiary rocks are as much as 1,300 ft thick at the west end of the State and thin to extinction about two-thirds of the distance eastward across the State (fig. 4). Extensive exposures of these rocks are limited to the upland parts of the North and South Platte River subbasins. Throughout the remainder of the western two-thirds of the Platte River Basin, Tertiary rocks are covered almost everywhere by unconsolidated deposits of Quaternary age. Quaternary deposits also cover the consolidated rocks in the eastern third of the State (fig. 4). These deposits are as much as 300-400 ft thick where they fill valleys in the underlying rock; but where they cover hills, they are thinner and in a few places are absent. As much as a third of the Quaternary deposits consists of coarse-textured alluvium, and the remainder is fine-textured alluvium, dune sand, loess, and glacial drift. In the Platte River valley, coarse-textured alluvium is either exposed or thinly covered by loess; but in upland areas it generally is more thickly covered by fine-textured alluvium, loess, or glacial drift.

# GROUND-WATER RESOURCES

Ground water plays an important role in the economic life of the basin. Development of ground water for irrigation has been extensive in both valley and upland areas, particularly in the eastern two-thirds of the basin. This development is evident by the number of registered irrigation wells shown in figures 5 and 6.

Municipal ground-water developments adjacent to the Platte River at Grand Island, Fremont, Lincoln, and Omaha were designed to ensure a perennial water supply by inducing recharge from surface water sources to maintain water levels and yields of wells. Developments in other valley areas also have induced recharge to the aquifer.

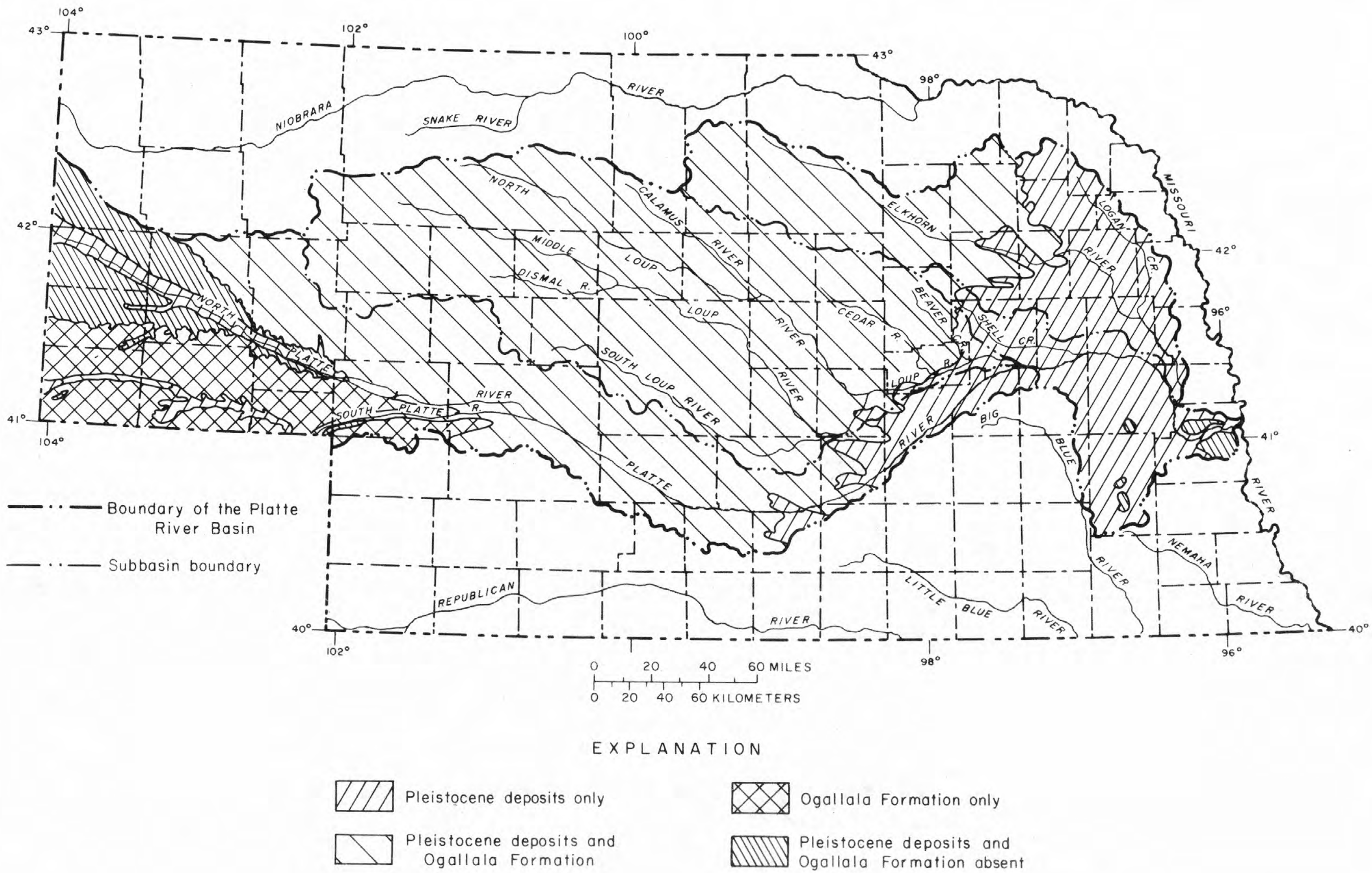



Figure 4.--Distribution of Pleistocene deposits and Ogallala Formation.

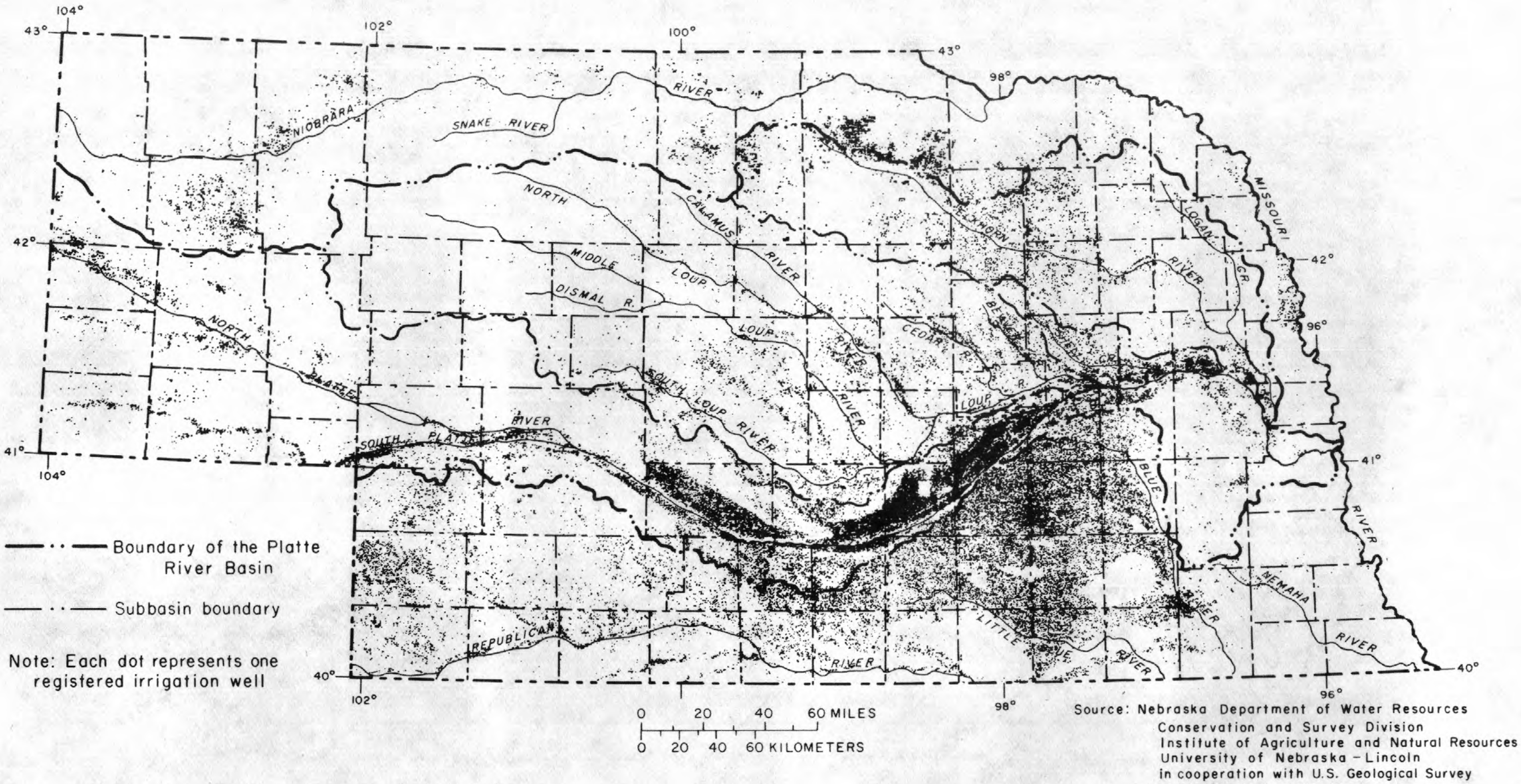



Figure 5.--Location of irrigation wells registered through 1975.

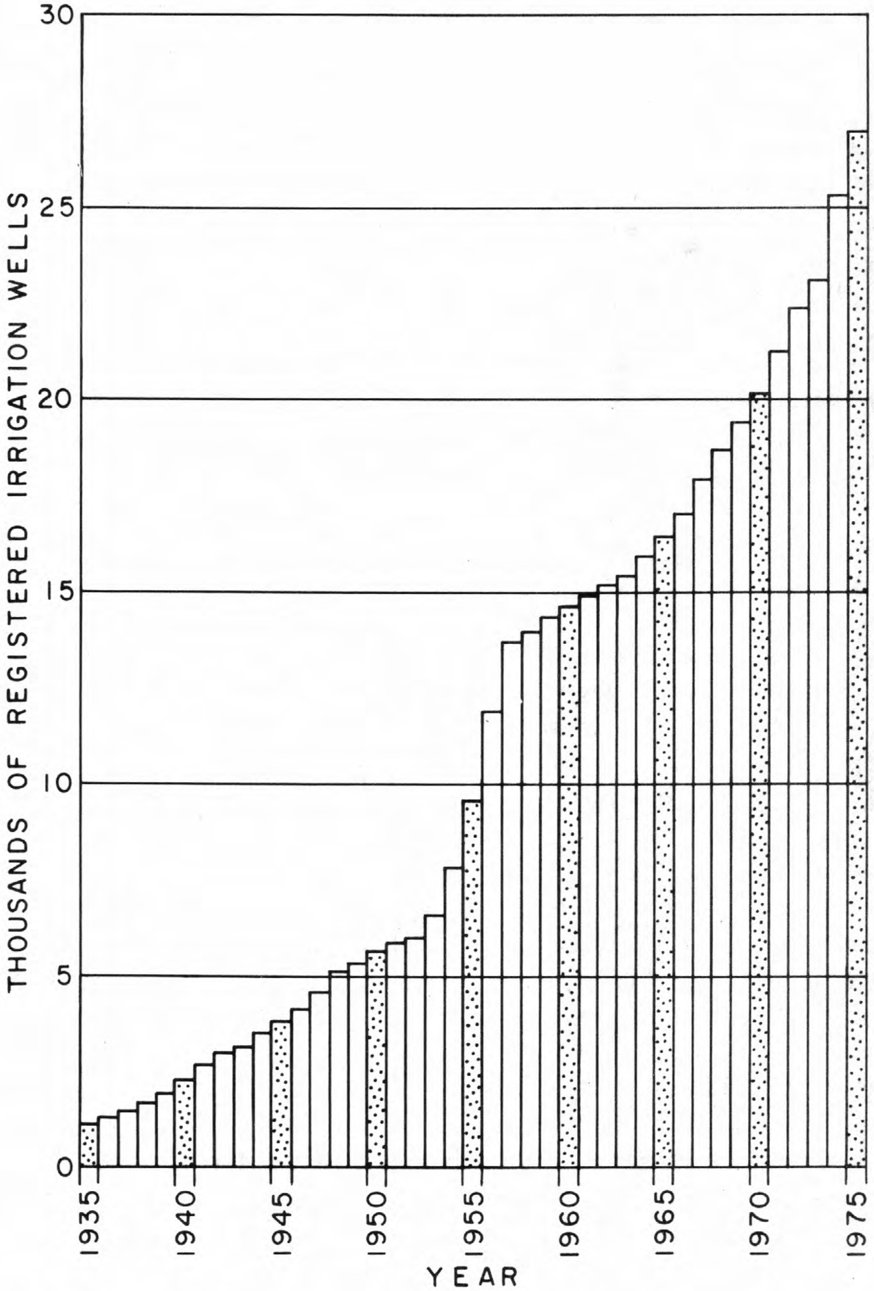



Figure 6.--Cumulative number of irrigation wells registered from 1935 to 1975.

Of the water beneath the land surface, only that in permanent or virtually permanent zones of saturation is called ground water (soil moisture and water in ordinarily nonsaturated zones are not included). In a few localities, the top of a saturated zone may coincide with the land surface; but in most places, water-saturated rocks can be reached only by digging or drilling. An aquifer is a 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.

If not overlain by a confining bed, the uppermost aquifer at a given locality is referred to as a water-table or unconfined aquifer, and the water in it is said to occur under water-table conditions. In a well that taps such an aquifer, the water level coincides with the water table at the well site. The elevation of the water table is considered as total hydraulic head.

The water table refers to the interface between the saturated and unsaturated zones. The separation between these areas is assumed to be a well-defined surface. However, the interface is a zone of gradation from unsaturated to saturated conditions. This zone is referred to as the capillary fringe. This zone is thickest in fine-grained sediments such as silt or silty clay and thinnest in coarse-grained sediments such as sand or gravel.

The hydraulic conductivity of an aquifer is the volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow, expressed as gallons per day per square foot.

Transmissivity is the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to the hydraulic conductivity times the effective depth of flow (usually the thickness of the zone of saturation). It is expressed as gallons per day per foot.

The degree of hydraulic connection between streams and lakes and aquifer is determined by the head difference between the aquifer and the free water surface and the hydraulic conductivity of the bed of the stream or lake. When an unsaturated zone exists between the bed of a stream or lake and the water table, the stream or lake is said to be perched.

The specific yield of an aquifer is the change that occurs in the volume of water in storage per unit area of unconfined aquifer as the result of a unit change in head, and is expressed as a dimensionless ratio to the dewatered volume or the drainable porosity. Rigorous definition of drainable porosity includes its variation with the time of drainage. However, this study considers specific yield to be time invariant.

Unconsolidated coarse-grained sediments, such as well-sorted sand and gravel, have a large capacity both for storing and for transmitting water and thus make very productive aquifers.

Unconsolidated fine-grained sediments, such as silt and clay, and their consolidated equivalents such as siltstone, shale, and mudstone, may have a storage capacity as great as the coarse-grained sediments, but they transmit water much less readily.

Transfer of water from the land surface to the zone of saturation is referred to as recharge. It is natural recharge if it is due to natural infiltration of precipitation and influent seepage from streams. It is artificial recharge if it is due to man's intentional construction of facilities such as recharge wells, ponds, and surface irrigation systems that deliver water in excess of crop consumptive-use requirements.

The relationship among processes of the ground-water portion of the hydrologic cycle is shown in figure 7.

Transfer of water from the aquifer to other aquifers, to the unsaturated zone, or to the land surface is referred to as discharge. Natural discharge includes seepage to lakes, springs, and streams; evapotranspiration from the capillary fringe; and leakage to other aquifers. Artificial discharge includes withdrawal of ground water by wells, drains constructed to intercept the water table, and evaporation from excavations below the water table that form ponds or lakes, and from impoundments on streams that have significant inflow from ground water.

The principal source of ground-water recharge is infiltration of precipitation. The intensity and amount of precipitation, the absorptive capacity of the soil, the depth to water, the vegetation, and the topographic characteristics are factors that influence the amount of recharge. Seepage from stream channels is another source of ground-water recharge.

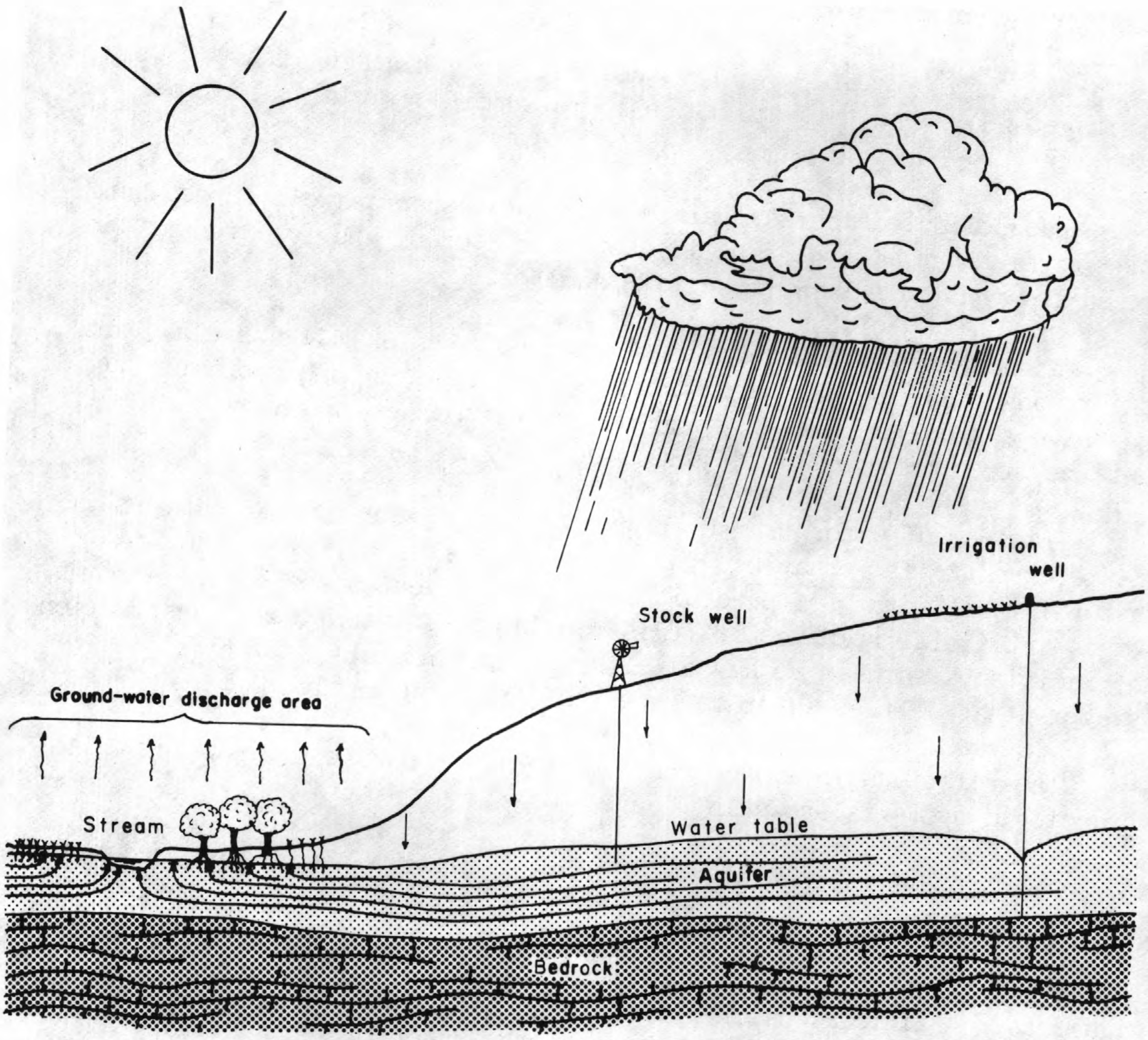



Figure 7.--Sketch of the hydrogeologic system.

In flood-plain areas, the quantity of recharge resulting from temporary flooding may greatly exceed that resulting from precipitation over the same area during several months or even years.

Seepage from canals and reservoirs, leakage from water-distribution systems, and outflow from septic tanks are all examples of unintentional ground-water recharge caused by man's activities. Such recharge has occurred in nearly all areas irrigated with diverted streamflow.

Under natural conditions (no pumping from wells and no artificial recharge), the average recharge balances the average discharge of ground water and the system is considered to be in equilibrium.

Pumping from wells affects the natural balance between discharge and recharge of ground water. The decrease in the volume of ground water in storage is progressive unless a new balance between discharge and recharge can be established by decreasing the rate of natural discharge, increasing the rate of recharge, or both. Where sufficient hydraulic connection exists between a stream and an aquifer, pumping from wells close to the stream may induce seepage from the stream.

Evapotranspiration from the aquifer occurs when roots of plants extract water directly from the capillary fringe. The depth to which plants will withdraw water from the capillary fringe may be as great as 40-50 ft for plants such as alfalfa. For most native vegetation, evapotranspiration from the aquifer is assumed to be insignificant where the water table is deeper than 10 ft below land surface.

Evapotranspiration salvage is the process by which the amount of evapotranspiration from the capillary fringe is reduced by lowering the water table. The amount of reduction is considered to be salvaged and available to be withdrawn by wells. Salvage of evapotranspiration is a continuing process. That is, if the water table is maintained at a lower level, the resulting effect is that the amount of salvage by the original lowering of the water table is continually being derived. The salvage process as considered in this report assumes that plant roots do not grow fast enough to keep up with the lowering water table.

## OCCURRENCE AND AVAILABILITY OF GROUND WATER

The quantity of ground water available in the Platte River Basin of Nebraska exceeds that of any other basin in the Missouri River Basin. An estimated 1.57 billion acre-ft of ground water is stored in the aquifers underlying the basin. This is more than 60 percent of the total amount estimated for the State. Table 1 summarizes pertinent hydrologic data for the modeled area of each subbasin.

Unconsolidated and semiconsolidated rocks of Tertiary and Quaternary age make up the principal aquifers of the Platte River Basin in Nebraska. The Ogallala Formation, which is the uppermost Tertiary stratigraphic unit, and deposits of Quaternary age are the principal aquifers. Where Quaternary deposits directly overlie the Ogallala Formation, the two constitute a single aquifer. In a large part of the basin, these aquifers supply large amounts of ground water for irrigation, municipal supply, and industrial use. In this report the Ogallala Formation and the Quaternary deposits are referred to as a single aquifer and they were modeled as a single unconfined unit. Figure 4 shows the distribution of the Ogallala Formation and Pleistocene deposits that constitute the modeled aquifer.

The annual discharge given in table 1 is equal to the annual recharge because the stream-aquifer systems are assumed to be in equilibrium. Recharge is that portion of all water applied, including precipitation, return flow of irrigation water, and reservoir and canal leakage that reaches the water table. Discharge includes base flow of streams, evapotranspiration from the water table, and withdrawals from wells. Volumes of ground water in storage given in table 1, which were computed using aquifer thickness and specific yield, do not represent all of the water in storage but are the upper limits on the volume of recoverable water. Transmissivity values given in table 1 are those used in model predictions and are the result of model calibration discussed under the section on Hydrologic Models.

## GROUND-WATER USE

Ground-water use varies from year to year depending upon the amount and seasonal distribution of precipitation and evapotranspiration and the availability of surface water. The estimated amount of pumped ground water consumed by irrigated crops during 1970 is shown in the following table. (Source: U.S. Bureau of Reclamation, written commun.)

Table 1.--Summary of hydrologic data by subbasins

| Model | Area modeled (mi²) | Altitude (ft) | Precip-itation (in/yr) | Ground water in storage 1/ (acre-ft) | Aquifer thickness 1/ (ft) | Transmis-sivity 1/ (1,000 gal/d/ft) | Annual discharge 2/ (in/yr) |
|---|---|---|---|---|---|---|---|
| Elkhorn | 7,810 | 1,070-2,700 | 21-31 | $2.46X10^{8}$ | 0-915 | 0-200 | 4.10 |
| Loup | 15,680 | 1,420-4,000 | 20-26 | $1.01X10^{9}$ | 30-1,200 | 20-330 | 4.70 |
| Middle Platte | 3,960 | 1,420-3,500 | 20-25 | $1.36X10^{8}$ | 40-610 | 10-220 | 2.21 |
| Upper (Twin) Platte | 7,180 | 2,790-5,420 | 15-20 | $1.73X10^{8}$ | 0-730 | 0-225 | 4.33 |
| Lower Platte | 1,170 | 940-2,100 | 27-31 | $9.16X10^{6}$ | 0-210 | 0-200 | 6.56 |

1/ Modeled area only.

2/ Based on steady-state modeling methods.

| Modeled area | Consumptive use of ground water |
|---|---|
| | (acre-ft) |
| Elkhorn | 70,000 |
| Loup | 160,000 |
| Middle Platte | 425,000 |
| Upper (Twin) Platte | 130,000 |
| Lower Platte | 45,000 |
| Total Platte Basin | 830,000 |

The amount of ground water used for municipal and industrial purposes was very small compared to that consumed by irrigation. More detailed information on ground-water use is included in the "Agricultural Water" Technical Paper (Missouri River Basin Commission, 1975a).

The most obvious effect of the use of ground water has been a depletion of ground-water storage. Figure 8 shows the effect of this depletion as measured by declines in water levels in wells. Accretions to ground-water storage have also occurred as shown in figure 8. These increases are caused by increased recharge from canal seepage and deep percolation of irrigation water applied in excess of consumptive crop requirements and soil-moisture-storage capacities.

## SURFACE-WATER RESOURCES

Models described in this report that simulate the stream-aquifer systems in the Platte River Basin include streams and lakes that are in hydraulic connection with the aquifer. A comprehensive discussion of the flow characteristics of surface-water systems is not included here, but can be found in the "Hydrology and Hydraulics" Technical Paper (Missouri River Basin Commission, 1975b).

Streams and lakes that are in hydraulic connection with the aquifer are important to the ground-water system. Reaches of streams that receive ground-water discharge are sinks for the ground-water system. The amount of base flow generated by the ground-water system in those reaches is a measure of the strength of the sink. Losing reaches of

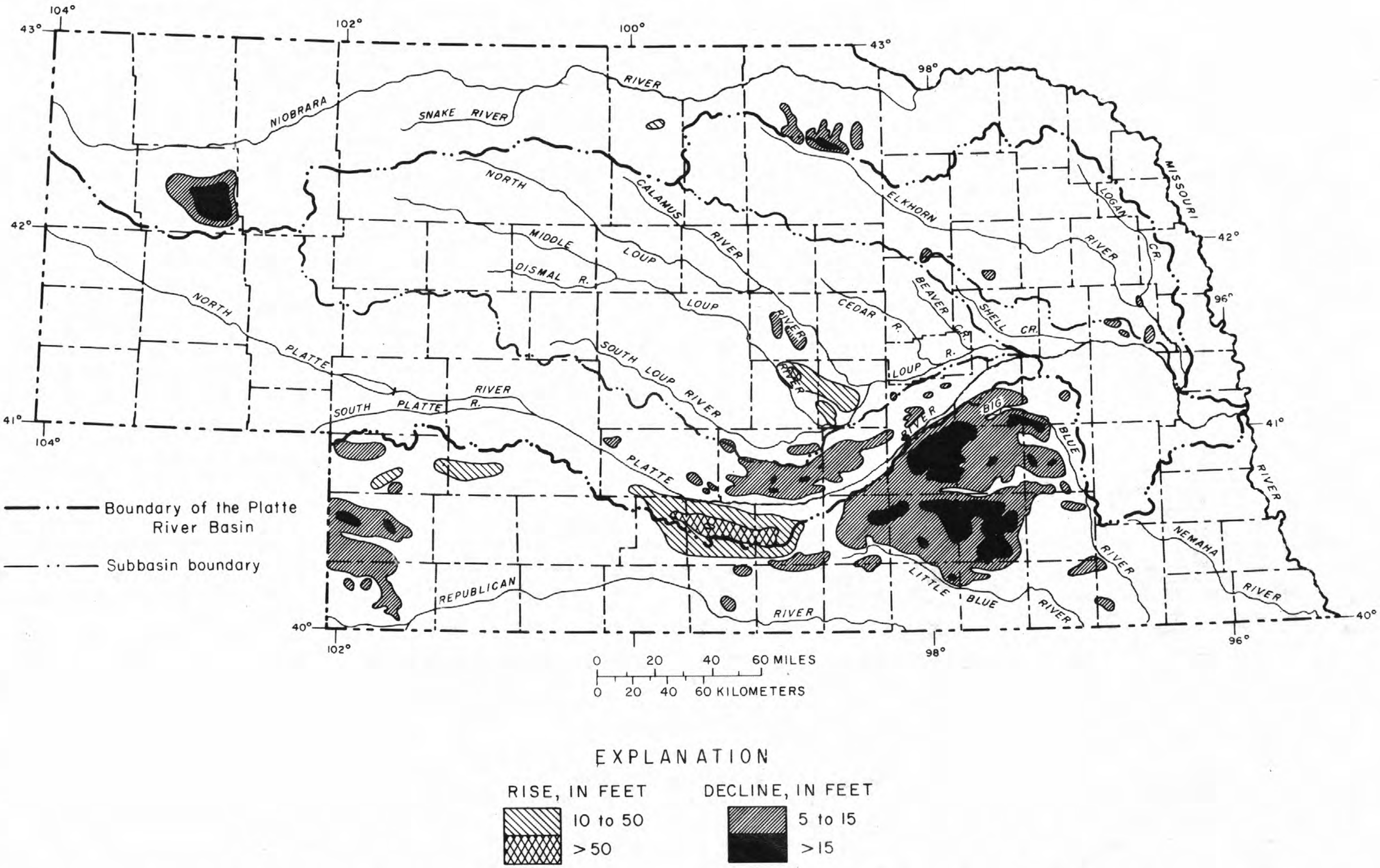



Figure 8.--Net change in ground-water levels between beginning of ground-water withdrawals for irrigation and 1975.

streams are sources of water to the ground-water system. The amount of water that can be lost to the ground-water system from streams is limited to the available flow in the stream. In both cases, the streams and lakes act as controls on the ground-water system.

Base flow of perennial streams was used in model calibration and prediction as described in the Hydrologic Models section. Base flows were determined by examining hydrographs of mean monthly flow for the months of September, October, and November. These months represent a base-flow period relatively free of surface-water operations, ice effects, and evapotranspiration from the capillary fringe adjacent to the stream. Typical hydrographs for stations in the Elkhorn and Loup subbasins are shown in figure 9. The assumption implicit in using these base flows is that average conditions existed over the period of record and resulted in average conditions of ground-water discharge.

The degree of hydraulic connection between streams and the aquifer also was important in the study of stream-aquifer systems. Perfect stream-aquifer hydraulic connection was assumed. That is, restriction on flow to or from the aquifer by silt or clay in the streambed was not considered. Reaches of streams considered to be in hydraulic connection with the aquifer were determined by examining topographic maps, water-table contour maps, and streamflow records.

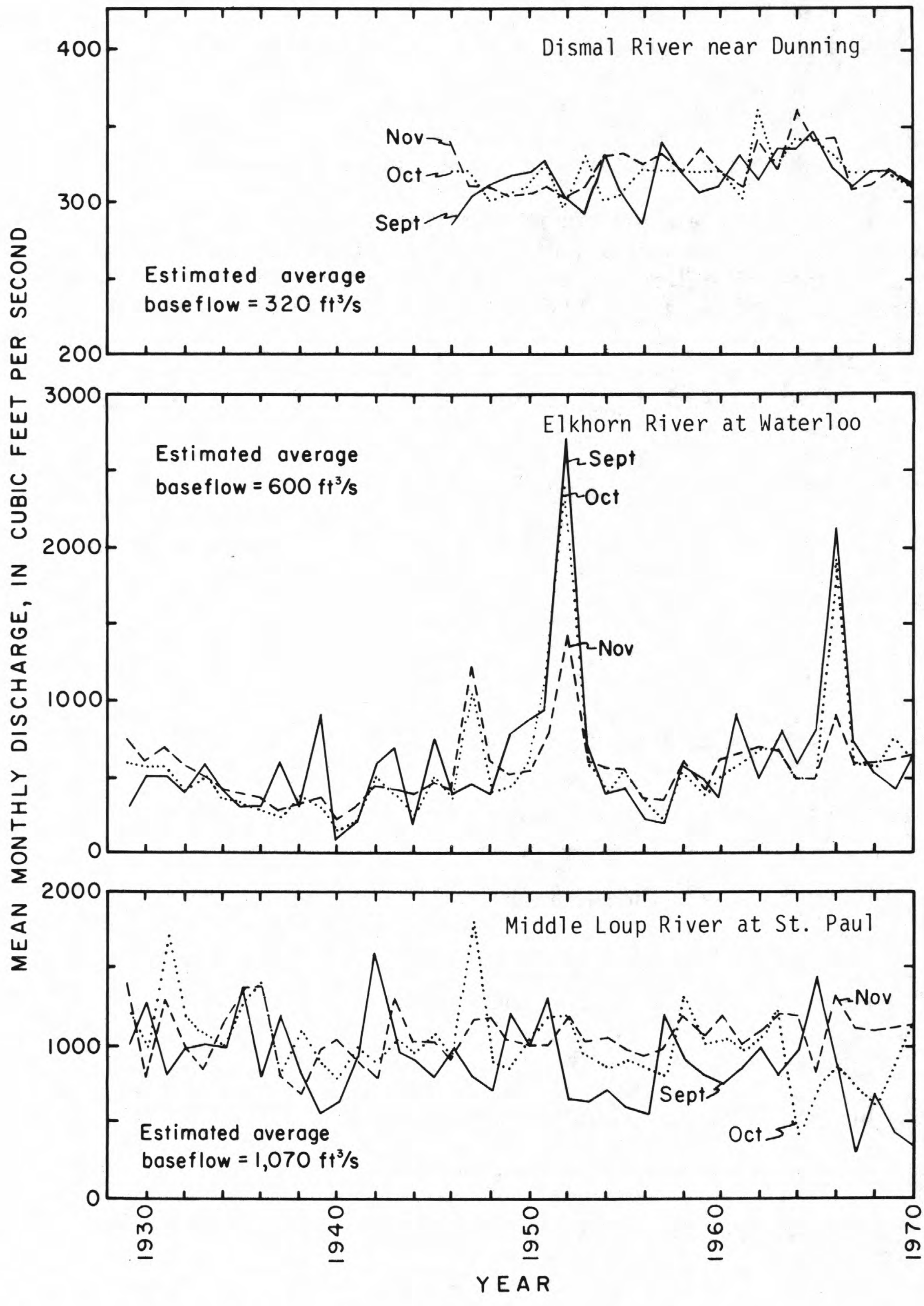



Figure 9.--Typical data used to determine the average base flow of streams.

## Digital Models of Stream-Aquifer Systems

### Mathematical Base for Digital Models and Assumptions

The digital models used in the analysis of stream-aquifer systems were used to solve the partial differential equation describing unsteady two-dimensional flow through an unconfined, nonhomogeneous aquifer with sources and sinks of varying strength:

$$\frac{\partial}{\partial x}(K_{xx} b\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_{yy} b\frac{\partial h}{\partial y}) = S_y \frac{\partial h}{\partial t} - Q(x,y,t) - \frac{k'}{b'}(H_r - h_a) \quad (1)$$

subject to the initial condition

$$h(x,y,t) = h_o(x,y)$$

and boundary conditions

$$H_r = \text{constant on } \mathcal{L}_r$$

$$\frac{\partial h}{\partial n} = \text{constant on } \mathcal{L}_d$$

where $\mathcal{L}_r + \mathcal{L}_d = \mathcal{L}$, the total boundaries on the system and n is the normal direction to $\mathcal{L}_d$,

where $K_{xx}$, $K_{yy}$ = principal components of the hydraulic conductivity tensor, $LT^{-1}$,

$h(x,y,t)$ = hydraulic head in the aquifer, L,

$h_o(x,y)$ = initial hydraulic head, L,

$b(x,y)$ = saturated thickness of the aquifer, L,

x, y = coordinate directions, L,

$S_y(x,y)$ = specific yield, dimensionless,

$t$ = time, T,

$Q(x,y,t)$ = source/sink term, including pumping and (or) recharging wells, evapotranspiration from the capillary fringe, recharge from precipitation, and application of surface water, $LT^{-1}$,

$K'$ = hydraulic conductivity of stream or lakebed, $LT^{-1}$,

$b'$ = thickness of stream, lake, or canal bed, L,

$H_r$ = head in stream, lake, or canal, L,

$h_a$ = head in aquifer underlying stream, lake, or canal, L.

Equation 1 is quasilinear in the unknown variable h. This is because h is a function of the saturated thickness:

$$h = b + c, \qquad (2)$$

where c is the elevation of the base of the aquifer.

The solution method used assumes that the nonlinearity in equation 1 can be approximated with sufficient accuracy by defining the transmissivity of the aquifer to be:

$$T_{xx} = K_{xx}b \text{ and } T_{yy} = K_{yy}b, \qquad (3)$$

and for application to this study, nonhomogeneous but isotropic conditions are assumed, and equation 1 becomes:

$$\frac{\partial}{\partial x}(T\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T\frac{\partial h}{\partial y}) = (S_y\frac{\partial h}{\partial t}) + Q(x,y,t) = \frac{K'}{b'}(H_r - h_a) \qquad (4)$$

This equation is approximated by a finite-difference analog which is solved by an alternating-direction implicit method modified from Pinder (1970). As the solution proceeds forward in time, the transmissivity is adjusted based on equations 2 and 3. This adjustment of transmissivity is the approximation used to linearize equation 1.

The application of this solution method required discretizing the parameters in equation 1. This was done by subdividing the area to be modeled into rectangular areas, or nodes. The nodes in this study were

13,050 ft x 13,050 ft, or an area of about 6.25 $mi^2$ for all models except that of the Lower Platte which used a 1 $mi^2$ nodal area. The areas covered by each model are shown in figure 2.

Values of the following parameters were entered for each nodal area as initial data for each model:

1. Hydraulic head in the aquifer, expressed as the altitude of the water table during 1970, in feet.

2. Estimated average transmissivity of the aquifer, in square feet per second.

3. Altitude of the base of the aquifer, in feet.

4. Specific yield of the aquifer, dimensionless.

The following assumptions are inherent in the use of and solution method for equation 1 in this study:

1. Vertical flow in the aquifer is negligible in comparison to lateral flow.

2. The aquifer can be considered isotropic but nonhomogeneous at the scale of modeling used.

3. Fluid flow is incompressible.

4. Specific yield is not a function of time.

5. Recharge and discharge rates from all sources remain constant over discrete time intervals.

6. Transmissivity at a node is constant over a given time step, but is corrected by the change in saturated thickness after each time step.

## Data for Digital Models

Data used as input to the digital models of the four subbasins include the following: Altitude of the water table and location of streams and rivers in hydraulic connection with the aquifer (plate 1); altitude of the base of the aquifer (plate 2); transmissivity (plate 3); depth to water (plate 4); and saturated thickness (plate 5). Reliability of data is indicated on figure 10. This reliability map is based upon the density and quality of the data used to compile the map.

The configuration of the water table (plate 1) is given as of 1970. This map was prepared using 1970 water-level measurements in developed areas, supplemented by measurements made prior to 1970 in undeveloped areas. The bedrock surface (plate 2) was mapped using logs of selected test holes and irrigation wells that completely penetrated the aquifer.

Transmissivity values (plate 3) used in the models were determined by using two methods. The first method consists of assigning hydraulic-conductivity values to grain-size classes and sorting found in each sampled interval (Keech and Dreeszen, 1959).

Transmissivity (T) at the control point was then determined by:

$$T = \sum_{j=1}^{n} K_j b_j \qquad (5)$$

where $K_j$ = hydraulic conductivity of interval j, $LT^{-1}$,

$b_j$ = thickness of interval j, L,

and n = number of sampled intervals below the water table.

The second method of determining transmissivity was based upon use of the ratio of discharge to drawdown in the production well, as reported on irrigation-well registrations. This method has been described by Theis and others (1963).

Specific yield was assumed to be a constant value of 0.18 for all subbasins except the Middle Platte reach of the Upper Platte subbasin. Variable specific yield values were used in the Middle Platte reach because this was the only area with water-level changes that were areally extensive enough to justify calibration under transient conditions. Initial estimates of specific yield for this area were determined by the

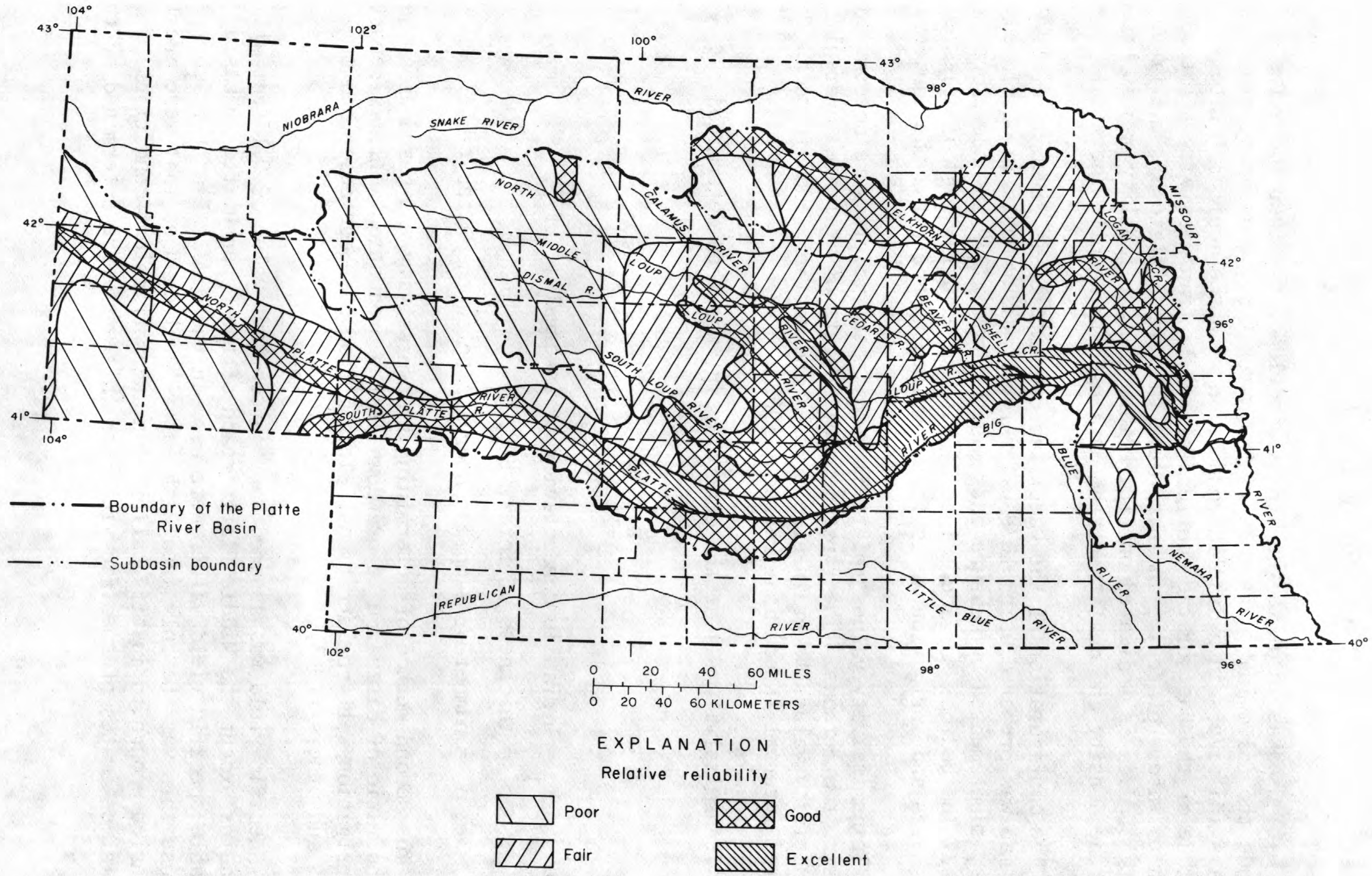



Figure 10.--Relative reliability of data used for models of the hydrologic system.

method described by Olmstead and Davis (1961). This method uses sample descriptions from test-hole logs and specific-yield values for different grain-size classes as shown below. (Modified from Johnson, 1967.)

| Grain size | Specific yield |
|---|---|
| Sand and gravel | 0.25 |
| Sandstone | .20 |
| Silt | .10 |
| Siltstone | .05 |

The specific-yield values are determined by weighting each interval by the thickness of the interval:

$$S_y = \frac{\sum_{j}^{n} S_{y_j} b_j}{B} \qquad (6)$$

where $S_{y_j}$ = specific yield of the predominant grain size present in interval j,

$b_j$ = thickness of interval,

$B = \sum_{j=1}^{n} b_j$,

and n = number of intervals in the total thickness.

For the initial specific-yield map of the Middle Platte reach, about 200 test holes were used.

Initial values of specific yield for the Middle Platte reach and of the transmissivity for all models were refined during model calibration as described subsequently. The values shown on plates 3 and 6 are the result of the calibration process. It should be noted that the calibrated specific yield values for the Central Platte model are representative of those materials dewatered during the calibration period. However, it was assumed that the calibrated values were representative of materials dewatered during predictive analyses.

## Digital Model Calibration

Models of stream-aquifer systems usually are calibrated by imposing a known set of flux conditions upon the modeled system and attempting to match historical changes in water levels and (or) streamflow caused by those conditions. Calibration involves adjustment of some of the parameters in equation 4 until a sufficiently good match is achieved. This procedure presupposes the existence of measured changes in the system. The Middle Platte reach of the Upper Platte subbasin was the only area modeled in which observed water-level changes were defined well enough to use this method.

The lack of these changes in the Elkhorn, Loup, Upper Platte, and Lower Platte subbasins required a different method of calibration which incorporates the following assumptions:

1. The stream-aquifer system is in a state of dynamic equilibrium (quasi-steady-state conditions exist throughout the system).

2. The 1970 configuration of the water table and the long-term average base flow of streams are the principal measurable manifestations of the steady-state conditions.

3. The configuration and altitude of the water table are known within reasonable limits of accuracy, particularly along perennial stream valleys.

4. Long-term average base flow can be estimated within reasonable limits of accuracy.

5. Unrestricted hydraulic connection exists between streams and the aquifer where they are connected.

6. The configuration of the water table is a function only of the net flux across the water table and the transmissivity of the aquifer.

Using the above assumptions, the digital model was used to solve the following equation for the strength of sources and sinks that are required to maintain the given water-table configuration:

$$\nabla \cdot T \, \nabla h = Qss(x,y) \qquad (7)$$

where $\nabla\cdot$ = divergence,

$\nabla$ = del operator or gradient,

T = transmissivity $L^2T^{-1}$,

h = scaler function of head, L,

and Qss = source, sink term, or steady-state flux, $L^3T^{-1}$.

Equation 7 was solved using the following finite difference algorithm for constant grid spacing $\Delta x$ and $\Delta y$.

For any node m,

$$Qss_m = [T_{m-\frac{1}{2}\Delta x}(h_{m-\Delta x}-h_m)+T_{m+\frac{1}{2}\Delta x}(h_{m+\Delta x}-h_m) + T_{m-\frac{1}{2}\Delta y}(h_{m-\Delta y}-h_m)+T_{m+\frac{1}{2}\Delta y}(h_{m+\Delta y}-h_m)] \,/(\Delta x\,\Delta y) \quad (8)$$

where $T_{m-\frac{1}{2}\Delta x}$, $T_{m+\frac{1}{2}\Delta x}$, $T_{m-\frac{1}{2}\Delta y}$, $T_{m+\frac{1}{2}\Delta y}$ are the values of transmissivity at the edges of node m and are computed using a harmonic mean, e.g.:

$$T_{m-\frac{1}{2}\Delta x} = \frac{2(T_{m-\Delta x}T_m)}{(T_{m-\Delta x}+T_m)} \quad (9)$$

The harmonic mean was used to be consistent with the solution algorithm used in the remainder of the model.

Since $Qss_m$ in equation 8 is a function of transmissivity and the slope of the water table in the vicinity of node m, the value of $Qss_m$ may be adjusted by varying either T or h in the vicinity of node m.

For this study, a physical interpretation of Qss at any particular node, m, in the model is the following:

$$Qss_m = QP_m + QET_m \pm QL_m \qquad (10)$$

(sign convention: positive = movement from aquifer
negative = movement to aquifer)

where $QP_m$ = recharge to the aquifer from precipitation,

$QET_m$ = discharge from the aquifer by evapotranspiration from the capillary fringe,

and $QL_m$ = leakage to or from streams and lakes.

However, the error introduced into Qss by the previously listed assumptions, inaccurate data, and numerical approximation must be included. Consequently, the following expression is the correct interpretation of $Qss_m$:

$$Qss_m = QP_m + QL_m + QET_m + Qe_m + \sum_{j=1}^{n} Qf_j \qquad (11)$$

where $Qe_m$ = error at node m,

and $\sum_{j=1}^{n} Qf_j$ = error effects of n adjacent nodes surrounding node m.

No attempt to evaluate the magnitude of the error component was made during this study. The assumption is implicit that its magnitude is small compared to the remaining terms. This assumption is reasonable along hydraulically connected streams but may be restrictive elsewhere (Lappala, 1978). The major source of numerical error is the linear approximation to the first derivative terms in equation 7. However, the low water-table gradients over most of the modeled areas minimize this type of error.

Calibration for the Loup and Elkhorn models was achieved by adjusting transmissivity until the values for Qss met the following criteria:

1. Net recharge to the aquifer was less than 50 percent (arbitrary) of the normal annual rainfall over most of the modeled areas.

2. Base flow computed by summing Qss at stream nodes agreed reasonably well with estimates of long-term average base flow.

Table 2 shows estimated and computed base flow for the Elkhorn and Loup subbasins. The computed base flow for the Elkhorn subbasin resulted after satisfying criterion No. 1 only.

Table 2.-Comparison of estimated and computed base flow

| Gaging station | Estimated base flow | Computed base flow |
| --- | --- | --- |
| | ($ft^3/s$) | |
| ELKHORN SUBBASIN | | |
| Elkhorn River at Ewing........................ | 60 | 59 |
| South Fork Elkhorn River at Ewing............. | 36 | 30 |
| Elkhorn River at Neligh....................... | 160 | 166 |
| Elkhorn River near Norfolk.................... | 240 | 245 |
| North Fork Elkhorn River near Pierce.......... | 40 | 16 |
| Maple Creek near Nickerson.................... | 15 | 30 |
| Elkhorn River at Waterloo..................... | 600 | 628 |
| LOUP SUBBASIN | | |
| Middle Loup River at Dunning.................. | 388 | 358 |
| Dismal River near Thedford.................... | 190 | 245 |
| Dismal River at Dunning....................... | 324 | 353 |
| Middle Loup River at Arcadia.................. | 842 | 772 |
| Mud Creek near Sweetwater..................... | 20 | 10 |
| South Loup River at St. Michael............... | 181 | 220 |
| Middle Loup River at St. Paul................. | 1,068 | 1,045 |
| North Loup River at Taylor.................... | 494 | 482 |
| Calamus River near Burwell.................... | 297 | 288 |
| North Loup River at Ord....................... | 874 | 845 |
| North Loup River near St. Paul................ | 916 | 891 |
| Cedar River near Spalding..................... | 140 | 157 |
| Cedar River near Fullerton.................... | 202 | 206 |
| Loup River near Genoa (+LPPD Canal).......... | 2,103 | 2,184 |
| Beaver Creek at Genoa......................... | 81 | 63 |
| Loup River at Columbus (+LPPD Canal).......... | 2,283 | 2,264 |
| Shell Creek near Columbus..................... | 13 | 12 |

Initial calibration runs for the Loup subbasin model indicated that neither of the calibration criteria was met by the initial transmissivity and head distributions. However, over large areas both the transmissivity and the watertable maps were based on sparse data (plates 1 and 3) and both were adjusted during calibration. Parts of the water-table map, particularly in the interfluve areas, were recontoured resulting in the configuration shown on plate 1. As a result of the new contours, water-table altitudes were adjusted no more than 10 ft. Transmissivity was also adjusted during calibration by as much as ± 100 percent at individual nodes, and was reduced by an average of 18 perccent over the entire model. Considering the approximate nature of the initial transmissivity distribution, these adjustments are not unduly large.

Models of the Twin Platte reach of the Upper Platte subbasin and the Lower Platte subbasin could not be calibrated by methods used for the Loup, Elkhorn, and Middle Platte models. No well defined water-level changes exist in the subbasins, and streamflow is severely regulated above and (or) within the modeled areas. Calibration of these models consisted of adjusting transmissivity until net recharge as indicated by the steady-state flux (Qss) was less than one-half of the mean annual precipitation over most of the modeled areas.

Calibration for the digital model of the Middle Platte reach of the Upper Platte subbasin was accomplished by matching measured and computed water-level changes from October 1968 to October 1971 (plate 7). Net seasonal ground-water withdrawals and recharge used in calibration were obtained from the Bureau of Reclamation recharge model explained later in this report. These values were obtained for subareas based upon soil type (plate 8). Specific yield and transmissivity were adjusted within the model until differences between measured and computed water-level changes were less than 1 ft over at least 90 percent of the modeled area. Sensitivity analyses indicated a higher sensitivity to specific yield and net ground-water withdrawal than to transmissivity. Consequently, specific yield was adjusted more than transmissivity. No adjustment of net withdrawal rates was made during calibration. Specific-yield adjustments ranged from -60 percent to +20 percent and averaged -14 percent. Transmissivity adjustments ranged from -50 percent to +50 percent and averaged +25 percent.

## Modifications to the Digital Model

Several modifications of the digital model described by Pinder (1970) were required to meet special problems encountered in the Platte River Basin and to simulate adequately the response of the stream-aquifer system to changes in flux rates imposed by different management schemes. These modifications are described below:

1. Salvage of evapotranspiration due to water-level changes.

2. Accounting of changes in base flow.

3. Changing ground-water withdrawals as a function of time.

4. Reducing ground-water withdrawals as saturated thickness decreases.

5. Stopping surface-water applications when land becomes waterlogged.

6. Maintaining a constant water-table gradient along parts of the model boundaries.

Simulation of evapotranspiration salvage.--Incorporation of evapotranspiration (ET) salvage into the model required a function relating the rate of ET from the capillary fringe to the change in the depth to water. Some investigators have used nonlinear functions to define this relationship (Emery, 1970, and White, 1932). The shape of this salvage function is not known for vegetation occurring in the basin. Sensitivity analyses using the Elkhorn model showed that the amount of salvage is relatively insensitive to the shape of the function. Consequently, a linear function was used (figure 11). Incorporating ET salvage reduced net withdrawals from the aquifer at the point where salvage occurred. The amount of reduction was equal to the amount of salvage.

The maximum rate of ET salvage was the difference between ET from the aquifer by vegetation before water levels declined and ET from above the aquifer by vegetation after water levels declined. For this study, this difference was assumed to be approximated by the difference between recharge and discharge components of the steady-state flux (page 32).

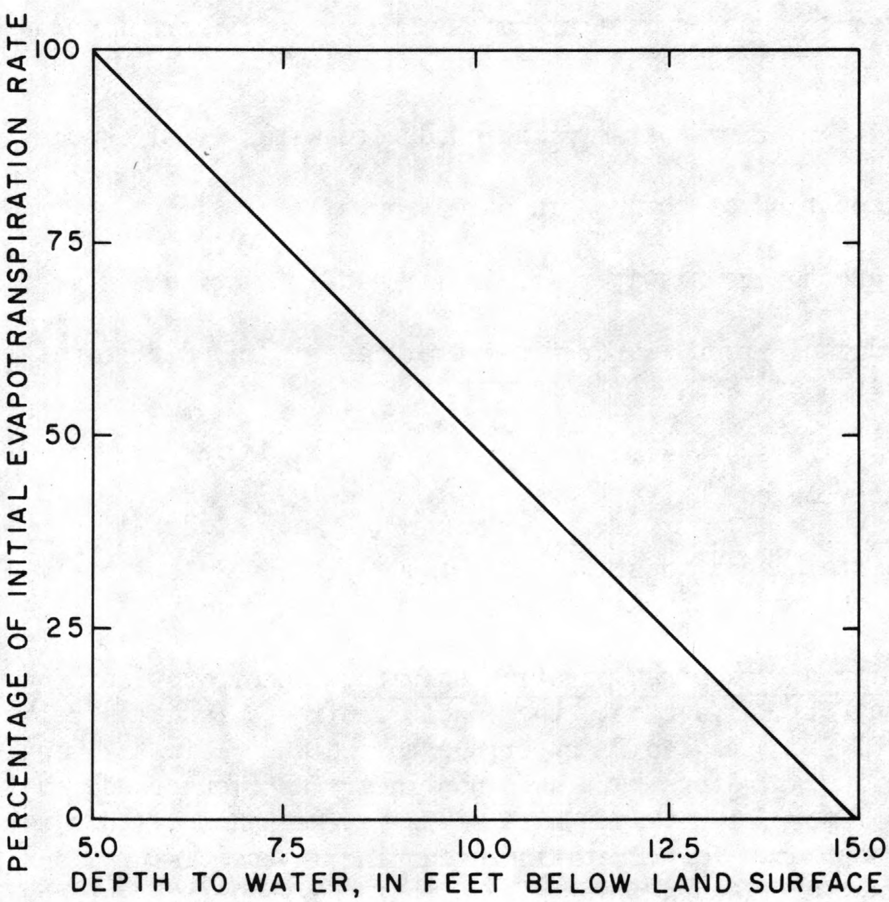



Figure 11.--Simulated relationship between change in rate of evapotranspiration from the capillary fringe and change in depth to water.

A modification of equation 11 that assumes no leakage from the streams and lakes and no error is:

$$Qss_m = QET_m - QP_m \qquad (12)$$

Figure 12 shows that the maximum rate of ET salvage was the excess of $QET_m$ over $Qp_m$, or $Qss_m$ in areas of net discharge.

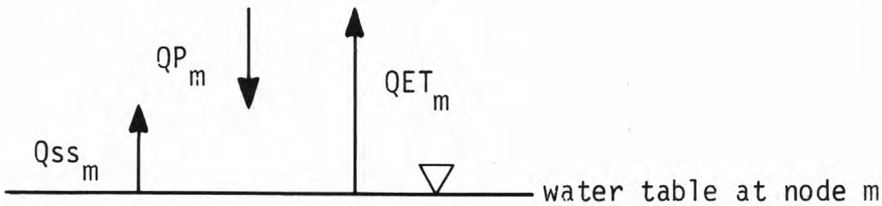



Figure 12.--Simulated components of steady-state flux to or from the ground-water system.

The initial (1970) rate of ET from the water table was set equal to Qss in those areas where Qss was positive. This initial ET rate was assumed to occur only where the initial depth to water was a maximum of 10 ft, or an average of 5 ft. The maximum rate of ET salvage was computed for each node by multiplying $Qss_m$ by the percentage of the nodal area having a depth to water of 10 ft or less. ET salvage was simulated when the water table was lowered between 0 and 10 ft below the 1970 level, or when the average depth to water was increased from 5 to 15 ft.

ET salvage was not simulated at constant-head (stream and lake) nodes because water levels at these nodes were held constant over time. ET from ground water was high in these areas of all subbasins due to a shallow water table. However, it was assumed that if a wet stream is maintained, water levels will not change enough to permit significant ET salvage.

Accounting for changes in baseflow.--The simulation of changes in streamflow by ground-water withdrawals followed the procedure outlined by Pinder and Bredehoeft (1968). The accounting of the streamflow was accomplished by considering the stream network to be represented by a binary tree structure. When depletion due to ground-water withdrawals occurred at a node, all downstream nodes were depleted by the same amount using an algorithm to traverse the binary tree structure (R. E. Booker, U.S. Geological Survey, Lincoln, Nebr., written commun., 1974). Streamflow depletions were limited to base flow for the Elkhorn and Loup models and to 1931 through 1970 average flows for the Middle, Twin, and Lower Platte models.

When available flow at a point on the stream network was exceeded due to ground-water withdrawals, hydraulic connection was broken between the stream and the aquifer by setting the streambed permeability to zero.

The model was also modified to compute the effect on streamflow by pumping from nodes occupied by a stream. This was necessary because these nodes included areas of ground-water withdrawal, while the model assumed that the stream occupied the entire nodal area. Streamflow depletions at these nodes were computed using analytical solutions for the rate and volume of stream depletion described by Jenkins (1968). Changing rates of well discharge were used in model analyses. Strictly speaking, the use of these equations to compute stream depletions with increasing discharge resulted in a slight overestimation of stream depletion rates. The error introduced, however, was small (E. P. Weeks, U.S. Geological Survey, Lubbock, Texas, oral commun., 1975).

Rate of streamflow depletion is:

$$q/Q = \text{erfc} \sqrt{\frac{sdf}{4t}} \tag{13}$$

Volume of streamflow depletion is:

$$V/Qt = \left[\left(1 + \frac{sdf}{2t}\right) \text{erfc} \sqrt{\frac{sdf}{4t}}\right] - \left(\sqrt{\frac{sdf}{4t}}\right) \frac{2}{\pi} \exp\left(- \frac{sdf}{4t}\right) \tag{14}$$

where erfc = complementary error function,
exp = exponential function,
$q$ = rate of streamflow depletion, $L^3T^{-1}$,
$Q$ = discharge of well, $L^3T^{-1}$,
$t$ = time since pumping began, $T$,
$V$ = volume of stream depletion, $L^3$,

sdf = stream depletion factor = $a^2S/T$, T,

where
$a$ = distance from stream, L,
$S$ = storage coefficient or specific yield, dimensionless,
$T$ = transmissivity, $L^2T^{-1}$.

The distance "a" was set at 1 mi for models of all subbasins except the Lower Platte, where a distance of 500 ft was used. Streamflow depletions computed using equation 14 were added to depletions or accretions caused by changing water levels adjacent to stream nodes.

Changing ground-water withdrawals as a function of time.--The model was modified to allow ground-water withdrawal rates and (or) rates of surface-water application to change continuously over the development period. Withdrawals and surface-application rates were changed every time step by an amount equal to the rate of development. A constant time step of 1 year was maintained during the period of changing rates of withdrawal or application.

Limitations on withdrawals and application rates.--Decline in well yield was simulated as saturated thickness was reduced by using the following:

$$Q_c = \frac{Q_o(b-b_m)}{(b_c-b_m)} \qquad (15)$$

where
$Q_c$ = curtailed pumping rate, $L^3T^{-1}$,
$Q_o$ = initial pumping rate, $L^3T^{-1}$,
$b$ = current saturated thickness, L,
$b_m$ = minimum saturated thickness below which the well fails,
$b_c$ = critical saturated thickness below which yield declines.

In this study, 30 ft was used for $b_c$ and 15 ft for $b_m$. These limits were arbitrary, but were those generally required to maintain discharges greater than 100 gal/min with hydraulic conductivities ranging from 70 to 100 ft/d and pumping durations of 30 to 60 days.

This modification also reduced the occasional numerical instability caused by drying up the aquifer at a point and not simultaneously reducing withdrawals.

The model was also modified to prevent water levels from rising above the land surface by reducing the applications of surface water when the water level rose within 10 ft of the land surface. Land-surface altitudes used were nodal averages unless a well-defined drain was evident in the node, in which case the average of altitudes along the drain was used.

Maintaining constant water-table gradient.--All boundaries of the modeled areas in this study did not correspond to impermeable boundaries as assumed by the original model (Pinder and Bredehoeft, 1968). Boundaries used in this study were often arbitrary. To avoid erroneous water-level changes, the model was modified to maintain the gradient in the water table at the original value for specified sections of the model boundaries. This was accomplished by calculating after every time step the net flux required to maintain the original gradient along those sections. The effect of this assumption was simulation of equal rates of development (withdrawal or recharge) on both sides of the boundary of the modeled area.

## Sensitivity analyses

After calibration of the digital models, it was assumed for the simulation runs that the values of the parameters in the approximation to equation 1 represented the actual field conditions. However, the calibration methods used in this study did not assure a unique set of the values of these parameters for any area. In fact, no calibration method can ensure a unique set of these parameters due to inaccuracies in measurement or estimation and the extrapolation of point measurements over large areas. However, reasonable limits, based upon knowledge of the geology of a modeled area, can be placed on these parameters. Sensitivity analyses consisted of evaluating the models' response to variations in these parameters between the above limits. Sensitivity of the models to changes in specific yield, transmissivity, net withdrawal, and salvaged evapotranspiration was determined. These analyses gave reasonable upper and lower bounds on the accuracy of the simulation runs.

Sensitivity analyses were made for all models. Although sensitivity relationships were not identical for all subbasins, or within each subbasin, the type (direct or inverse) and the shape (linear or nonlinear) of the functions showing sensitivities were similar for all models. Examples of sensitivity functions for specific yield, transmissivity, and net withdrawal are presented in figures 13 through 18 for the Elkhorn subbasin. These functions are presented in dimensionless form and can be used to indicate the change in predicted water-level decline or streamflow depletion that would result if the aquifer parameters were in error. For example, using figure 14, an error of 40 percent in specific yield would cause an error of -20 percent in the predicted water-level decline. All percentages were computed with respect to values of parameters resulting from model calibration and water-level declines and streamflow depletions presented in the section "Subbasin Analyses."

## Soil-Zone Model

Net ground-water withdrawals required for irrigated crops were computed with a water-balance model of the soil zone developed by the Nebraska Reclamation Office, U.S. Bureau of Reclamation, Grand Island, Nebr. The model operates on a monthly basis and is adapted from the daily irrigation scheduling program developed by Jensen and others (1969). The soil zone was modeled as a lumped system for a given topography, soil type, and crop distribution. Inputs and outputs from the soil zone are shown in figure 19. Inputs to the model are monthly values of precipitation and potential evapotranspiration (ET). Potential ET was computed using the Jensen-Haise method (Jensen and others, 1969). Runoff was abstracted from precipitation using monthly rainfall-runoff relationships derived from data obtained by the Agricultural Research Service at Rosemont, Nebr. (U.S. Department of Agriculture, 1956-68.) These relationships considered soil type, slope, crop cover, and farming practices.

Outflow from the soil zone consisted of gravity drainage and ET. Gravity drainage, or assumed recharge to the water table, occurred when infiltration from precipitation and applied irrigation water exceeded ET plus soil-moisture-retention capacity. Net ground-water recharge for land irrigated with ground water was equal to recharge from precipitation plus irrigation seepage minus total ground-water withdrawal. For land irrigated with surface water, net ground-water recharge was equal to recharge from precipitation plus seepage losses. Potential ET was

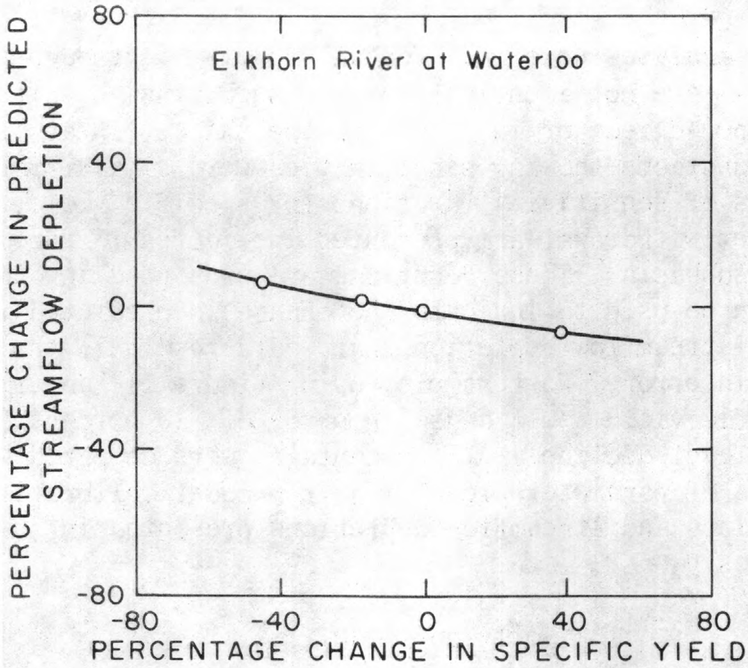



Figure 13.--Sensitivity of simulated depletion of streamflow to changes in specific yield.

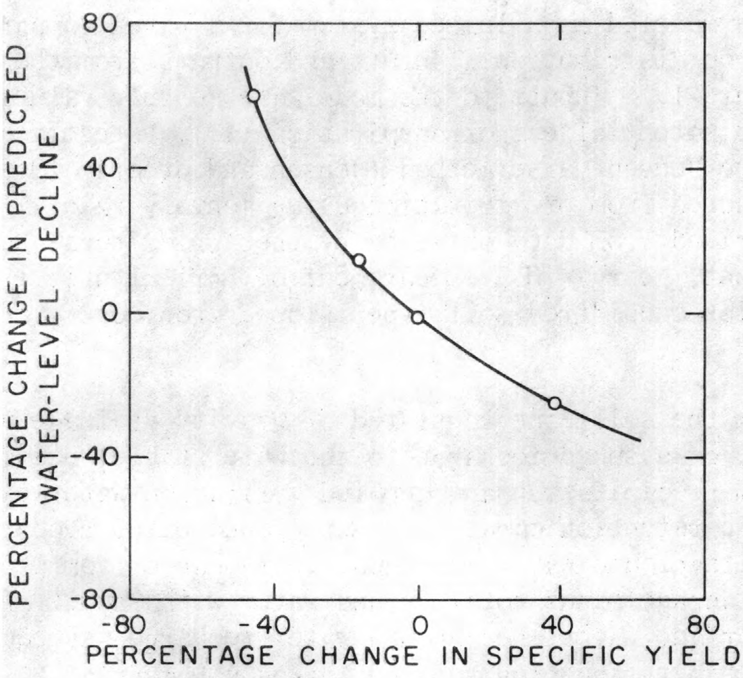



Figure 14.--Sensitivity of simulated changes in water level to changes in specific yield.

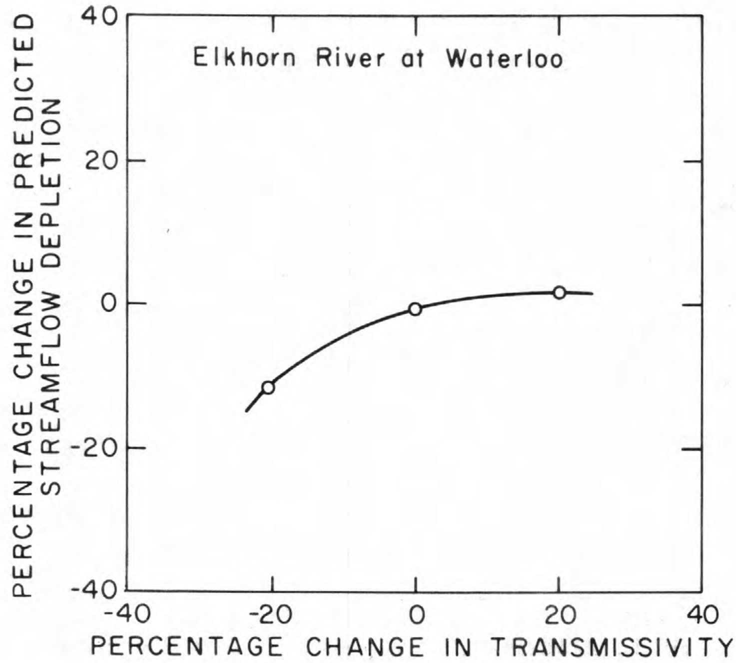



Figure 15.--Sensitivity of simulated depletion of streamflow to change in transmissivity.

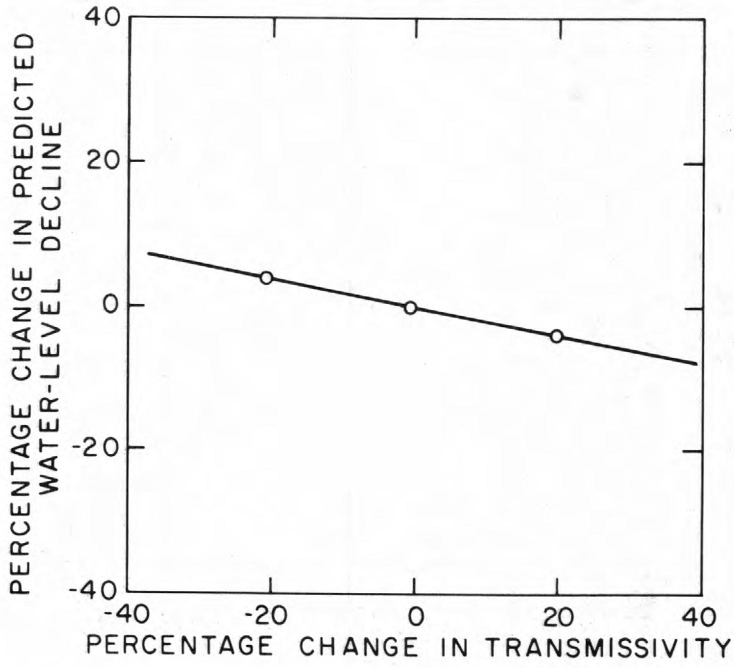



Figure 16.--Sensitivity of simulated change in water level to change in transmissivity.

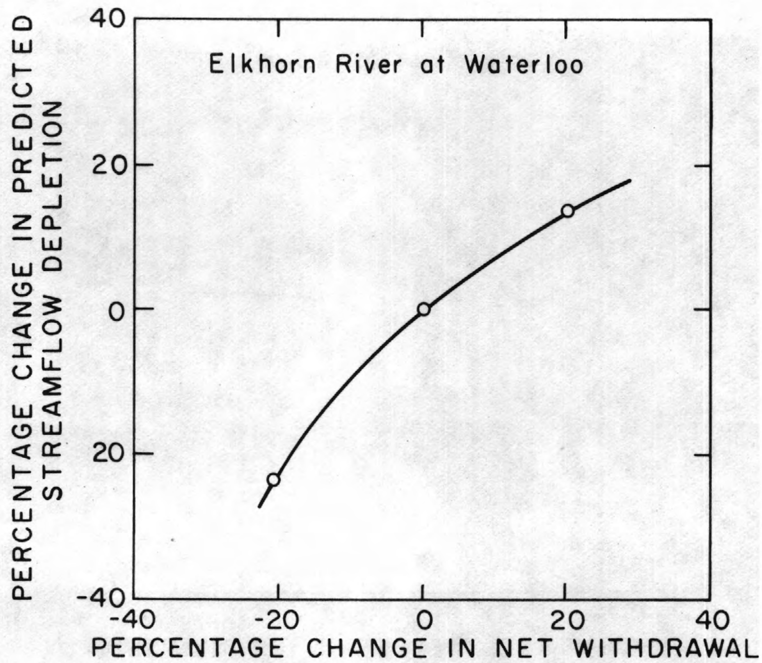



Figure 17.--Sensitivity of simulated depletion of streamflow to change in net withdrawals.

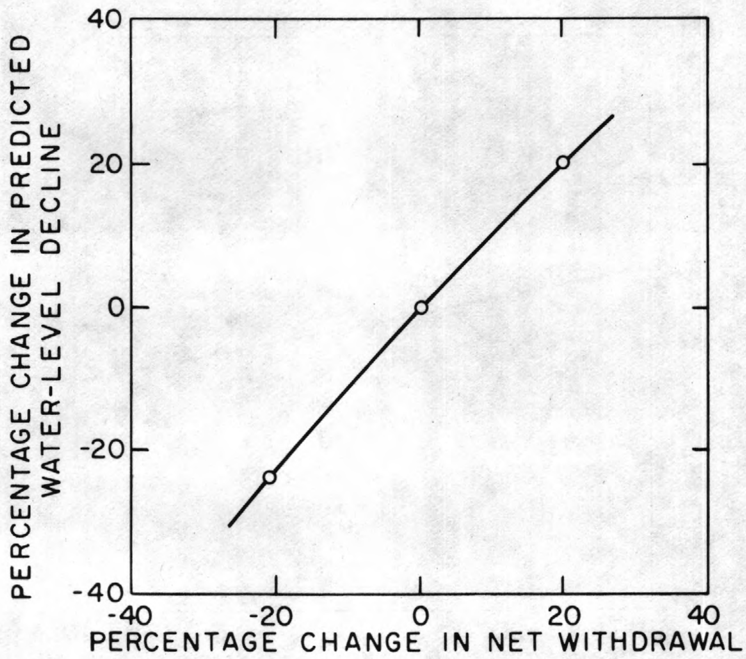



Figure 18.--Sensitivity of simulated change in water level to change in net withdrawals.

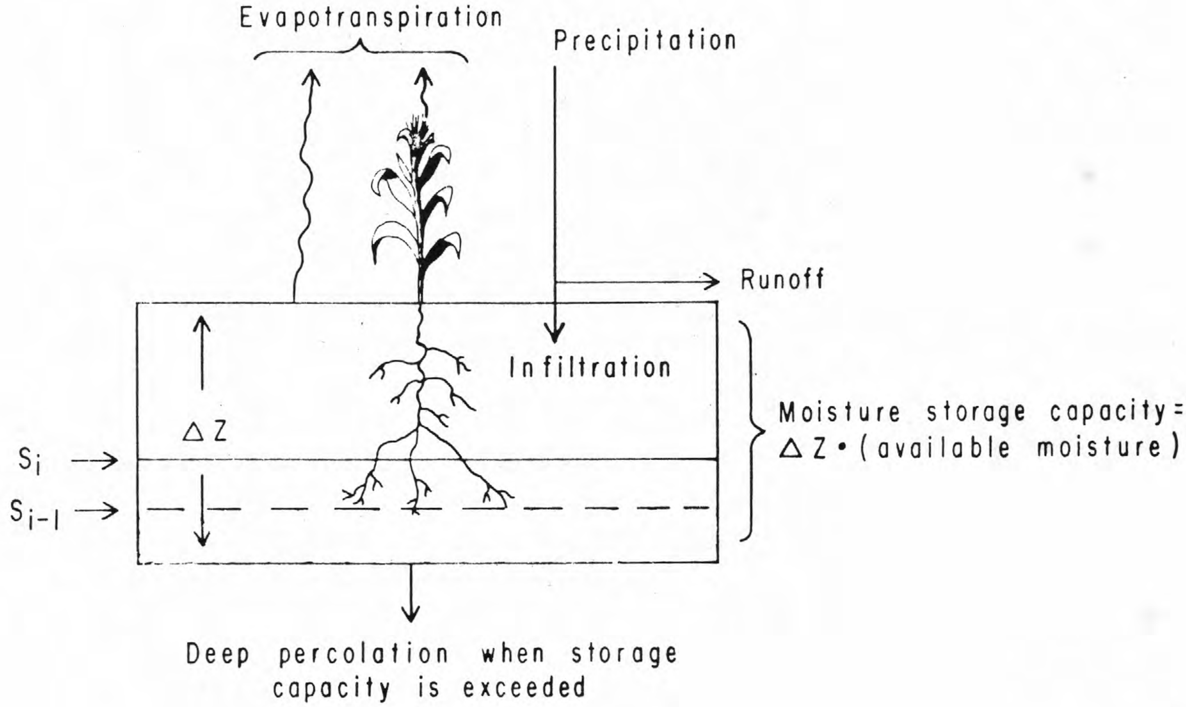



Figure 19.--Simulated components of the soil zone.

computed for 29 stations within the basin (plate 8) by using air temperature and solar radiation (Jensen and others, 1969). Relative humidity, elevation, and crop type were used to adjust potential ET to obtain actual consumptive use. Four major crop types were used for this study: Row crops, small grains, alfalfa, and pasture. Annual net recharge to the water table and ground-water withdrawals, given in table 3 were computed by soil associations, shown on plate 8, using typical cropping patterns for these crops under dryland conditions and irrigation with ground water and surface water. The farm delivery requirement given in table 3 is the sum of the consumptive-irrigation requirement and delivery-system losses to evaporation, runoff, and deep percolation.

Table 3.--Ranges of net ground-water recharge and farm delivery requirements

| Soil association | Net recharge | | | | Consumptive irrigation requirement | | Farm delivery requirement | |
|---|---|---|---|---|---|---|---|---|
| | Dryland | | Row crops irrigated with surface water | | | | | |
| | (ft/yr) | | (ft/yr) | | (ft/yr) | | (ft/yr) | |
| | West | East | West | East | West | East | West | East |
| Valentine-Dunday | 0.10 | 0.45 | 0.78 | 0.98 | 1.30 | 0.50 | 2.10 | 1.55 |
| Thurman-Valentine | .20 | .40 | .68 | .85 | .17 | .50 | 1.20 | 1.00 |
| Moody-Crofton | .07 | .16 | .59 | .74 | .45 | .19 | 1.10 | .94 |
| Leshara-Platte | .10 | .40 | .67 | .95 | .70 | .01 | 1.37 | .89 |
| Luton-Haynie | .25 | .35 | .88 | .75 | .18 | .01 | .97 | .89 |
| Sharpsburg-Marshall | .10 | .18 | .60 | .75 | .35 | .25 | 1.03 | .95 |
| Hall-Wood River | .05 | .12 | .63 | .77 | .69 | .32 | 1.34 | 1.08 |
| Holdrege-Colby | .02 | .06 | .43 | .60 | 1.16 | .51 | 1.59 | 1.11 |
| McCook-Las | .01 | .08 | .52 | .59 | 1.52 | 1.19 | 2.06 | 1.73 |
| Keith-Rosebud | .03 | .06 | .45 | .40 | 1.30 | 1.12 | 1.70 | 1.60 |
| Rough, broken land | .10 | .16 | ---- | ---- | ---- | ---- | ---- | ---- |
| Anselmo-Keith | .04 | .08 | .54 | .56 | 1.45 | 1.13 | 1.90 | 1.65 |
| Mitchell-Tripp | < | .01 | .52 | .50 | 1.60 | 1.40 | 2.10 | 1.95 |

Models of each subbasin were used to predict water-level changes and streamflow depletions resulting from three basic private development plans: (1) No additional ground-water development (Present Plan), (2) development at the average rate occurring over the period of historical development (Plan Alpha), and (3) development of the approximate rate occurring over the past decade (Plan Beta). Figure 20 shows an example of the development rates used for plans Alpha and Beta for the Elkhorn subbasin. Ground-water withdrawals used for these plans were computed by applying a consumptive-irrigation requirement to available irrigable land within each model.

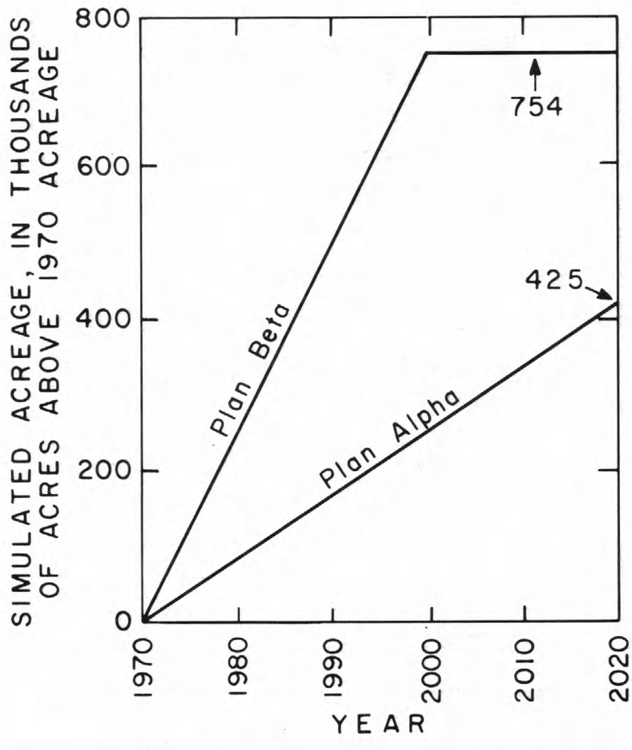



Figure 20.--Method of simulating varying rates of irrigation development, Elkhorn subbasin.

Irrigable land was classified by the Agricultural Water Task Force on the basis of soil type and slope into (1) land with slight to moderate irrigation limitations and (2) land with severe irrigation limitations. (See plate 9.)

Irrigable land shown on plate 9 was omitted from predictive analyses if (1) water supply beneath the land was considered inadequate based on saturated thickness and transmissivity or (2) depth to water precluded economic installation and operation of wells. A more complete discussion of the use of these criteria in eliminating land is found in the "Plan Formulation" Technical Paper (Missouri River Basin Commission, 1975c). Criteria for each subbasin are shown in table 4. The irrigation suitability criteria used in determining irrigable land for predictive analyses was based upon requirements for gravity flow irrigation systems. Consequently, some land that can be irrigated with pivot-type sprinkler systems was not included as irrigable.

Table 4.--Criteria used to eliminate irrigable lands from subbasins for predictive analyses
[Source: Level B Planning Team]

| | Criteria | | |
|---|---|---|---|
| Model | Transmissivity | Saturated thickness | Depth to water |
| | [(1,000 gal/d)/ft] | (ft) | (ft) |
| Elkhorn | < 50 | < 100 | < 200 |
| Loup | < 50 | < 100 | < 200 |
| Middle Platte | < 50 | < 100 | < 200 |
| Twin Platte | < 25 | < 50 | < 200 |
| Lower Platte | < 50 | < 100 | < 200 |

For predictive analyses, land with slight to moderate limitations that met the above criteria was considered separately from land with severe limitations that met the criteria. Ground-water withdrawals required to convert 1 acre of dryland to 1 acre of irrigated cropland under average (1931-70) climatic conditions (plate 8) were applied to part or all of the above acreages for Plans Alpha and Beta. These requirements were computed using the USBR recharge-discharge model discussed in the previous section.

Water requirements for the Present Plan were computed using average (1931-70) climatic conditions applied to a percentage of the 1970 acreage. The total 1970 acreage could not be used for the following reason: The steady-state flux computed with the model (page 30) was a function of the position of the water table in 1970. Any effect of the current level of development was reflected in the 1970 water-table configuration. Consequently, the steady-state flux included the net withdrawals occurring prior to 1970 that had measurably affected the water table.

To account for the effect of the 1970 level of development that had not measurably affected the water table, the percentage of development that occurred between 1961 and 1970 was used for computing withdrawals for the Present Plan. This percentage varied among models, but averaged about 10 percent of the development occurring from 1961 to 1970.

The models were also used to evaluate the effect of the following proposed U.S. Department of Interior surface-water irrigation projects.

| Model | Project |
|---|---|
| Elkhorn | Highland - Norfolk |
| Loup | North Loup and Cedar Rapids |
| Middle Platte | Midstate |

The relative effect of a particular development plan on streamflow and water levels is shown by a comparison of the sources of water pumped for any given plan. All water pumped in the basin must come from some combination of:

1. Storage depletion (declining water levels).
2. Streamflow depletions.
3. Salvaged evapotranspiration.

These comparisons are presented for each model in the following sections for the year 2000, or after 30 years of simulation for each plan.

Streamflow depletions in the following sections were due to ground-water withdrawals only.

## Elkhorn Model

Three basic development plans were tested with the Elkhorn model (Source: Level B Planning Team):

| Plan | Total irrigated acreage by end of development period[1/] | Additional irrigated acreage | Percent of irrigable lands with: Slight to moderate limitations | Percent of irrigable lands with: Severe limitations | Date of maximum development |
|---|---|---|---|---|---|
| Present | 96,000 | 0 | - | - | 1970 |
| Alpha | 470,000 | 374,000 | 50 | 50 | 2020 |
| Beta | 850,200 | 754,200 | 80 | 75 | 2000 |

[1/] Includes present (1970) irrigated acreage.

Predicted water-level changes by the year 2020 for Plans Alpha and Beta are shown on figures 21 and 22. No map is included for the present development plan, as all predicted water-level changes by 2020 were less than the accuracy of the water-table map ($\pm 5$ ft). Part of the Elkhorn model was not used in the predictive analyses because adequate data to describe the hydrologic system were not available (figs. 21, 22). This area is underlain by glacial till. Predicted changes in streamflow by 1985, 2000, and 2020 computed with the Elkhorn model are shown in table 5. Predicted changes for the present development plan were less than 5 percent of the estimated base flow and, therefore, are not shown in the table.

Sources of water pumped at the end of 30 years of simulation (2000) are given below.

| Source of water | Plan: Alpha | Plan: Beta |
|---|---|---|
| Pumpage (acre-ft/yr) | 121,740 | 405,070 |
| Storage depletion (acre-ft/yr) | 24,640 | 192,030 |
| Percent of pumpage | 20 | 48 |
| Streamflow depletion (acre-ft/yr) | 75,360 | 163,770 |
| Percent of pumpage | 62 | 40 |
| Salvaged evapotranspiration (acre-ft/yr) | 21,740 | 49,280 |
| Percent of pumpage | 18 | 12 |
| Percent of maximum possible salvage | 18 | 40 |

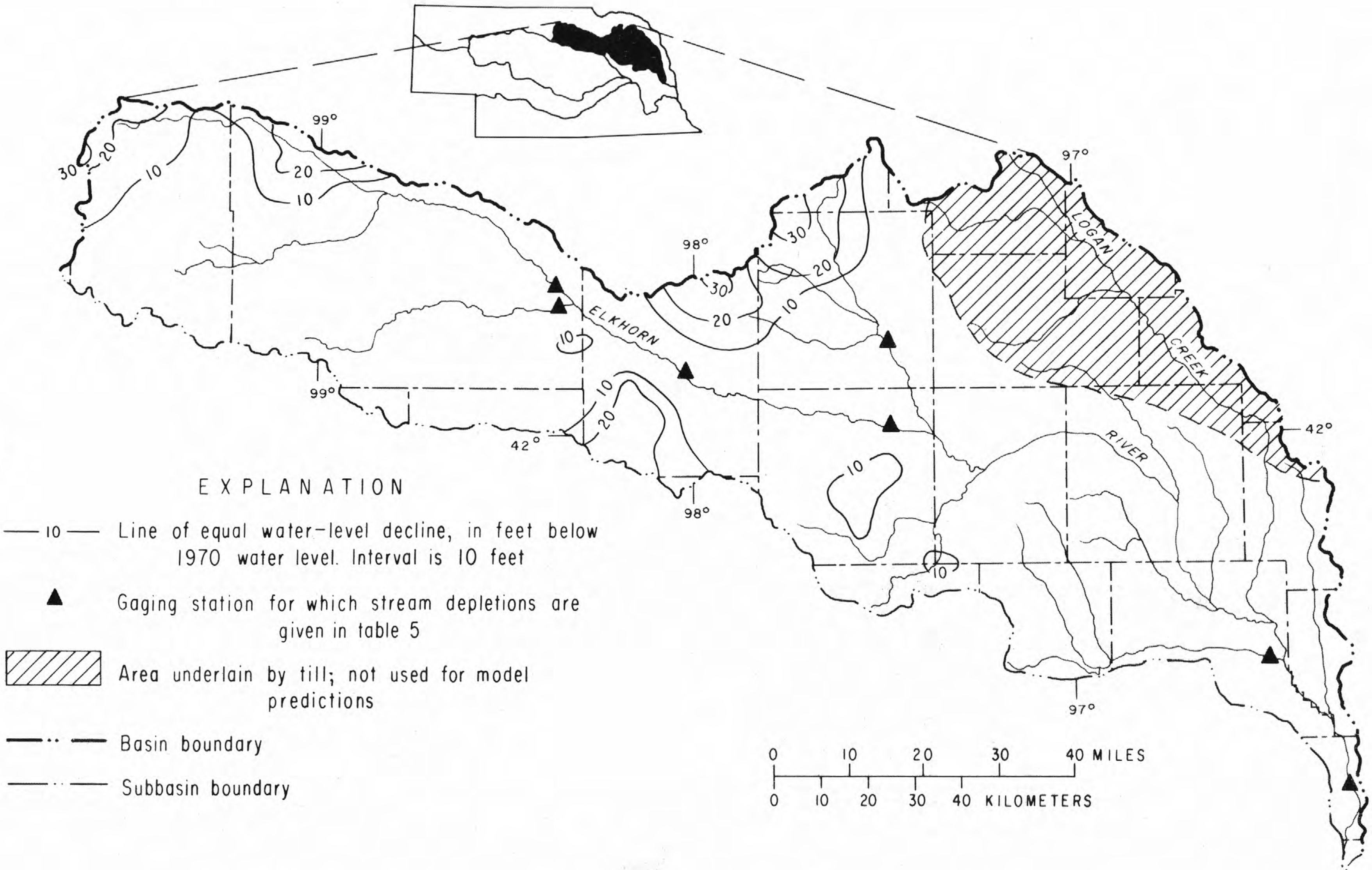



Figure 21.--Simulated water-level declines from 1970 to 2020, plan Alpha, Elkhorn subbasin.

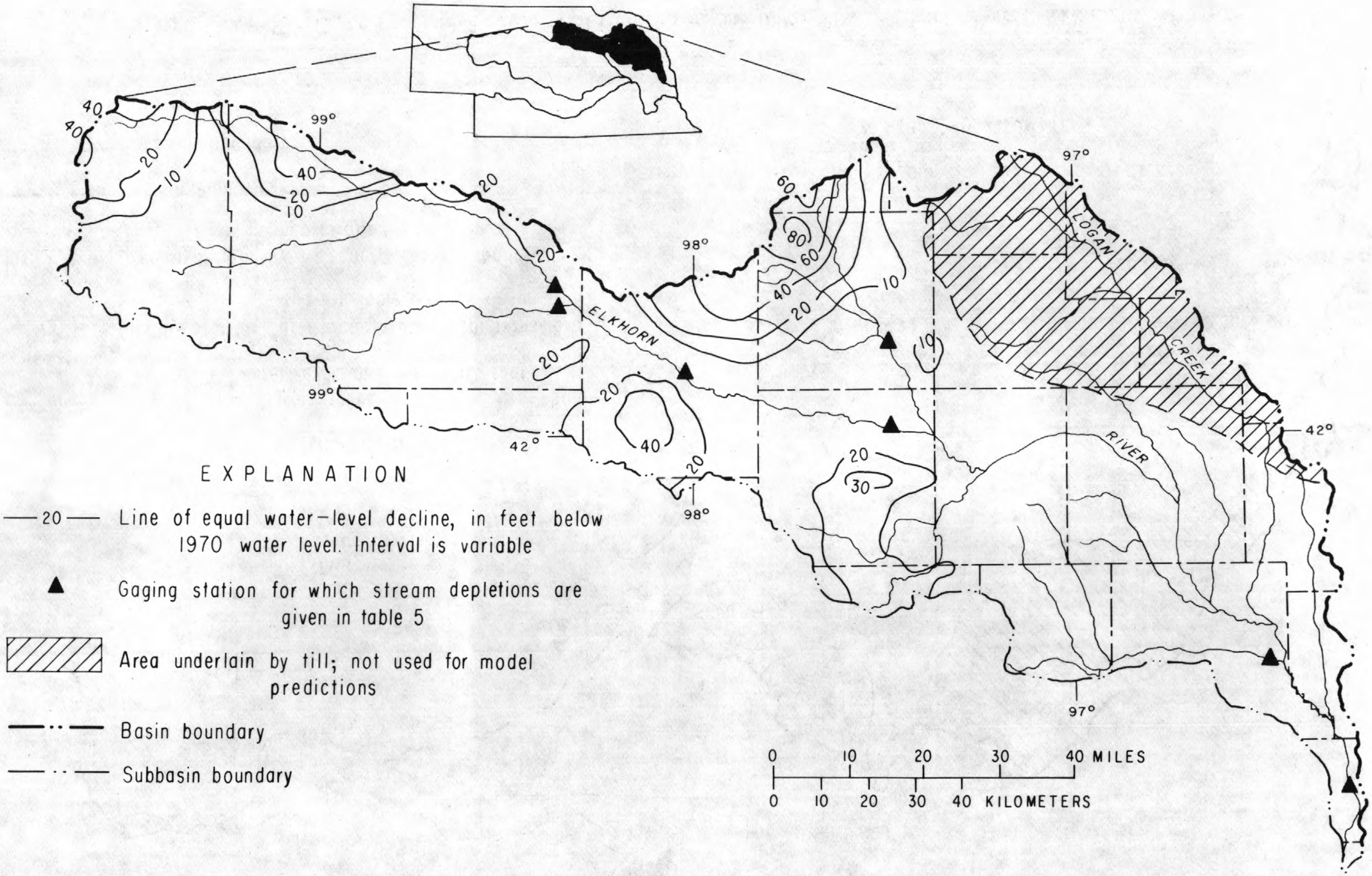



Figure 22.--Simulated water-level declines from 1970 to 2020, plan Beta, Elkhorn subbasin.

Table 5.--Predicted streamflow depletion, Elkhorn Model

| Gaging station | Computed annual base flow | Streamflow depletion | | | | | |
|---|---|---|---|---|---|---|---|
| | | Plan Alpha | | | Plan Beta | | |
| | | 1985 | 2000 | 2020 | 1985 | 2000 | 2020 |
| | | ($ft^3/s$) | | | | | |
| Elkhorn River at Ewing........ | 59 | 9 | 15 | 26 | 20 | 40 | 47 |
| So. Fork Elkhorn River at Ewing...................... | 30 | 4 | 6 | 8 | 7 | 13 | 14 |
| Elkhorn River at Neligh....... | 166 | 26 | 45 | 71 | 53 | 100 | 121 |
| Elkhorn River near Norfolk.... | 245 | 37 | 62 | 94 | 69 | 129 | 156 |
| No. Fork Elkhorn River near Pierce..................... | 16 | 2 | 4 | 6 | 4 | 9 | 10 |
| Maple Creek near Nickerson.... | 30 | 3 | 6 | 10 | 8 | 17 | 21 |
| Elkhorn River at Waterloo..... | 628 | 59 | 104 | 158 | 115 | 226 | 265 |

The Elkhorn model was also used to evaluate the effects on water-level changes and streamflow caused by superposing the Highland Unit on Plans Alpha and Beta. The Highland Unit involves construction of a reservoir and delivery system to irrigate 25,000 acres in southeastern Antelope and northwestern Madison Counties. A more complete description of this project is found in the "Agricultural Water" Technical Paper (Missouri River Basin Commission, 1975a).

Water-level changes by 2020 with the Highland Unit included are shown on figures 23 and 24. Streamflow depletions due to ground-water withdrawals were not significantly different from depletions without the unit.

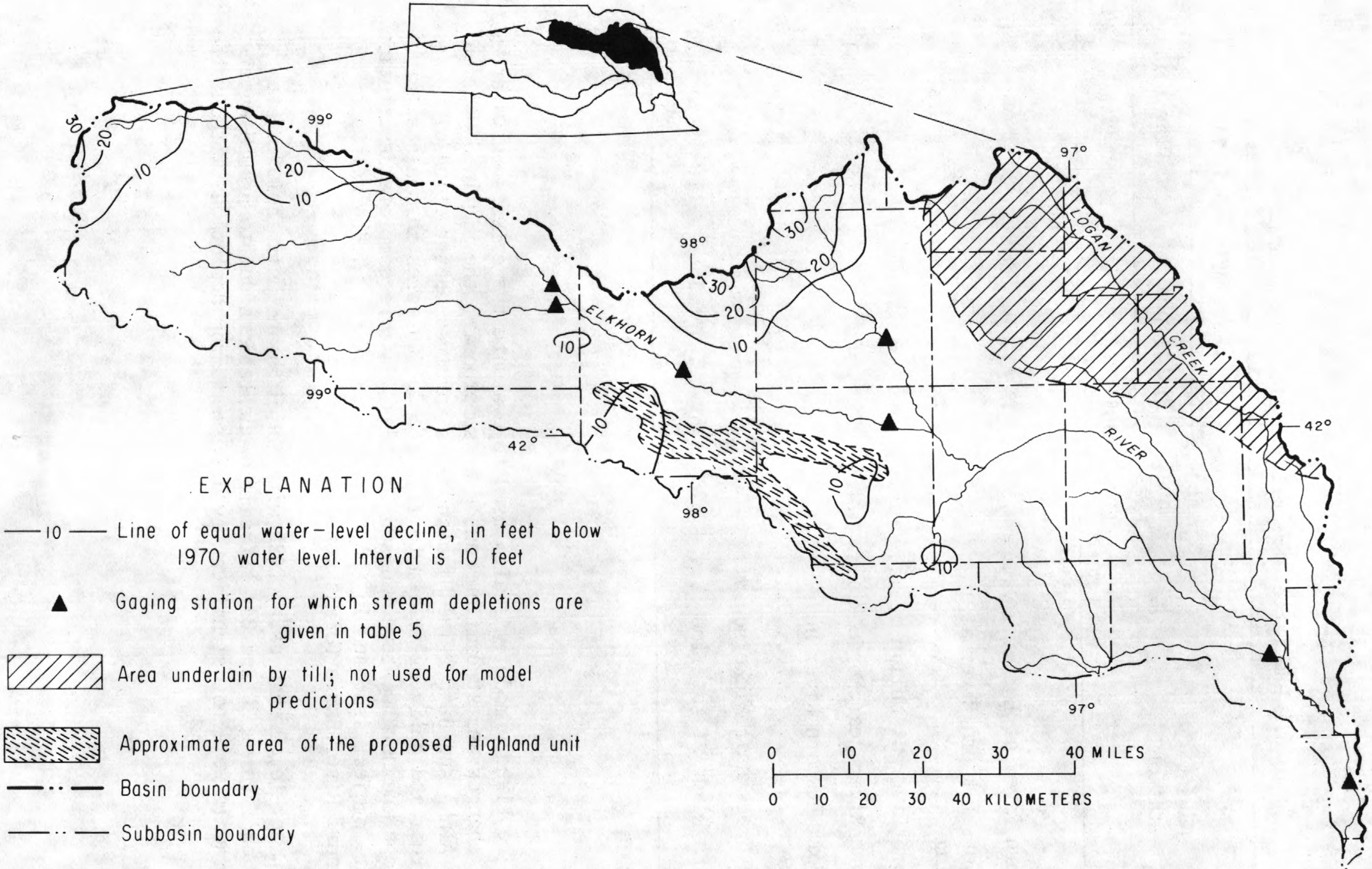



Figure 23.--Simulated water-level declines from 1970 to 2020, plan Alpha plus the proposed Highland unit, Elkhorn subbasin.

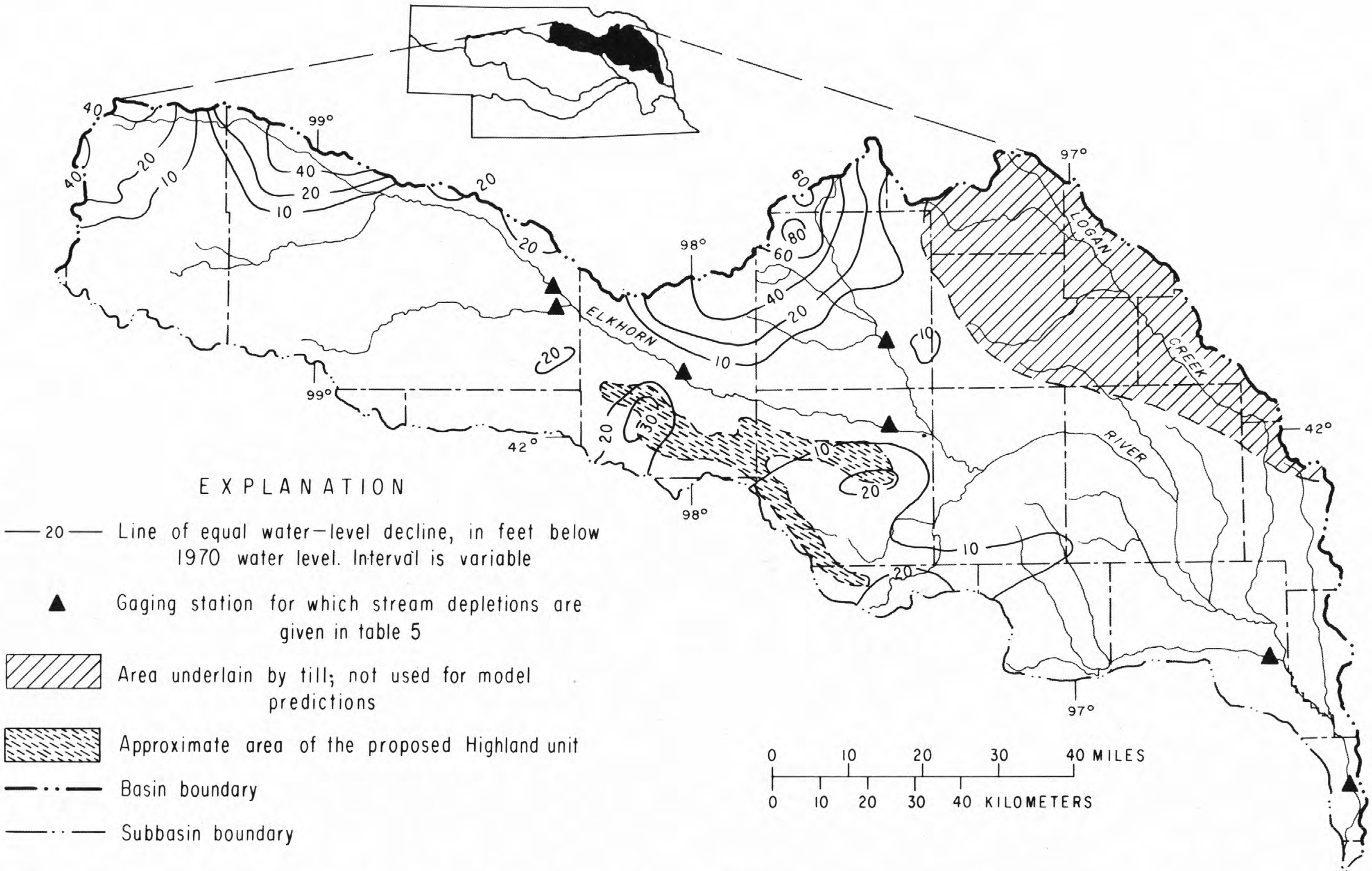



Figure 24.--Simulated water-level declines from 1970 to 2020, plan Beta plus the proposed Highland unit, Elkhorn subbasin.

## Loup Model

Three basic development plans were tested on the Loup model (Source: Level B Planning Team):

| Plan | Total irrigated acreage by end of development period[1/] | Additional irrigated acreage | Percent of irrigable lands with: Slight to moderate limitations | Percent of irrigable lands with: Severe limitations | Date of maximum development |
|---|---|---|---|---|---|
| Present | 198,000 | 0 | - | - | 1970 |
| Alpha | 880,000 | 682,000 | 60 | 25 | 2020 |
| Beta | 1,540,000 | 1,342,000 | 100 | 100 | 2000 |

[1/] Includes present (1970) irrigated acreage.

Predicted water-level changes for Plans Alpha and Beta by 2020 are shown on figures 25 and 26. No map is included for the Present Plan as all predicted water-level changes by 2020 were within the accuracy of the water-table map (±5 feet).

Predicted changes in streamflow by 1985, 2000, and 2020 at gaging stations computed with the Loup model are shown in table 6. No predicted changes are given for the present development plan as they were within the accuracy of the estimated base flow (±5 percent).

Sources of water pumped at the end of 30 years of simulation (2000) are given below.

| Source of water | Plan: Alpha | Plan: Beta |
|---|---|---|
| Pumpage (acre-ft/yr) | 323,190 | 1,108,700 |
| Storage depletion (acre-ft/yr | 72,460 | 491,300 |
| Percent of pumpage | 22 | 44 |
| Streamflow depletion (acre-ft/yr) | 250,720 | 617,390 |
| Percent of pumpage | 78 | 56 |
| Salvaged evapotranspiration (acre-ft/yr) | 100 | 100 |
| Percent of pumpage | < 1 | < 1 |
| Percent of maximum possible salvage | 100 | 100 |

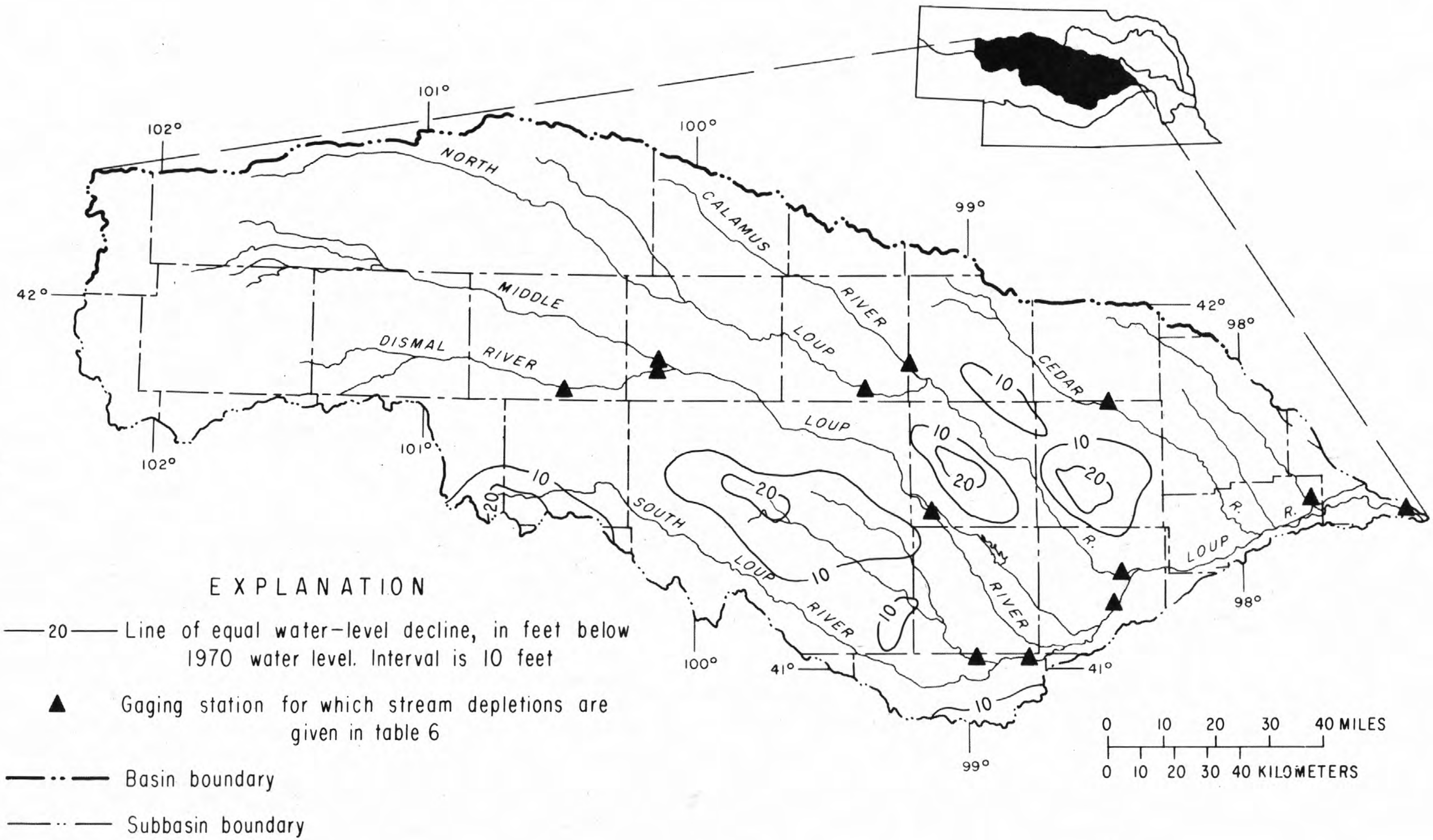



Figure 25.--Simulated water-level declines from 1970 to 2020, plan Alpha, Loup subbasin.

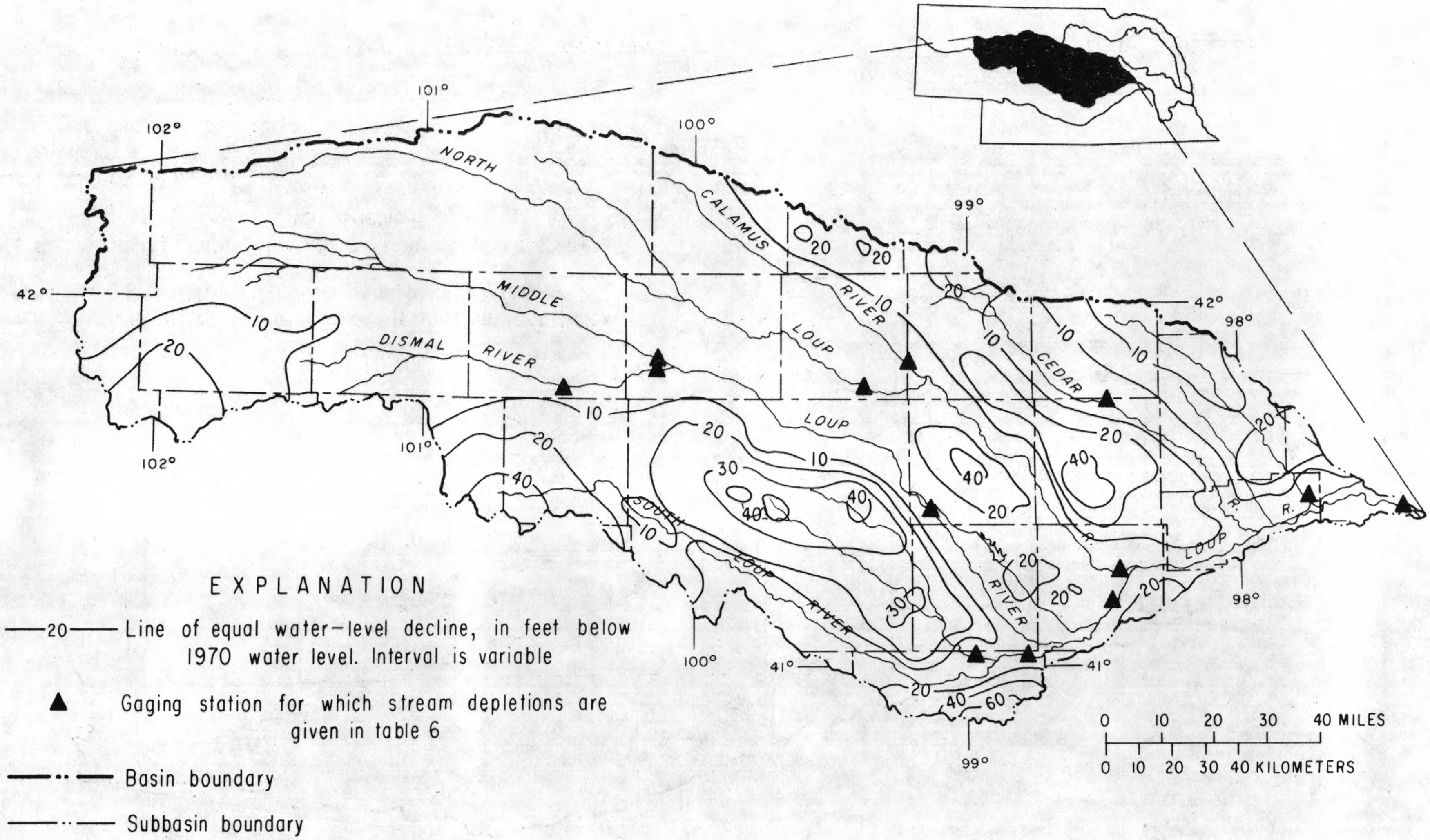



Figure 26.--Simulated water-level declines from 1970 to 2020, plan Beta, Loup subbasin.

Table 6.--Streamflow depletions, in cubic feet per second, of Loup subbasin with and without North Loup and Cedar Rapids Projects

| Station | Plan Alpha | | | | | | Plan Beta | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1985 | | 2000 | | 2020 | | 1985 | | 2000 | | 2020 | |
| | With | Without | With | Without | With | Without | With | Without | With | Without | With | Without |
| Middle Loup at Dunning | 3 | 3 | 8 | 8 | 15 | 15 | 12 | 12 | 33 | 33 | 44 | 44 |
| Dismal nr. Thedford | 2 | 2 | 6 | 6 | 13 | 13 | 9 | 9 | 25 | 25 | 38 | 38 |
| Dismal at Dunning | 4 | 4 | 11 | 11 | 23 | 23 | 14 | 14 | 40 | 40 | 60 | 60 |
| M. Loup at Arcadia | 29 | 22 | 61 | 46 | 106 | 80 | 66 | 53 | 166 | 137 | 233 | 181 |
| Mud Cr. nr. Sweetwater | 1 | 1 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 5 |
| S.Loup at St. Michael | 32 | 32 | 65 | 65 | 99 | 99 | 73 | 73 | 163 | 163 | 214 | 214 |
| M. Loup at St. Paul | 70 | 62 | 143 | 133 | 232 | 215 | 159 | 152 | 376 | 354 | 505 | 469 |
| N. Loup at Taylor | 23 | 23 | 44 | 44 | 69 | 69 | 56 | 56 | 120 | 120 | 133 | 133 |
| Calamus nr. Burwell | 10 | 10 | 23 | 23 | 41 | 41 | 26 | 26 | 64 | 64 | 81 | 81 |
| N. Loup at Ord | 47 | 41 | 92 | 80 | 149 | 128 | 106 | 98 | 235 | 219 | 281 | 250 |
| N. Loup nr. St. Paul | 61 | 40 | 114 | 82 | 181 | 132 | 125 | 100 | 275 | 234 | 337 | 274 |
| Cedar nr. Spalding | 8 | 8 | 17 | 17 | 27 | 27 | 18 | 18 | 42 | 42 | 49 | 49 |
| Cedar nr. Fullerton | 21 | 12 | 37 | 25 | 57 | 42 | 38 | 26 | 82 | 61 | 101 | 86 |
| Beaver Cr. nr. Genoa | 15 | 15 | 26 | 26 | 40 | 40 | 30 | 30 | 61 | 61 | 63 | 63 |
| Loup nr. Genoa | 160 | 112 | 310 | 239 | 495 | 391 | 337 | 330 | 766 | 656 | 986 | 850 |
| Loup at Columbus | 182 | 131 | 346 | 272 | 552 | 441 | 378 | 336 | 852 | 738 | 1060 | 938 |
| Shell Cr. nr. Columbus | 7 | 7 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |

The Loup model was also used to evaluate the effects of the proposed Cedar Rapids and North Loup surface-water irrigation projects on water levels and streamflow. The proposed Cedar Rapids project would divert water from the Cedar River and irrigate 26,800 acres of land in Nance and Boone Counties. The proposed North Loup project would divert water from the Calamus and North Loup Rivers and irrigate 53,000 acres in Valley and Nance Counties. More complete descriptions of these projects are found in the "Agricultural Water" Technical Paper (Missouri River Basin Commission, 1975a). Water-level changes from 1970 to 2020 resulting from the combination of these projects with plans Alpha and Beta are shown in figures 27 and 28. Stream depletions with the projects are shown in Table 6.

Stresses used for evaluating the effects of the two projects were computed as follows. A net recharge was applied to land within the project boundary. This recharge was the difference between the comsumptive irrigation requirement and the farm delivery requirement. Net recharge from canal seepage was also applied to areas underlain by canals. Canal losses used were supplied by the U.S. Bureau of Reclamation, Grand Island, Nebr. (written commun.)

## MIDDLE PLATTE MODEL

Three basic development plans were tested with the Middle Platte model (Source: Level B Planning Team):

| Plan | Total irrigated acreage by end of development period[1/] | Additional irrigated acreage | Percent of irrigable lands with: Slight to moderate limitations | Percent of irrigable lands with: Severe limitations | Date of maximum development |
|---|---|---|---|---|---|
| Present | 450,000 | 0 | - | - | 1970 |
| Alpha | 1,138,100 | 688,100 | 100 | 100 | 2020 |
| Beta | 1,138,100 | 688,100 | 100 | 100 | 1990 |

[1/] Includes present (1970) irrigated acreage.

Predicted water-level changes by 2020 for all three plans are shown on figures 29, 30, and 31. These changes shown for the Present Plan

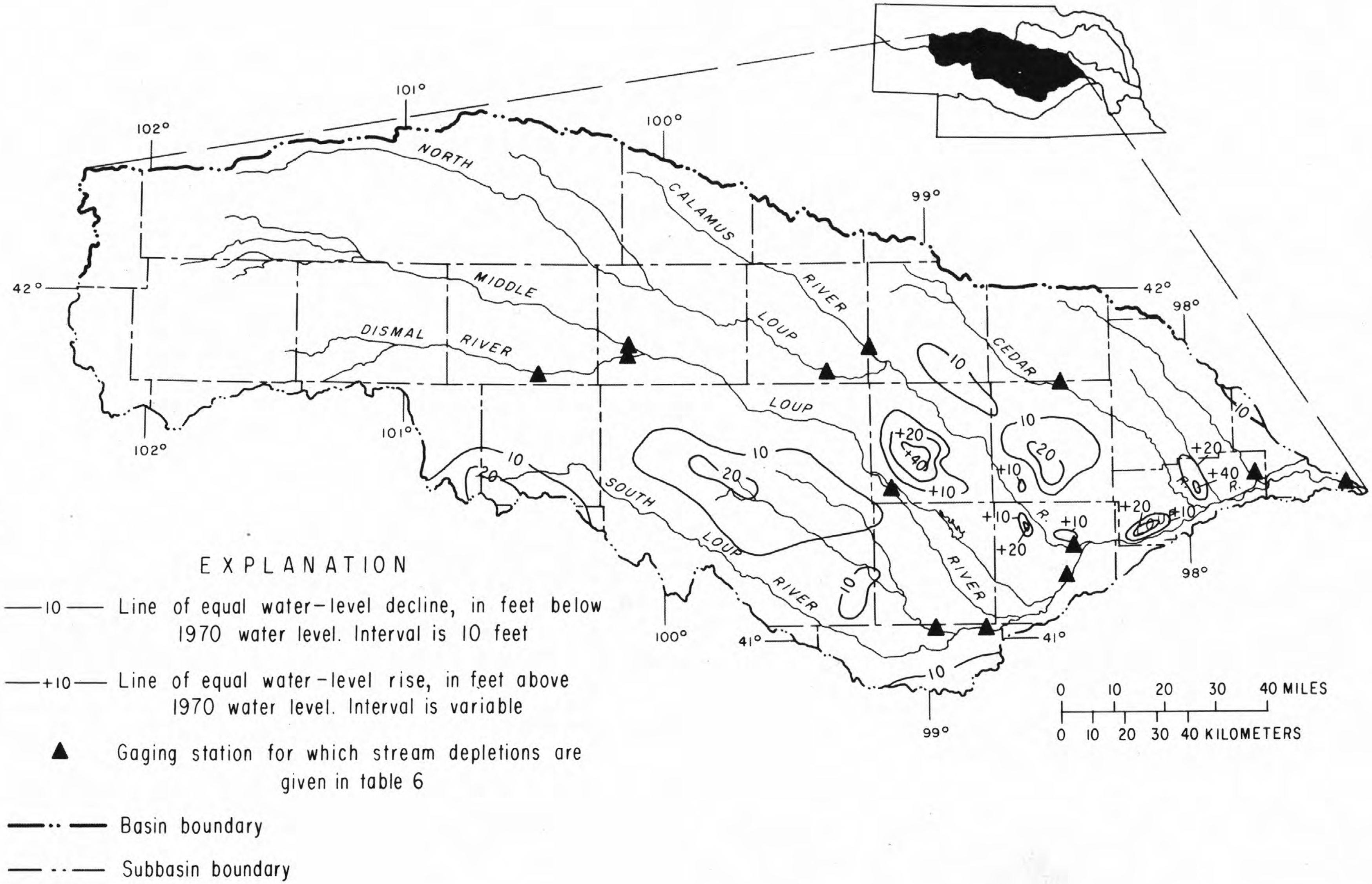
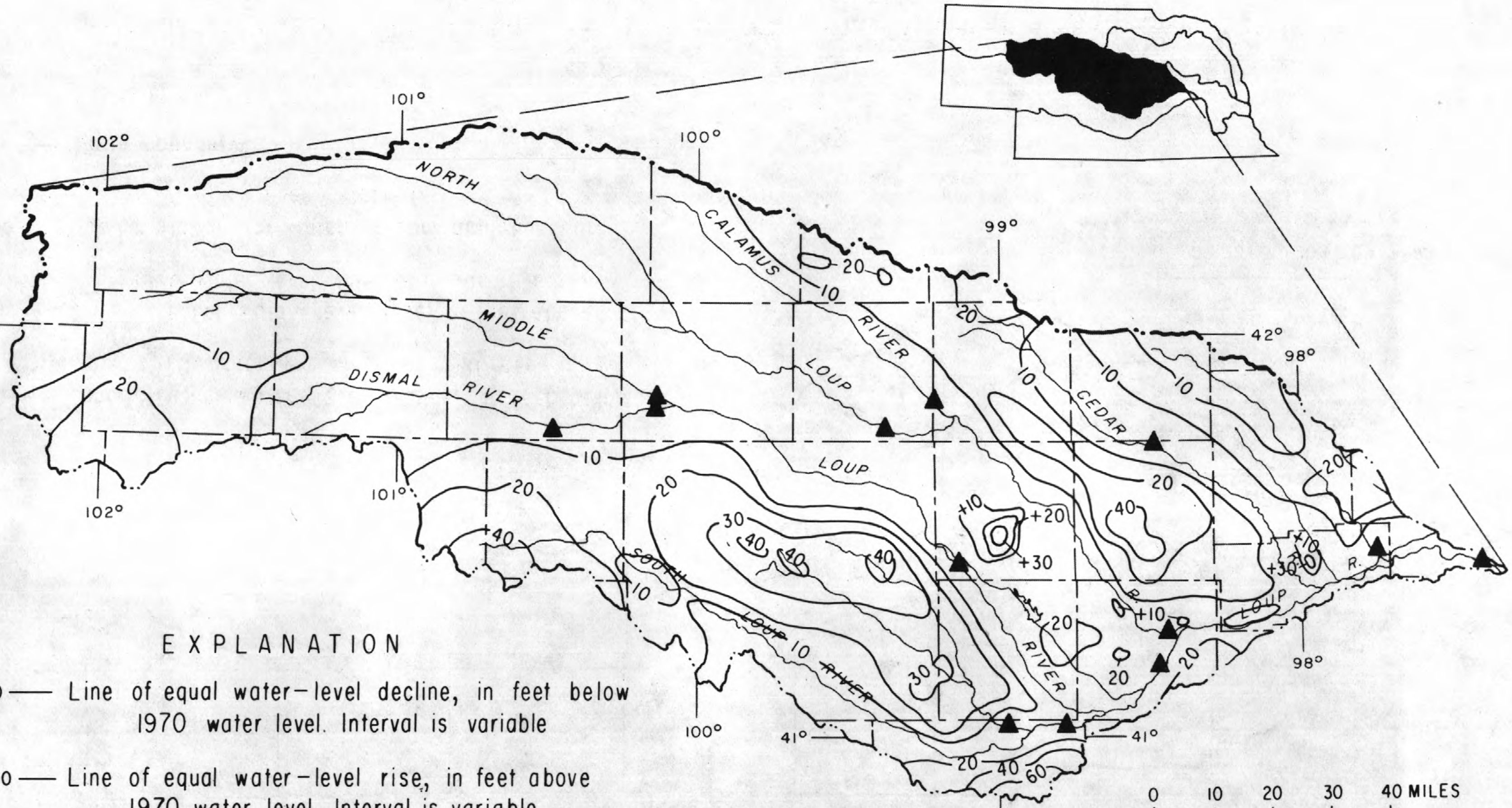



Figure 27.--Simulated water-level changes from 1970 to 2020, plan Alpha plus the proposed Cedar Rapids and North Loup projects, Loup subbasin.




EXPLANATION

—20— Line of equal water-level decline, in feet below 1970 water level. Interval is variable

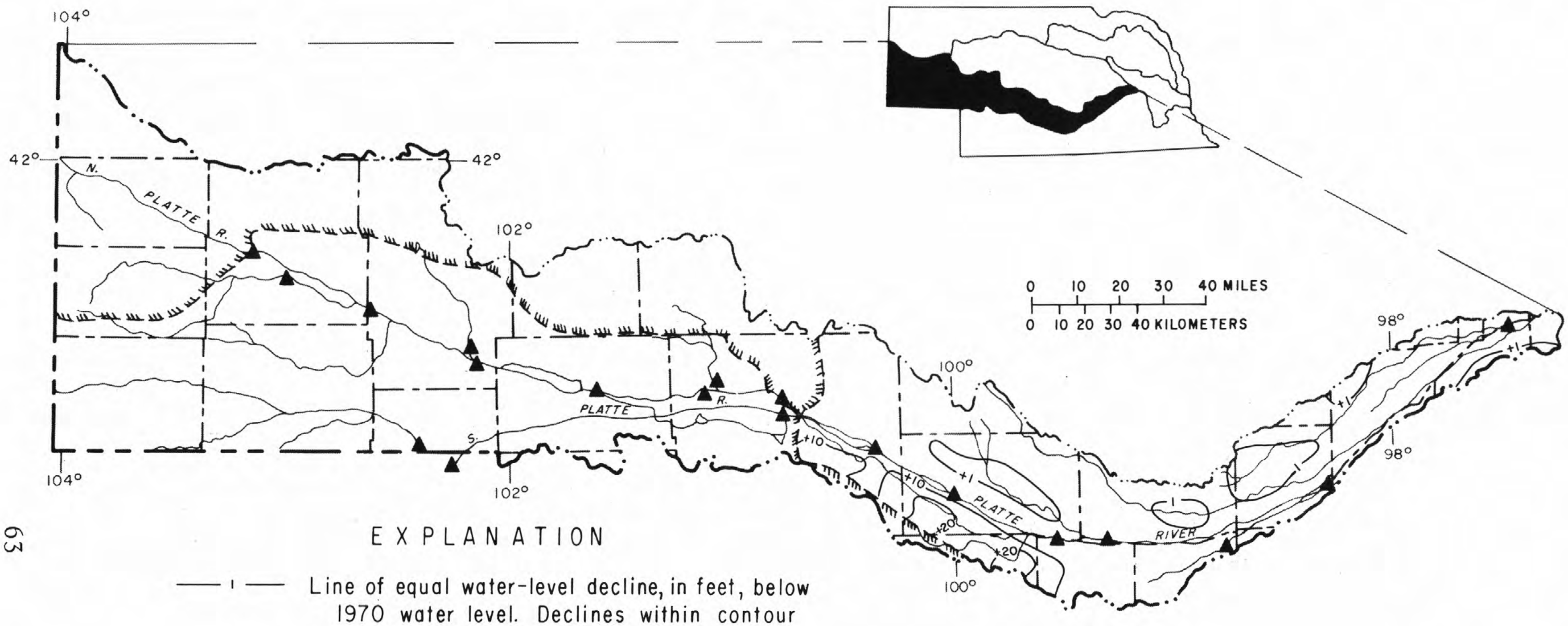
—+10— Line of equal water-level rise, in feet above 1970 water level. Interval is variable

▲ Gaging station for which stream depletions are given in table 6

—·-— Basin boundary

—··— Subbasin boundary

Figure 28.--Simulated water-level changes from 1970 to 2020, plan Beta plus the proposed Cedar Rapids and North Loup projects, Loup subbasin.




EXPLANATION

—— 1 —— Line of equal water-level decline, in feet, below 1970 water level. Declines within contour range from 1 to 10 feet

—— +10 —— Line of equal water-level rise, in feet, above 1970 water level. Interval is variable

▲ Gaging station

Boundary of modeled area

Basin boundary

Subbasin boundary

Figure 29.--Simulated water-level changes from 1970 to 2020, present plan, Upper Platte subbasin.

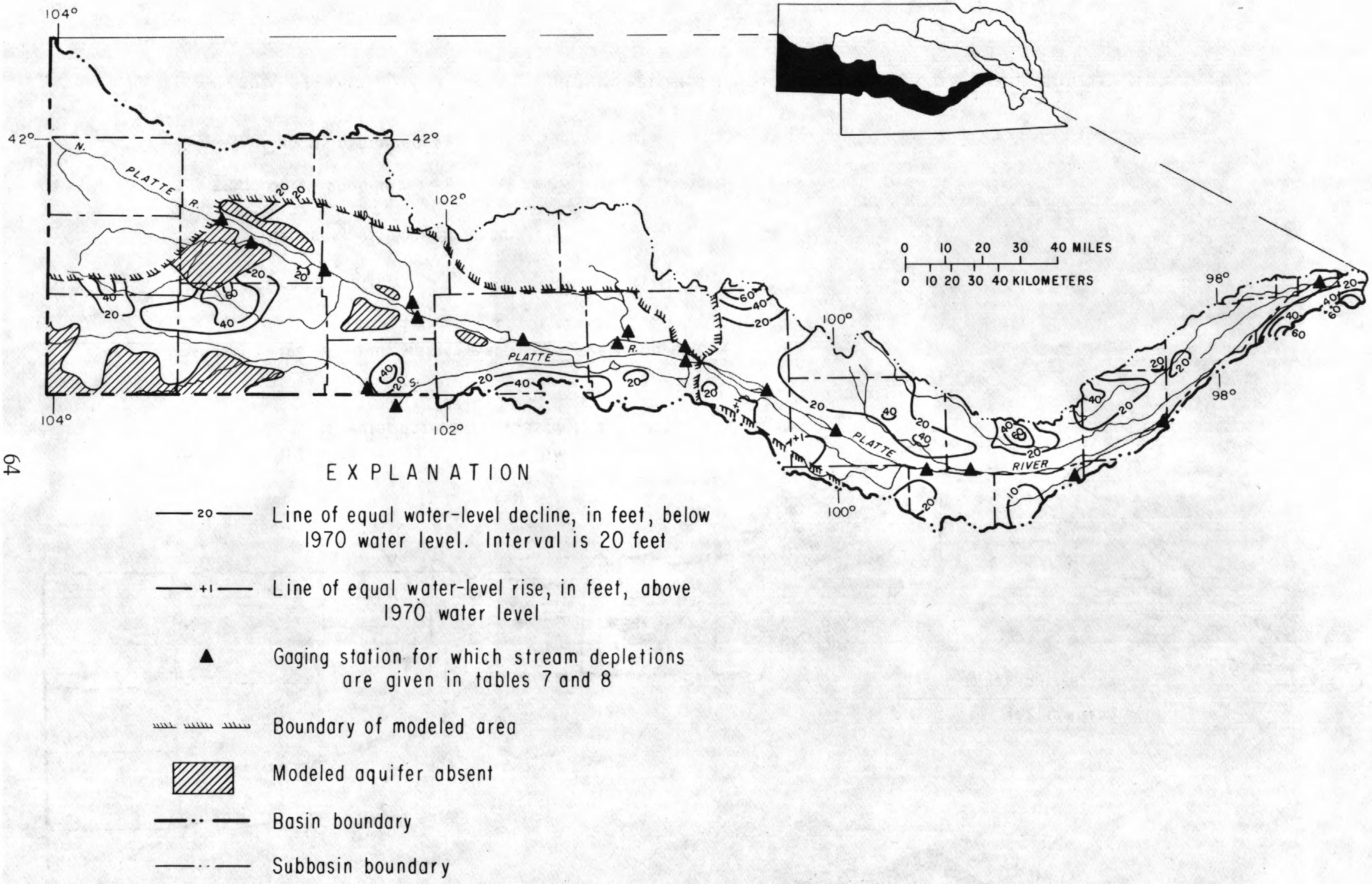
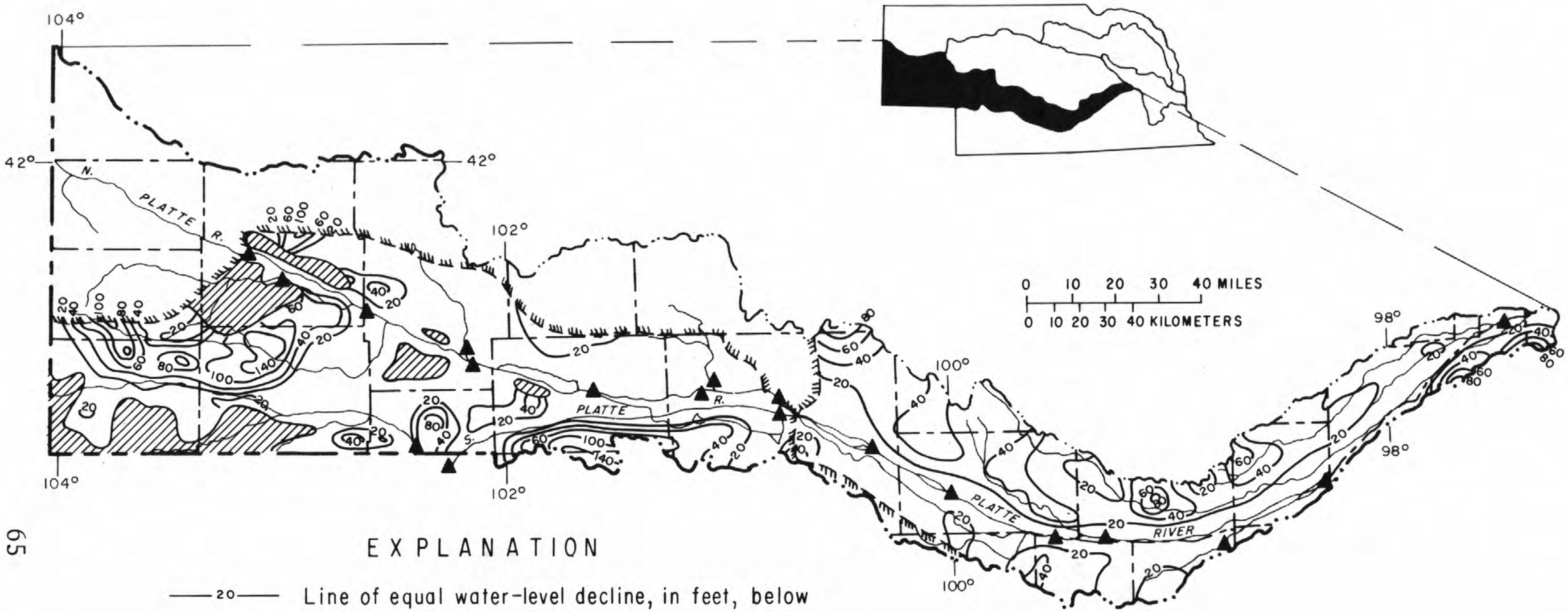



Figure 30.--Simulated water-level changes from 1970 to 2020, plan Alpha, Upper Platte subbasin.




EXPLANATION

—20— Line of equal water-level decline, in feet, below 1970 water level. Interval is variable

▲ Gaging station for which stream depletions are given in tables 7 and 8

Boundary of modeled area

Modeled aquifer absent

Basin boundary

Subbasin boundary

Figure 31.--Simulated water-level changes from 1970 to 2020, plan Beta, Upper Platte subbasin.

(fig. 29) are consistent with the past history of water levels in this subbasin, particularly along the Tri-County Canal in the southwestern part of the modeled area.

Predicted changes in streamflow by 1985, 2000, and 2020 for plans Alpha and Beta are shown in table 7. These changes probably exceed those that would actually occur, as no reach of the Platte River was allowed to go dry during the predictive periods. This would not be the case during a normal cycle of dry and wet periods. Streamflow depletions for the present plan were less than 5 percent of streamflow used for the predictive periods.

In addition to plans Alpha and Beta, the Middle Platte model was used to evaluate the effects on water levels and streamflow of the proposed Midstate Project. The project would divert water from the Platte River near Overton and irrigate about 140,000 acres in Buffalo, Hall, and Merrick Counties.

Net recharge applied to the model for these analyses was computed in the same manner as for the proposed North Loup and Cedar Rapids projects in the Loup subbasin and was supplied by the U.S. Bureau of Reclamation, Grand Island, Nebr.

Simulated water-level changes for the combination of the proposed Midstate Project plus plans Alpha and Beta are shown in figures 32 and 33. Stream depletions with the project are shown in table 7.

Sources of water pumped at the end of 30 years of simulation (2000) are shown below.

| Source of water | Plan: Alpha | Plan: Beta |
|---|---|---|
| Pumpage (acre-ft/yr) | 322,460 | 536,960 |
| Storage depletion (acre-ft/yr) | 195,650 | 278,980 |
| Percent of pumpage | 61 | 52 |
| Streamflow depletion (acre-ft/yr) | 80,430 | 192,030 |
| Percent of pumpage | 25 | 36 |
| Salvaged evapotranspiration (acre-ft/yr) | 46,380 | 65,940 |
| Percent of pumpage | 14 | 12 |
| Percent of maximum possible salvage | 70 | 100 |

Table 7.--Streamflow depletions, in cubic feet per second, of Central Platte subbasin with and without Midstate Project

| Station | Plan Alpha | | | | | | Plan Beta | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1985 | | 2000 | | 2020 | | 1985 | | 2000 | | 2020 | |
| | With | Without | With | Without | With | Without | With | Without | With | Without | With | Without |
| Platte River at Brady | 0 | 0 | 4 | 4 | 19 | 19 | 6 | 6 | 19 | 19 | 21 | 21 |
| Platte River near Cozad | 2 | 2 | 20 | 20 | 59 | 59 | 22 | 22 | 60 | 60 | 76 | 76 |
| Platte River near Overton | 4 | 4 | 38 | 38 | 110 | 110 | 42 | 42 | 110 | 110 | 138 | 138 |
| Platte River near Odessa | 6 | 6 | 48 | 48 | 132 | 132 | 52 | 52 | 133 | 133 | 169 | 169 |
| Platte River near Grand Island | 9 | 14 | 67 | 80 | 183 | 204 | 77 | 84 | 190 | 204 | 236 | 240 |
| Platte River near Duncan | 9 | 25 | 72 | 111 | 199 | 267 | 83 | 113 | 214 | 265 | 267 | 316 |
| Wood River at Riverdale | 0 | 2 | 1 | 5 | 4 | 10 | 1 | 4 | 4 | 10 | 6 | 10 |
| North Dry Creek near Kearney | 0 | 0 | 7 | 7 | 15 | 15 | 8 | 8 | 15 | 15 | 15 | 15 |

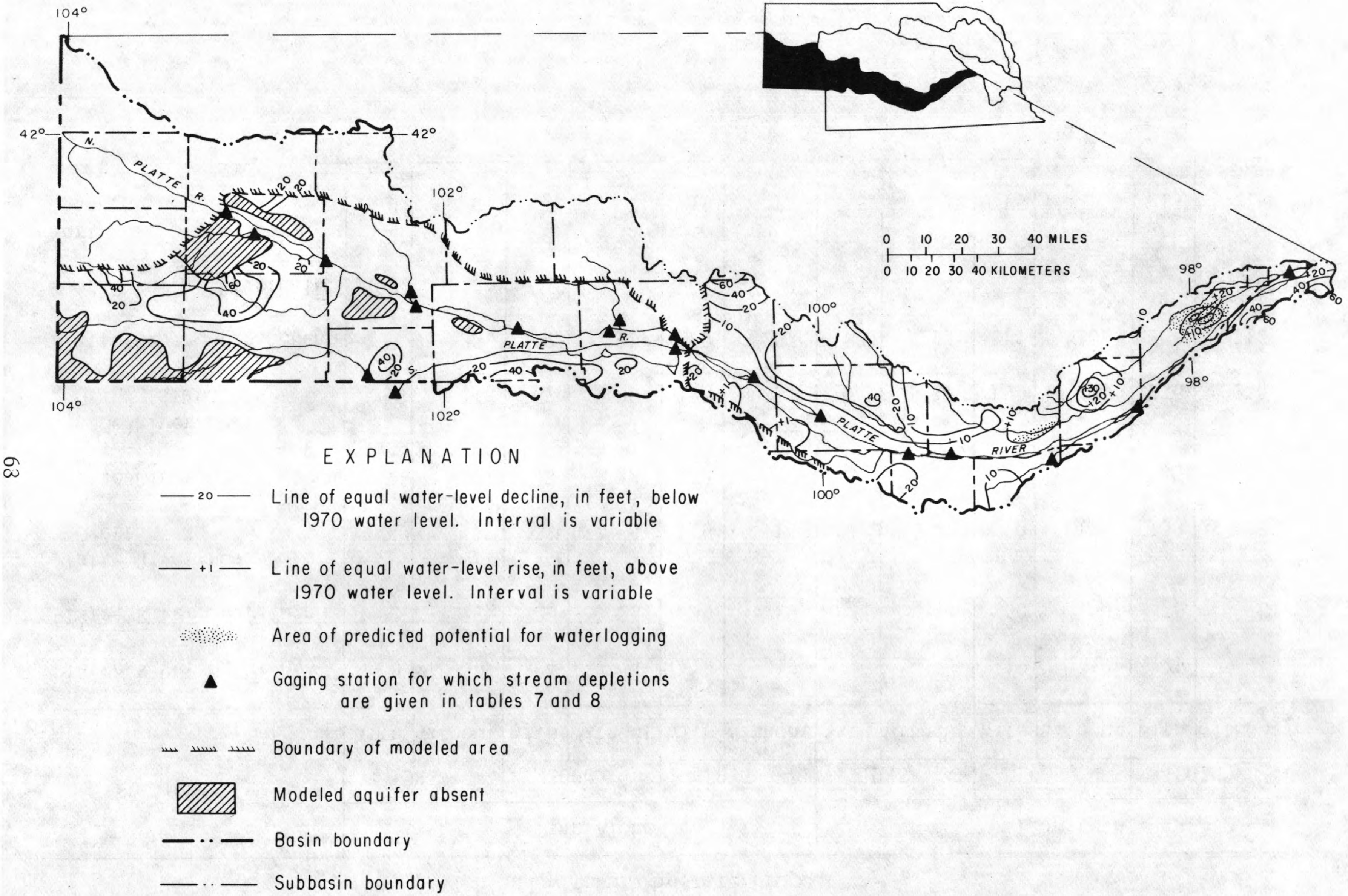
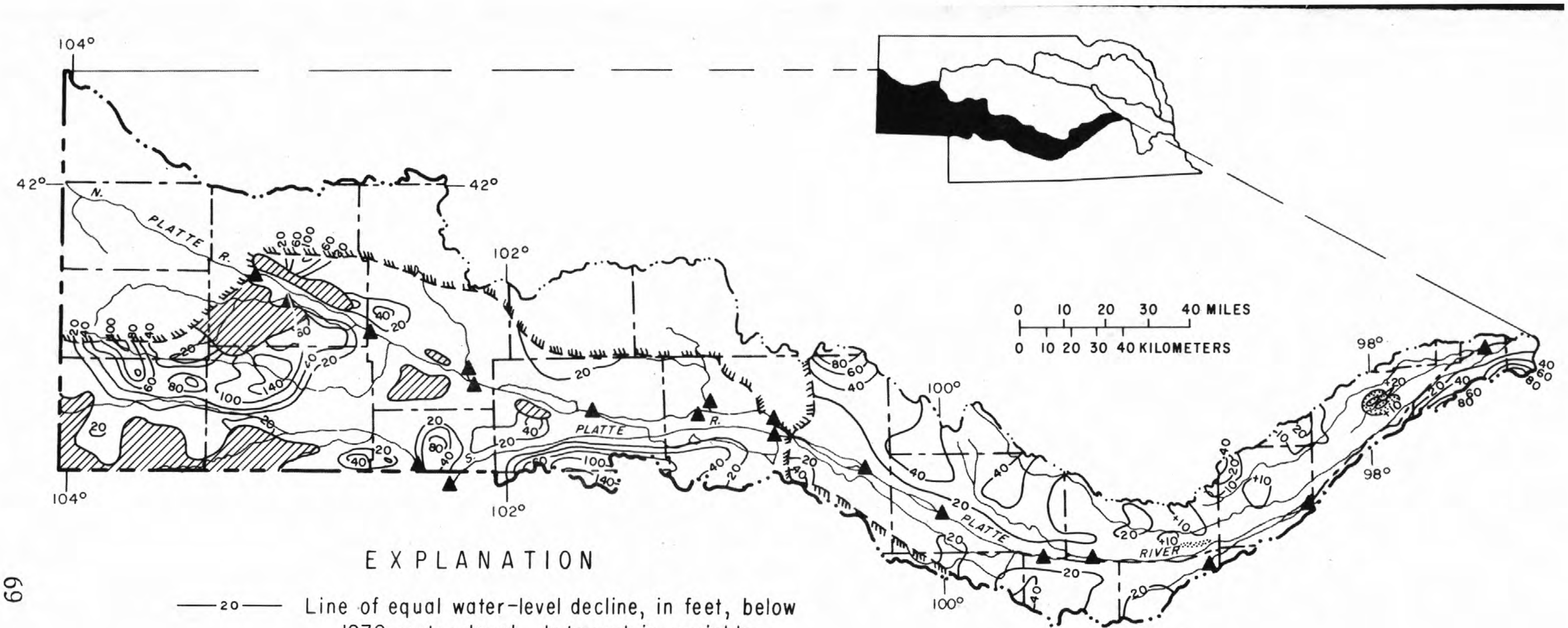



Figure 32.--Simulated water-level changes from 1970 to 2020, plan Alpha plus proposed Midstate project, Upper Platte subbasin.




EXPLANATION

—20— Line of equal water-level decline, in feet, below 1970 water level. Interval is variable

—+10— Line of equal water-level rise, in feet, above 1970 water level. Interval is 10 feet

Area of predicted potential for waterlogging

▲ Gaging station for which stream depletions are given in tables 7 and 8

Boundary of modeled area

Modeled aquifer absent

Basin boundary

Subbasin boundary

Figure 33.--Simulated water-level changes from 1970 to 2020, plan Beta plus proposed Midstate project, Upper Platte subbasin.

## Twin Platte Model

Three basic development plans were tested with the Twin Platte model (Source: Level B Planning Team):

| Plan | Total irrigated acreage by end of development period[1/] | Additional irrigated acreage | Percent of irrigable lands with: Slight to moderate limitations | Percent of irrigable lands with: Severe limitations | Date of maximum development |
|---|---|---|---|---|---|
| Present | 76,000 | 0 | - | - | 1970 |
| Alpha | 392,390 | 316,390 | 50 | 50 | 2020 |
| Beta | 708,780 | 632,780 | 100 | 100 | 2000 |

[1/] Includes present (1970) irrigated acreage.

Predicted water-level changes by 2020 for the Alpha and Beta Plans are shown on figures 30 and 31. Predicted changes in streamflow by 1985, 2000, and 2020 are shown in table 8. No streamflow depletions or water-level changes are given for the present development plan because they were within accuracy of measurement. Streamflows at the beginning of the simulation period were computed using the 1931 through 1970 average flows of the North Platte River at Bridgeport, Nebr., and the South Platte River at Julesburg, Colo., and historical canal diversions and return flows for the same period.

Table 8.--Predicted streamflow depletion, Twin Platte Model

| Gaging station | Average annual historical flow (ft³/s) | Streamflow depletion (ft³/s) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Plan Alpha | | | Plan Beta | | |
| | | 1985 | 2000 | 2020 | 1985 | 2000 | 2020 |
| Lodgepole Creek at Bushnell | 11 | 0 | 0 | 1 | 0 | 1 | 1 |
| Lodgepole Creek at Ralton | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| So. Platte R. at Julesburg | 478 | 10 | 19 | 22 | 23 | 51 | 63 |
| So. Platte R. at North Platte | 230 | 48 | 110 | 194 | 138 | 230 | 230 |
| No. Platte R. at Bridgeport | 1,084 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pumpkin Creek at Bridgeport | 32 | 0 | 0 | 0 | 0 | 0 | 0 |
| No. Platte River at Lisco | 1,116 | 1 | 5 | 13 | 7 | 23 | 36 |
| Blue Creek at Lewellen | 70 | 0 | 1 | 1 | 1 | 1 | 2 |
| No. Platte R. at Lewellen | 1,159 | 3 | 11 | 25 | 14 | 43 | 67 |
| No. Platte R. at Keystone | 574 | 5 | 14 | 33 | 19 | 58 | 87 |
| No. Platte R. at Sutherland | 448 | 7 | 19 | 42 | 25 | 75 | 109 |
| Birdwood Creek at Hershey | 150 | 1 | 3 | 6 | 4 | 11 | 14 |
| No. Platte R. at North Platte | 598 | 9 | 24 | 52 | 32 | 91 | 131 |

Sources of water pumped at the end of 30 years of simulation (2000) are shown below.

| Source of water | Plan Alpha | Plan Beta |
|---|---|---|
| Pumpage (acre-ft/yr) | 237,680 | 791,300 |
| Storage depletion (acre-ft/yr) | 133,330 | 515,220 |
| Percent of pumpage | 56 | 65 |
| Streamflow depletion (acre-ft/yr) | 97,100 | 232,610 |
| Percent of pumpage | 41 | 30 |
| Salvaged evapotranspiration (acre-ft/yr) | 7,250 | 43,480 |
| Percent of pumpage | 3 | 5 |
| Percent of maximum possible salvage | 17 | 100 |

## Lower Platte Model

Three basic development plans were tested with the Lower Platte model (Source: Level B Planning Team):

| Plan | Total irrigated acreage by end of development period[1/] | Additional irrigated acreage | Percent of irrigable lands with: Slight to moderate limitations | Percent of irrigable lands with: Severe limitations | Date of maximum development |
|---|---|---|---|---|---|
| Present | 11,410 | 0 | - | - | 1970 |
| Alpha | 107,740 | 96,330 | 66 | 66 | 2020 |
| Beta | 150,060 | 138,650 | 100 | 100 | 2000 |

[1/] Includes present (1970) irrigated acreage.

Predicted water-level changes for the Alpha and Beta Plans without proposed municipal well-field expansion are shown in figures 34 and 35. Predicted streamflow depletions by 1985, 2000, and 2020 under these conditions are shown in table 9. Water-level declines for the present development plan are everywhere less than 4 feet by 2020, and streamflow depletions are less than 5 percent of measured flow.

Streamflows at the beginning of the simulation period were averages for 1931 through 1970 for all stations listed in table 9.

Sources of water pumped at the end of 30 years of simulation (2000) are shown below.

| Source of water | Plan: Alpha | Plan: Beta |
|---|---|---|
| Pumpage (acre-ft/yr) | 24,640 | 62,320 |
| Storage depletion (acre-ft/yr) | 6,520 | 15,940 |
| Percent of pumpage | 26 | 26 |
| Streamflow depletion (acre-ft/yr) | 18,120 | 44,200 |
| Percent of pumpage | 73 | 71 |
| Salvaged Evapotranspiration (acre-ft/yr) | 720 | 2,170 |
| Percent of pumpage | 1 | 3 |
| Percent of maximum possible salvage | 1 | 3 |

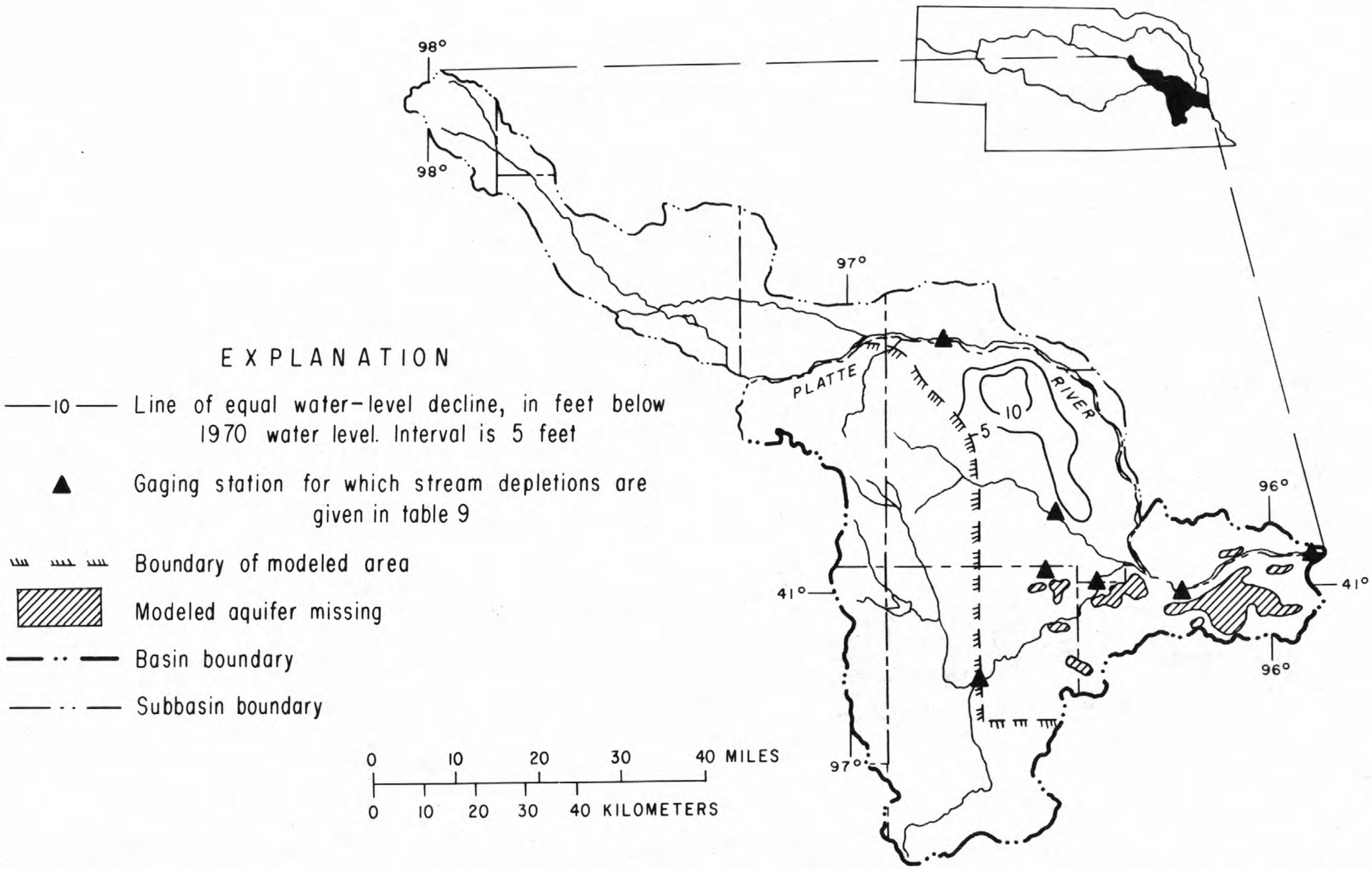



Figure 34.--Simulated water-level declines from 1970 to 2020, plan Alpha, Lower Platte subbasin.

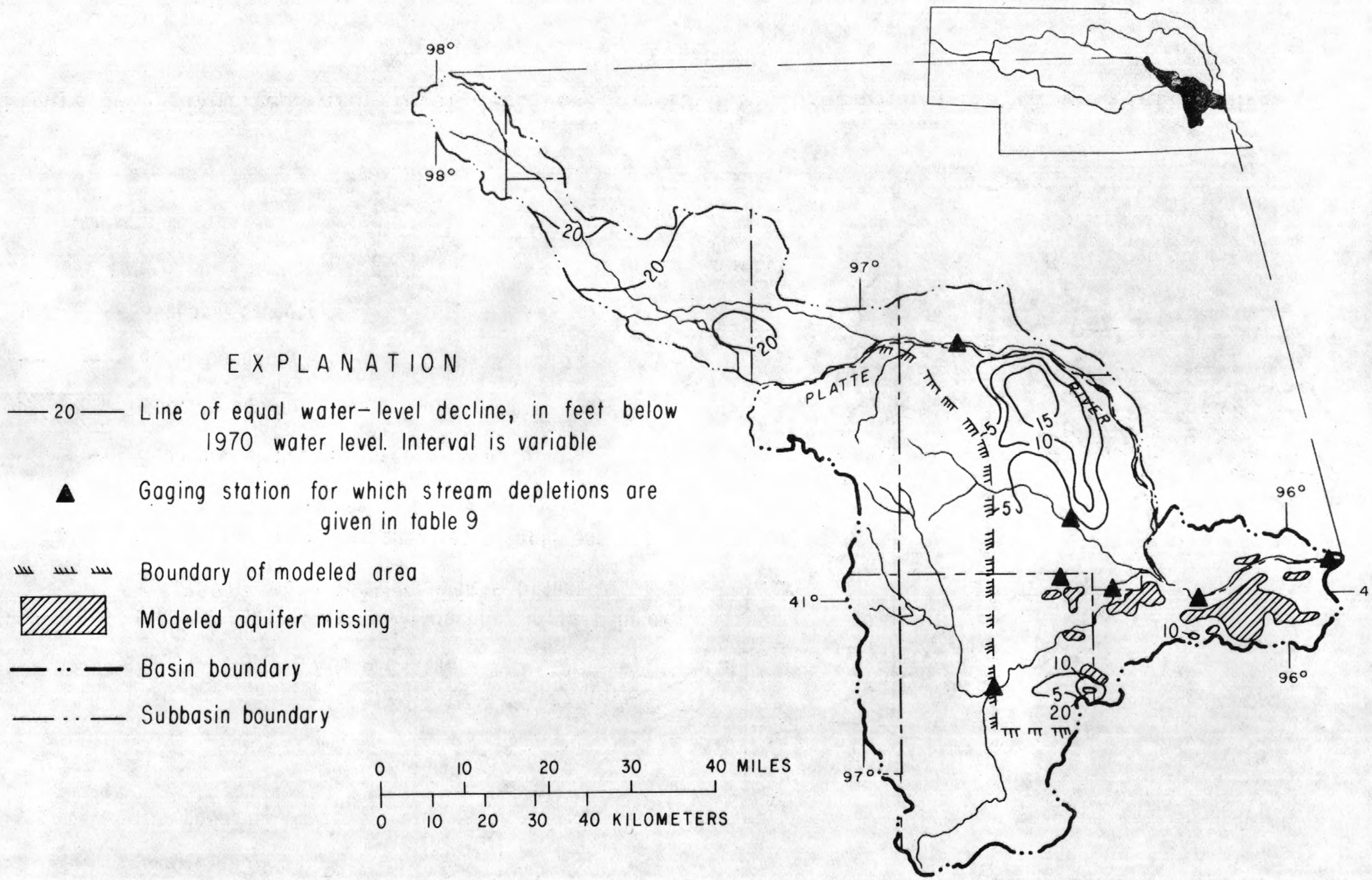



Figure 35.--Simulated water-level declines from 1970 to 2020, plan Beta, Lower Platte subbasin.

Table 9.--Predicted streamflow depletion without municipal well field effects, Lower Platte subbasin

| Gaging station | Average annual historical flow (ft³/s) | Streamflow depletion (ft³/s) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Plan Alpha | | | Plan Beta | | |
| | | 1985 | 2000 | 2020 | 1985 | 2000 | 2020 |
| Platte River at North Bend | 3,820 | 0 | 0 | 0 | 0 | 0 | 0 |
| Elkhorn River at Waterloo | 1/600 | 0 | 0 | 0 | 0 | 0 | 0 |
| Platte R. below confluence of upper Clearwater Creek | ----- | 2 | 6 | 11 | 6 | 14 | 16 |
| Platte River above Ashland | ----- | 3 | 7 | 13 | 7 | 17 | 20 |
| Salt Creek at Lincoln | 1/2 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rock Creek near Ceresco | 1/1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Salt Creek at Greenwood | 1/23 | 0 | 0 | 0 | 0 | 0 | 1 |
| Wahoo Creek at Ithaca | 1/28 | 3 | 6 | 10 | 8 | 17 | 17 |
| Platte River at Ashland | 2/5,170 | 9 | 18 | 29 | 21 | 44 | 44 |
| Platte River at South Bend | 5,400 | 12 | 25 | 42 | 28 | 61 | 64 |
| Platte River near Plattsmouth | ----- | 12 | 25 | 42 | 28 | 61 | 64 |

1/ Annual base flow used for these stations.

2/ Record through 1953.

In addition to irrigation development, three plans (A, B, and C) to meet municipal demands for Lincoln and Omaha (table 10) were analyzed. Pumping from four well fields adjacent to the Platte River was considered in this analysis: Omaha Metropolitan Utilities District's (MUD) Platte River site in northern Cass County; Omaha MUD's proposed site near Valley, in western Douglas County; Lincoln's existing well field near Ashland in southeastern Saunders County; and a proposed northward extension of Lincoln's Ashland field.

Table 10.--Municipal requirements to be supplied by ground water, Omaha and Lincoln

| Plan | Omaha | | | | | | | | Lincoln (Ashland) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Platte River site | | | | Valley site | | | | Existing | | | | Extension | | | |
| | 1970 | 1985 | 2000 | 2020 | 1970 | 1985 | 2000 | 2020 | 1970 | 1985 | 2000 | 2020 | 1970 | 1985 | 2000 | 2020 |
| | (Mgal/d) | | | | | | | | | | | | | | | |
| A | 28 | 28 | 45 | 45 | 0 | 0 | 23 | 50 | 31 | 43 | 45 | 45 | 0 | 0 | 15 | 52 |
| B | 28 | 38 | 55 | 55 | 0 | 30 | 53 | 107 | 31 | 43 | 45 | 45 | 0 | 0 | 15 | 52 |
| C | 28 | 28 | 28 | 28 | 0 | 0 | 40 | 66 | 31 | 43 | 45 | 45 | 0 | 0 | 15 | 52 |

The assumption was made that proximity of wells to the Platte River in the two proposed well fields would be similar to that found in the existing well fields. Because all wells fall within constant-head nodes of the Lower Platte model, stream depletion was computed by the analytical equation 13 (p. 38). The aquifer properties and distance from the stream were used to compute the time required for 98 percent of withdrawals by continuous pumping to be coming from the Platte River ($t_{98}$). These times are shown in table 11.

In all cases the time required for essentially all of the pumpage to be derived from the Platte River was less than 3 years. Assuming that: (1) new well fields were installed over a relatively short period of time, and (2) pumping at the rates given in table 10 commenced at least 3 years prior to the times that the demands were to be met, stream depletions could be considered equal to pumpage.

Table 11.--Hydrologic data for municipal well fields

| Well field | Number of wells | Trans-missivity, T[1/] | Well distance from stream[1/] | Specific yield S[1/] | sdf[2/] | $t_{98}$ |
|---|---|---|---|---|---|---|
| | | (1,000 gal/d/ft) | (ft) | | (days) | (years) |
| Valley (MUD) | ? | 175 | 1,000 | 0.18 | 1.03 | 1.69 |
| Platte (MUD) | 30 | 100 | 1,000 | .18 | 1.80 | 2.96 |
| Ashland (Lincoln) | 33 | 200 | 500 | .18 | .22 | .36 |
| Ashland Extension (Lincoln) | ? | 125 | 500 | .18 | .36 | .59 |

1/ Assumed average values for entire well field.

2/ $sdf = a^2S/T$.

## SUMMARY AND CONCLUSIONS

Digital models describing the operation of stream-aquifer systems within the Platte River Basin, Nebraska, were prepared to enable prediction of water-level declines and streamflow depletion under a limited set of development plans. These plans were designed to evaluate the location and approximate magnitude of effects of a range of probable water-resources development. Models were developed covering all or parts of the Elkhorn, Loup, Central Platte, Upper Platte, or Lower Platte subbasins. Development plans tested on the models included private development of ground water for irrigation, Federal development of surface-water systems for irrigation, and development of ground water to supply municipal demands for the two major population centers--Lincoln, in the basin, and Omaha, outside the basin.

The digital models were prepared by using existing geohydrologic data as input to ground-water flow models developed by the U.S. Geological Survey. Calibration methods for the quasi-steady-state systems that exist in the basin were developed and utilized.

This study indicated that changes in water levels and streamflow prior to 1970 have occurred, but are small. Streamflow depletions are within the assumed accuracy of measurement (±5 percent). Sustained water-level declines over large areas have also occurred, but are small. However, localized areas have experienced declines that may be considered significant (about 10 feet in 30 years in parts of the Central Platte subbasin).

Analyses made with digital models for this study showed that salvage of evapotranspiration may be significant in the future operation of hydrologic systems in the basin. Salvage rates were as great as 14 percent of the rate of pumpage in the Middle Platte reach of the Upper Platte subbasin, and 18 percent of the pumpage rate in the Elkhorn subbasin. The actual significance of a given maximum rate of evapotranspiration salvage depends upon the area over which shallow water-table conditions initially occur and the true shape of the salvage function.

## Accuracy of Model Predictions

The accuracy of predicted water-level changes and streamflow depletions determined for each of the subbasins was not uniform but was a function of the accuracy of the basic data, modeling scale, assumptions made in model analyses, and method of calibration. The effect of these factors was discussed in the Hydrologic Models section. No quantitative statement was made regarding the relative accuracy of model predictions. However, a qualitative consideration of all the factors affecting predictive results was made to give the relative reliability of the models. The estimates of accuracy shown in figure 35 should be considered when utilizing the predictive results of the models.

Another factor affecting the accuracy of predictions in this study was the method of modeling subbasins separately. Although models were overlapped to ensure continuity of boundary conditions, the interdependence of water-level declines and streamflow depletions among subbasins must be considered. Maintenance of constant-head boundary conditions in a particular subbasin was dependent upon the available flow in the streams of that subbasin. Streamflow depletions resulting from upstream development may not ensure sufficient flow in downstream reaches of streams to maintain this condition. For example, streamflow depletions in subbasins above the Lower Platte subbasin may be large enough to result in a no-flow condition in the Platte River below the confluence of the Elkhorn and Platte Rivers. The Platte River downstream from this point would then no longer be a control on water levels in the aquifer, and predicted water-level declines would be too small.

## Need for Additional Studies

This study resulted in a comprehensive and accurate compilation of basic data needed for digital models at the scale used. Analyses of additional development plans with these models must consider modeling scale. More detailed studies require better definition of the data base in some areas. Based upon sensitivity analyses, parameters requiring the best definition are specific yield and net withdrawal from the aquifer.

In the near future, some areas within the basin will develop critical problems of ground-water supply that were not considered adequately in model analyses for this study. Adequate definition was not possible owing to either a poor data base or the existence of aquifers being developed that were not modeled. These conditions exist in two areas of the Upper Platte subbasin: (1) The Cheyenne tableland in Garden, Cheyenne, and Kimball Counties is being developed, but the data base used for model predictions was of questionable accuracy; (2) Pumpkin Creek valley is currently undergoing rapid development of ground water from an aquifer that was not modeled. Detailed modeling for water-resources management in these and other areas shown on figure 36 requires better definition of the water table and bedrock surfaces. The reliability of the data base for future digital stream-aquifer models in the basin could be improved significantly by concerted effort to define the storage properties of the aquifers and the historical net withdrawals from those aquifers.

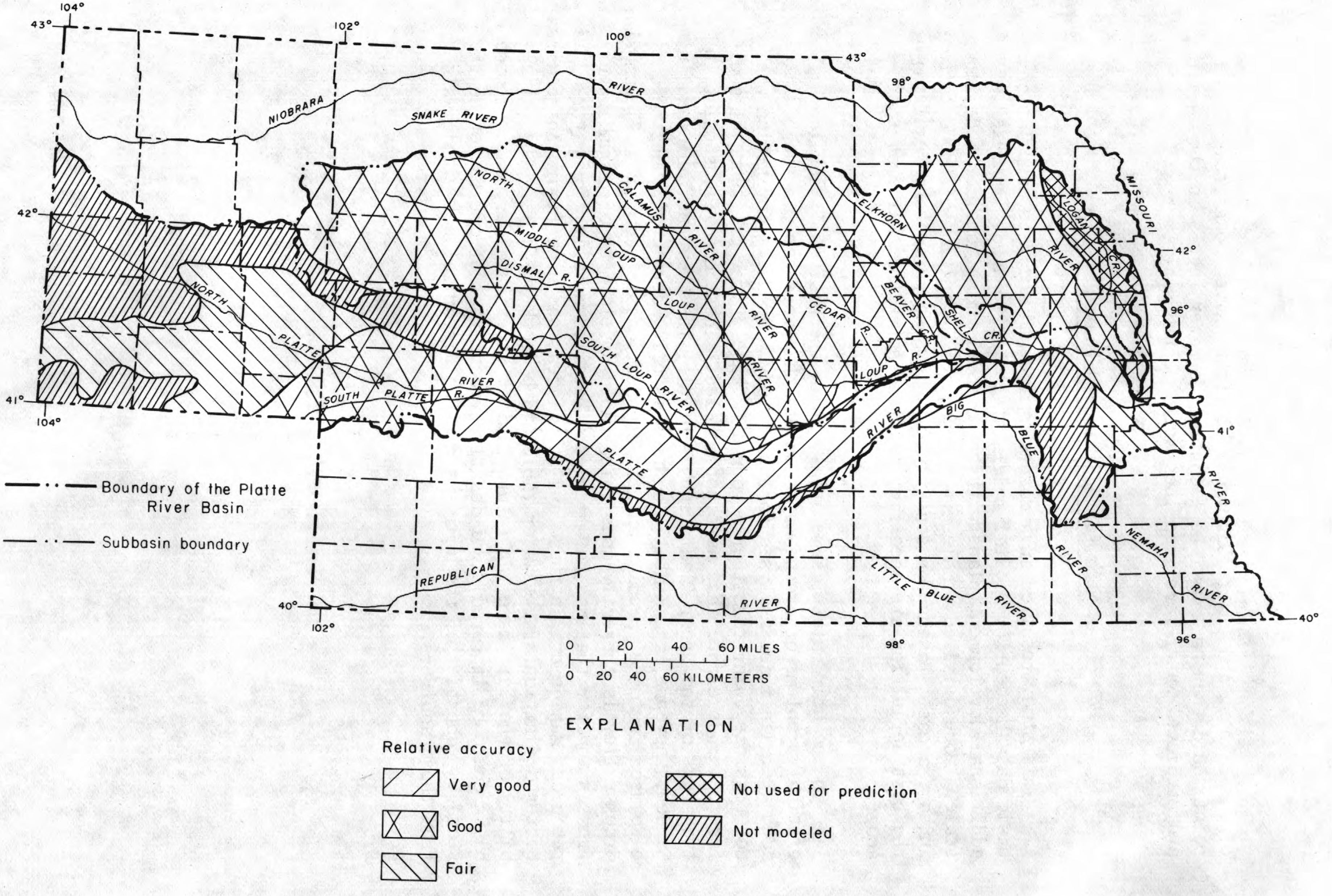



Figure 36.--Relative accuracy of model predictions.

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