An Appraisal of Ground Water for Irrigation in the Wadena Area, Central Minnesota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1983

Prepared in cooperation with the West Central Minnesota Resource Conservation and Development Project and the Minnesota Department of Conservation, Division of Waters, Soils and Minerals

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By GERALD F. LINDHOLM

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By Gerald F. Lindholm

ABSTRACT

The Wadena area is part of a large sandy plain in central Minnesota whose soils have low water-holding capacity. Drought conditions which adversely affect plant growth frequently occur in the summer when moisture is most needed. To reduce the risk of crop failure in the area supplemental irrigation is on the increase.

This study was made to evaluate the ground-water resources of the area and to determine possible effects of development on them. About half the area's approximately 102,000 acres is considered irrigable at the present time. In 1967, about 1,100 acres were under irrigation.

Outwash sand and gravel, which forms the water-table aquifer, is the main source of water presently known. Saturated thickness ranges from 0 to 70 feet and averages about 36 feet. Sandy till underlies the outwash. Within the till are sand and gravel lenses whose distribution and water-yielding characteristics were not determined.

Average annual precipitation at the U.S. Weather Bureau station in Wadena from 1934 to 1967 was 26.4 inches, of which about 22.5 inches was lost by evapotranspiration, and the balance of 3.9 inches was surface runoff. Even in wet years, evapotranspiration during the summer months exceeds precipitation, and a moisture deficiency for optimum plant growth occurs.

In 1967, about 8 inches of the total precipitation of 19.3 inches reached the water table. Recharge to the water table in 1967 was about 70,000 acre-feet.

Result of field aquifer (pumping) tests were used to estimate transmissivity values at test-hole sites. Information gained by auger test drilling was the basis for estimating transmissivity values elsewhere. Transmissivity of the water-table aquifer in most of the Wadena area ranges from 15,000 to 120,000 gallons per day per foot. A map was prepared to show the maximum yield, in gallons per minute, which might be obtained from individual wells completed in the water-table aquifer. The map indicates that in about 60 percent of the area, individual wells can be pumped at rates greater than 300 gallons per minute for a 30-day period if drawdown in the pumped well is two-thirds the saturated thickness after correction for dewatering.

Quality of both ground and surface waters is such that they are well suited for irrigation. Locally, nitrate concentrations in ground water, in excess of the U.S. Public Health Service's drinking water standards, might be related to a local source of organic pollution or to the increased use of fertilizers which accompanies irrigation.

An electric analog model of the water-table aquifer in the Wadena area was built and used to analyze possible effects of ground-water development on the hydrologic system. The model was designed to simulate existing hydrologic conditions and used to predict changes in the system which might result from development. The withdrawal of large quantities of ground water would lower the water table, thereby reducing evapotranspiration losses and making more water available for beneficial use. Additional water would be salvaged when normal ground-water discharge to streams is intercepted by pumping from wells.

Analyses were made to determine effects of development on ground-water levels under different development schemes both after a single irrigation season and after 5 and 20 successive years of irrigation. Where development is concentrated, some interference between wells can be expected. Although water levels recover rapidly when pumps are shut off, recovery will not be complete prior to the next irrigation season in heavily developed areas. After several years of water-table lowering, yields from wells will decrease because of decreased saturated thickness, unless climatic changes result in abnormally high amounts of recharge.

INTRODUCTION

Successful agricultural practices today involve intensified land use, better seed, more and better fertilizer, improved cultivation, and increased use of chemicals for weed and pest control. As a result, a large cash outlay is necessary each year, and because of several limiting factors which govern field crop development, a satisfactory financial return is not guaranteed. Water is one of the limiting factors, and it must be available in adequate amounts when needed. If the amount or timing of precipitation is not suitable, potential production losses are great. To eliminate such losses, supplemental irrigation is used increasingly in Minnesota. Areas having sandy soils with low water-holding capacity have been the first to benefit from irrigation. Some of the benefits of supplemental irrigation are drought insurance, greater diversity of crops, increased production, improved quality, and earlier crop maturity.

Increasing demands for water make necessary an evaluation of the water resources. Where might water be obtained in the area of interest? Is there an adequate supply of recoverable water to support irrigation? Is the quality of available water suitable for irrigation? What will be the effects of development on the ground-water system? The need for answers to these and other questions concerning the water resources points out the necessity of a ground-water study in the Wadena area.

LOCATION AND EXTENT

The study area, in central Minnesota, includes parts of Otter Tail, Todd, and Wadena Counties (fig. 1). Because about 80 percent of the total area is in Wadena County, the entire area of study is referred

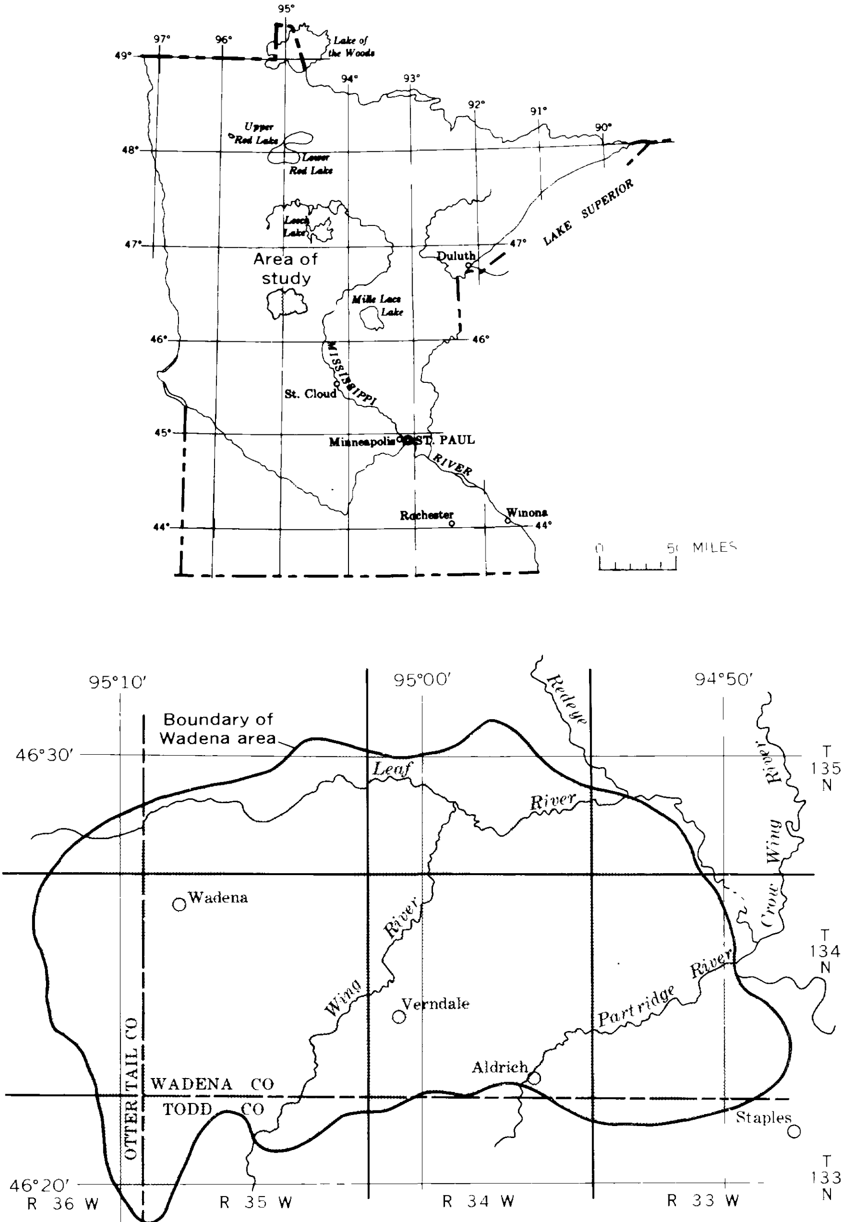

FIGURE 1.—Location and extent of the Wadena area.

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to in this report as the Wadena area. It is approximately 160 square miles in extent and constitutes a part of a more extensive north-south-trending outwash body. The Wadena area is a part of the Crow Wing River watershed unit designated by the State Department of Conservation (Minn. Div. Waters, 1959). It is not a complete geologic or hydrologic unit but was selected on the basis of droughty soil types, interest in irrigation in the area, and local recognition of the need for a ground-water study.

PURPOSE OF INVESTIGATION

This report describes the occurrence, availability, and quality of ground-water resources in the Wadena area and probable effects of their development on the hydrologic system. Emphasis is directed toward the increasing use of water for irrigation. Recent increases in both the number of irrigators and in total pumping of water for irrigation are shown graphically in figure 2. Irrigation pumping centers, as of 1967 when approximately 1,100 acres were irrigated, are shown in figure 3. To date (1967), most of the water for irrigation

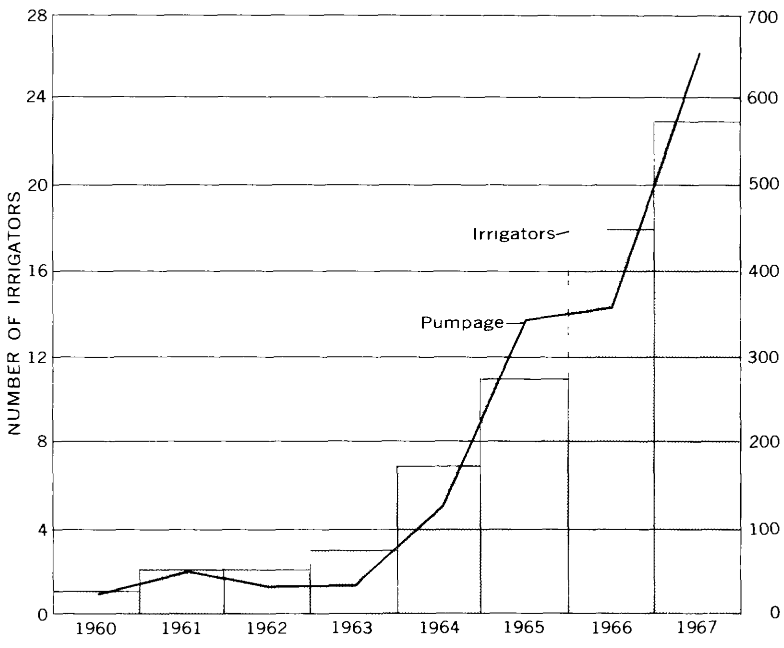

FIGURE 2.—Rate of increase in number of irrigators and in pumping of water for irrigation.

has been obtained from shallow outwash sand and gravel deposits that are generally less than 75 feet thick. This report primarily concerns the water-table aquifer, and only brief reference is made to deeper aquifers. Results of this investigation are intended to provide a basis for future management of water resources in the Wadena area.

PREVIOUS INVESTIGATIONS

Winchel and Upham (1888) summarized the geology and natural history of central Minnesota, including the study area. Leverett (1932), in the first comprehensive report on the glacial geology, mentioned the drumlins that are the most distinctive geomorphic feature in the Wadena area. Wright (1954) delineated and applied the designation Wadena drumlin field to the drumlin complex. Additional studies by Wright (1956, 1957, 1962), which emphasize the drumlin complex, resulted in some reinterpretation and modification of Leverett's earlier interpretation of the area's glacial history.

Schneider (1961) described in considerable detail stratigraphic and geomorphic relations in central Minnesota and their significance in interpreting late Wisconsin glacial history.

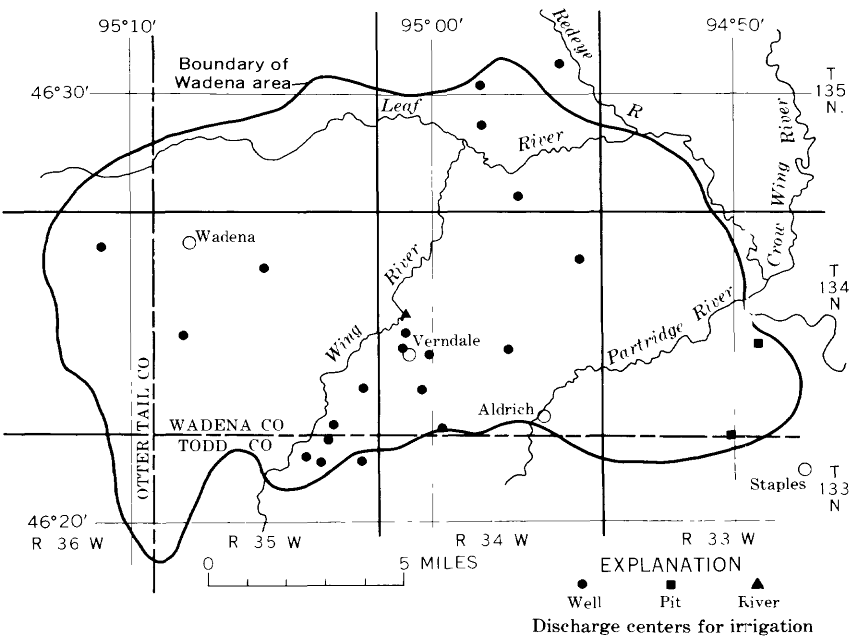

FIGURE 3.—Irrigation pumping centers as of 1967.

Little detailed work has been done to evaluate the area's water resources. Cursory mention of water resources was made by Winchell and Upham (1888). In a report by Allison (1932), some well information is given in addition to selected data on water quality. As part of a statewide study of major watershed units being conducted by the U.S. Geological Survey in cooperation with the Minnesota Department of Conservation, Division of Waters, Soils and Minerals, a hydrologic atlas has been completed on the Crow Wing River watershed Lindholm and others, 1970). The atlas gives reconnaissance-type information on the geology and hydrology of the area but in less detail than this report.

METHODS OF PRESENT INVESTIGATION

The present investigation was begun in the summer of 1966 and completed in 1968.

Test drilling, using both power-auger and hydraulic-rotary methods, provided much of the information used in compiling this report. Augering was used to obtain information on shallow outwash deposits, whereas rotary methods were necessary to obtain information below 100 feet. Test-hole information was supplemented with information from local drillers, municipal officials, and private well owners. Four pumping tests were made to determine hydraulic coefficients.

An observation-well network, consisting of wells installed by the U.S. Geological Survey and existing irrigation wells, was established. Water-level data were obtained from continuous recorders or by periodic taping of wells. Streamflow data on major perennial streams were obtained. Increase or loss of streamflow along major streams was determined during two seepage runs. Water samples were taken at selected sites for quality determinations.

Effects of past, present, and hypothetical future development on the ground-water system were determined by use of an electric analog model of the area.

WELL AND TEST-HOLE NUMBERING SYSTEM

The system of numbering wells and test holes in Minnesota is based on the U.S. Bureau of Land Management's system of subdivision of public lands. The Wadena area is in the fifth principal meridian and base-line system. The first segment of a well or test-hole number indicates the township north of the base line; the second, the range west of the principal meridian; and the third, the section in which the well or test hole is located. The lowercase letters, a, b, c, and d, following the section number, locate the well within the section. The first letter denotes the 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract as shown in figure 4. The letters are assigned in a counterclockwise direction beginning in the northeast quarter. Within one 10-acre tract, successive well numbers, beginning with 1, are added as suffixes. Figure 4 illustrates the method of numbering a well or test hole. The number 133.35.2cbb1 indicates the first well or test hole located in the NW¼NW¼SW¼ sec. 2, T. 133 N., R. 35 W.

ACKNOWLEDGMENTS

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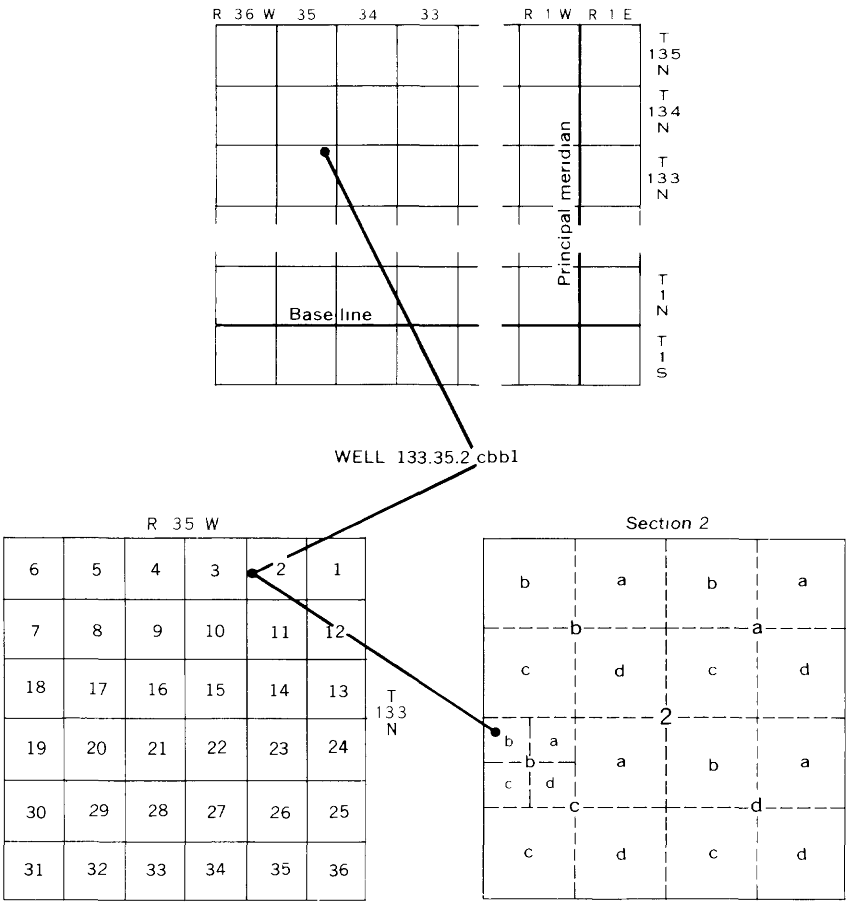

FIGURE 4.—Well-numbering system in Minnesota.

tion, Division of Waters, Soils and Minerals. It resulted from coordinating efforts by the Resource Conservation and Development Project Committee whose objectives include the assessment of natural resources and the development of ways and means to best utilize and conserve them.

Well drillers and owners, village and county officials, and many others provided data used in the preparation of this report. To them the author expresses his appreciation. Special appreciation is extended to those irrigators who permitted use of their wells and equipment for pumping tests.

GEOLOGY

Basic to an understanding of the hydrologic system is a knowledge of the geologic framework in which it operates. Geologic parameters that control water occurrence, distribution, and movement include topography, distribution of rock types, and porosity and hydraulic characteristics of those rocks. These parameters must be considered before the hydrologic system can be defined.

PHYSIOGRAPHY AND GLACIAL HISTORY

Continental glaciation during the Pleistocene Epoch was important in forming the present landscape of much of Minnesota, including the Wadena area. Although multiple stages of glaciation occurred, the most recent ice advances, during the late Wisconsin Glaciation, were the primary architects of today's topography. Figure 5 (modified from Wright and Ruhe, 1965) outlines the major glacial features in and surrounding the Wadena area and shows the direction of ice advances which produced them. As interpreted by Wright and Ruhe (1965, p. 33), ice of the Hewitt phase of the Wadena lobe originated in southeastern Manitoba. It flowed southeastward into Minnesota until it was diverted by the contemporaneous Rainy lobe advancing from the northeast. Ice of the Wadena lobe thus flowed southwestward as it crossed the Wadena area. This interpretation is based on the orientation and fan-shaped distribution of drumlins, the inclusion of Paleozoic carbonates, and the absence of Cretaceous shale in the Wadena till. The eastern limit of the Wadena drumlin field is the St. Croix moraine, which is composed of younger drift from the Lake Superior basin. On the west and south, the drumlin field is bounded by drift of the Alexandria morainal complex. On the north, the drumlin field is buried or partially buried by out-

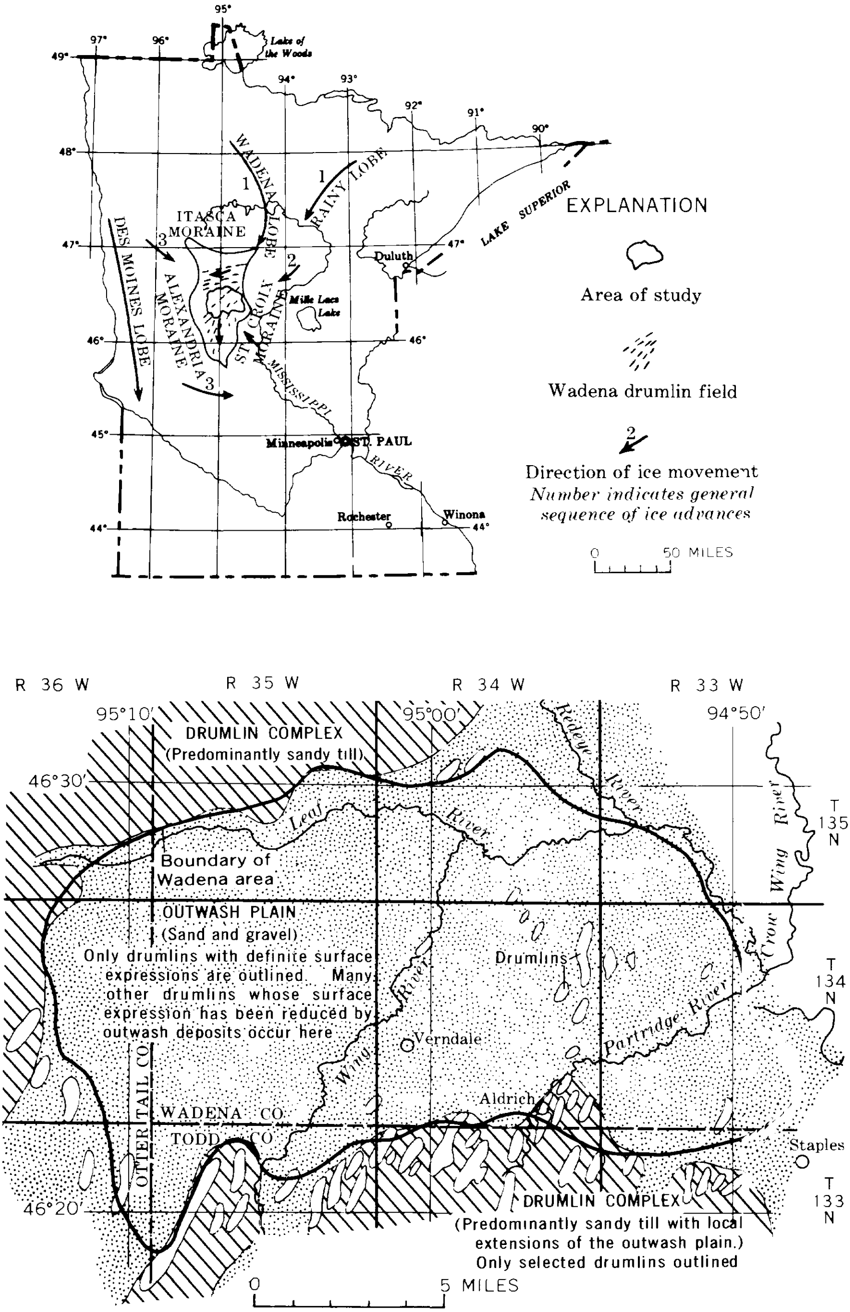

FIGURE 5.—Major glacial features in and surrounding the Wadena area and the ice advances which produced them.

wash deposits frontal to the Itasca moraine, which represents a later (Itasca) phase of the Wadena lobe.

As a result of glacial activity, three major geomorphic features are predominant in the region: drumlins, outwash plains, and moraines. Only the drumlins and the outwash plains and the materials constituting them will be considered in detail in this report.

TILL (DRUMLINS)

Virtually all till in the Wadena area, including that forming the drumlins, is sandy and calcareous. It is yellowish brown when oxidized and commonly dark greenish gray when unoxidized. Unoxidized Wadena till was frequently found at depth in drill holes, and it forms the aquiclude beneath outwash deposits throughout the area. In the subsurface, the first several feet of Wadena till are very sandy with few exceptions. Beneath the sandy zone, a variety of textural types occur. In several widely scattered test holes, the upper few feet of the aquiclude is a smooth tight gray clay. Gravel, in which the coarse fraction is predominantly carbonates, is found in many places and at various depths within the till. It occurs as probable lenses which are commonly less than 5 feet thick. In several areas, clean sand and gravel, tens of feet thick, are found beneath the till.

In a rotary test hole at 134.33.18daa1, yellowish-brown till at 157 feet grades to medium-grayish-brown till below that depth. This may be indicative of a pre-Wadena lobe ice advance.

OUTWASH (OUTWASH PLAIN)

Outwash deposits in the study area are part of a more extensive outwash plain (Leverett, 1932).

The nature and distribution of outwash deposits in the study area were determined by auger test drilling. Outwash is thickest in the swales between drumlins and thinnest where it overlies buried drumlins. Stratigraphic relationships between till (drumlins) and outwash deposits are shown diagrammatically in figure 6. Figure 6 also demonstrates the influence of drumlins on the deposition and distribution of outwash deposits.

The outwash is composed of glaciofluvial sand and gravel. Texture of the outwash, as determined by sieve analysis, is predominantly sand and lesser amounts of gravel and clay. The median grain size of most of the materials sampled is medium to coarse sand. Areal variations in texture are shown by particle-size distribution curves on plate 1. The slope of each curve is indicative of the size range of component

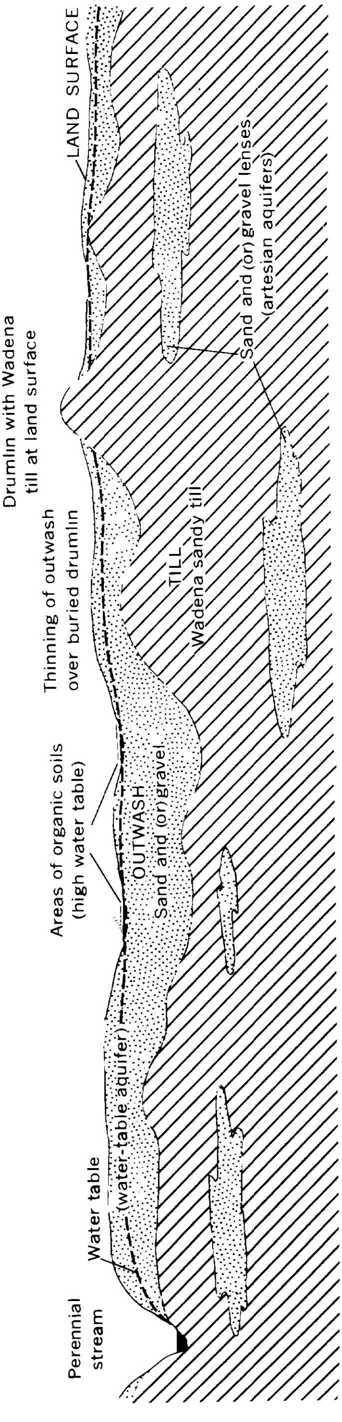

FIGURE 6.—Diagrammatic section illustrating stratigraphic relationships between till (drumlins) and outwash deposits.

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materials and the degree of sorting; the more nearly vertical the curve, the more uniform the material. The outwash materials are well sorted, having an average sorting coefficient (the square root of the ratio of the 75-percent-finer size to the 25-percent-finer size) of 1.8 for 36 random samples. Both lateral and vertical textural changes commonly occur within short distances and are difficult to predict locally. Regionally, however, distinct textural types can be mapped with reasonable reliability.

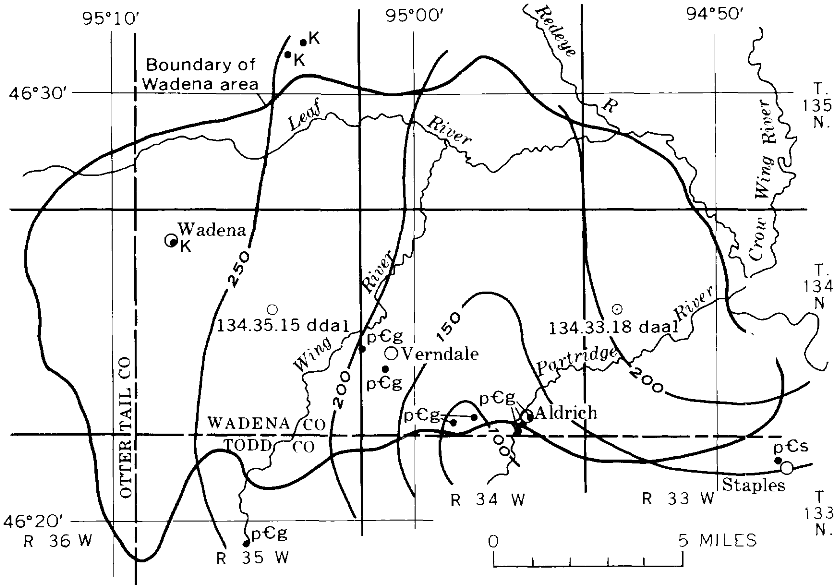
The coarsest outwash occurs within former drainage courses and is most common in the western and southern parts of the study area. This supports the theory that melt waters from the Alexandria morainal complex spread outwash fans over the outer part of the Wadena drumlin field (Wright, 1962, p. 96). Coarse alluvial deposits constitute the broad flood plain of the Leaf River. Although the outwash and the alluvium are not stratigraphic time equivalents, their similar stratigraphic position and similar composition make it possible to consider them as a single hydrologic unit. Areas of fine-grained sand are scattered throughout the Wadena area. Fine- to medium-grained sands predominate south of the Partridge River between Aldrich and Staples and north of the Partridge River to the Leaf River flood plain. Carbonate rock fragments predominate in the coarse fraction, and a variety of igneous rock types and quartz constitute most of the remainder.

BEDROCK

Little information is available concerning the bedrock in the Wadena area. Cretaceous or "Cretaceous-like" sediment has been reported in several localities (Allison, 1932, p. 231). Varicolored clays, lignite, pyrite, and sand, characteristic of Cretaceous sediments in central Minnesota, have been reported in the Wadena area. Precambrian slates occur beneath the drift in the vicinity of Staples, and granites occur elsewhere. Drift thickness, or depth to bedrock, is variable (fig. 7). Granite is reported at less than 100 feet in the vicinity of Aldrich, whereas more than 250 feet of drift is reported in the western part of the study area. Rotary test holes at 134.33.18daa1 and 134.35.15dda1, having total depths of 194 and 202 feet, respectively, failed to reach bedrock and bottomed in glacial drift.

GROUND-WATER HYDROLOGY

Most ground water in the Wadena area occurs in pores or openings between rock particles in the glacial drift. The quantity of water contained therein is a function of the rocks' porosity. Water moves



EXPLANATION

•K •p€s • p€g

Well bottomed in bedrock
K, *Cretaceous*
p€s, *Precambrian slate*
p€g, *Precmabrian granite*

⊙
134.35.15 ddal
U.S.G.S. rotary test hole and number

—— 200 ——
Line of equal drift thickness
Interval 50 feet

FIGURE 7.—Drift thickness and location of known wells bottoming in bedrock.

through the ground-water reservoir at a relatively slow rate from areas of recharge to areas of discharge. The ability of water to move through the reservoir is dependent upon the hydraulic conductivity of the enclosing rock. Water quality is dependent upon a number of solutional and decompositional processes which occur as water moves through the hydrologic cycle.

OCCURRENCE AND MOVEMENT

In this report, the part of the ground-water reservoir examined in some detail is the water-table aquifer which consists of outwash sand and gravel overlying till. Although other water-bearing zones may be present below the water-table aquifer, little is known about them.

Depth to the water table in the outwash area is dependent upon location and time, and varies from 0 to 25 feet (fig. 8). The water table is generally 10 to 20 feet below land surface in upland (buried

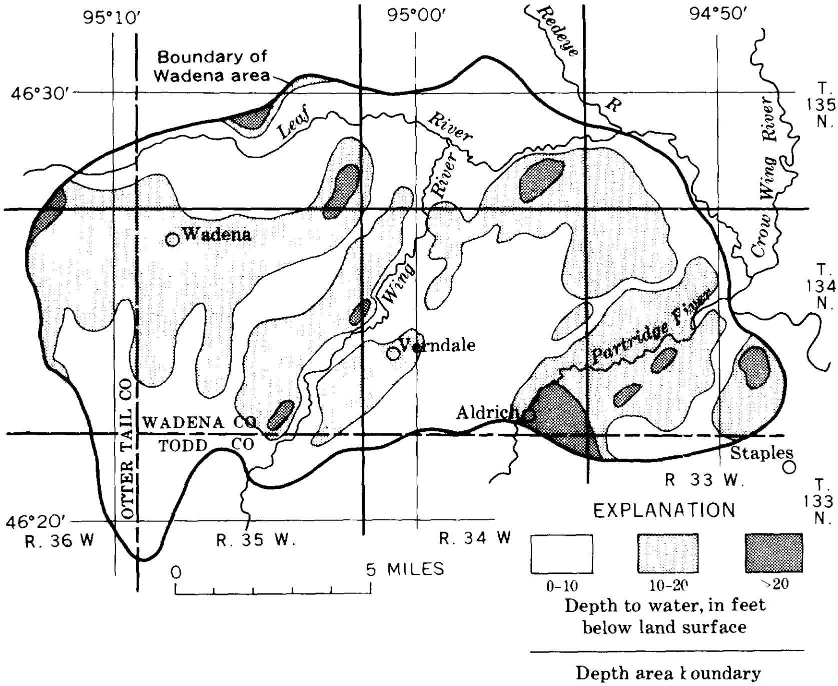


FIGURE 8.—Depth to water table.

drumlin?) areas. In former drainage ways, in swales between buried or partially buried drumlins, and in the flood plain of the Leaf River, the water table is shallower, generally from 0 to 10 feet below land surface. Areas of high water table generally coincide with areas of organic soil (pl. 2). Depth to water is greatest in upland areas near major streams where dissection of the outwash plain is the greatest.

The shape of the water table is shown on plate 2. Because water moves from higher to lower head, the general horizontal direction of ground-water movement can be determined from the water-table map. In areas of fairly uniform lithology, ground-water flow paths are approximately at right angles to the water-table contours. Regionally, water movement south of the Leaf River is north-northeastward toward the Leaf and Crow Wing Rivers. Locally, water movement is toward tributaries to these rivers or toward local depressions. North of the Leaf River, water moves southeastward toward the river.

In areas of surficial till and beneath outwash areas, water available to wells occurs in sand and gravel lenses within the till. The level to which water will rise in a pipe open to such a lens is dependent upon the position of that lens in the ground-water flow system. Although the range of pressure heads from artesian aquifers in the Wadena area is great, water in wells open to artesian aquifers commonly rises to within 30 to 50 feet of the land surface.

WATER-LEVEL FLUCTUATIONS

Ground-water levels fluctuate naturallly in response to a sequence of climatic events and to constraints imposed by hydrogeologic parameters. In the spring, after the ground thaws, water levels in the outwash aquifer rise rapidly owing to recharge from snowmelt and spring rains. In the summer, when evaporation and transpiration rates exceed available moisture from precipitation, recharge to the water table is negligible and water levels decline. In the fall, when evaporation and transpiration losses decrease, water levels may rise slightly in response to rainfall. A gradual decline of the water table occurs in the winter when the soil is frozen and precipitation is stored on the land surface as ice and snow. Water levels typically reach an annual low just prior to the spring thaw.

Water-level fluctuations are not uniform throughout the Wadena area. They are dependent not only on climatic conditions but also on varying physical characteristics of the soil and the unsaturated zone, on depth of the water table, on morphology of the surrounding area, and on proximity of points of recharge and discharge.

Variations in the pattern of water-level fluctuations are shown by selected hydrographs on plate 3. The range of fluctuations is greatest and most directly related to rainfall in areas of high water table on the flood plain of the Leaf River and in old drainage courses. These areas also contain the coarsest aquifer materials, as shown by particle-size distribution curves (pl. 1). The range of water-level fluctuations is smallest and least directly related to rainfall where depth to water is greatest, where finer sands predominate, and where dissection of the outwash plain is greatest. Because water-level records are available for only a 2-year period, the range of water-level fluctuations for any single year may be greater or less than those shown on plate 3.

Knowing the amount of water-level fluctuation is important not only for pump settings but also because of the change in the amount of water in storage. To determine changes in the amount of water in storage, it is necessary to know the specific yield of the materials in which the water level fluctuates. Specific yield is defined as the volume of water involved in the gravity drainage or refilling divided by the volume of the zone through which the water table moves (Ferris and others, 1962, p. 76). Specific yields were determined in the laboratory on selected samples taken during test drilling. The amount of water-table fluctuation multiplied by the specific yield of the material through which it fluctuates determines the net effective recharge, as illustrated in figure 9. Figure 10 shows areal variations in net effective recharge to the water-table aquifer in 1967, as determined by the above method. Total recharge to the water-table aquifer over the entire study area in 1967 was approximately 70,000 acre-feet of water, as determined from data in figure 10.

AQUIFER DISTRIBUTION

The areal distribution of outwash sand and gravel was mapped using data obtained by auger test drilling and from well logs. Data from 152 auger test holes show that the sand and gravel range in thickness from 0 to 70 feet and average 36 feet. These deposits con-

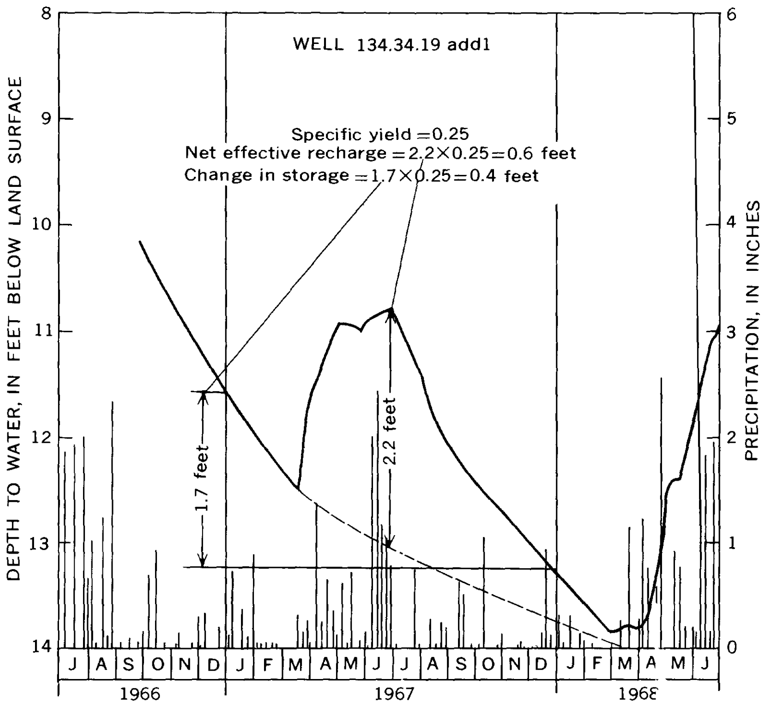


FIGURE 9.—Hydrograph illustrating method used to determine net effective recharge and changes in amount of water in storage in the water-table aquifer.

stitute the water-table aquifer, the major known source of ground water in the Wadena area. Although hydraulic conductivity differences do occur, saturated thickness is one of the main factors governing the amount of water available to wells. The distribution of saturated outwash above the first massive clay (greater than 5 ft thick) is shown on plate 4. It is this part of the outwash which is analyzed in the present study as to its water-yielding potential. Variations in thickness of outwash reflect the occurrence of buried or partially buried drumlins.

Superimposed on the saturated-thickness map of the water-table aquifer (pl. 4) are areas of known artesian aquifers. Although exceptions do occur, it seems probable that an artesian aquifer may be found at some depth within the glacial drift in much of the study area. It is not known if the water-yielding potential of artesian aquifers is sufficient for irrigation because evaluation of these aquifers was beyond the scope of this investigation.

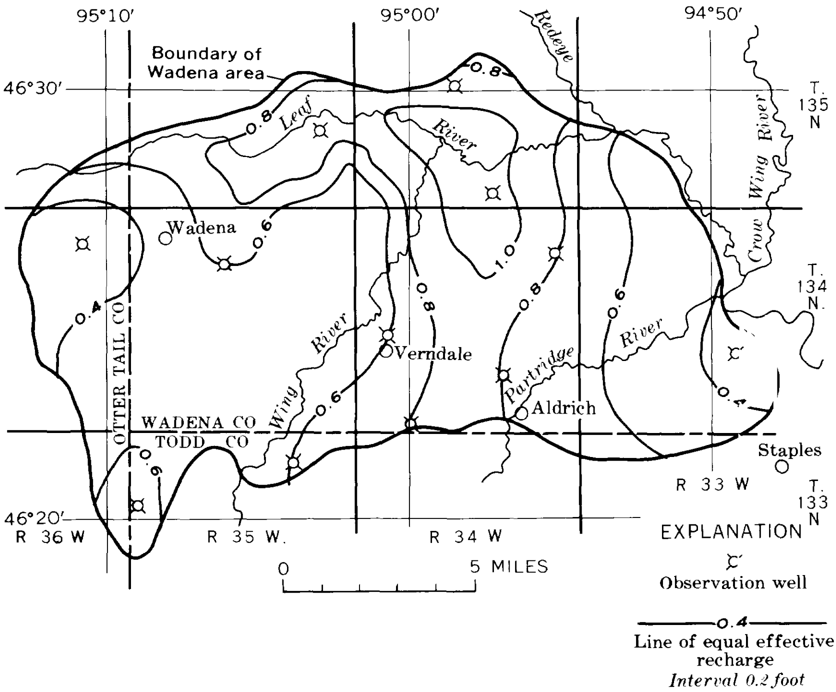


FIGURE 10.—Areal variations in net effective recharge to the water-table aquifer in 1967.

HYDRAULIC CHARACTERISTICS OF AQUIFERS

The capacity of an aquifer to transmit water to wells is a function of the aquifer's hydraulic conductivity and transmissivity. Hydraulic conductivity (coefficient of permeability), *K*, is defined as the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at a temperature of 60° F (Ferris and others, 1962, p. 72). Transmissivity is used in field practice as a means of expressing flow rates through the entire saturated zone of an aquifer and is equal to the hydraulic conductivity multiplied by the saturated thickness. It is a regional spatial average and may not be representative of any particular section of material. Transmissivity (coefficient of transmissibility), *T*, is defined as the rate of flow of water, in gallons per day, at the prevailing water temperature, through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer, under a hydraulic gradient of 100 percent (Ferris and others, 1962, p. 73). Total storage within an aquifer varies as the water level fluctuates. The storage coefficient, *S*, of an aquifer is defined as the volume of water the aquifer releases from, or takes into, storage per unit surface area of the aquifer per unit change in component of head normal to that surface (Ferris and others, 1962, p. 74).

Although a number of methods are available to determine these characteristics, in this study, field pumping tests were considered the most accurate. Four pumping tests were conducted—three in the water-table aquifer and one in a leaky artesian aquifer. Analysis was by the type-curve method for water-table aquifers (Boulton, 1963). Corrections were made when necessary to allow for dewatering of the aquifer and partial penetration. Results obtained from field aquifer tests are summarized in table 1.

TABLE 1.—*Results of field aquifer tests in the Wadena area*

[gpm, gallons per minute; gpd per sq ft, gallons per day per square foot]

Well	Saturated aquifer thickness (ft)	Pumping rate (gpm)	Length of test (hr)	Drawdown in pumped well (ft)	Specific capacity	Transmissivity (gpd per ft)		Average hydraulic conductivity (gpd per sq ft)	Storage coefficient
						Estimated from specific capacity	Computed by type-curve method		
Water-table aquifer									
134.34.12bad2	34	370	12	16.3	22.6	32,000	82,000	2400	0.18
134.34.19abd1	45	400	24	15.5	25.8	45,000	65,000	1440	.11
134.34.32dcb1	37	580	12	14.6	39.7	50,000	66,000	1780	.16
Leaky artesian aquifer									
134.36.2dcc1	46	450	24	9.5	47.4	80,000	117,000	2550	.014

Theis (Theis and others, 1963, p. 331–340) devised a method of estimating *T* values by using specific-capacity data from pumped wells. Specific capacity of a well is the yield, in gallons per minute per foot of drawdown, for a selected period of continuous pumping. Transmissivity values thus obtained cannot be considered exact because other factors such as well diameter, type and length of screen, amount of aquifer open to the well, and degree of development must be considered. Because of these factors, *T* values estimated from specific-capacity data are usually minimum values.

Hydraulic conductivity and transmissivity were determined at aquifer test sites. Because of the similarity of outwash materials elsewhere in the area to those at test sites, *K* and *T* were estimated for sites where data were obtained from wells and test holes only. Hydraulic-conductivity values were estimated for different lithologies on the basis of sample examination during test drilling, aquifer test results, laboratory analyses, and published data. Based on these criteria, the following *K* values were used as a guideline for estimating the *K* of outwash materials in the Wadena area:

Wentworth size classification	*Estimated hydraulic conductivity (gpd per sq ft)*
Clay	0–100
Sand, very fine	100–300
Sand, fine	300–600
Sand, medium	600–900
Sand, coarse	900–1,200
Sand, very coarse	1,200–1,500
Sand and gravel	1,500–3,000

Hydraulic-conductivity values, intermediate to those listed, were assumed for mixtures of materials (taking into account sorting and packing as well as grain size).

On the basis of the saturated thickness and assumed *K* values for the saturated zone, *T* values were estimated for each logged well and test hole. Transmissivity values of the water-table aquifer in most of the Wadena area range from 15,000 to 120,000 gpd per ft (gallons per day per foot). (See pl. 5.)

To relate transmissivity to yield and to determine effects of pumping on water levels, a series of theoretical time and distance drawdown curves were computed (figs. 11, 12, 13). Transmissivity values were varied on each set, with *S* (storage coefficient) and *Q* (rate of discharge, in gallons per minute) being held constant. By knowing *T*, *S*, and *Q*, it is possible, with certain exceptions, to estimate from the drawdown curves future water levels at any time after pumping began and at any distance from the pumped well. Because dewatering of

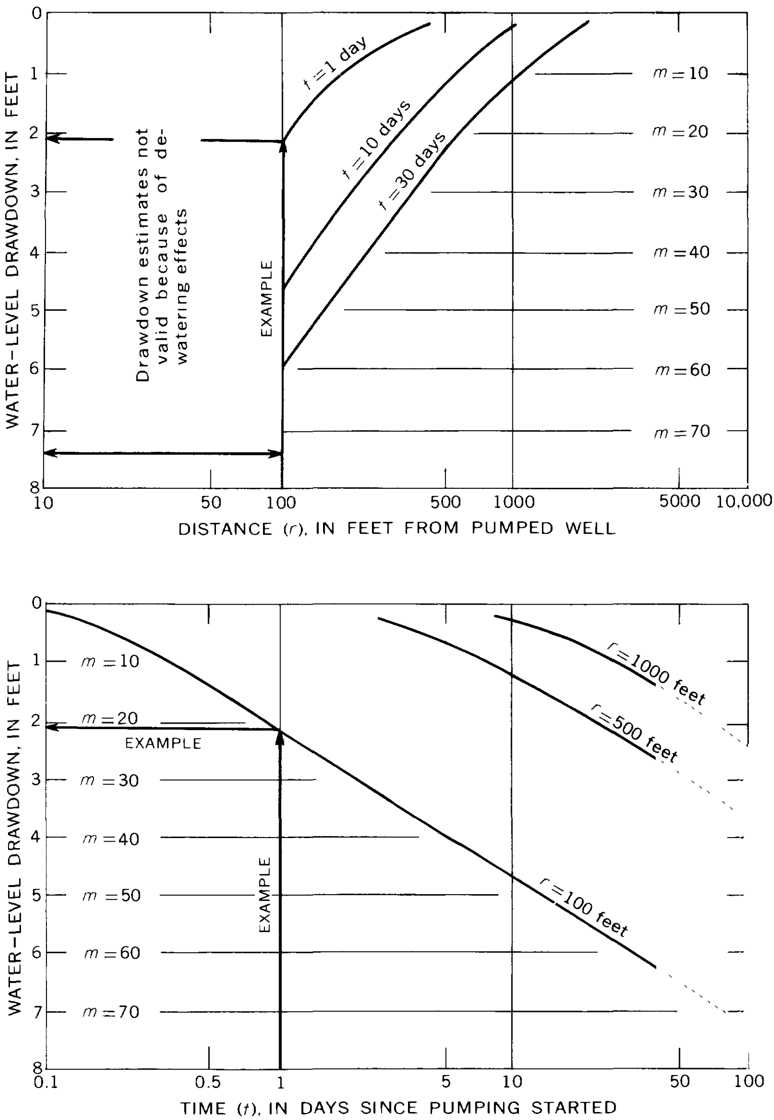


FIGURE 11.—Theoretical time and distance drawdown curves for the water-table aquifer. T=30,000 gallons per day per foot; S=0.15; Q=300 gallons per minute; and m=original saturated thickness, in feet.

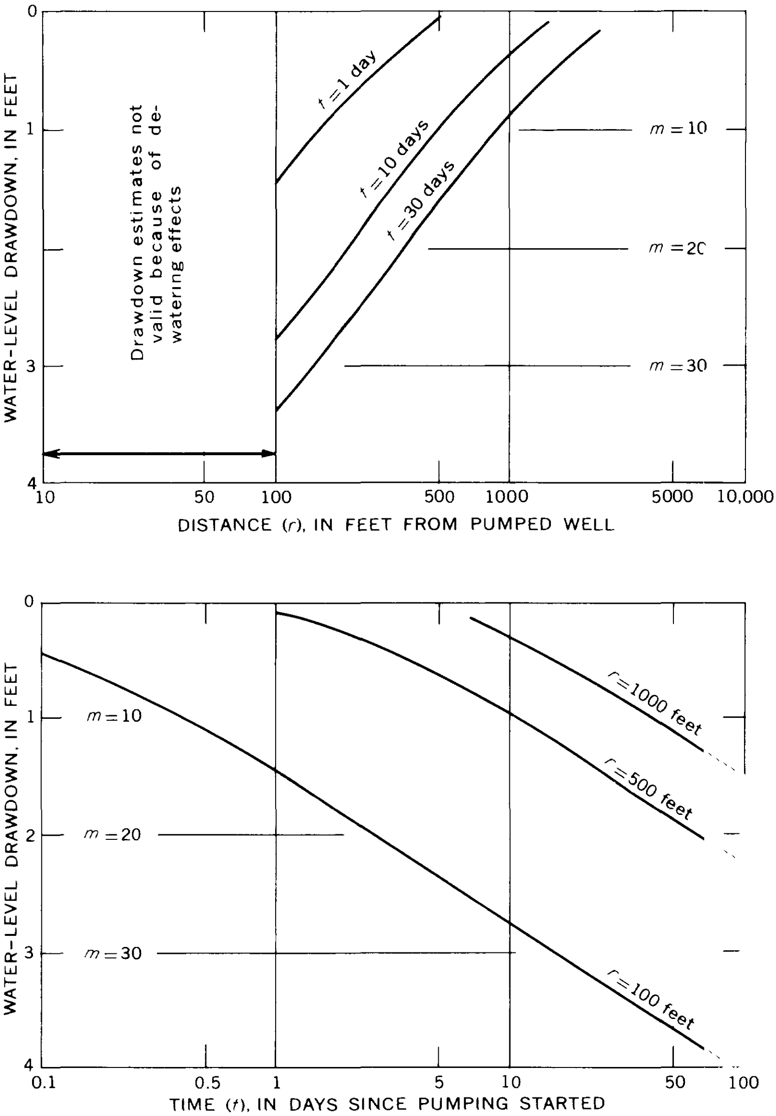


FIGURE 12.—Theoretical time and distance drawdown curves for the water-table aquifer. T=60,000 gallons per day per foot; S=0.15; Q=300 gallons per minute; and m=original saturated thickness, in feet.

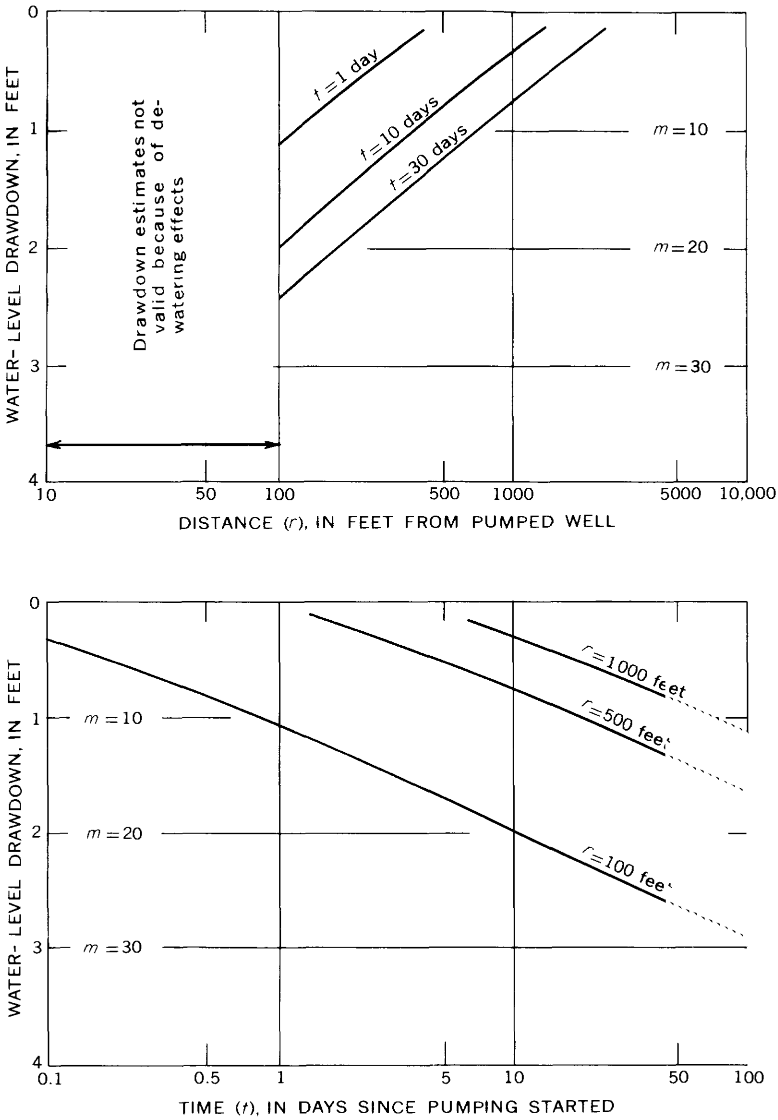


FIGURE 13.—Theoretical time and distance drawdown curves for the water-table aquifer. T=90,000 gallons per day per foot; S=0.15; Q=300 gallons per minute; and m=original saturated thickness, in feet.

a water-table aquifer occurs within the cone of depression created by the pumped well, drawdown is not directly proportional to yield near the well, as is true for an artesian aquifer. Away from the immediate vicinity of the pumped well, dewatering effects decrease. When the ratio of dewatered aquifer to original total saturated thickness becomes small (less than about 10 percent), for practical purposes, it can be assumed that drawdown is essentially proportional to yield. Data collected during aquifer tests indicate that this generally occurs when distance from the pumped well is greater than about 100 feet and when period of pumping does not exceed 30 days. It is therefore assumed that estimates of minimum drawdown at different pumping rates can be made from the included drawdown curves at distances greater than 100 feet from the pumped well. For example, where T is 30,000 gpd per ft and m (saturated thickness) is 30 feet, after 1 day's pumping at 300 gpm (gallons per minute), the theoretical drawdown 100 feet from the pumped well is 2.1 feet, as shown in figure 11. If the yield, is doubled (Q=600 gpm) and drawdown is proportional to yield, the theoretical drawdown would be 4.2 feet. The theoretical drawdown at 600 gpm is greater than 10 percent of the original saturated thickness and therefore may be invalid. If, in the example given, the original saturated thickness were greater than 42 feet, drawdown for up to 9 days of continuous pumping would not exceed 10 percent, and drawdown predictions might be considered valid. Because dewatering occurs when pumping from a water-table aquifer, saturated thickness is very important in determining an area's water-yielding potential. Where saturated thickness is small, caution must be exercised so that yield limitations resulting from dewatering are not exceeded.

Boundary conditions were not accounted for in computing theoretical drawdowns. Recharge boundaries, such as streams or swamps, will tend to decrease water-level declines if intercepted by the cone of depression. Impermeable boundaries such as till adjacent to outwash will result in increased water-level declines if intercepted by the cone of depression.

AVAILABILITY

The main purpose of this study is to describe the availability of ground water from the water-table aquifer in the Wadena area. For practical uses by potential irrigators, a map was derived which indicates the probable yield that might be obtained from large-diameter (15 in.) wells. The following assumptions and corrections were made:

1. Saturated thickness and transmissivity data as mapped regionally on plates 4 and 5 fit each local situation.

2. Optimum well yield is obtained when allowable drawdown is two-thirds of the saturated thickness of the aquifer after adjusting for dewatering.
3. Period of pumping was set at 30 days continuous pumping to place an extreme stress upon the system. Except under prolonged drought conditions, it is doubtful that pumping periods will approach this extreme.

Plate 6 is the resultant estimated maximum-yield map. If 100 gpm from a single well is assumed to be the minimum economic pumping rate, the water-yielding potential of the water-table aquifer in about 15 percent of the study area may be inadequate for irrigation. In such areas, another water source, possibly a deeper artesian aquifer, could be developed for successful irrigation.

In about 25 percent of the area, yields of 100 to 300 gpm might be obtained. Although a single well may yield an inadequate supply, more than one well might be developed to meet minimal irrigation requirements. In such areas, deeper aquifers should be considered as a possible water source.

In about 60 percent of the study area, the water-yielding potential of the water-table aquifer is in excess of 300 gpm from a single well and appears favorable for supplemental irrigation. The maximum yield in 40 percent of the area is estimated to be from 300 to 600 gpm, in 10 percent of the area from 600 to 900 gpm, and in 10 percent of the area in excess of 900 gpm.

Estimated maximum yields shown on plate 6 are for single wells only. Total ground water in storage is greater in all areas, but some means other than single wells must be used to extract that water. Withdrawal at the estimated yields would impose an extreme stress upon the ground-water system. In actual practice, such stress is highly improbable. Instead of 30 days continuous pumping for any one irrigation season, cyclic pumping is practiced over about a 90-day period. After a period of pumping, water levels commonly recover to within a small fraction of prepumping levels before irrigation might again be necessary.

RELATION OF SURFACE WATER TO GROUND WATER

Almost all surface water in the Wadena area occurs as streamflow. Impounded water (lakes and ponds) occupies less than 1 percent of the total area. All streams in the study area are gaining streams—that is, they receive ground-water discharge. During periods of sustained dry weather, streamflow approaches a minimum and consists largely of ground-water discharge. Low flow generally occurs during the late summer when evaporation and transpiration are at a maximum and during the winter when precipitation is stored as snow and ice. In 1967, two seepage runs were made to determine the amount of ground-water discharge to streams. Discharges were determined on selected streams at 2 to 3 mile intervals. The first was made on the Wing and Partridge Rivers on July 17 and 18 when evaporation, transpiration, and ground-water withdrawal approached a maximum. A second, more complete series of discharge measurements was made October 16–18 on all streams of significance in the study area. At that time, transpiration losses were at a minimum, evaporation losses were small, and there was no withdrawal for irrigation. Precipitation during the last half of 1967 was below normal, and therefore it was assumed that all flow in the streams represented ground-water discharge. A comparison of discharge measurements made in July and October shows that the ratio of pickup along selected short reaches of the Wing and Partridge Rivers to total pickup along the entire stream was similar both times. Higher discharges were recorded in July when water levels in wells were also higher. Under the present stage of development, there is no discernible decrease in streamflow due to the interception of ground water by irrigation wells.

Relative amounts of discharge, measured during the October 1967 seepage run, are shown by width of flow bands on plate 7. Significant amounts of ground-water pickup were recorded within the outwash area; whereas, pickup was considerably less in surrounding till areas. This is substantiated by comparing instantaneous yields from outwash with yields from till in the Wing and Partridge River drainage basins. An instantaneous yield of 0.43 cfs per sq. mi. (cubic feet per second per square mile), from the outwash of the Wing River basin, compares with a yield of 0.33 cfs per sq mi, from the outwash of the Partridge River basin. The lower yield from the Partridge River basin is probably due to the presence of finer grained sands which have a lower capacity for transmitting water. In contrast to the high yields from outwash areas, an instantaneous yield of 0.08 cfs per sq mi was determined from the till of the Wing River drainage basin and 0.01 cfs per sq mi from the till of the Partridge River basin. The higher yield from the Wing River basin is probably due to considerable amounts of water draining from outwash in its headwaters area.

WATER QUALITY

The chemical quality of ground water is related to the composition of the geologic formations through which the water moves, the rate at which the water moves, and the total contact time of the water with surrounding rock types.

Water to be used for irrigation must be of such a quality that it does not impair plant growth or alter soil characteristics. Among the factors to be considered are total dissolved solids, relative proportions of certain ions, and concentration of certain individual constituents. The significance of each of these varies from area to area, and therefore the determined chemical quality must be considered in the light of other known factors such as soil and subsoil characteristics, climate, irrigation water requirements, method of water application, and kind of crops grown.

Table 2 and plate 8 show chemical characteristics of water obtained from various glacial-drift aquifers in and surrounding the study area. On the basis of the most abundant cation and anion, respectively, ground water in the Wadena area can be classified as being of the calcium bicarbonate type. It is characteristically very hard; total hardness for each sample was in excess of 180 mg/l (milligrams per liter). The hardness of the water can be attributed to the abundance

TABLE 2.—*Chemical analyses of*

[Analytical results in milligrams per liter, except temperature, sodium-adsorption-ratio, specific
U.S. Geological

Well		Aquifer type and Composition (all are glacial drift)	Sample		Analysis by	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)
Location	Depth (ft)		Date of collection	Temperature ° (Celsius)					
133.33.12bab	73	Artesian, gravel	6-22-64	11	USGS	21	2.6	0.26	88
133.35.2cab	16	Water table, sand	4-14-67	9	USGS	12	.01	.01	57
133.35.15cdd	150	Artesian, sand			MDH		1.7	.04	88
134.33.23bcc	13	Water table, sand	4-13-67		USGS	17	.03	.39	97
134.33.34baa	81	Artesian, sand	5- 8-67	8	USGS	24	.88	.17	55
134.34.12bad	28	Water table, sand and gravel.	9- 7-66	10	USGS	16	1.8	.31	75
134.34.19abd	50	do	7-21-66	9	USGS	17	.32	.03	96
134.34.30aab	41	do	7- -65		MDH		.73	.23	100
134.34.32dcb	42	do	10- 4-66	9	USGS	16	4.5	.77	93
134.34.35bdd	110	Artesian	7- -66		MDH		.48	.02	60
134.35.5ccc	30	Water table, sand and gravel.	9- 9-66		MDH		.14	.02	116
134.35.7bcb	227	Artesian, sand	9- 9-66		MDH		1.40	.02	64
134.35.10cdc	12	Water table, sand	5- 8-66	7	USGS	10	.13	.11	54
134.36.2dcc	80	Artesian, sand and gravel.	11-21-67	7	USGS	15.2	.05	.07	67
134.36.11bba	30	Water table, sand	5- 8-67	8	USGS	19	.06	.02	98
134.36.36aab	20	do	4-14-67	7	USGS	14	.02	.33	75
135.33.30dcd	50	Artesian, sand	5-15-67		USGS	16	.02	.00	72
135.34.16dbc	60	Water table, sand and gravel.	4-13-67	7	USGS	17	.51	.09	53
135.35.9cca2	141	Artesian, gravel	9-13-65	7	USGS		.74		96
135.35.27dad	14	Water table, sand and gravel.	4-14-67	6	USGS	18	2.1	.72	97

of carbonate rock fragments that are present both in the outwash sand and gravel and in the till.

A relationship exists between the total dissolved-solids concentration and the electrical conductivity of a solution. Figure 14 is a plot of that relationship determined for ground and surface waters in the Wadena area. It can be used to estimate the total dissolved solids in a water sample once the easily obtained specific conductance has been determined.

The sodium-adsorption-ratio is a means of evaluating the risk involved when using water containing sodium for irrigation (U.S. Salinity Lab., 1954). If sodium is present in large amounts, it may be exchanged for calcium and magnesium in the soil with possible deleterious changes in soil structure. Both ground and surface water from the Wadena area have a low sodium hazard as shown in figure 15. The salinity hazard shown in figure 15 is medium to high. This indicated hazard will not be a problem in the Wadena area because good drain-

ground water from the Wadena area

conductance, pH, and color. Agency making analysis: MDH, Minnesota Department of Health; USGS, Survey]

Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Flouride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids (residue on evaporation at 180° C)	Hardness as $CaCO_3$: Total	Hardness as $CaCO_3$: Noncarbonate	Sodium-adsorption-ratio	Specific conductance (micromhos at 25° C)	pH	Color	Use
16	25	1.9	252	96	23	0.10	0	0.24	425	284	77	0.6	639	7.4	5	Municipal.
15	1.3	1.3	240	8.5	1.8	.1	6.5	.09	223	204	7	0.0	382	8.0	4	Domestic.
37	32	1.0	451	55	1.8	.26	7.9	----	610	350	----	.88	760	7.3	----	Municipal (fire protection).
26	4.2	1.4	329	16	16	.1	58	.02	407	349	79	.1	659	7.8	4	Stock.
16	5.7	1.6	255	5.8	1.7	.2	.1	.01	234	203	0	.2	385	8.2	2	Domestic.
21	2.9	1.0	278	14	6.7	.1	31	.02	315	274	46	.1	513	7.8	2	Irrigation.
28	13	1.5	296	37	25	.1	75	.05	441	353	110	.3	715	7.8	2	Do.
24	15	4.0	392	57	15	.18	4.4	----	------	350	----	.35	------	6.9	----	Municipal.
23	3.6	1.3	366	18	6.0	.2	4.6	.04	371	326	26	.1	585	7.6	44	Irrigation.
24	5.6	1.0	415	6.1	10	.35	11.4	----	470	250	----	1.55	655	7.3	----	Creamery.
5	28	1.0	293	54	52	.05	22.3	----	730	320	----	.69	950	7.5	----	Municipal (backwash).
24	27	1.0	366	6	4.3	.31	4.8	----	370	260	----	.73	580	7.5	----	Municipal.
12	1.9	0.4	204	14	3.6	.2	.7	.01	212	184	17	0.0	343	7.7	4	Domestic.
20	2.5	1.5	251	17	5.1	.2	30.5	.02	290	249	44	.07	481	7.9	2	Irrigation.
29	3.5	1.2	261	27	13	.2	138	.02	493	364	150	.10	712	7.8	2	Domestic.
19	9.6	9.8	315	20	7.9	.2	14	.02	330	265	7	.2	551	7.7	5	Stock.
19	2.6	1.0	246	12	3.9	.4	54	.01	306	258	56	.1	491	7.7	2	Do.
20	5.3	1.4	258	12	1.6	.1	0	.02	236	214	2	.2	405	8.0	1	Domestic.
32	9.7 Na+K		469	3.2	2.3	.2	1.7	----	397	372	0	.22	664	8.2	----	Municipal (military).
25	5.2	1.5	410	8.5	6.0	.2	.1	.04	377	345	9	.1	614	7.9	6	Domestic.

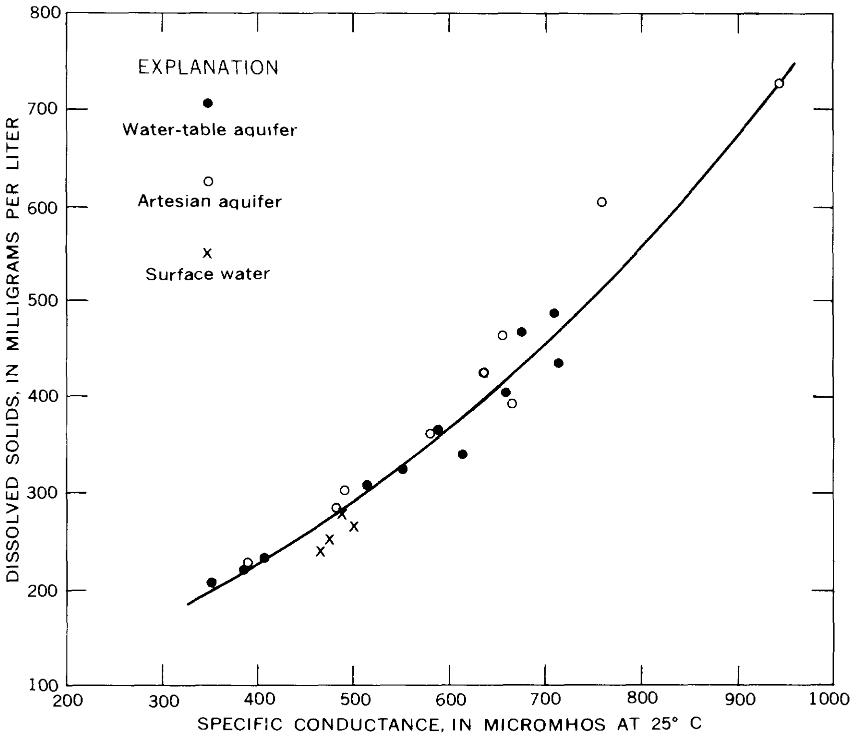


FIGURE 14.—Relationship of specific conductance to total dissolved solids for water from various sources.

age characteristics of soils in the area permit a flushing or leaching of the root zone, and potentially hazardous accumulations of salt will not materialize as they would in an arid region.

Boron was present in small amounts in all waters analyzed, and the maximum concentration of 0.24 mg/l is well below the toxic level even for boron-sensitive plants.

Nitrate concentrations in ground water from the Wadena area are highly variable: determined values range from 0 to 138 mg/l. The local presence of large amounts of nitrate in water can usually be related to activities of man or animals. High concentrations of nitrate often occur in water from shallow water-table aquifers which are subject to pollution from barnyards, septic-tank effluent, or similar sources. Another source of nitrate is agricultural fertilizers, the use of which increases with irrigation. As a result, a nitrate buildup may occur in the ground water in heavily irrigated areas. Caution must be exercised in the use of water for domestic purposes in these areas because a

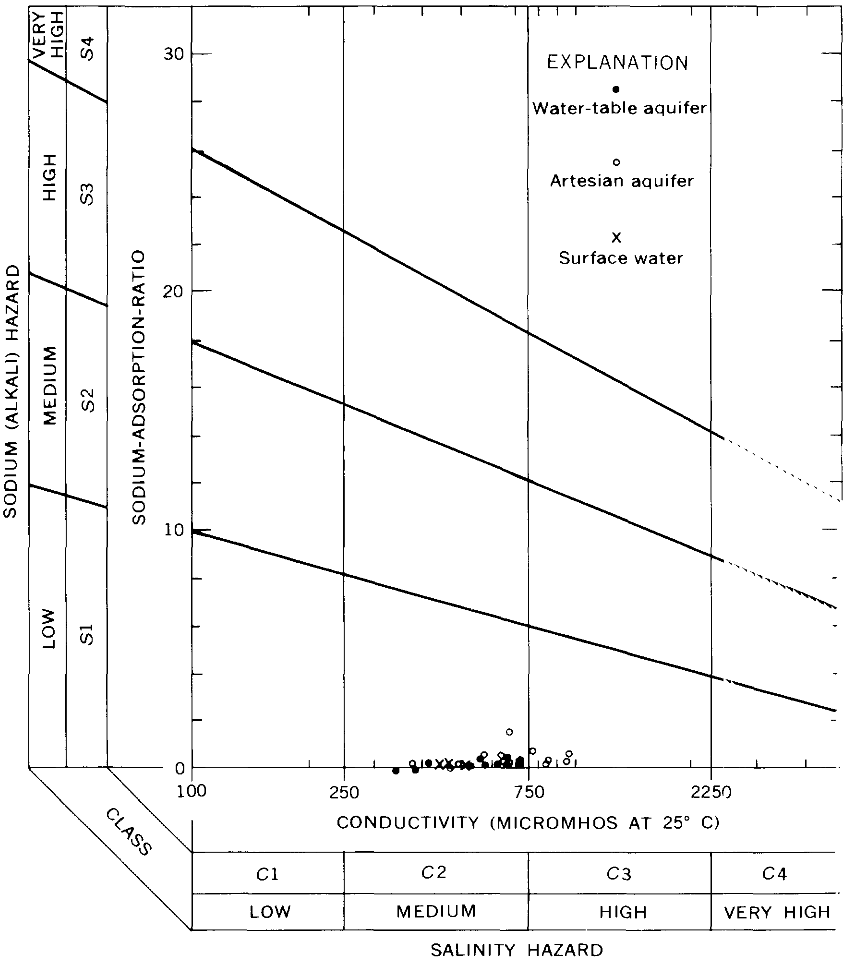


FIGURE 15.—Suitability of ground and surface water for irrigation in terms of sodium-adsorption-ratio and conductivity.

definite link has been determined between nitrate in water and methemeglobinemia in infants, the so-called "blue-baby" disease. Although infants react differently to nitrate poisoning, the U.S. Public Health Service (1962, p. 50) recommends a concentration of 45 mg/l of nitrate as a limit which should not be exceeded.

Locally, dissolved iron and manganese are present in the water in amounts which exceed the U.S. Public Health Service's (1962, p. 43, 47) recommended drinking-water standards of 0.3 mg/l and 0.05 mg/l, respectively. When present in excess, both iron and manganese are objectionable for either domestic or industrial use, but there are no apparent harmful effects on plants if waters containing them are used for irrigation.

Except for generally lower total dissolved solids, surface water in the Wadena area is of the calcium bicarbonate type, and is similar in quality to ground water (table 3 and pl. 8). Surface-water samples listed were collected at near base-flow conditions in October 1967, when nearly all streamflow consisted of ground-water effluent. A decrease in total dissolved solids can be expected at higher discharges.

THE HYDROLOGIC SYSTEM

Continuously operating on and in the geologic framework is the hydrologic cycle. The hydrologic cycle (fig. 16) is the movement of water from the atmosphere to the earth and the ultimate return of water to the atmosphere. Water is thus constantly in motion, although in different forms and at different rates. Over a long period of time, a hydrologic balance is achieved, and inflow to the hydrologic system must be equal to outflow from the system. For any single year, positive or negative changes in the amount of water in storage may occur. When considered over a long period of time, storage gains are balanced by storage losses, and the net change is assumed to be zero.

It is the potential effect of pumping on the natural system which necessitates the present study. Possible changes in the hydrologic system which might result from development are considered later in this report.

INFLOW TO THE SYSTEM

Inflow to the hydrologic system consists of precipitation, streamflow, and underflow. The contribution of each was approximated for 1967 to aid in evaluating the total system.

TABLE 3.—*Chemical analyses of*

[Analysis by U.S. Geological Survey. Analytical results in milligrams per liter, except

Station		Site location	Date of collection	Discharge (cfs)	Temperature (°Celsius)	Silica (SiO_2)	Aluminum (Al)
Identification number	Name						
052452AA	Partridge River near Aldrich.	134.33.15cbb	10-17-67	5.1	8	9.8	0.4
052452AB	Redeye River near Aldrich	135.34.13ddc	10-17-67	22.6	7	13	.4
052452AC	Wing River near Verndale	134.34.8baa	10-16-67	22.2	8	14	.5
052452AD	Leaf River near Verndale	135.34.19daa	10-17-67	44.5	5	5.7	.7

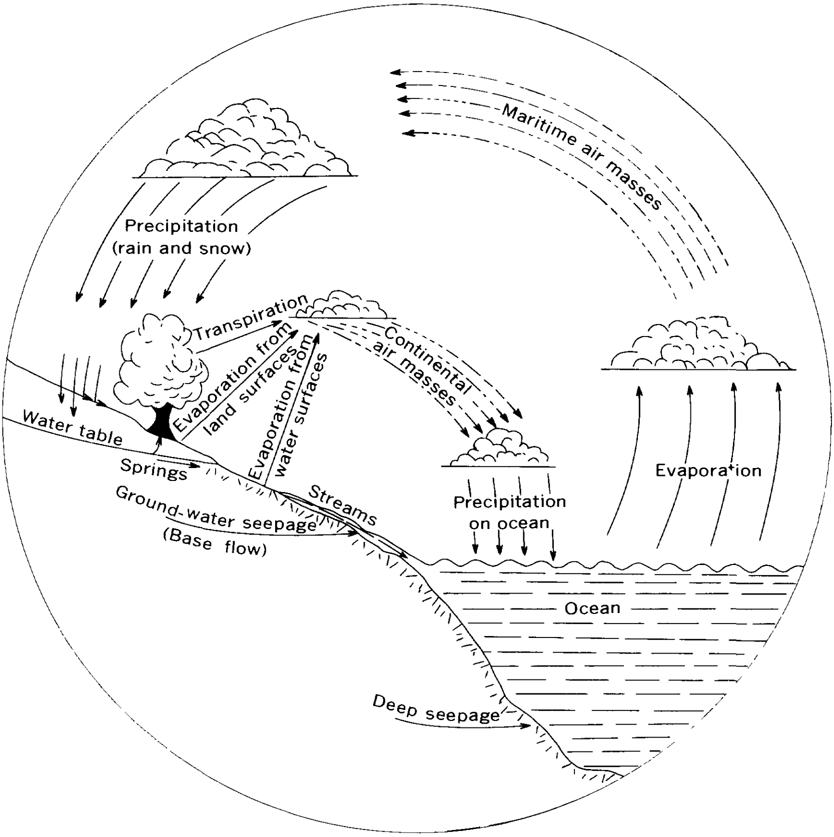


FIGURE 16.—The hydrologic cycle.

surface water from the Wadena area

discharge, temperature, sodium-adsorption-ratio, specific conductance, pH, and color]

Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (HO_3)	Phosphate (PO_4)	Boron (B)	Dissolved solids (residue on evaporation at 180° C)	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Noncarbonate	Sodium-adsorption-ratio	Specific conductance (micromhos at 25° C)	pH	Color
0.03	0.06	70	21	6.6	2.1	297	20	6.4	0.2	3.1	0.06	0.02	286	261	17	0.18	487	7.6	14
.03	.13	66	20	7.0	1.7	302	5.2	3.0	.1	.2	.12	.02	276	246	0	.17	462	7.8	12
.04	.07	72	22	5.2	1.5	299	20	3.6	.1	8.4	.01	.03	297	270	25	.14	500	9.8	11
.03	.19	65	23	6.0	1.9	304	13	3.6	.2	.2	.02	.03	290	256	7	.16	473	8.0	11

PRECIPITATION

Precipitation is the largest source of inflow to the hydrologic system in the Wadena area. A frequency-distribution curve of annual precipitation at the U.S. Weather Bureau station in Wadena indicates the recurrence intervals of the amounts of precipitation received in years antecedent to and coincident with the period of study (fig. 17). Specific years shown represent above-normal (1965), near-normal (1966), and below-normal (1967) precipitation. Average annual precipitation for the period of record was 26.4 inches, of which 67 percent occurred during the growing season (May–September). The amount of precipitation during the growing season is highly variable, ranging from 45 to 87 percent of the yearly total. Precipitation in the nongrowing

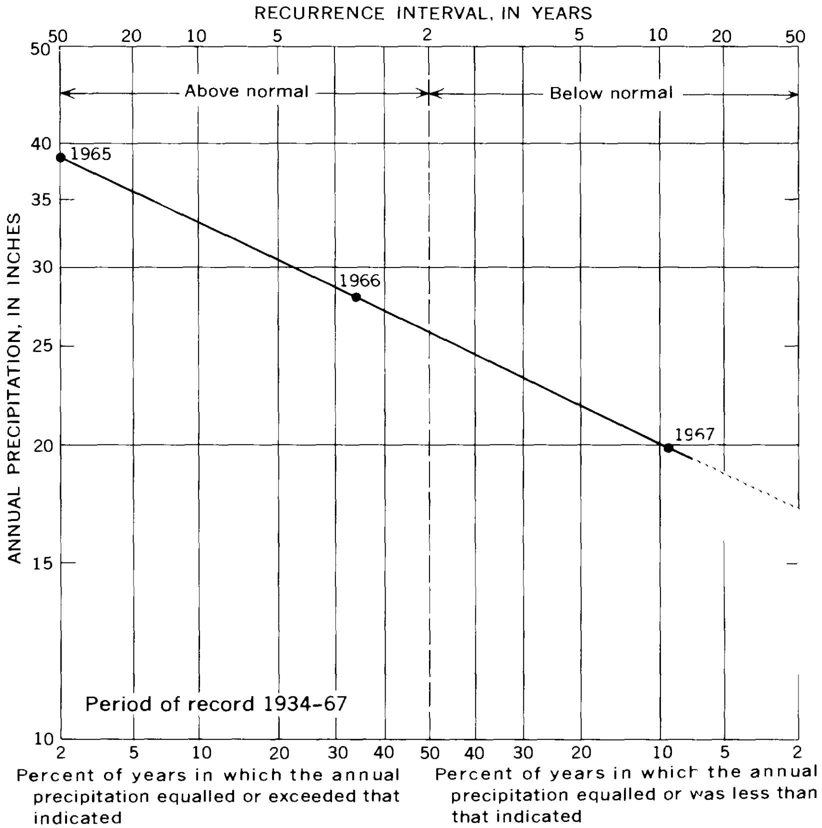


FIGURE 17.—Precipitation-frequency curve based on data from the United States Weather Bureau Station in Wadena.

season falls mainly as snow and is available for recharge in the spring when thawing occurs. Precipitation values plotted as totals for 5-day intervals are shown with ground-water hydrographs on plate 3. The local nature and the timing of summer thunderstorms and the wide range in total rainfall during the growing season point out the unreliability of natural precipitation as the only source of water for crop production.

In 1967, precipitation falling on the Wadena area accounted for approximately 163,000 acre-feet of water.

STREAMFLOW

Water in streams entering the study area is potentially available for use within the area. Streamflow entering the area during October 16–18, a period of low flow, was about 41 cfs, as shown on plate 7. In the spring and early summer, considerably larger flows can be expected. Provisional records from a gaging station on the Crow Wing River at Nimrod (10 miles north of the study area) indicate that discharge at that station during October 16–18, 1967, was about 360 cfs, or 60 percent of the 1967 average discharge. If flow characteristics of streams in the Wadena are comparable to those of the Crow Wing River, total inflow as streamflow into the Wadena area in 1967 was approximately 50,000 acre-feet. A flow duration curve for the Crow Wing River at Nimrod (fig. 18) indicates that the discharge during October 16–18, 1967, is exceeded about 50 percent of the time. If similar flow characteristics are assumed for streams in the Wadena area, about half of the time inflow as streamflow can be expected to exceed that determined in October, 1967.

UNDERFLOW

The study area is in part bounded by relatively impermeable till through which underflow is minimum (fig. 5). Where permeable outwash deposits extend beyond the study area, underflow is considerably greater. Preliminary calculations indicate that the amount of water entering the study area as underflow in 1967 was about 1,000 acre-feet. Most of the underflow enters the study area along the southwestern extension of the outwash deposits.

OUTFLOW FROM THE SYSTEM

Outflow from the hydrologic system consists of evaporation, transpiration, streamflow, and underflow. The amount of water leaving the Wadena area by each of the processes was approximated for 1967.

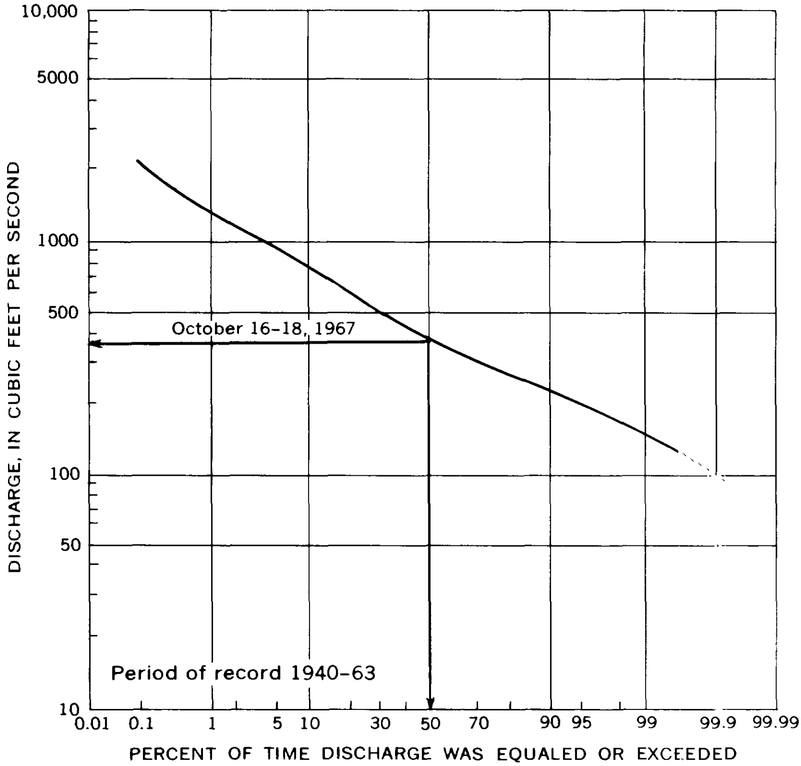


FIGURE 18.—Flow duration curve for the Crow Wing River at Nimrod.

EVAPORATION AND TRANSPIRATION

Water losses to the atmosphere, by evaporation from land and water surfaces and by transpiration from plants, are large in the Wadena area. They are, in large part, a function of temperature and time of precipitation; therefore they vary considerably throughout the year. An empirical method for calculating the combined water losses through evapotranspiration (evaporation and transpiration) was developed by Thornthwaite and Mather (1957). To demonstrate differences in evapotranspiration during dissimilar climatic years, calculations of evapotranspiration were made for 1965, a wet year, 1966, a near normal precipitation year, and 1967, a dry year (fig. 19).

Late winter snows followed by excessive spring rainfall produced a large moisture surplus in the first half of 1965. In spite of this, low precipitation during the summer resulted in a period of moisture deficiency at a time when moisture was needed most for plant growth. Precipitation was better distributed in 1966, and moisture conditions for plant growth were more favorable. Even then, some moisture deficiencies did occur in the early summer and fall. Climatic conditions during the following winter and spring were such that there was little moisture surplus in the first half of 1967, and abnormally low precipitation in the last half of the year resulted in extreme moisture deficiencies. Each year, periods of insufficient moisture for optimum plant growth occurred during the growing season, when the potential for evapotranspiration exceeded the available soil moisture. Precipitation which falls during the growing season is in large part lost as evapotranspiration or is utilized by plants and is not available for recharge to the water table.

The Thornthwaite diagram for 1934–67 shows that, on the average, moisture deficiencies are greatest during June, July, and August. Because the time of moisture deficiencies coincides with the prime growing season, supplemental irrigation is needed.

Development of the ground-water supply will result in increased evapotranspiration losses in irrigated areas, where more water is made available to plants and to the land surface. By the same token, the withdrawal of large quantities of ground water produces a lowering of the water table and a resultant decrese in evapotranspiration losses in areas of high water table. As water levels drop, evaporation losses decrease in areas of open water or high water table; transpiration losses from water-wasting plants which grow in these areas also decrease. A controlled lowering of the water table may therefore be desirable so that a larger part of the total water available can be put to beneficial use. Calculations by the Thornthwaite method indicate that approximately 143,000 acre-feet of water was available for evapotranspiration in 1967.

STREAMFLOW

Streamflow losses from the area include direct overland runoff and that part of the total flow which originated as ground-water discharge. Based on comparative records from the Nimrod gaging station, total streamflow from the Wadena area in 1967 was approximately 115,000 acre-feet. The difference between streamflow leaving and streamflow entering (total streamflow pickup) was about 65,000 acre-feet.

UNDERFLOW

The amount of water leaving the Wadena area as underflow is small compared with that leaving as evapotranspiration and streamflow. In 1967, underflow amounted to less than 500 acre-feet, most of which occurred along the southeastern extension of the outwash deposits. Changes in the amount of underflow are reflected by head changes as indicated by fluctuating ground-water levels. Because water-level changes are generally small with respect to the total saturated thickness, changes in underflow must be correspondingly small.

WATER BUDGET

A compilation of inflow-outflow items results in the following hydrologic budget for the Wadena area in the 1967 calendar year:

	Inflow (acre-ft of water)		*Outflow (acre-ft of water)*
Precipitation	163,000	Evapotranspiration	143,000
Streamflow	50,000	Streamflow	115,000
Underflow	1,000	Underflow	-------
Total	214,000	Total	258,000

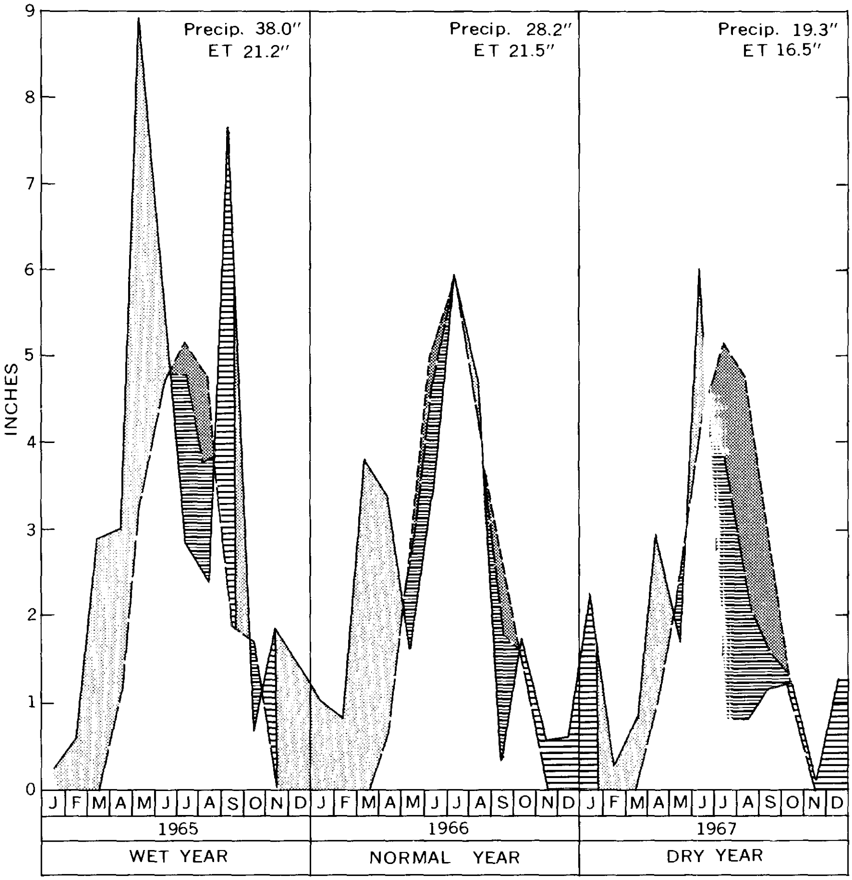
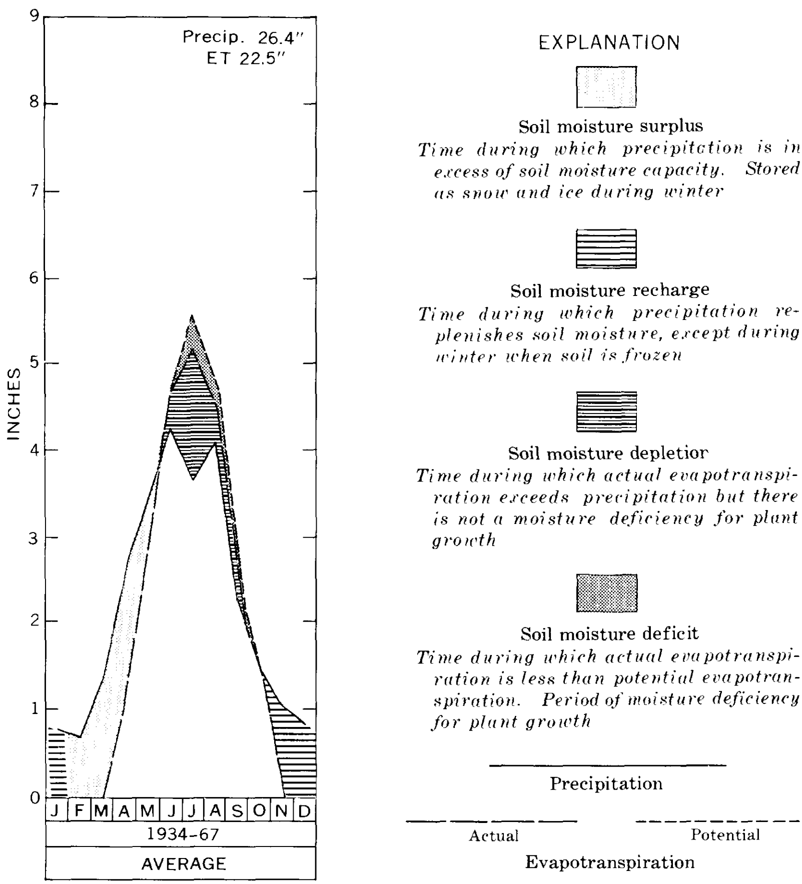


FIGURE 19.—Effects of evapotranspiration (ET) on soil-moisture conditions by the

Because 1967 was a relatively dry year, negative changes in the amount of water in storage resulted. For this study, changes in ground-water storage only were determined; changes in surface-water storage and in soil-moisture storage were considered negligible. The amount of change in ground-water storage was determined from hydrographs (pl. 3) by multiplying the specific yield of the aquifer by the net decline of water levels between January 1, 1967, and January 1, 1968 (fig. 9). Total change in ground-water storage over the entire study area in 1967 was calculated to be about −44,000 acre-feet of water. This agrees with the amount by which outflow exceeded inflow in 1967, as shown above.



during dissimilar climatic years compared with long-term averages determined Thornthwaite method.

ELECTRIC ANALOG MODEL

Electric analog techniques aid in the understanding of the hydrologic system and in the determining of effects of development on that system. Basic geologic and hydrologic information is represented in the model by an analogous electrical component. Because of the complexity of most hydrologic systems, generalizations must be made for modeling purposes. Assumptions made in modeling the aquifer and its hydrologic characteristics are: (1) The aquifer is isotropic and homogeneous; (2) all flow in the aquifer is two dimensional, and no vertical component is modeled; and (3) prior to each pumping period, the hydrologic system is at equilibrium. Although the above generalizations do not permit detailed analysis around a single well site, regional effects of development on water levels can be approximated. Advantages of the electric analog approach include (1) relative simplicity of design of a complex natural system, (2) speed of analysis in determining long-term effects of pumping from a large ground-water system, (3) ability to manipulate on the electrical model those variables whose actual hydrologic equivalent might be difficult to determine, and (4) availability of the basic model for future analysis when more hydrologic data becomes available. No attempt will be made to elaborate on the theory of electric analog modeling. Rather, discussion is directed toward hydrologic principles involved and the predicted effects of development on the hydrologic system. The theory and instrumentation of electric analog modeling have been described in detail by Skibitzke (1960). Design methods for simulating pumped-well characteristics have been described by Prickett (1967); such detail is not necessary for a regional evaluation of the hydrologic system.

PRINCIPLES OF ELECTRIC ANALOG MODELING

The flow of electric current through conducting materials is analogous to the flow of water through porous media. An expansion of this analogy resulted in the use of electric analog models in water-resources investigations. The analog model is basically a regular network of resistors and capacitors which represent a scaled-down version of the shape, size, and hydrologic characteristics of the aquifer being studied. Resistors are inversely proportional to transmissivity. They impede the flow of electricity in a manner similar to the way the aquifer itself impedes the flow of water. Capacitors are in direct ratio to storage coefficient. They store electrical energy in a manner similar to the storage of water in the aquifer. Proportionalities also exist between hydraulic head and voltage, and between volume rate of ground-water flow and electrical current flow.

CONSTRUCTION OF THE WADENA ANALOG MODEL

An analog model of the water-table aquifer in the Wadena area was constructed by the Analog Model Unit of the U.S. Geological Survey in Phoenix, Ariz. (fig. 20). The two-dimensional resistor-capacitor network was constructed at a scale of 1 inch equals half a mile. Resistors used to simulate transmissive characteristics of the aquifer are representative of transmissivity values generalized from plate 5.

The model was first constructed to simulate a steady-state condition in which inflow to the system equals outflow from the system. After a reasonable electronic representation of the real system was achieved under steady-state conditions, the model was altered so that stress variations with time might be analyzed. Capacitors simulating a uniform storage coefficient of 0.15 were added to represent electrically the storage of water in the aquifer.

VERIFICATION—STEADY STATE

To check the similitude of the analog model with its actual physical counterpart, the analog model was first tested under steady-state conditions—that is, apart from variables such as pumping and precipitation which might act upon it. In the steady-state condition, the long-term average inflow to the hydrologic system is assumed to be equal to the long-term average outflow from the system. Inflow-outflow relationships for 1967 were used as a guide in estimating long-term inflow-outflow entries used in designing the model. An electrical current representing inflow-outflow characteristics was passed through the resistance network. The established distribution of electrical potential on the model was compared with hydraulic potential established by the flow of water in the aquifer (water-table map, pl. 2). When a reasonable match is obtained between the electrical potentials in the model and hydraulic potentials in the real system, the model can be inferred to be a reasonable representation of the hydrologic system. Once so verified, the model can be used with some degree of confidence to analyze the effects of stresses which might be applied to the hydrologic system.

DESIGN—NONSTEADY STATE

A hydrologic system operates in response to a complex set of conditions which vary in degree and time. As a result, at any given time, steady-state conditions in which inflow equals outflow are approached but not realized in the actual hydrologic system. To allow for such variations in the hydrologic system, capacitors representing storage characteristics of the aquifer were added to the model. When the water-table aquifer is stressed (pumped), all water removed from it does not come from storage. Induced changes in the hydrologic system which might result from pumping are illustrated in figure 21. As a result of these changes, additional water is made available for beneficial use. A brief discussion of each of the possible changes and the means by which it was simulated in the electric model follows.

SALVAGED EVAPOTRANSPIRATION

Thirty to forty percent of the study area consists of organic soils, peat, and muck. (See pl. 2.) Most such areas have a high water table, commonly less than 2 feet below land surface. In wet years, considerable areas of open water may occur in the spring and early summer. Water losses by evaporation from such areas and transpiration losses from plants growing in and along them may be considerable. As determined by the Thornthwaite method (fig. 19), average evapotranspiration losses are generally in excess of 20 inches per year. If the water table were lowered owing to stresses placed upon the groundwater system (pumping), some of the water previously lost through

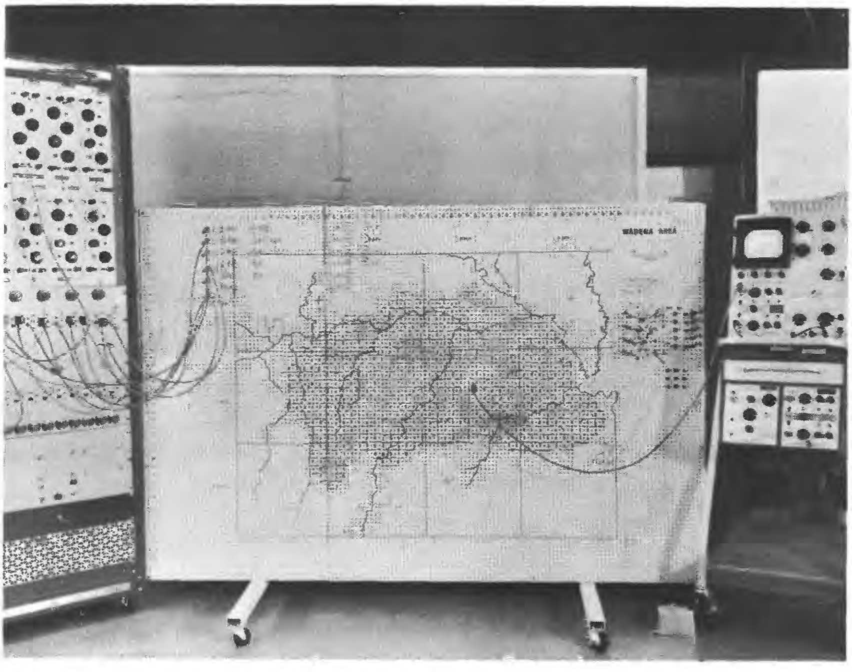


FIGURE 20.—Wadena analog model and electronic equipment used in analysis.

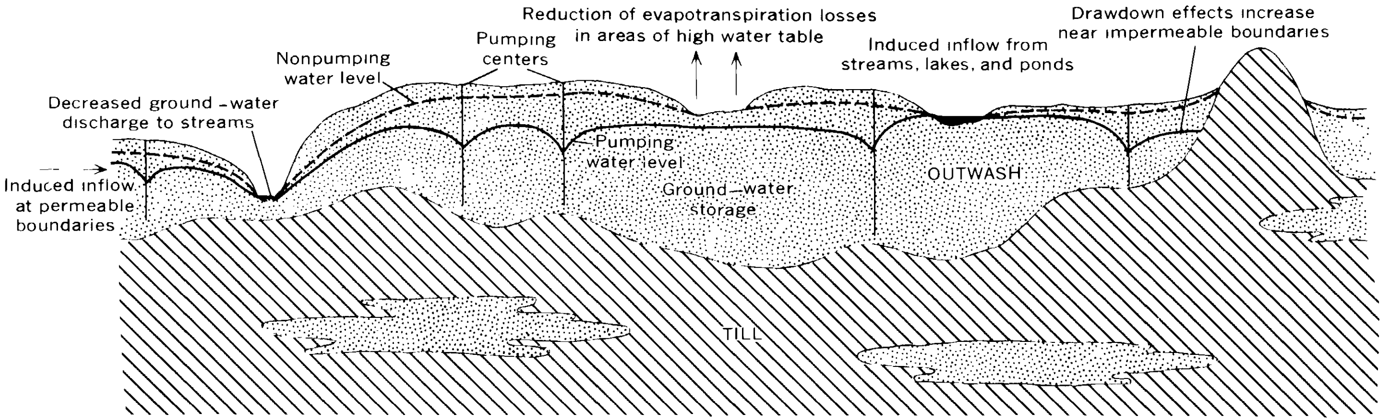


FIGURE 21.—Diagrammatic section illustrating changes in the hydrologic system which might result from pumping.

evapotranspiration could be salvaged for beneficial use. Although actual amounts of salvagable evapotranspiration are not known, a maximum of 10 inches over the entire area was assumed. It was further assumed that salvage begins when lowering of the water table begins and that it continues until the water table is lowered 5 feet. After a 5-foot lowering of the water table, water losses by evapotranspiration are minimized, and a maximum amount of potential water loss is salvaged. On the analog model, salvagable evapotranspiration is represented by current-limiting field-effect diodes. Although excessive lowering of the water table is to be avoided, a controlled lowering may be desirable because more water is made available for beneficial use.

STREAMS

All streams in the study area are gaining streams—that is, they receive ground-water discharge. Because of this, water which might be available for beneficial use within the study area flows out of the area. Some of that water might be salvaged by pumping from the water-table aquifer, thereby intercepting ground water which would otherwise reach the stream. If a stream originates outside the study area, only that part of the discharge which originates within the study area was assumed to be available to wells. As modeled, total recoverable streamflow during any single year is about 55,000 acre-feet, which is about 85 percent of the average annual streamflow pickup in the Wadena area. On the analog model, streams were modeled as 2- to 3-mile scaled segments along which base-flow pickup was designated as determined in the field.

BOUNDARIES

The study area is part of a larger outwash body and does not represent a distinct geologic or hydrologic unit. Conditions surrounding the study area must be considered because water and its movement have no respect for arbitrary study-area boundaries.

Boundary conditions as modeled are shown in figure 22. Where the outwash deposits extend beyond the limits of the study area, the model was also extended to simulate underflow. Where bounded by a perennial stream, a constant-head boundary was assumed. For practical purposes, till boundaries were modeled as being impermeable.

ANALYSIS

To simulate pumping stresses which might be applied to the hydrologic system, electric current pulses were applied to the analog model by electronic function generators. Voltage changes across the

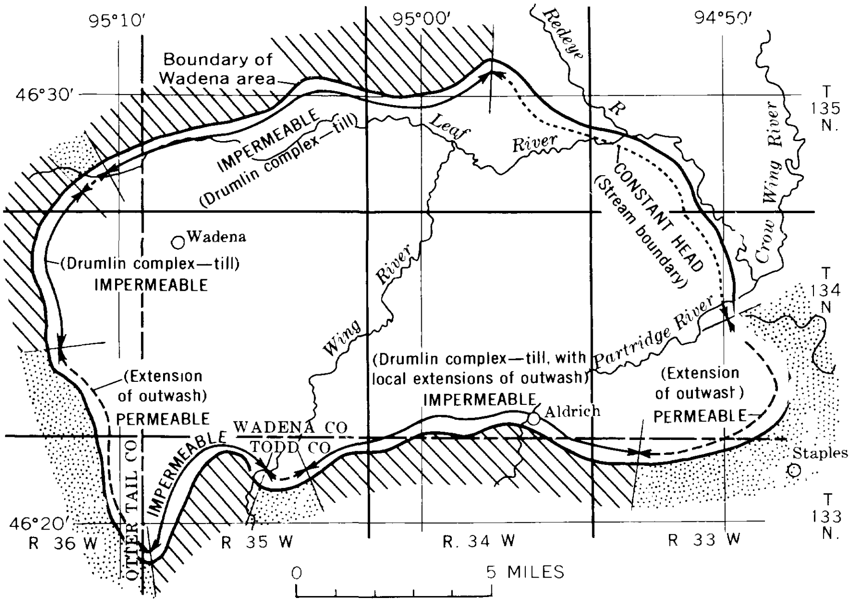


FIGURE 22.—Modeled boundary conditions.

resistor-capacitor network were measured with an oscilloscope and converted to equivalent water-level changes. Applied stresses represent ground water pumped from a selected pattern of development for a selected period of time. Assumptions made concerning simulated wells and effects of pumping them are:

1. All wells fully penetrate the water-table aquifer.
2. All wells have a large radius, and water-level change predictions cannot be made closer to the well than the simulated well radius. However, the model was designed so that pumping at rates indicated on plate 6 will result in a drawdown of two-thirds the saturated thickness in an actual well having a radius of 7.5 inches.
3. The decrease in saturated thickness and the resultant change in transmissivity, which occurs when an unconfined aquifer is stressed, was compensated for by theoretically decreasing the available saturated thickness.

Some comments relative to the effect of each of the above assumptions are necessary.

In actual practice, most irrigation wells in the area are fully penetrating; therefore, partial-penetration effects require no further discussion.

By use of a method derived by Prickett (1967, p. 39–41), it can be shown that the wells simulated on the Wadena model have a radius of about 550 feet. This is many times larger than the radius of any wells which might actually be used. Because of this, water-level changes at a pumped-well junction actually represent changes which might occur 550 feet from the center of the well. Water-level changes closer than 550 feet from a pumped well will be in excess of those determined from the model. Although Prickett (1967, p. 41–42) has shown that a well with any given radius can be simulated, for the purposes of this regional evaluation, such detail was not considered necessary.

Saturated thickness of the surficial outwash aquifer is highly variable in the Wadena area (pl. 4). Where the aquifer is thin, desired large yields may be unobtainable from a single well. In such areas, several properly spaced wells of lower yield might be the most practical way to obtain the desired yield without adversely causing dewatering of the aquifer.

The answers to two specific questions were sought by use of the analog model: (1) what are the effects of pumping on the ground-water system under various plans of development during a single irrigation season, and (2) what are the cumulative effects of pumping on recovery water levels under various plans of development after 5 and 20 successive years of pumping? Because pumping effects are dependent upon both the degree of development and the period of pumping, analyses were made at the single-well rate for present development, for a hypothetical 5-year development plan, and for a hypothetical 10-year development plan. The 5-year and 10-year development plans include existing irrigation wells plus wells arbitrarily located in areas favorable for irrigation where future development is most likely to occur (personal communication with farmers, U.S. Department of Agriculture, and County Extension Service personnel). Hypothetical wells were not placed in areas where ground-water potential of the water-table aquifer does not appear to be adequate for irrigation.

In some areas, because of existing topographic, hydrologic, or soil conditions, supplemental irrigation is not feasible at the present time. Hypothetical wells were not placed in such areas under the 5-year and 10-year development plans. To evaluate the potential of the water-table aquifer throughout the entire study area a regional analysis was made with uniformly spaced pumping centers. A single pumping center was assumed for each section (1 sq mi, or 640 acres). Analysis was made to determine water-level changes when pumping at a rate equivalent to two wells per pumping center.

On the basis of past irrigation practices and with allowance for possible extreme drought conditions, the maximum total pumping time for any one irrigation season was assumed to be 30 days. This would represent an extreme stress which might be appiled to the groundwater system. Shorter pumping periods would have correspondingly less effect on the system.

PRESENT DEVELOPMENT

During 1967, water for supplemental irrigation was withdrawn from the water-table aquifer at 16 pumping centers. One of the pumping centers on the analog model represents the village of Verndale's public-supply well which is completed in the water-table aquifer. Pumping centers shown may or may not coincide with actual well sites. Locations depend upon the scale of the analog model and the mesh size of the resistor-capacitor network. Quantities of water withdrawn were 1967 actual pumping totals for each existing pumping center. Declines in pumping water levels just prior to the end of the irrigation season are shown on plate 9. Declines shown are the result of pumping only and do not include normal seasonal fluctuations. They are regional approximations and are not indicative of what might happen in proximity to the pumped well. Water-level declines in the immediate vicinity of the pumped well will at all times be in excess of those shown.

Under the present pattern of development, water-level declines as a result of pumping for 30 days are less than 2 feet, with a single exception. The exception occurs in section 22, T. 134 N., R. 33 W., where the pumping is from a dug pit at a rate in excess of that which might be obtained from a well.

Within 2 weeks after simulated pumps were turned off at the end of the irrigation season, water levels recovered to essentially the level they would have attained had there been no pumping. Total pumpage from the water-table aquifer for irrigation in 1967 was about 625 acre-feet.

HYPOTHETICAL 5-YEAR DEVELOPMENT PLAN

Fifty-one pumping centers are represented on the hypothetical 5-year development plan. They represent the 17 existing centers, as of 1967, plus an additional 34 hypothetical pumping centers. For uniformity and ease of analysis, pumping rates of 300, 600, or 900 gpm were applied as indicated. Plate 6 was used as a guide for assigning hypothetical pumping rates for each well for this and the 10-year development plan.

Plate 10 shows the resultant pumping water-level decline just prior to the end of a single irrigation season of 30 days. Where development is spotty, water-level declines are negligible. Where wells are grouped, the effects of interference between wells become apparent. The largest concentration of wells is in the vicinity of Verndale, where, despite relatively high ground-water potential (pl. 5), considerable water-level declines occur. Large declines in the vicinity of sections 1 and 2, T. 134 N., R. 34 W., can be related to highly variable geologic and hydrologic conditions where average ground-water potential is relatively low. When simulated pumping was terminated at the end of the irrigation season, recovery was rapid and essentially complete in all areas prior to the start of the next irrigation season. Cumulative residual drawdown of water-level (change in water-level due to incomplete recovery after pumping) after 5 and 20 successive years of cyclic pumping was determined. Although water-level recovery is not complete locally, in no area is the residual drawdown in excess of 1 foot prior to the start of the next irrigation season. Figure 23 is a

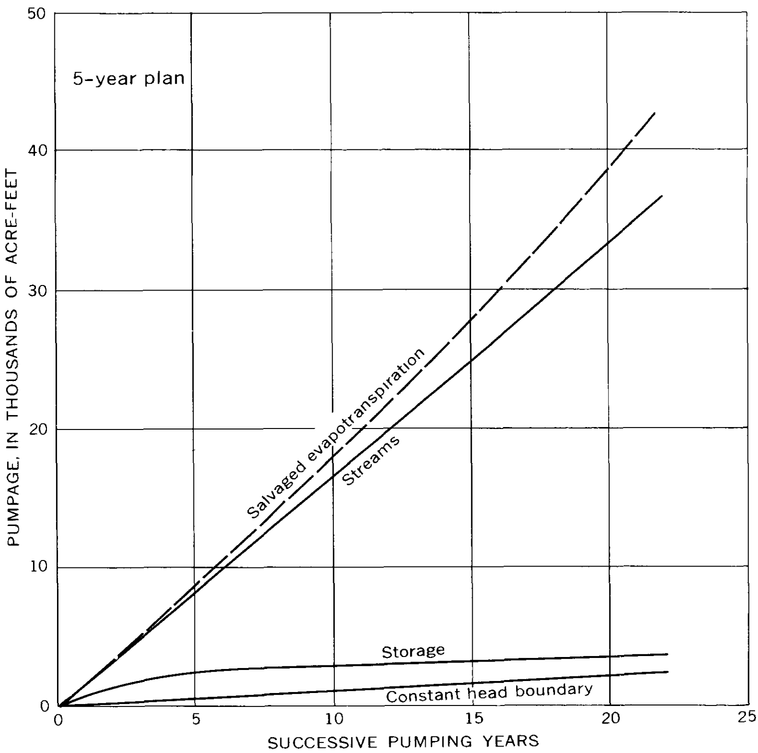


FIGURE 23.—Time-volume relationships of water withdrawn from each modeled component of the hydrologic system for the 5-year development plan.

time-volume graph indicating the relative amounts of water withdrawn from each modeled component of the hydrologic system for the 5-year development plan.

At any selected time, total cumulative withdrawal can be estimated by summing all of the modeled components. For example, after pumping wells comprising the 5-year development plan for 5 years, total withdrawal is about 20,000 acre-feet of water, or 4,000 acre-feet per year. Of the 20,000 acre-feet total, 8,800 acre-feet is salvaged evapotransportation losses, 8,200 acre-feet is salvaged streamflow, 2,500 acre-feet is from storage, and 500 acre-feet is from the constant-head stream boundary.

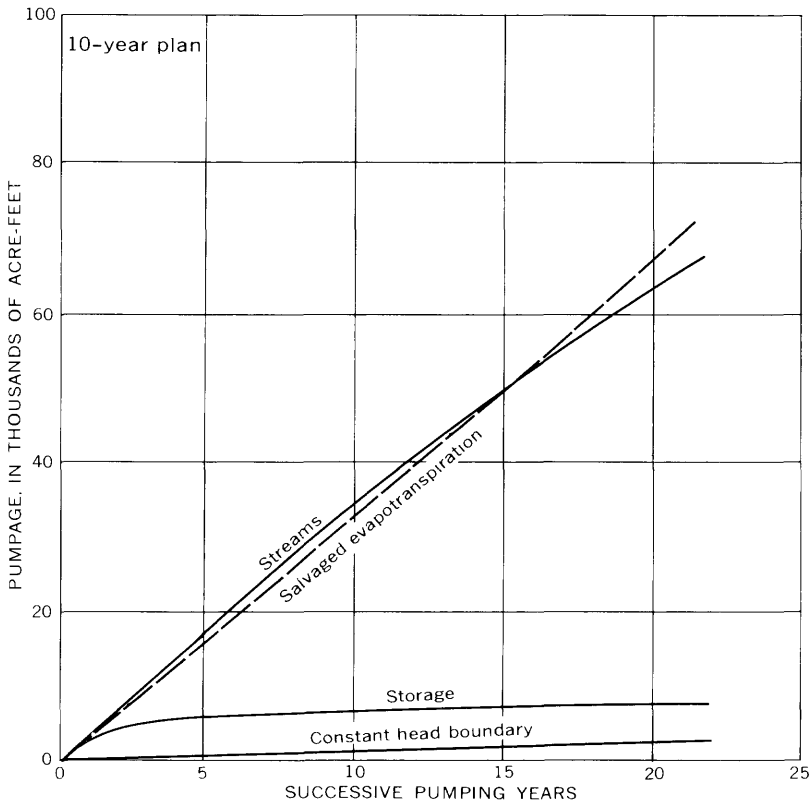


FIGURE 24.—Time-volume relationships of water withdrawn from each modeled component of the hydrologic system for the 10-year development plan.

HYPOTHETICAL 10-YEAR DEVELOPMENT PLAN

The addition of 46 pumping centers to the hypothetical 5-year development plan comprises the hypothetical 10-year plan. Just prior to the end of a single irrigation season, the pumping water-level de-lines shown on plate 11 might be anticipated. With increasing development, the amount of lowering of the water table as a result of pumping increases. In some areas, the regional decrease in saturated thickness may result in decreased discharge at the well, thereby necessitating the drilling of additional wells to meet water requirements. Water-level recovery after a single irrigation season is essentially complete prior to the beginning of the next irrigation season. After 5 successive years of cyclic pumping, cumulative residual drawdown exceeds 1 foot in several areas, as shown on plate 11. Total residual drawdown after 20 successive years of cyclic pumping is essentially the same as after 5 years. This indicates that after 5 years of pumping, a pseudo-equilibrium is reached each year during the recovery period and prior to the next pumping cycle. The proximity of pumping centers to impermeable boundaries along the southern edge of the study area results in accentuated water-level declines. Figure 24 is a time-volume graph indicating the relative amounts of water withdrawn from each modeled component of the hydrologic system for the 10-year development plan.

Total withdrawal after 5 years of pumping (determined by summing all of the modeled components) is about 40,000 acre-feet of water, or 8,000 acre-feet per year.

HYPOTHETICAL MAXIMUM DEVELOPMENT PLAN

To determine the maximum ground-water potential of the water-table aquifer, hypothetical pumping centers were uniformly spaced at 1-mile intervals throughout the area of study. A total of 150 such pumping centers are represented in the selected hypothetical maximum development plan. The pumping rate for each discharge site is based on the average hydrologic characteristics for that section (1 sq mi) in which the discharge site is centered. It was assumed that one well pumping at the selected rate would not exceed aquifer potential; therefore analysis was made at pumping rates equivalent to two wells per pumping center (at rates of 600, 1,200, and 1,800 gpm). Withdrawal at these rates may not be possible from a single well. Instead, several wells, properly spaced, might be necessary to obtain the designated yields.

To avoid mapping excessively large drawdowns near pumping centers if the model is stressed at rates greater than that for a single well, the model was probed at grid junctions greater than one grid interval (half a mile) from pumping centers. By analyzing in this manner, only theoretical regional water-level declines were determined. Water-level declines in the vicinity of each simulated pumping well will always be greater. The resultant regional residual drawdown of water-level after 20 successive years of cyclic pumping is shown on plate 12. Declines shown are essentially the same as those obtained after 5 years of cyclic pumping, which indicates that a pseudo-equilibrium is reached each year during the recovery period and prior to the next pumping cycle. Figure 25 is a time-volume graph indicating the relative amounts of water withdrawn from each modeled component of the hydrologic system when withdrawal is at rates equivalent to two wells per section. Total withdrawal after 5 years of pumping,

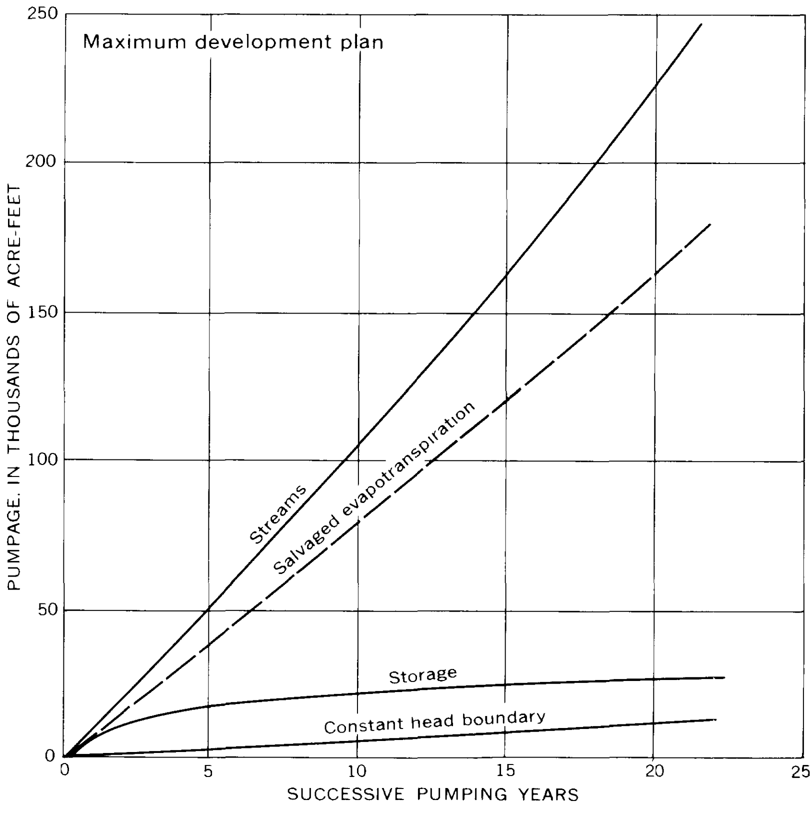


FIGURE 25.—Time-volume relationships of water withdrawn from each modeled component of the hydrologic system for the maximum developmert plan.

determined by summing all of the modeled components, is about 115,000 acre-feet of water, or 23,000 acre-feet per year.

In each development plan, streams contribute the largest, or nearly the largest, amount of water. Because of this, some of the smaller tributary streams which originate in the study area would probably be dry each year during the pumping period, even before development nears a hypothetical maximum. Larger perennial streams such as the Leaf and Wing Rivers will continue to flow, but flow may be limited to the amount of water that they carry into the study area. For the 5-year and 10-year development plans, nearly equal amounts of water are withdrawn from streams and salvaged evapotranspiration. The percentage of water withdrawn from storage decreases rapidly after the first several years when changes in the hydrologic system result in greater contribution from the other components.

In the 5-year, 10-year, and maximum development plans, applied pumping rates are hypothetical. Because of this, caution must be used in interpreting the water-level-decline maps. Where small or no water-level declines are shown, applied pumping rates may be minimum approximations, and the area's ground-water potential may be greater than anticipated. Conversely, where large water-level declines occur, applied pumping rates may be greater than those which the area might safely support. It follows that changing the pumping rates would increase or decrease the resultant water-level declines. With this in mind, the water-level-decline maps based on data obtained by electric analog analysis can be used to estimate practical pumping rates for any selected area.

CONCLUSIONS

The water-table aquifer is the most readily available source of large quantities of good quality ground water in the Wadena area. The aquifer is composed of well-sorted outwash sand and gravel and has a low clay content. Ground-water availability, which is not uniform throughout the area, is dependent upon texture and saturated thickness of the aquifer materials. The distribution of outwash sand and gravel is in large part dependent upon position with respect to buried or partially buried drumlins. Outwash materials are thickest in swales between drumlins and thinnest on the crests of buried drumlins. Depth to water is greatest in upland areas near major streams, where the water table may be 20 feet below land surface; and it is least in former drainage courses and flood-plain areas, where it is commonly less than 5 feet below land surface.

Ground-water availability is greatest in alluvial deposits on the flood plain of the Leaf River. In the eastern quarter of the study area, water-yielding capacity of the water-table aquifer is less because of the fine texture and uneven distribution of outwash materials. Transmissivity of the water-table aquifer in most of the study area ranges from 15,000 to 120,000 gpd per ft. In approximately 60 percent of the area, the water-table aquifer should be capable of supplying more than 300 gpm to a well for an assumed pumping period of 30 days if drawdown in the pumped well is two-thirds the saturated thickness after correction for dewatering.

Recharge to the water-table aquifer is not uniform in all areas, as evidenced by variations in the pattern of water-level fluctuations. In 1967, recharge to the surficial aquifer averaged 8 inches of water, or 40 percent of the total precipitation for that year.

Ground and surface water are closely interrelated in the Wadena area. Induced changes in one will result in changes in the other. The withdrawal of large quantities of ground water will decrease ground-water discharge to streams. If it is desirable that some minimum base flow be maintained in larger streams, the amount of ground-water withdrawal near these streams may have to be regulated.

Water quality in the Wadena areas is generally good for irrigation purposes. Large amounts of carbonate rock fragments in the glacial drift result in very hard water and correspondingly high total dissolved solids. Because of the excellent drainage characteristics of soils in the area, there is little danger of harmful salt accumulations in the soil as a result of irrigation. Locally, nitrate concentrations, potentially harmful to infants, occur in the ground water because of contamination from barnyard or sewage effluent or owing to the increased use of fertilizers in irrigated areas.

Calculations based on 1934–67 climatic records indicate that about 85 percent of the area's average annual precipitation of 26.4 inches leaves the area by evapotranspiration. A reduction of evapotranspiration losses would make more water available for beneficial use. This could be accomplished by a controlled lowering of the water table by ground-water withdrawal. At the same time, ground-water discharge to streams would be diminished and additional water would be salvaged for use in the area.

An electric analog model of the water-table aquifer in the Wadena area was built to determine effects of different plans of development on the ground-water system. Under present development and actual pumping rates, ground-water withdrawal for irrigation has little discernible effect on the regional water table. When pumping is terminated at the end of an irrigation season, water levels recover rapidly to near the level they would have attained had there been no pumping. On all hypothetical development plans, pumping rates of 300, 600, or 900 gpm were applied, on the basis of existing hydrologic conditions. Where development is concentrated, interference can be expected between wells, resulting in an accentuated lowering of the water table.

Several hypothetical development plans were analyzed with the analog model to estimate total cumulative pumpage for any selected number of years and what part of that total is derived from each component of the modeled hydrologic system.

A hypothetical maximum development plan was analyzed to determine the degree of development which the water-table aquifer in the entire area of study might support. Analysis indicated that as much as 23,000 acre-feet of water might be withdrawn during a single irrigation season without seriously lowering water levels. However, it is highly improbable that such a degree of development will ever be reached; even if it is reached, total ground-water withdrawal for a single pumping season would be only a third of the recharge to the water-table aquifer, as determined for 1967. Such a rate of withdrawal is impractical because continued pumping at that rate would lower the water table and decrease saturated thickness in some areas so that required yields could no longer be attained.

ADDITIONAL DATA NEEDS

Although much was learned about water resources in the Wadena area during this study, many questions remain unanswered. Some of the answers can be obtained by more detailed local investigations, whereas others are time-dependent, and only the type of data needed can be indicated.

The purpose of this study was to provide a regional interpretation of the hydrologic system and to show possible effects of development on that system. The definition of local variations requires more detailed investigations. Test drilling pointed out the difficulties of predicting aquifer characteristics in glacial deposits. The need for test drilling to evaluate each local situation is emphasized.

Field aquifer tests are needed to determine water-yielding characteristics of the water-table aquifer in areas of fine-textured outwash. Where the water-yielding potential of the water-table aquifer is not adequate for irrigation supply, deeper drilling and testing is needed to determine the extent and potential of artesian aquifers.

Additional water-level records are needed to determine variations in water-level fluctuations during different climatic conditions and to monitor water-level changes which might result as increasing stresses are applied to the hydrologic system.

Additional streamflow data are needed to determine seasonal discharge variations and to establish a rating curve for the major streams in the study area.

Locally, water is of such a quality that it might be inadequate for all types of use. Periodic sampling is needed to check for possible deterioration of water quality where concentrations of people or livestock occur and where large amounts of agricultural fertilizer are used.

MINNESOTA WATER LAW

Since 1937, Minnesota has operated under the permit system for regulating large water users, as required by Minnesota statutes, chapter 105 (Nohre and Raup, 1961, p. 6). Permits are granted through the Department of Conservation, Division of Waters, Soils and Minerals. For agricultural use of water, a permit is required if more than 5 acres are to be irrigated. An appropriation of half an acre-foot of water per acre per year is allowed. If ground water is to be withdrawn from a well, a permit may be granted for any land which might be irrigated. If surface water is to be used, permits for irrigation are granted only for those 40-acre tracts or Government lots which are adjacent to the surface-water source. Annual pumping records are submitted to the Division of Waters, Soils and Minerals. Although rigid enforcement of the State's water laws pertaining to irrigation has not been necessary in the past, increased future demands may result in more stringent controls.

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UNITED STATES DEPARTMENT OF THE INTERIOR
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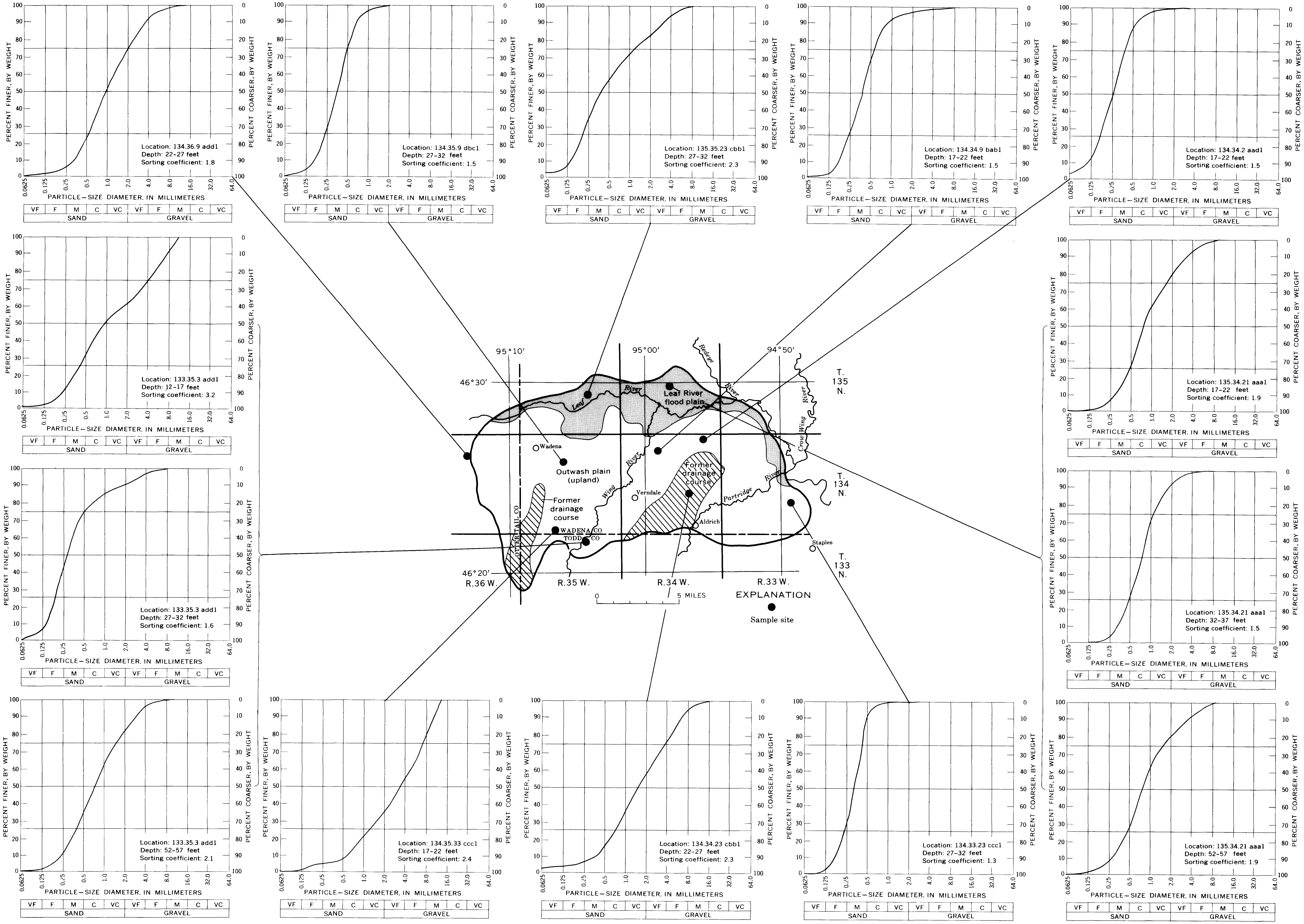
AND THE
MINNESOTA DEPARTMENT OF CONSERVATION, DIVISION OF WATERS, SOILS AND MINERALS

WATER-SUPPLY PAPER 1983
PLATE 1



PARTICLE-SIZE DISTRIBUTION GRAPHS ILLUSTRATING AREAL AND VERTICAL VARIATIONS IN THE TEXTURE OF OUTWASH DEPOSITS IN THE WADENA AREA, CENTRAL MINNESOTA

372-258 O - 71 (In pocket)

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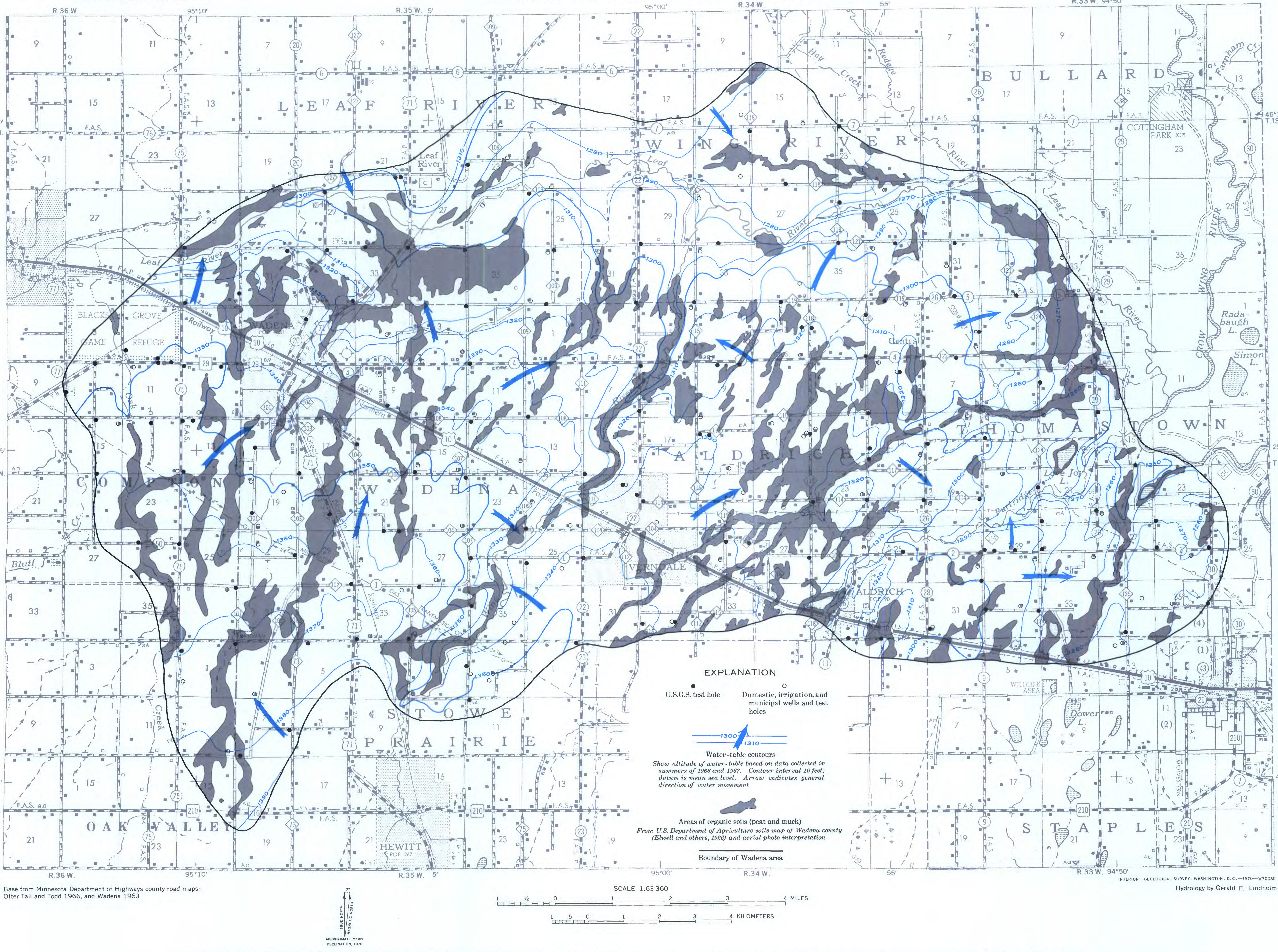
WATER-SUPPLY PAPER 1983
PLATE 2



Base from Minnesota Department of Highways county road maps: Otter Tail and Todd 1966, and Wadena 1963

SCALE 1:63 360

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1970—W70080

Hydrology by Gerald F. Lindholm

MAP SHOWING CONFIGURATION OF THE WATER-TABLE AND AREAS OF ORGANIC SOILS IN THE WADENA AREA, CENTRAL MINNESOTA

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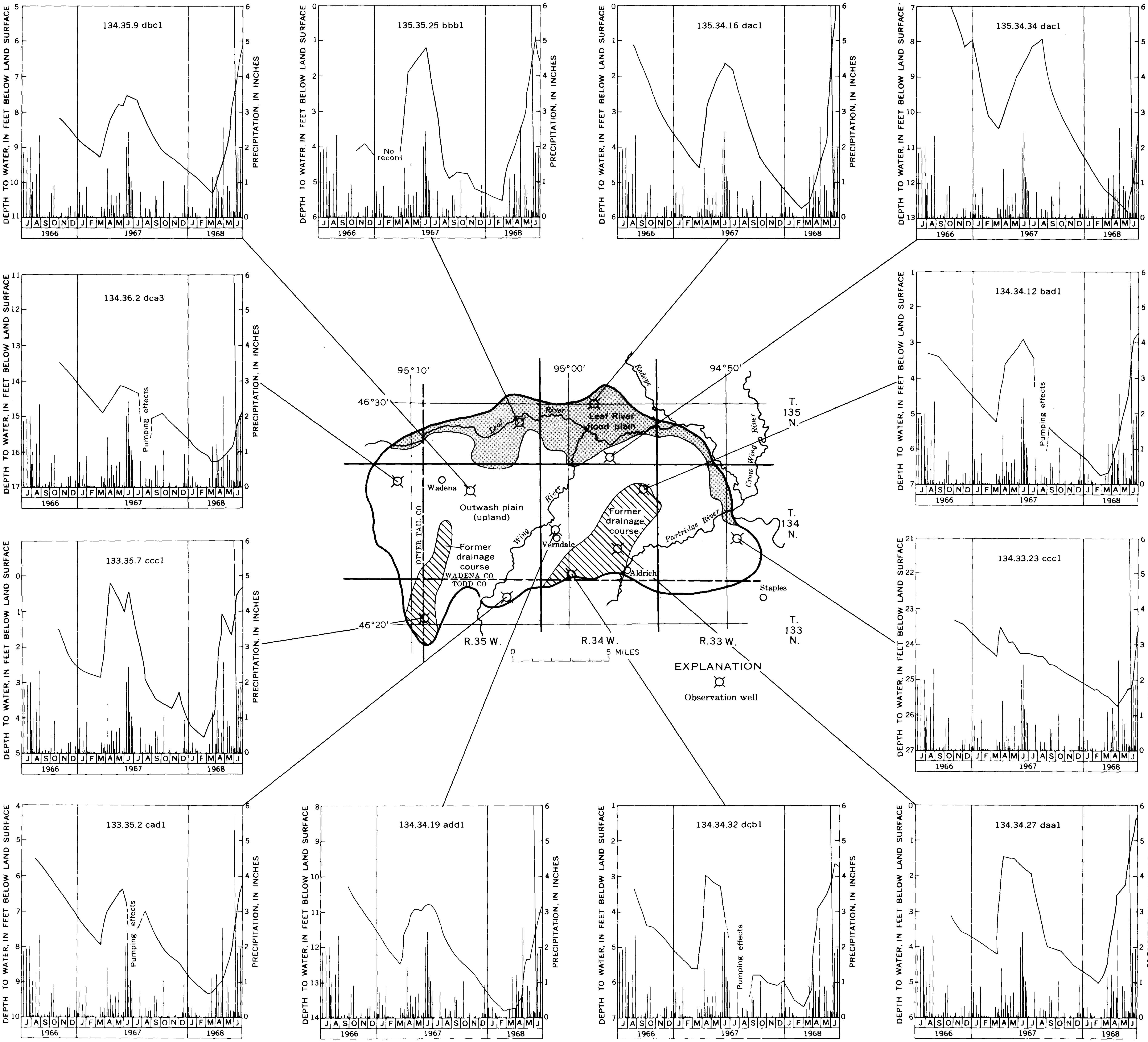

HYDROGRAPHS SHOWING VARIATIONS IN THE PATTERN OF GROUND-WATER-LEVEL FLUCTUATIONS IN THE WADENA AREA, CENTRAL MINNESOTA

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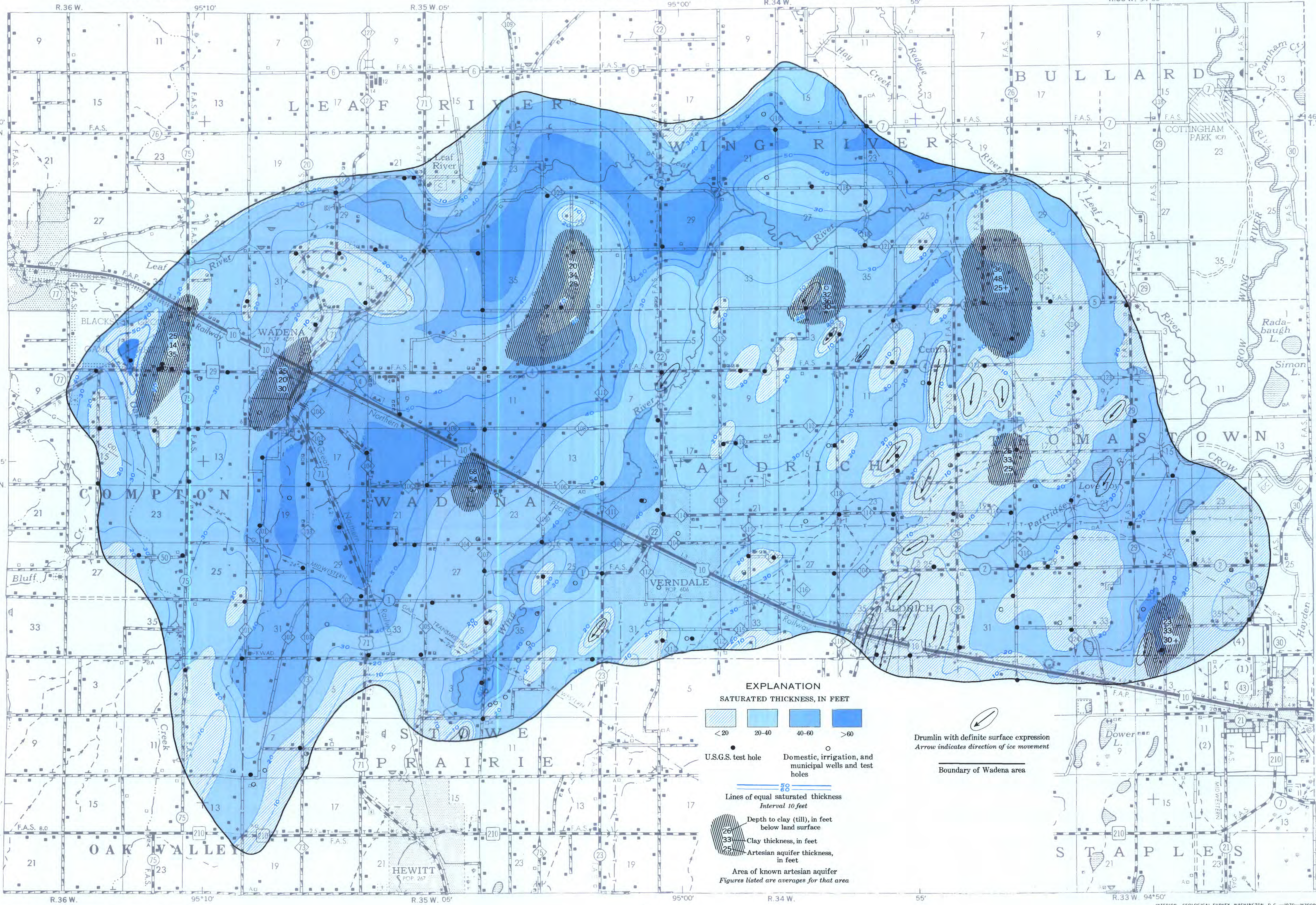

Base from Minnesota Department of Highways county road maps: Otter Tail and Todd 1966, and Wadena 1963

APPROXIMATE MEAN DECLINATION, 1970

SCALE 1:63 360

1 ½ 0 1 2 3 4 MILES

1 .5 0 1 2 3 4 KILOMETERS

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1970—W70080

Hydrology by Gerald F. Lindholm

MAP SHOWING THICKNESS OF SATURATED SAND AND GRAVEL ABOVE THE FIRST MASSIVE (GREATER THAN 5 FEET THICK) CLAY, AND AREAS OF KNOWN ARTESIAN AQUIFERS, WADENA AREA, CENTRAL MINNESOTA

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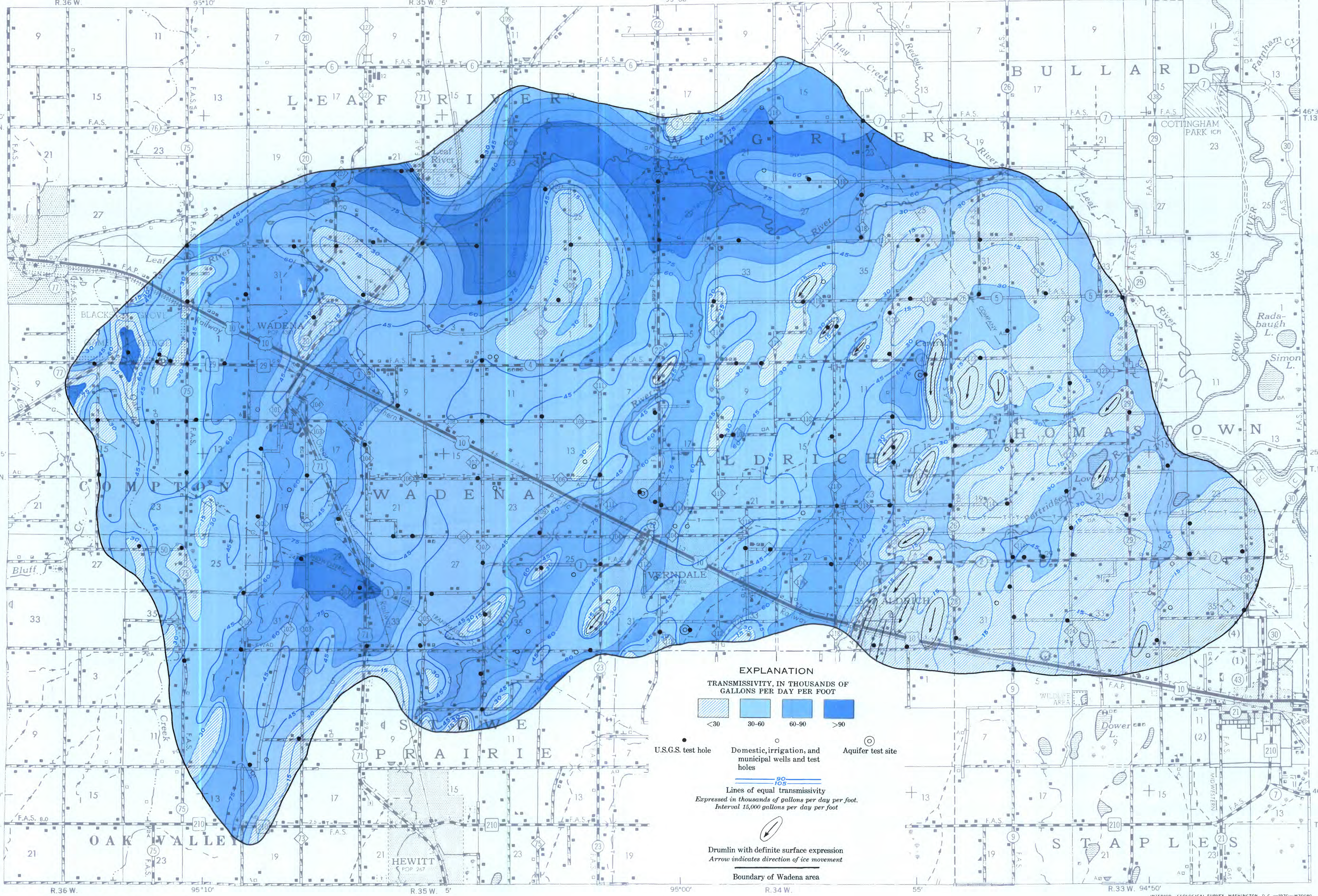
WATER-SUPPLY PAPER 1983
PLATE 5



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SCALE 1:63 360

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1 .5 0 1 2 3 4 KILOMETERS

APPROXIMATE MEAN DECLINATION, 1970

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1970—W70080

Hydrology by Gerald F. Lindholm

MAP SHOWING TRANSMISSIVITY OF THE WATER-TABLE AQUIFER IN THE WADENA AREA, CENTRAL MINNESOTA

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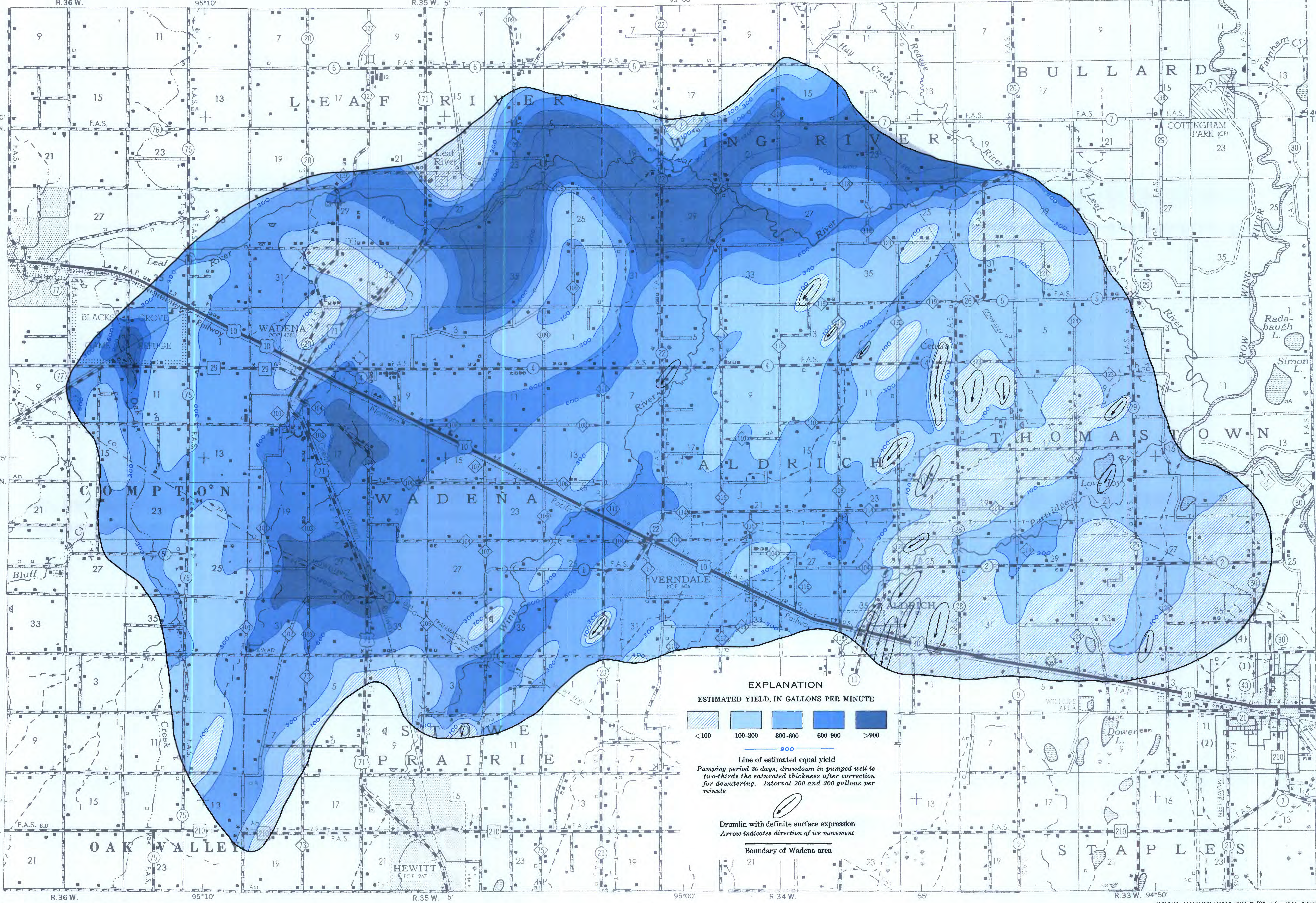

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SCALE 1:63 360

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1 .5 0 1 2 3 4 KILOMETERS

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Hydrology by Gerald F. Lindholm

MAP SHOWING THE ESTIMATED MAXIMUM YIELD TO A WELL COMPLETED IN THE WATER-TABLE AQUIFER IN THE WADENA AREA, CENTRAL MINNESOTA

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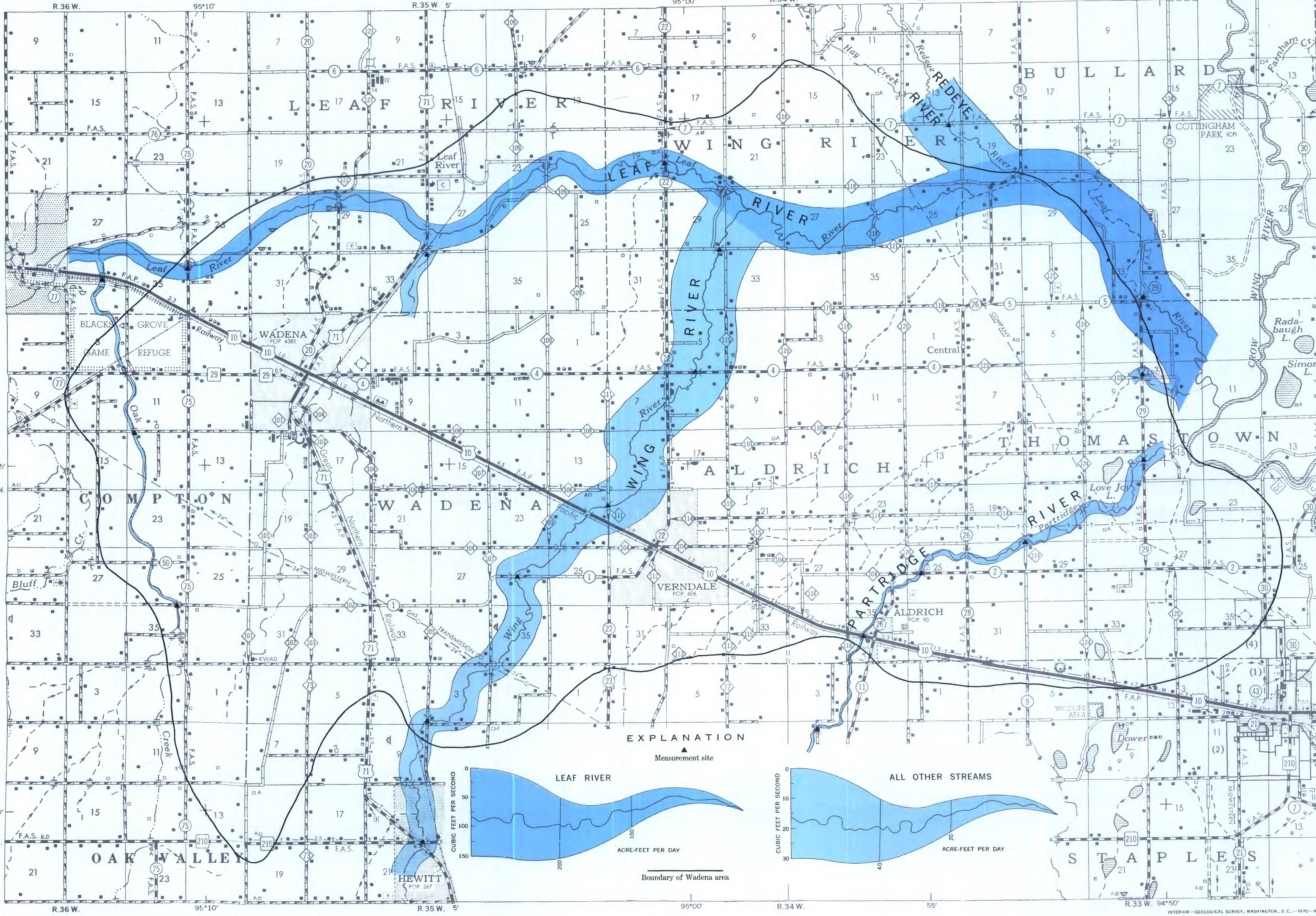
WATER-SUPPLY PAPER 1983
PLATE 7



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TRUE NORTH
MAGNETIC NORTH
7°
APPROXIMATE MEAN DECLINATION, 1970

SCALE 1:63 360

1 ½ 0 1 2 3 4 MILES

1 .5 0 1 2 3 4 KILOMETERS

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1970—W70080

Hydrology by Gerald F. Lindholm

MAP SHOWING APPROXIMATE STREAMFLOW IN THE WADENA AREA, CENTRAL MINNESOTA, OCTOBER 16-18, 1967

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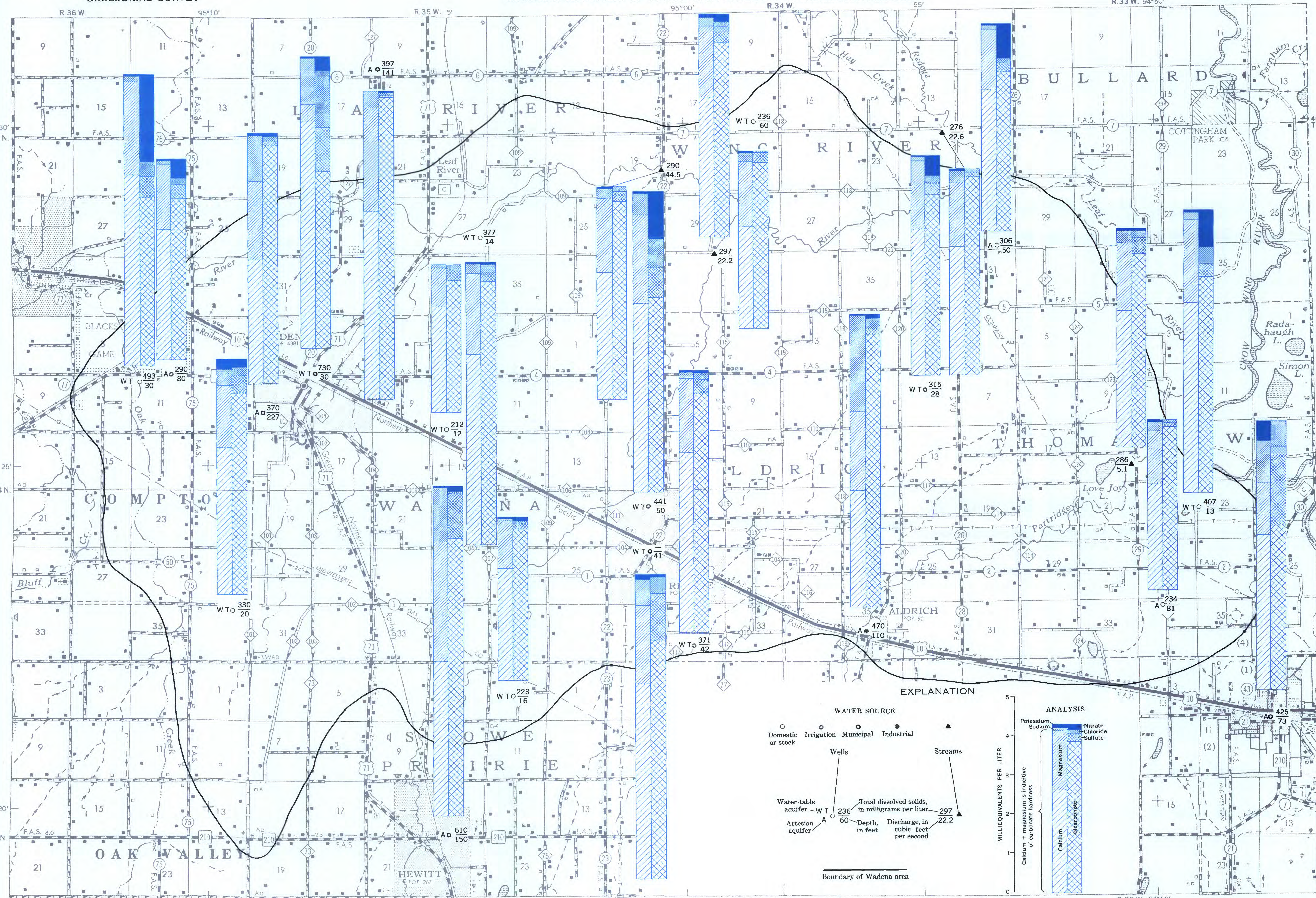
WATER-SUPPLY PAPER 1983
PLATE 8



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APPROXIMATE MEAN DECLINATION, 1970

SCALE 1:63 360

1 ½ 0 1 2 3 4 MILES

1 .5 0 1 2 3 4 KILOMETERS

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1970—W70080

Hydrology by Gerald F. Lindholm

MAP SHOWING GRAPHICAL REPRESENTATION OF GROUND- AND SURFACE-WATER QUALITY IN THE WADENA AREA, CENTRAL MINNESOTA

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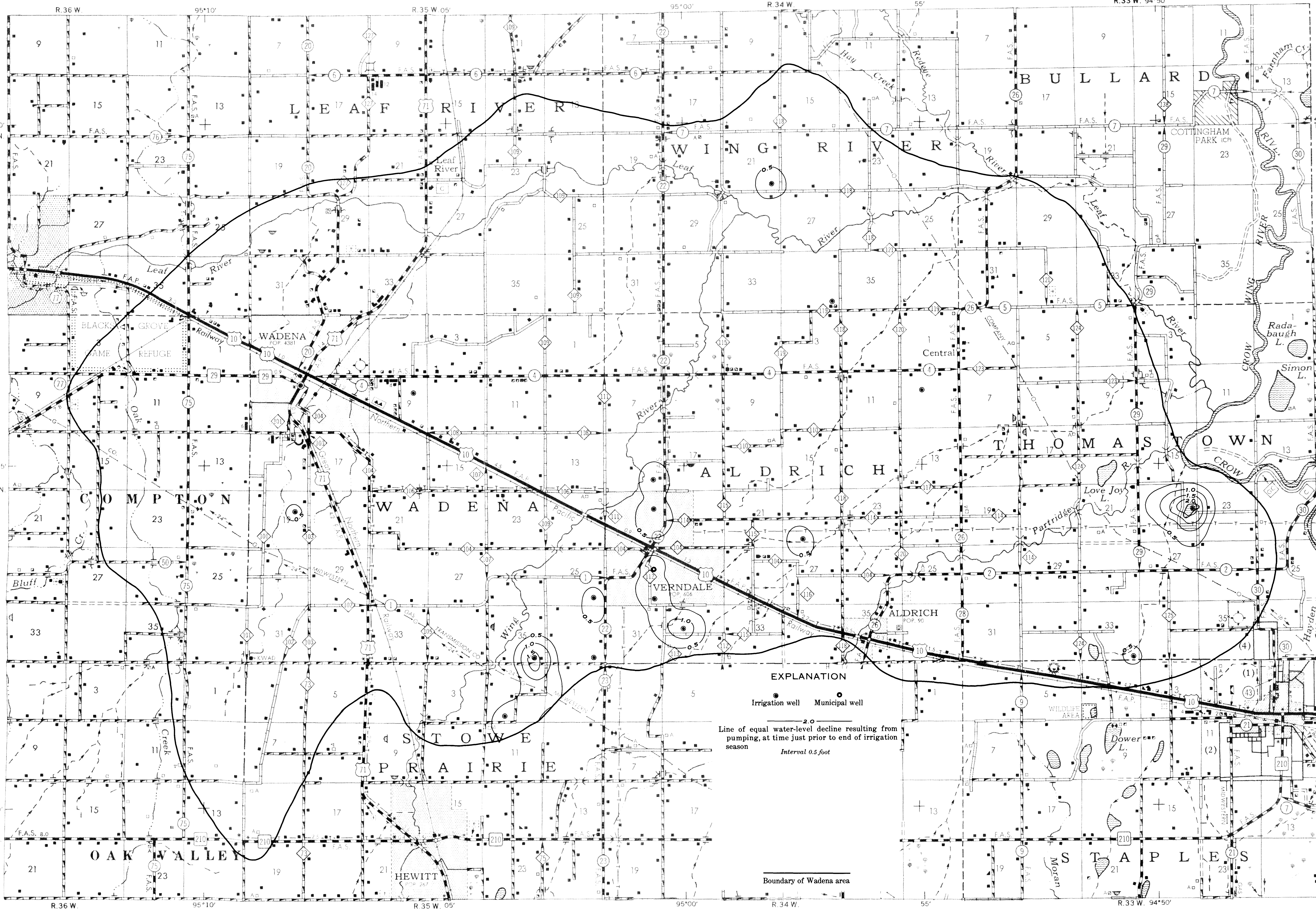
PLATE 9



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1 ½ 0 1 2 3 4 MILES

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Hydrology by Gerald F. Lindholm

MAP SHOWING THEORETICAL WATER-LEVEL DECLINE RESULTING FROM ACTUAL PUMPING FOR IRRIGATION IN 1967 IN THE WADENA AREA, CENTRAL MINNESOTA

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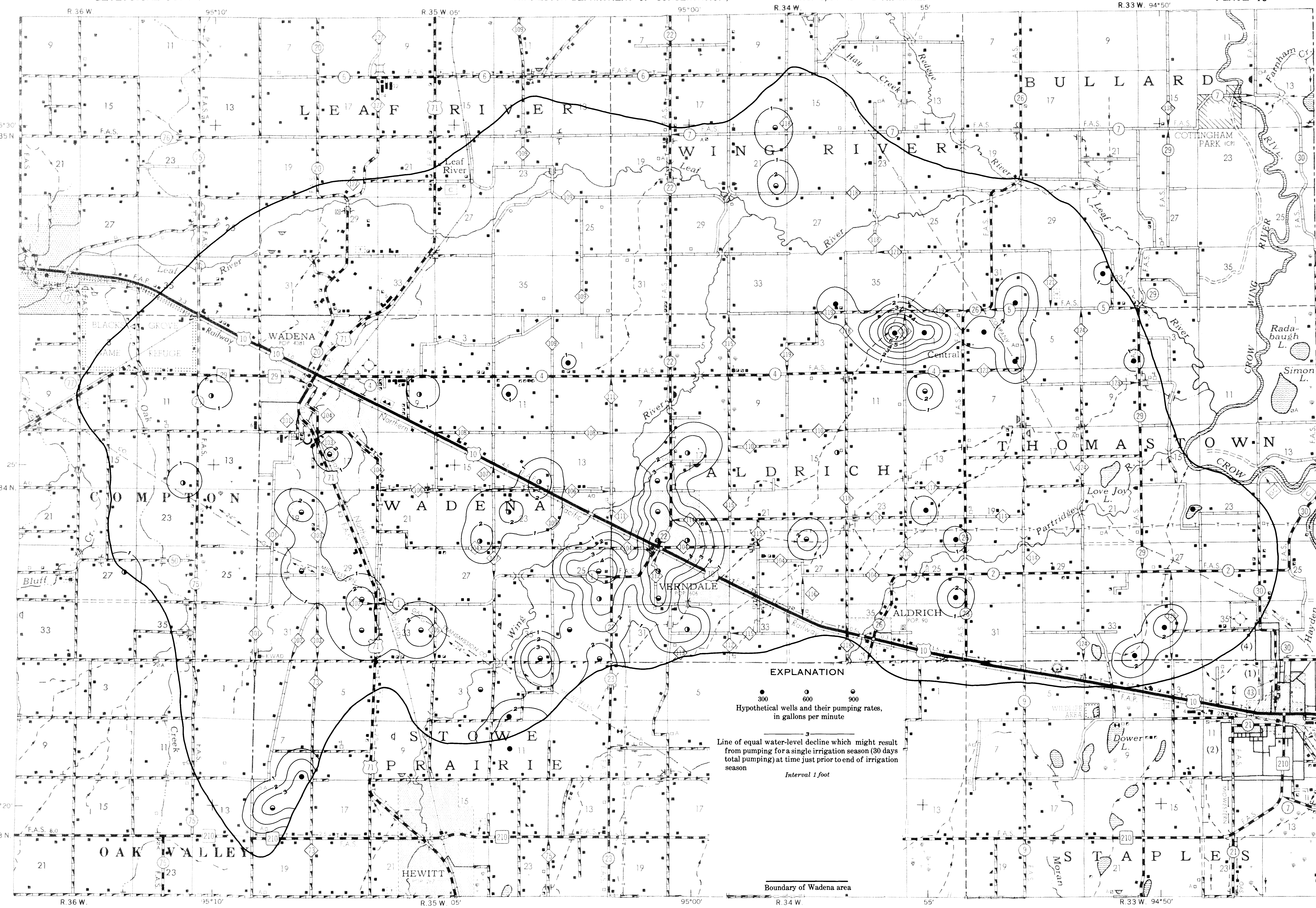
WATER-SUPPLY PAPER 1983
PLATE 10



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APPROXIMATE MEAN DECLINATION, 1970

SCALE 1:63 360

1 ½ 0 1 2 3 4 MILES

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Hydrology by Gerald F. Lindholm

MAP SHOWING THEORETICAL WATER-LEVEL DECLINE THAT MIGHT RESULT FROM PUMPING A HYPOTHETICAL 5-YEAR DEVELOPMENT PLAN IN THE WADENA AREA, CENTRAL MINNESOTA

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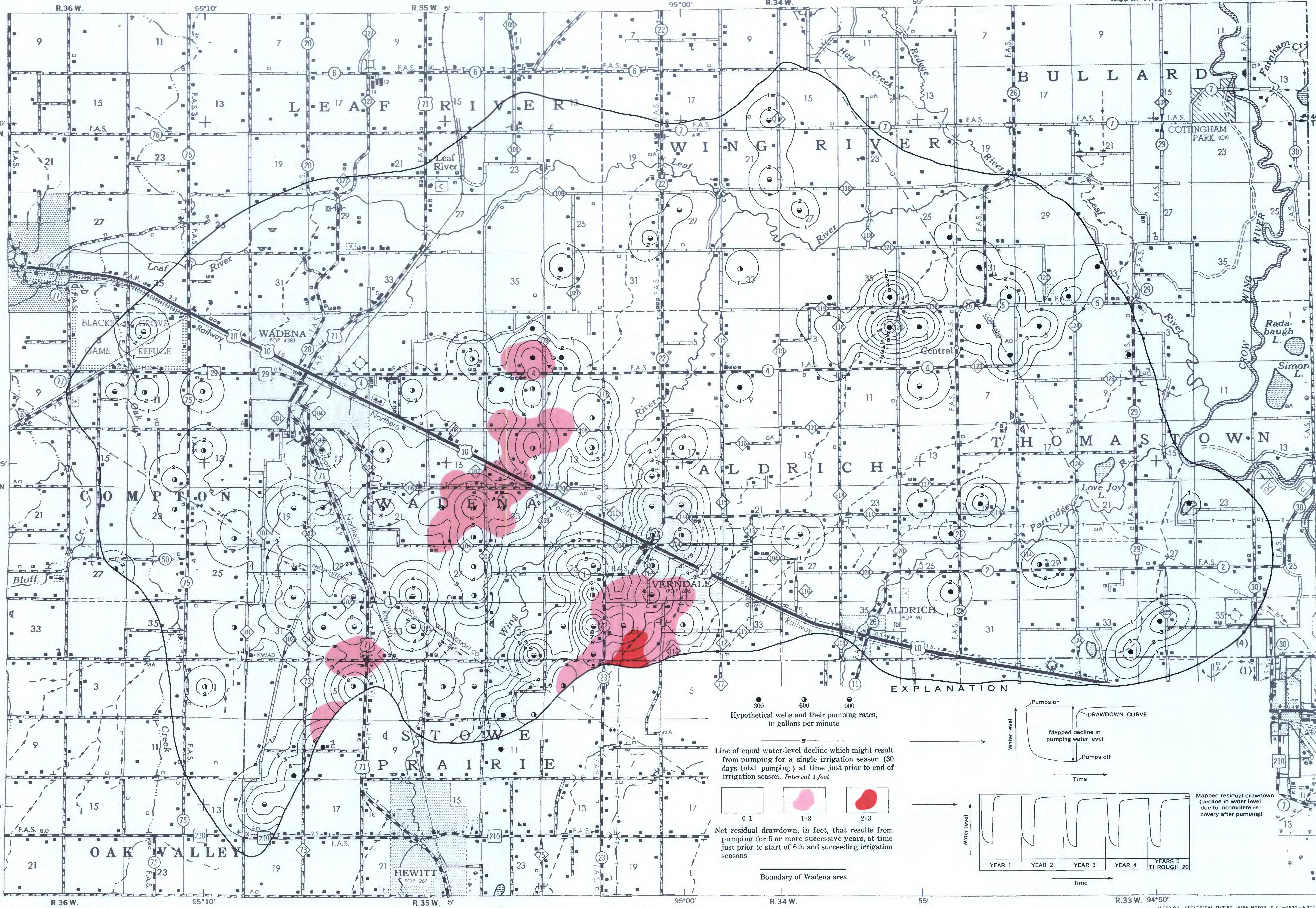

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1 ½ 0 1 2 3 4 MILES

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INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1970—W70080

Hydrology by Gerald F. Lindholm

MAP SHOWING THEORETICAL WATER-LEVEL DECLINE THAT MIGHT RESULT FROM PUMPING A HYPOTHETICAL 10-YEAR DEVELOPMENT PLAN IN THE WADENA AREA, CENTRAL MINNESOTA

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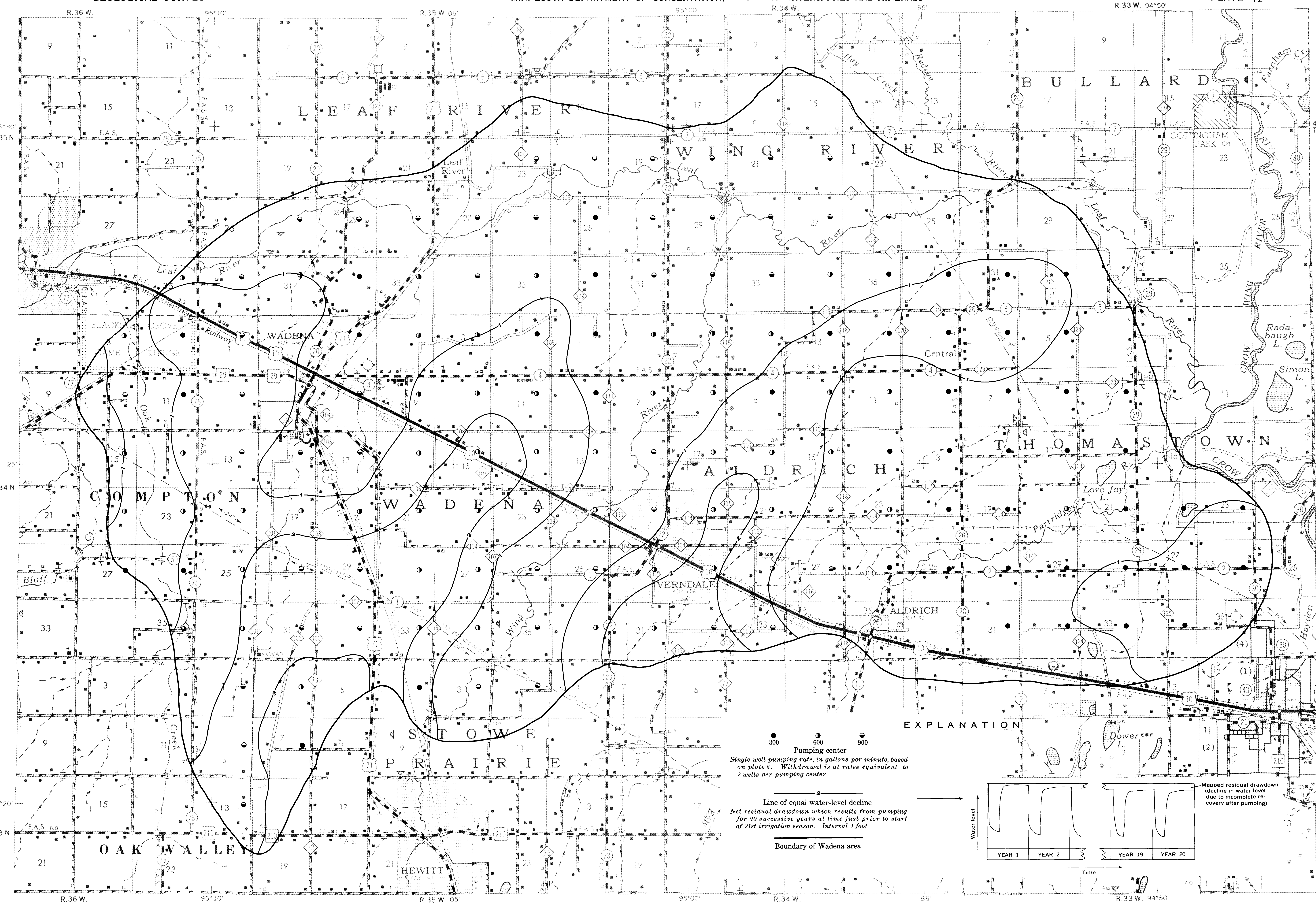
WATER-SUPPLY PAPER 1983
PLATE 12



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APPROXIMATE MEAN DECLINATION, 1970

SCALE 1:63 360

Hydrology by Gerald F. Lindholm

MAP SHOWING THEORETICAL RESIDUAL DRAWDOWN OF WATER LEVEL THAT MIGHT RESULT FROM PUMPING A HYPOTHETICAL MAXIMUM DEVELOPMENT PLAN AT RATES EQUIVALENT TO TWO WELLS PER PUMPING CENTER FOR 20 SUCCESSIVE YEARS IN THE WADENA AREA, CENTRAL MINNESOTA

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