Ground-Water Resources of the Uppermost Confined Aquifers, Southern Wadena County and Parts of Ottertail, Todd, and Cass Counties, Central Minnesota, 1997-2000

By R.J. Lindgren

Water-Resources Investigations Report 02–4023

Prepared in cooperation with the Minnesota Department of Natural Resources and the Wadena Soil and Water Conservation District

U.S. DEPARTMENT OF THE INTERIOR

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Mound View, Minnesota, 2002

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Water-Resources Investigations Report 02–4023

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	by	to obtain
Inch (in.)	2.54	centimeter
Inch per year (in./yr)	2.54	centimeter per year
Foot (ft)	0.3048	meter
Foot per day (ft/d)	0.3048	meter per day
Foot per mile (ft/mi)	.1894	meter per kilometer
Square mile (mi^2)	2.590	square kilometer
Foot squared per day (ft^2/d)	0.0929	meter squared per day
Cubic foot per second (ft^3/s)	0.02832	cubic meter per second
Gallon per minute (gal/min)	6.309×10^{-5}	cubic meter per second

Sea level: In this report, sea level refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order levels nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Ground-Water Resources of the Uppermost Confined Aquifers, Southern Wadena County and Parts of Ottertail, Todd, and Cass Counties, Central Minnesota, 1997–2000

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ABSTRACT

Water managers are concerned about the increase of ground-water withdrawals from high-capacity wells completed in the uppermost confined aquifers in southern Wadena County. The hydrogeologic units of primary interest in the study area are the surficial aquifer, the uppermost confining units, and the uppermost confined aquifers. The surficial aquifer underlies all but portions of the eastern, western, and south-central parts of the study area, and is as much as 70 ft thick. The thickness of the uppermost confined aquifers ranges from 0 to 72 ft. The thickness of the aquifers is greatest in the south-central and west-central parts of the study area, where thicknesses exceed 50 ft. Depth to the top of the uppermost confined aquifers ranges from 23 to 132 ft. The thickness of the uppermost confining units ranges from 4 to 132 ft.

The regional direction of flow in the uppermost confined aquifers is to the east, southeast, and southwest toward the Crow Wing River in the eastern part of the study area and toward the Leaf River in the western part. Sources of water to the uppermost confined aquifers are leakage of water through overlying till and clay and ground-water flow from adjoining aquifers outside the study area. Discharge from the uppermost confined aquifers is by withdrawal from wells and to the surficial aquifer in river valleys. The theoretical maximum well yields for the uppermost confined aquifers range from less that 175 gal/min to greater than 2,000 gal/min and are greatest in areas of greatest aquifer thickness and transmissivity.

The water budget for the calibrated steady-state simulation indicated that areal recharge to the surficial aquifer is 86.9 percent of the water to the aquifers, with leakage to the uppermost confined aquifers contributing 6.9 percent. The largest discharges from the aquifers are leakage to streams (54.5 percent) and ground-water evapotranspiration (41.4 percent). The simulated transient water budget for 1999 indicated that the principal sources of water to the aquifers were areal recharge to the surficial aquifer and release from storage. The principal discharges were stream-aquifer leakage, addition to storage, and ground-water evapotranspiration.

Results of the steady-state simulation with anticipated increases in ground-water withdrawals indicated maximum drawdowns of 0.3 ft in the surficial aquifer and 0.9 ft in the uppermost confined aquifers due to the anticipated increases in ground-water withdrawals. Model results indicate that the anticipated increases in withdrawals during a drought may lower water levels 2 to 4 ft regionally in much of both the surficial and uppermost confined aquifers. Water-level declines in the surficial aquifer of about 6 ft may occur in Wadena and in the central part of the aquifer south of the Leaf River. Results of the transient simulation indicate that the anticipated increases in withdrawals during a drought would increase seasonal declines in the surficial and uppermost confined aquifers less than 1 and 2 ft, respectively.

Model results indicate that greater than anticipated increases in withdrawals during periods of normal precipitation will have minimal effects on ground-water levels and streamflow in the area. In the uppermost confined aquifers, for example, water levels may decline an average of 0.13 ft regionally, with maximum declines of 0.8 to 2.1 ft near Wadena and Verndale. Greater than anticipated increases in withdrawals would cause decreases in ground-water discharge to streams of about 1.4 percent (2.5 ft^3/s) of 1998-99 steady-state conditions.

INTRODUCTION

Southern Wadena County is an agricultural area that is part of a large surficial glacial outwash plain in central Minnesota. Without irrigation crops are susceptible to failure during dry years in the sandy, well-drained soils. Increased demand for ground water in this region has resulted from installation of irrigation systems completed in the surficial aquifer (within the surficial glacial outwash) during the 1960's and early 1970's. Because of the increased demand for ground-water resources beginning in the mid 1970's, the source of water for irrigation shifted from the surficial aquifer to the deeper, uppermost confined aquifers. Currently, all new irrigation wells in southern Wadena County are completed in the uppermost confined aquifers.

Water managers of the Minnesota Department of Natural Resources (MDNR) and theWadena County Soil and Water Conservation District are concerned about the increase of ground-water withdrawals from high-capacity wells completed in the uppermost confined aquifers in southern Wadena County. Their concerns include uncertainty about the long-term yields of wells completed in the uppermost confined aquifers, the effects of pumping on water levels in the aquifers, and possible interference between nearby wells. Hydrogeologic information, including the areal extent of the uppermost confined aquifers, recharge and discharge areas and rates, hydrologic boundaries, and the hydraulic characteristics of the aquifers, is not well known. Although numerous wells and test holes have been completed in the uppermost confined aquifers, little is known about the continuity or the hydraulic responses of the aquifer to ground-water withdrawals. Additional water-level data and aquifer tests are needed to understand the hydraulic connection between the surficial and uppermost confined aquifers.

To address these concerns, and to evaluate the ground-water resources in the uppermost confined aquifers in southern Wadena County, an investigation was conducted during 1997–2000 by the U.S. Geological Survey (USGS), in cooperation with the Minnesota Department of Natural Resources and the Wadena Soil and Water Conservation District. The objectives of this investigation were to: (1) determine the areal extent, thickness, and hydraulic properties of the uppermost confined aquifers in southern Wadena County, (2) evaluate the vertical hydraulic connection between the surficial aquifer and the uppermost confined aquifers, (3) estimate the effects of anticipated increases in ground-water withdrawals on water levels, and (4) estimate the long-term yields of wells completed in the uppermost confined aquifers.

This report presents the results of the investigation. It describes data collection during 1997–99; sources and types of other data used; and construction, calibration, and application of a numerical ground-water-flow model. The primary area of interest and data-collection activities was southern Wadena County. Parts of Ottertail, Todd, and Cass Counties were included in the study area to minimize the effects of boundary conditions in the ground-water-flow model.

Description of Study Area

The study area covers approximately 720 mi^2 in southern Wadena County and parts of Ottertail, Todd, and Cass Counties in central Minnesota (fig. 1). Flat to gently undulating topography characterizes much of the area, with locally greater relief near major streams. Undeveloped lands include wetlands, scattered throughout the area, and forested areas in the northeastern part of the study area. Principal crops include corn and hay. Crops most commonly irrigated are corn, potatoes, and dry edible beans.

Glacial deposits ranging in thickness from 100 to 300 ft cover the entire study area. Surficial outwash consisting of sand and gravel underlies most of southern Wadena County (area indicated as surficial aquifer in fig. 1) and is generally of sufficient thickness and permeability to permit yields of large (100 to 1,000 gal/min) quantities of water to wells. In the moraine and till plain areas of the northwestern and southern parts of the study area, wells are usually completed in buried sand and gravel layers and at greater depths than those in areas of surficial outwash.

The study area is drained by the Crow Wing River and its tributaries. Flow in the main stem of the Crow Wing River is stable because of the regulating effect of lakes and wetlands at medium and high flows, and the sustaining effect of ground-water discharge (base flow) from outwash areas during low-flow periods. Minimum discharges for the Crow Wing River normally occur in January and February when the flow is sustained almost entirely by ground water. Instantaneous annual maximum flow may occur any time from March through October, but most periods of sustained high flow result from snowmelt in April. The major tributaries of the Crow Wing River in the study area are the Leaf, Wing, Partridge, and Red Eye Rivers. Approximate average flows measured in the study area for the Leaf, Wing, Partridge, and Red Eye Rivers for 1931–64 were 70, 25, 6, and 35 ft^3/s, respectively (Lindholm and others, 1972).

Mean annual precipitation during 1961–90 (normal precipitation) was 26.24 in. at Wadena (U.S. Department of Commerce, 1999). Precipitation during the growing season, April through September, generally comprises 75 to 80 percent of the annual

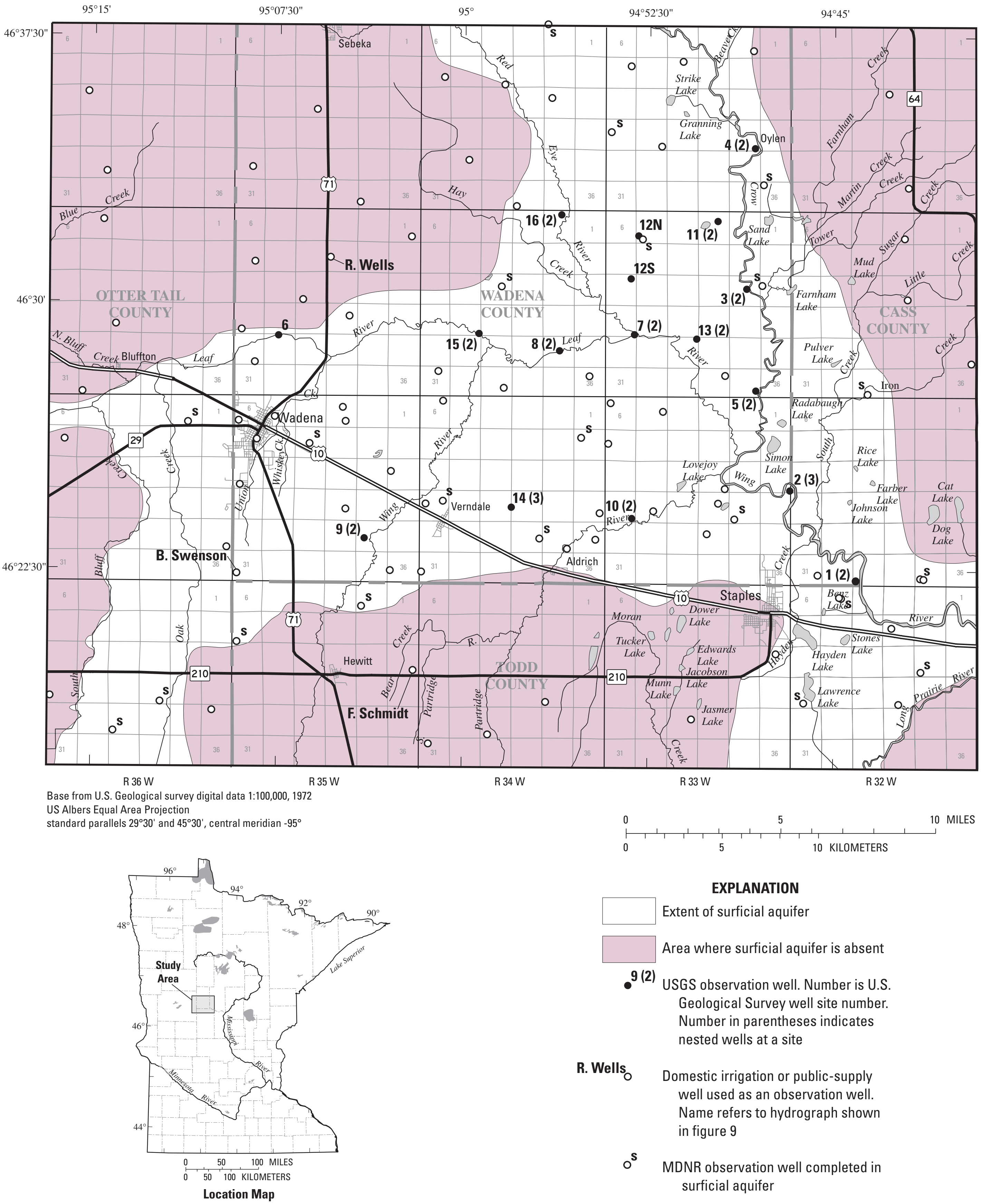


Figure 1. Location of study area, observation wells, and extent of surficial aquifer, southern Wadena County and parts of surrounding counties, Minnesota.

total. Moisture is adequate for optimum plant growth in spring and early summer during a normal year, but a typical moisture deficiency during August and September results in less than optimum growth. Rural and municipal water shortages were common during droughts in the 1930's, 1970's, and 1980's. Annual precipitation during 1998 and 1999 was above normal (34.78 and 31.41 in., respectively). In 1998, precipitation during May and June was 5.1 in. above normal (1961–90 mean), during August and September was 2.6 in. below normal, and during October was 6.3 in. above normal. In 1999, precipitation during May and June was 3.4 in. above normal, during July through September was 5.3 in. above normal, and during October was 1.8 in. below normal.

Mean annual potential evapotranspiration in the study area calculated by the Thornthwaite method is 22 to 23 in./yr (Baker and others, 1979). Evaporation from pans can also be used to estimate evapotranspiration, since the same physical process is involved (Baker and others, 1979). Pan evaporation usually shows an evaporation amount that is even greater than the potential evapotranspiration obtained by the Thornthwaite or other calculation methods. Pan evaporation has been measured at Staples, Minnesota during April-September since 1977. Average annual pan evaporation at Staples during 1977–99 was 39.43 in. (Mel Wiens, Central Minnesota Agricultural Center, Staples, Minnesota, written commun., 2000). Annual pan evaporation during 1998 and 1999 was 43.46 and 39.43 in., respectively. In 1998, pan evaporation during August through September was 2.5 in. above normal (1977–99 average), whereas in 1999 it was 1.2 in. below normal.

Methods of Investigation

Previously collected data on the hydrogeology, water use, and hydraulic properties of the glacial-deposit aquifers in southern Wadena County and of surrounding counties were compiled from water-well logs, geologic maps, State and Federal data bases, water-use records, published reports, and consultant reports. Additional test drilling, well installation, and measurements of water levels and stream discharge were done for this investigation. Observation-well and test-hole logs, water-level measurements, and stream-discharge measurements done for this investigation are on file at the USGS, Mounds View, Minnesota.

Log Data, Test Drilling, and Well Installation

Water-well and test-hole logs were obtained from the Minnesota Geological Survey's County Well Index and from the USGS Ground-Water Site Inventory data base for Wadena, Ottertail, Todd, and Cass Counties. Test drilling was conducted to: (1) install observation wells completed in the uppermost confined aquifers, (2) establish nests of observation wells completed in the surficial and uppermost confined aquifers, and (3) install observation wells near streams to determine relations between stream stages and aquifer hydraulic heads. Thirty-four test holes were drilled for this investigation at 17 sites, and observation wells were installed in 33 of the test holes (fig. 1). Nested observation wells were completed in the surficial and uppermost confined aquifers at 14 of the sites.

Water Levels and Stream Discharge

Water levels were measured monthly in the 33 observation wells, 22 MDNR observation wells completed in the surficial aquifer, and 71 domestic, irrigation, and public-supply wells (fig. 1). All of the 71 domestic, irrigation, and public-supply wells were completed in the uppermost confined aquifers. Pressure transducers were installed in 9 of the observation wells and water levels were recorded hourly. Stream stage was measured monthly during open water conditions at 11 sites on the Crow Wing, Leaf, Wing, Partridge and Red Eye Rivers in close proximity to observation wells (fig. 2). Stream stage was measured at varying time intervals at an additional 47 sites on the major rivers and selected tributaries (fig. 2).

The altitudes of all measurement points were determined by surveying from points of known land-surface altitudes (Greg Payne, U.S. Geological Survey, written commun., 1999). Altitudes of measuring points were measured with a precision of 0.10 ft.

Synoptic sets of low-flow discharge measurements were made to determine gaining and losing reaches of the major rivers and selected tributaries and to quantify streamflow gains and losses. Low-flow discharge measurements were made during August 1998, and during November 1999 (fig. 2; table 1). The uncertainty of individual streamflow measurements was 5–8 percent (table 1).

Theoretical Maximum Well Yields

Theoretical maximum well yields in the uppermost confined aquifers were estimated using a chart developed by Meyer (1963) that relates well diameter, specific capacity, values of transmissivity, and storage coefficient. The chart shows that for transmissivities between approximately 270 and 13,000 ft^2/d, the ratio of transmissivity to specific capacity is about 320 to 1. For confined aquifers with transmissivities of 13,000 ft^2/d or less, the specific capacity is approximated by dividing the transmissivity by 320. The theoretical maximum well yield at a site was estimated by multiplying the specific capacity by the available drawdown. The available drawdown, as defined for this report, is the difference between the altitudes of the static (nonpumping) water level in a well

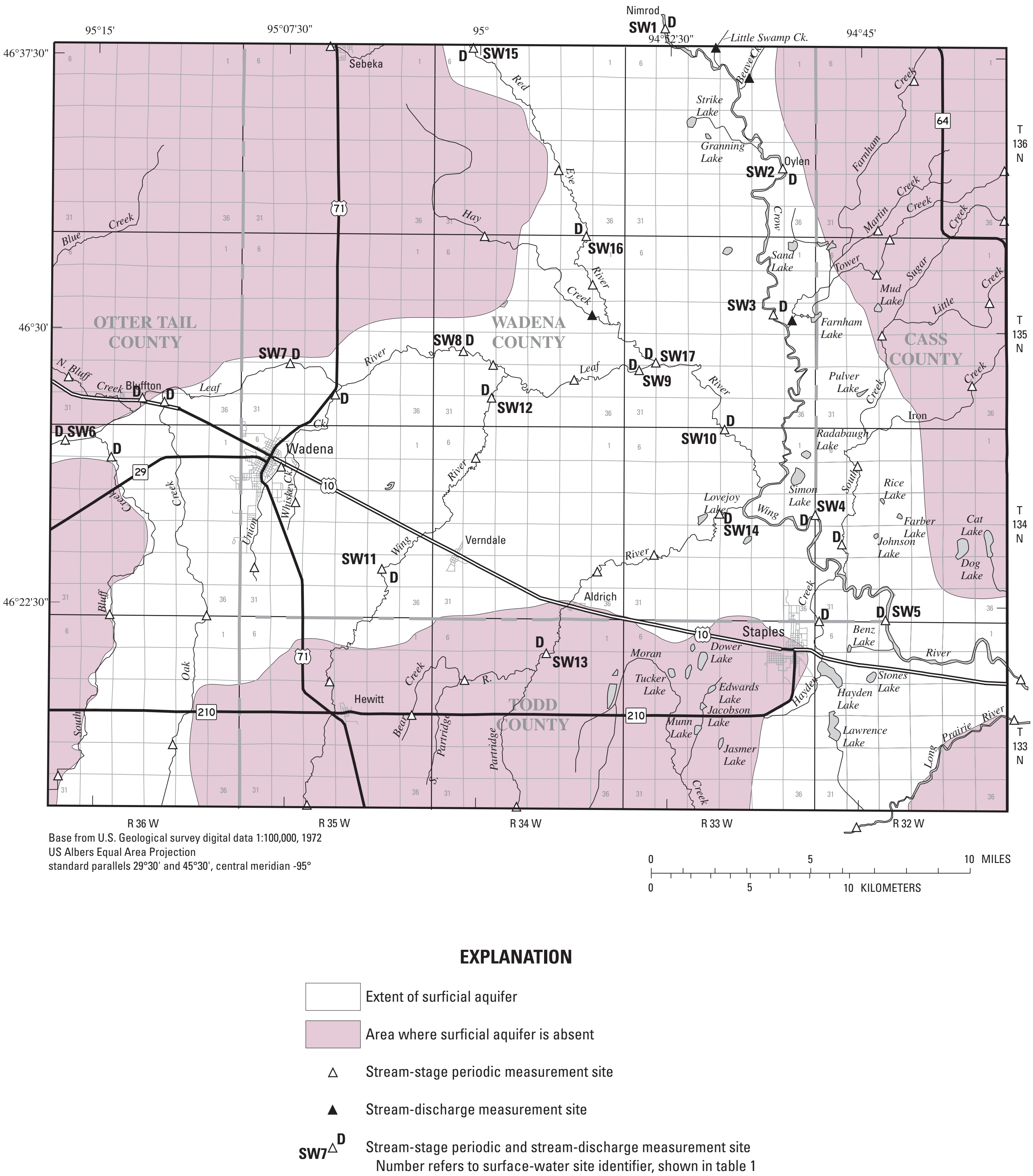


Figure 2. Location of stream-stage and stream-discharge measurement sites, and extent of surficial aquifer, southern Wadena County and parts of surrounding counties, Minnesota.

Table 1. Stream discharge and estimated stream-aquifer leakage under low-flow conditions during 1998-99, and model computed stream-aquifer leakage for the steady-state simulation, southern Wadena County and parts of surrounding counties, Minnesota

[All values in cubic feet per second unless otherwise noted; --, no measurement]

Site identifier (shown in fig. 2)	Tributary site	Discharge measurement uncertainty (percent)	Stream reach	Measured						Steady-state simulation
				August 1998			November 1999			
				Stream discharge	Tributary discharge	Stream-aquifer leakage gain(+) or loss (-) in streamflow	Stream discharge	Tributary discharge	Stream-aquifer leakage gain(+) or loss (-) in streamflow	Stream-aquifer leakage gain(+) or loss (-) in streamflow
				Crow Wing River						
SW1		5		335			474			
	Little Swamp Creek	8			1.0			0.8		
	Beaver Creek	8			1.0			6.9		
			SW1-SW2			+9.0			+148.3	+13.1
SW2		8		346			630			
			SW2-SW3			-6.0			-38	+9.0
SW3		5		340			592			
	Farnham Creek	5			4.0			17.1		
	Leaf River (SW10)				194			303		
	Partridge River (SW14)				12.1			14.2		
			SW3-SW4			-6.1			-19.3	+12.2
SW4		5		544			907			
	Hayden Creek	5			1.3			0.7		
	South Creek	5			2.1			14.2		
			SW4-SW5			+27.6			-39.9	+9.9
SW5		5		575			882			
				Leaf River						
SW6		5		--			74.0			
	South Bluff Creek	5			--			13.6		
	North Bluff Creek	5			--			9.9		
	Oak Creek	5			--			9.8		
			SW6-SW7			--			14.7	+12.3
SW7		5		65.2			122			
	Union Creek	8			5.2			14.3		
			SW7-SW8			+35.6			+24.7	+12.5
SW8		5		106			161			
	Wing River (SW12)				30.9			59.4		
			SW8-SW9			+18.1			+15.6	+17.2
SW9		5		155			236			

Table 1. Stream discharge and estimated stream-aquifer leakage under low-flow conditions during 1998-99, and model computed stream-aquifer leakage for the steady-state simulation, southern Wadena County and parts of surrounding counties, Minnesota (Continued)

[All values in cubic feet per second unless otherwise noted; --, no measurement]

Site identifier (shown in fig. 2)	Tributary site	Discharge measurement uncertainty (percent)	Stream reach	Measured: August 1998: Stream discharge	Measured: August 1998: Tributary discharge	Measured: August 1998: Stream-aquifer leakage gain(+) or loss (-) in streamflow	Measured: November 1999: Stream discharge	Measured: November 1999: Tributary discharge	Measured: November 1999: Stream-aquifer leakage gain(+) or loss (-) in streamflow	Steady-state simulation: Stream-aquifer leakage gain(+) or loss (-) in streamflow
	Red Eye River (SW17)				34.4			58.3		
			SW9-SW10			+4.6			+8.7	+6.7
SW10		5		194			303			
				Wing River						
SW11		8		16.2			50.6			
			SW11-SW12			+14.7			+8.8	+13.1
SW12		5		30.9			59.4			
				Partridge River						
SW13		5		0.4			7.9			
			SW13-SW14			+11.7			+6.3	+9.0
SW14		5		12.1			14.2			
				Red Eye River						
SW15		5		26.1			34.6			
			SW15-SW16			+10.9			+13.9	+12.5
SW16		5		37.0			48.5			
	Hay Creek				0.0			0.0		
			SW16-SW17			-2.6			+9.8	+4.9
SW17		5		34.4			58.3			

and the bottom of the uppermost confined aquifer penetrated. The available drawdown was estimated to be the sum of aquifer thickness and the artesian head (the hydraulic head above the altitude of the top of the uppermost confined aquifer). An average value of 35 ft was used for the artesian head, based on measured water levels and aquifer top altitudes from well logs. The estimates of theoretical maximum well yield included in this report were based on the following assumptions: (1) the aquifer is homogeneous, isotropic, and infinite in areal extent; (2) the well is screened through the entire thickness of the aquifer, is 100 percent efficient, and has a diameter of 12 inches; (3) the well is pumped continuously for 24 hours; (4) the effects of recharge, hydrologic boundaries, and other pumping wells are negligible.

Modeling of Ground-Water Flow

A numerical ground-water-flow model was constructed and calibrated to aid in understanding ground-water flow in the surficial and uppermost confined aquifers as well as interactions between the surficial aquifer and the major streams. The model was calibrated for both steady-state and transient conditions using hydraulic-property, water-level, and water-use data compiled during this investigation. The USGS modular three-dimensional, finite-difference ground-water-flow model (MODFLOW) (McDonald and Harbaugh, 1988), was used.

The model was constructed and calibrated using water levels in 127 observation, domestic, and irrigation wells; and stream stages at 37 sites (figs. 1 and 2). VISUAL MODFLOW was used as a pre-processor to input the required data, to run the MODFLOW simulations, and as a post-processor to visualize and analyze the results of the simulations (Guiguer and Franz, 1999).

Acknowledgments

The author is grateful to landowners who allowed the installation of observation wells on their property and who permitted water-level measurements. The author is also grateful to Don Sertich and Jeremy Maul of the Wadena Soil and Water Conservation District for obtaining monthly water-level measurements in domestic and irrigation wells. Thanks also are given to employees of the U.S. Geological Survey for their assistance with this investigation, particularly Michael Menheer, Christopher Sanocki, and Robert Borgstede.

HYDROGEOLOGY

Continental glaciation during the Pleistocene Epoch was important in forming the present landscape of most of Minnesota, including the Wadena area. Although multiple stages of glaciation occurred, the most recent ice advances during the late Wisconsin glaciation, were most influential in forming the current topography. Ice of the Hewitt phase of the Wadena lobe originated in southeastern Manitoba and flowed southeast into Minnesota until it was diverted by the contemporaneous Rainy lobe advancing from the northeast (Wright and Ruhe, 1965). Ice of the Wadena lobe then flowed southwest as it crossed the Wadena area, forming the Wadena drumlin field, which includes much of the study area. Drumlins are elongate hills of till whose long axis is parallel to the direction of ice movement. The eastern limit of the Wadena drumlin field is the St. Croix moraine in the northeastern part of the study area, which is composed of younger drift from the Lake Superior Basin. In the northwestern part of the study area, the drumlin field is bounded by drift of the Alexandria morainal complex.

Outwash deposits in the study area are part of a more extensive outwash plain (Leverett, 1932). Outwash is thickest in the swales between drumlins and thinnest where it overlies buried drumlins. The outwash is composed of glaciofluvial sand and gravel. All till in the Wadena area is sandy and calcareous. It is yellowish brown when oxidized and commonly dark greenish gray when unoxidized. Unoxidized Wadena-lobe till is frequently found at depth in drill holes, and it forms the confining unit beneath outwash deposits throughout the study area. The top several feet of Wadena-lobe till are very sandy, with few exceptions. Sand and gravel lenses ranging from less than five to tens of feet thick occur at various depths within the till. The thickness of glacial deposits is variable, generally ranging from about 100 ft in the southeastern and south-central parts of the study area to about 300 ft in the western part (Lindholm and others, 1972). The only known bedrock outcrop is a few miles northeast of Staples in T134N, R32W, section 27 (Helgesen, 1977).

The bedrock is deeply buried across most of the study area. The altitude of the bedrock surface is about 1,200 ft in the southeastern and south-central parts of the study area (Lindholm and others, 1972). The bedrock consists largely of Precambrian slate, graywacke, granite, gneiss, and schist. 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 glacial deposits in the vicinity of Staples.

Hydrogeologic Units

The hydrogeologic units of primary interest in the study area are the surficial aquifer, the uppermost confining units, and the uppermost confined aquifers. The surficial aquifer underlies all but portions of the eastern, western, and south-central parts of the study area (figs. 1–3). Texture of the outwash (which comprises most of the surficial aquifer) is predominantly medium to coarse sand, with lesser amounts of gravel and clay. The coarsest outwash is present within former drainage courses and is most common in the western and southern parts of the study area. Coarse alluvial deposits constitute the broad flood plain of the Leaf River. Although the outwash and the alluvial deposits are not stratigraphic time equivalents, their similar stratigraphic position and similar composition make it possible to consider them as a single hydrogeologic unit. Areas of fine-grained sand are scattered throughout the study 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. Over much of the area, the thickness of the surficial aquifer depends upon the proximity to drumlins, which have been partially or completely buried by the outwash. Data from 152 auger test holes analyzed by Lindholm (1970) showed that the thickness of the surficial sand and gravel in the southern part of the study area ranges from zero to 70 ft, with an average thickness of 36 ft. Saturated thickness of the surficial aquifer between the Redeye and Crow Wing Rivers and the area east of the Crow Wing River ranges from zero to about 60 ft (Helgesen, 1977). The water table in the surficial aquifer commonly is less than 20 ft below land surface.

Helgesen (1977, plate 3) calculated theoretical well yields, based on the equation of Theis (1935), ranging from less than 100 to 1,000 gal/min for the surficial aquifer in the area between the Redeye and Leaf Rivers and the Crow Wing River and the area east of the Crow Wing River. Lindholm (1970) estimated maximum well yields for the surficial aquifer in the central part of the study area (T134N and the southern one-half of T135N west of the Crow Wing, south-trending reach of the Leaf, and Red Eye Rivers) were in excess of 300 gal/min in about 60 percent of the area. High-capacity water-supply wells and dug pits are located predominantly in the central part of the study area south of the Leaf River (fig. 3). Dug pits are utilized as sources of water in areas where the water table is near land surface and supply yields similar to those for high-capacity wells.

An area of thick sand and gravel deposits near the Leaf River commonly contains thin (less than 5 ft thick), discontinuous clay and till layers that may locally confine underlying sand and gravel layers. The clay and till layers are not areally extensive or continuous and do not constitute a regional confining unit. This part of the aquifer, hereinafter termed the composite zone (fig. 4), may include uppermost confined aquifers locally. The composite zone ranges from approximately 20 to 73 ft thick and is probably in hydraulic connection with adjacent uppermost confined aquifers in some areas.

Buried sand and gravel lenses ranging in thickness from 25 to 67 ft underlie the study area in southern Wadena County (Lindholm, 1970). Although the uppermost sand and gravel lenses are not continuous within an altitude interval over the entire study area, some degree of hydraulic connection probably exists. Therefore, the uppermost confined sand and gravel lenses constitute the uppermost confined aquifers. The thickness of the uppermost confined aquifers ranges from zero to 72 ft, based on 141 test-hole and drillers' logs that fully penetrate each aquifer (fig. 4). The thickness of the aquifers is greatest in the south-central and west-central parts of the study area, where thicknesses exceed 50 ft. Depth to the top of the uppermost confined aquifers ranges from 23 to 132 ft, but generally is less than 50 ft in the northwestern and southeastern parts of the study area, based on 252 test-hole and drillers' logs that penetrate the aquifers (fig. 5).

Yields of several hundred gal/min are common from large-diameter wells completed in the uppermost confined aquifers. Wells in the northeastern part of the study area near the Crow Wing River may flow at land surface.

The uppermost confining units consist of clay and till and: (1) separate the surficial and uppermost confined aquifers in areas where the surficial aquifer is present; or (2) are present at land surface and overlie the uppermost confined aquifers in areas where the surficial aquifer is absent. The surficial aquifer is underlain by till or glacial lake deposits. Clay or silt beds remain in some areas where lakes formed during glacial recession. Most of the glacial-deposit material underlying the surficial aquifer is sandy till containing varying amounts of outwash sand and gravel. In moraine and till plain areas where the surficial aquifer is absent, sandy till overlies the uppermost confined aquifers. The thickness of the uppermost confining units ranges from 4 to 132 ft, based on 255 test-hole and drillers' logs that fully penetrate the confining units (fig. 6). The greatest thicknesses (greater than 120 feet) occur in the northwestern, west-central, and south-central parts of the study area (fig. 6), where the surficial aquifer is absent and the confining units are present at land surface. The uppermost confining units separating the surficial and uppermost confined aquifers generally are less than 50 ft thick.

Hydraulic Properties

Hydraulic properties of the glacial deposits are variable due to wide ranges in the composition, size, and degree of sorting of the material that

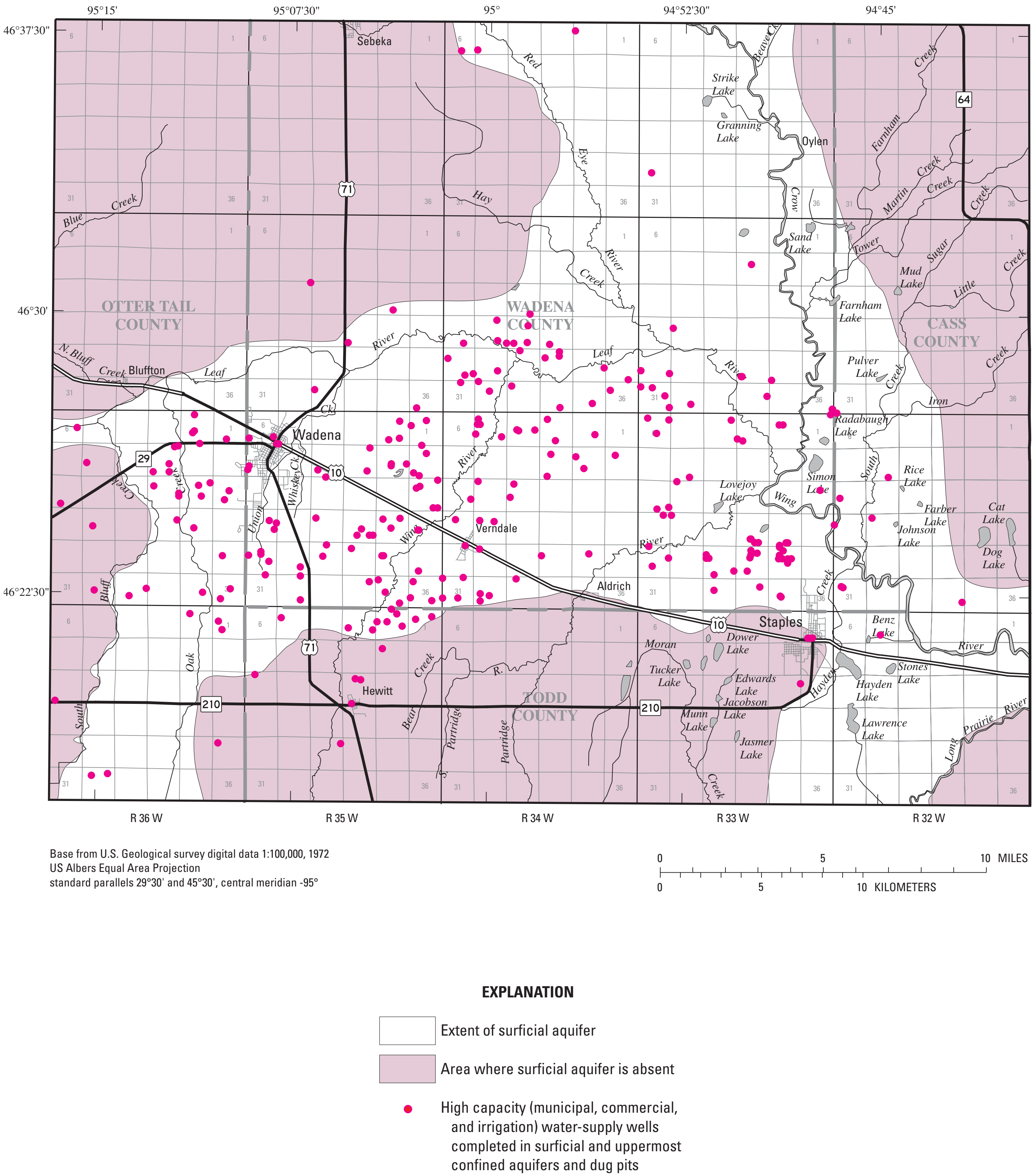


Figure 3. Location of high-capacity water-supply wells and dug pits, and extent of surficial aquifer, southern Wadena County and parts of surrounding counties, Minnesota.

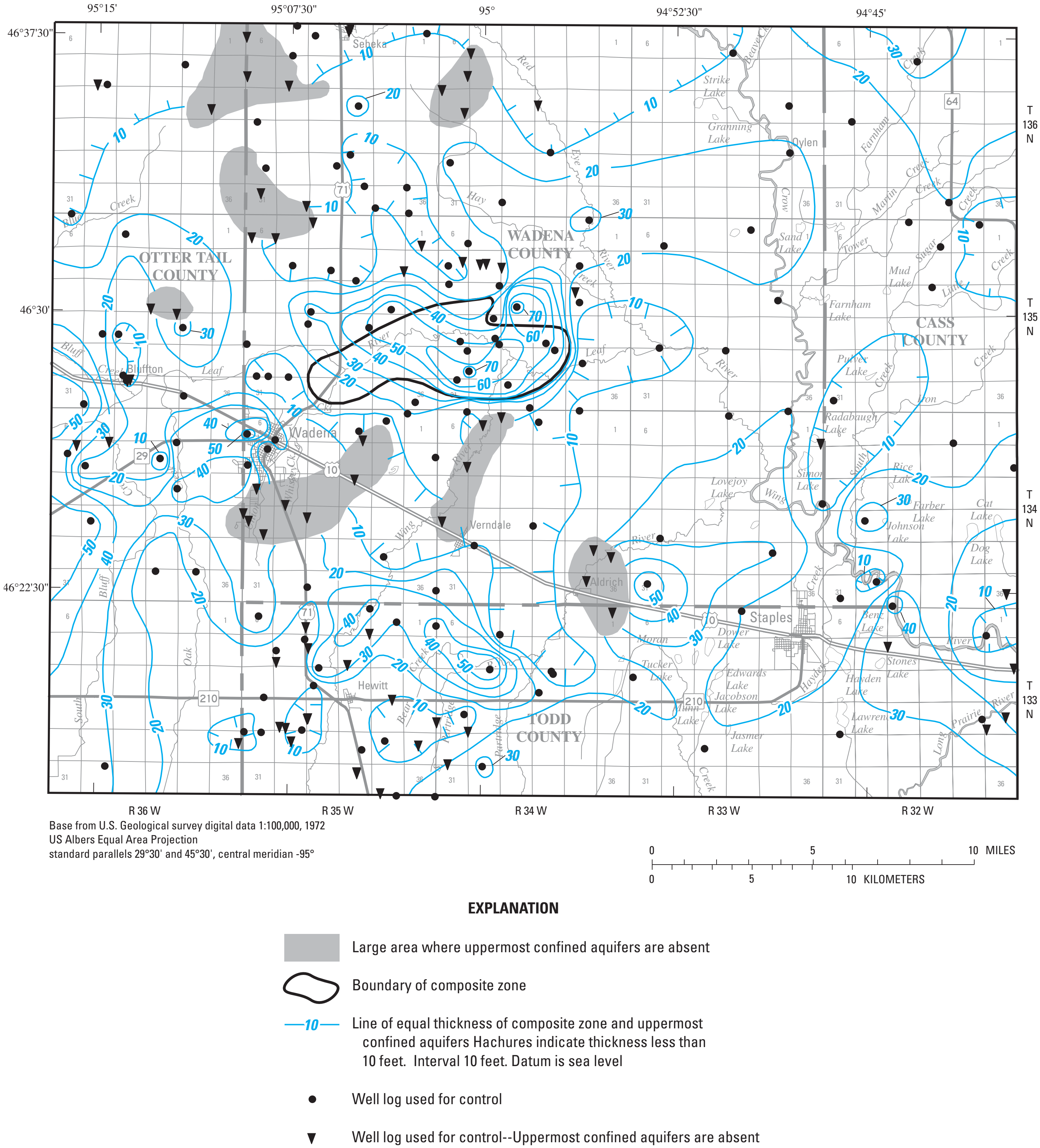
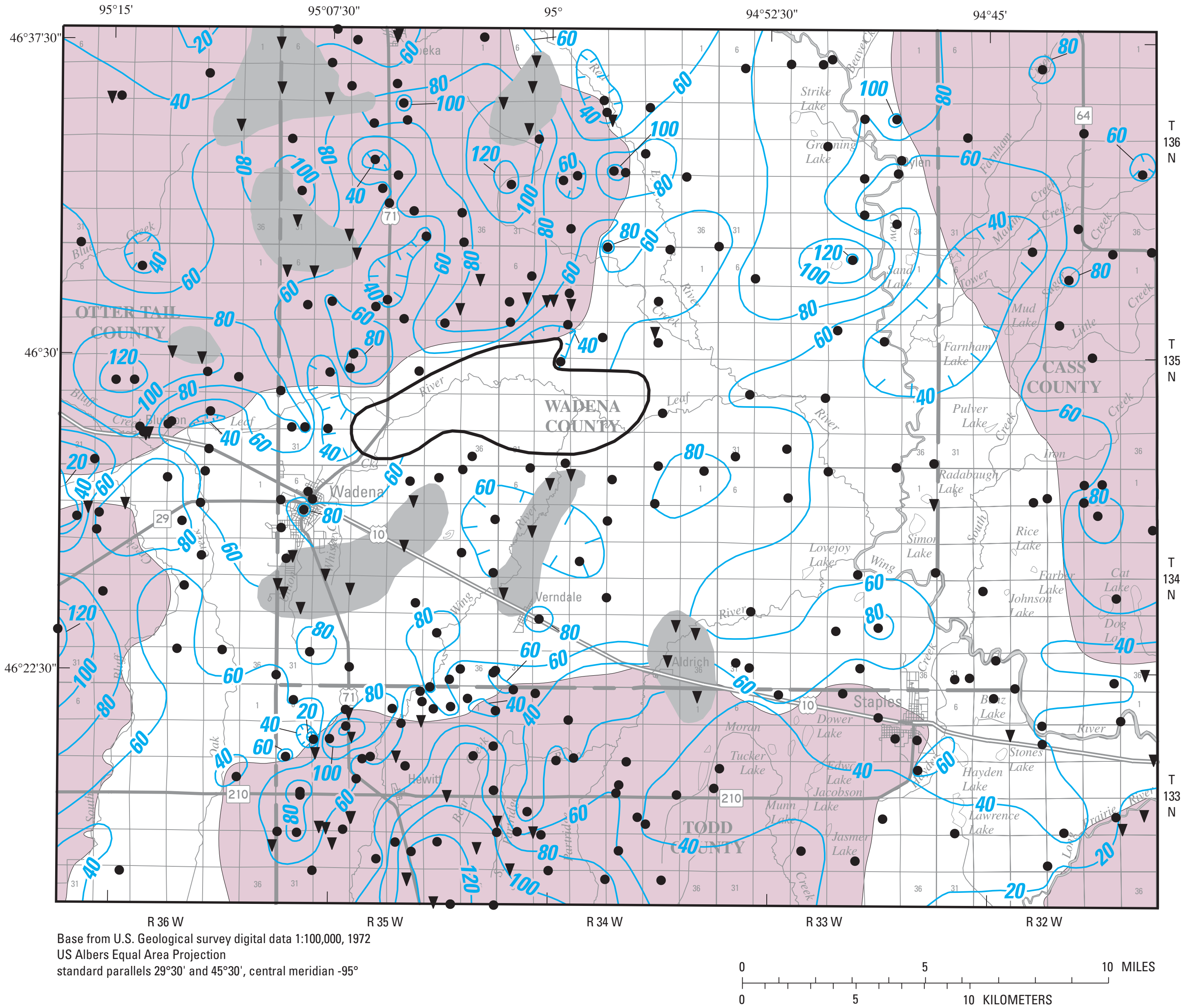


Figure 4. Thickness of composite zone and uppermost confined aquifers, southern Wadena County and parts of surrounding counties, Minnesota.



EXPLANATION

Extent of surficial aquifer

Area where surficial aquifer is absent

Large area where uppermost confined aquifers are absent

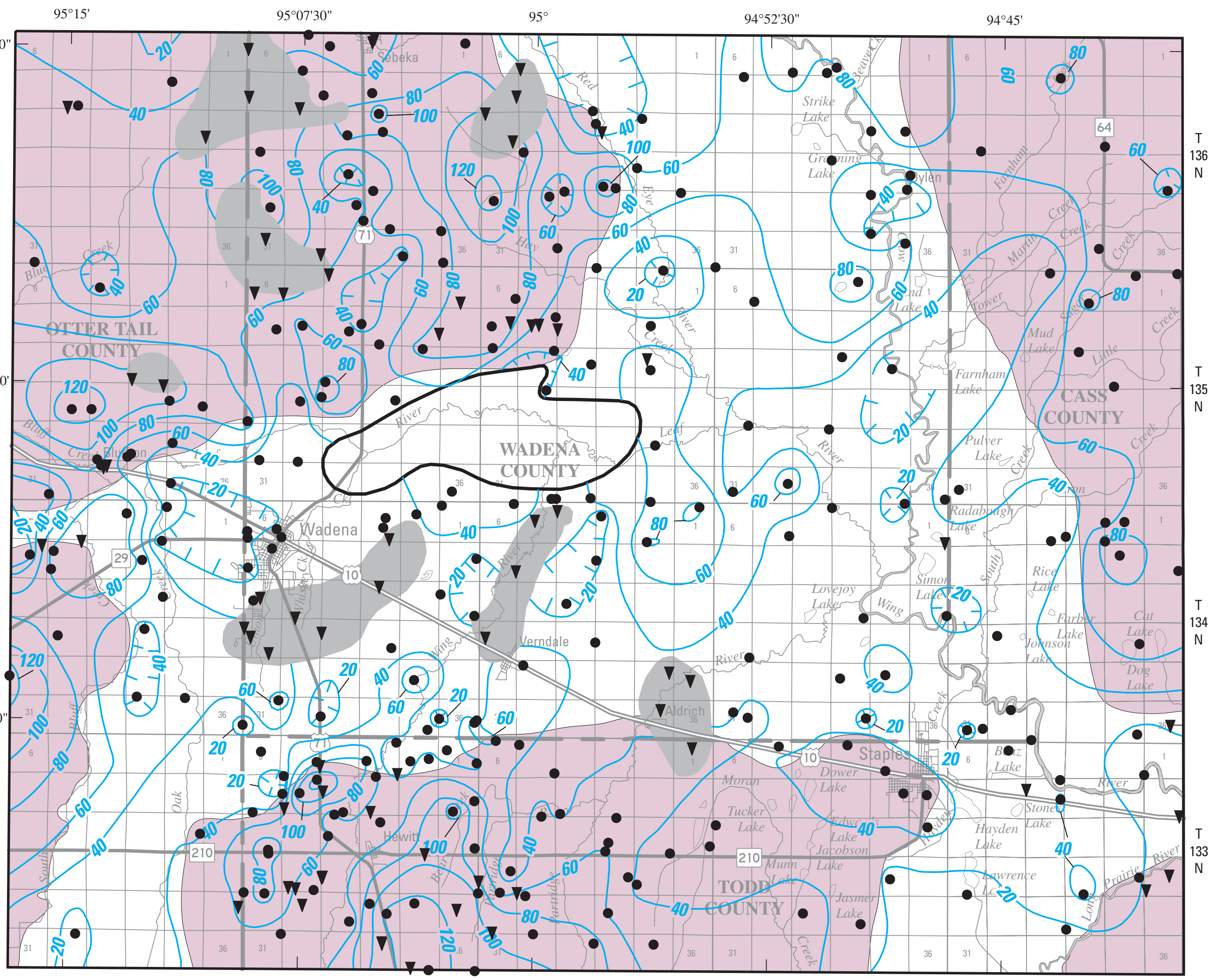
Boundary of composite zone

20 Line of equal depth to top of uppermost confined aquifers--Hachures indicate decreasing depth to top of aquifers. Interval 20 feet. Datum is sea level

Well log used for control

Well log used for control--Uppermost confined aquifers are absent

Figure 5. Depth to top of uppermost confined aquifers and extent of surficial aquifer, southern Wadena County and parts of surrounding counties, Minnesota.



Base from U.S. Geological survey digital data 1:100,000, 1972
US Albers Equal Area Projection
standard parallels 29°30' and 45°30', central meridian -95°

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

Extent of surficial aquifer

Area where surficial aquifer is absent

Large area where uppermost confined aquifers are absent

Boundary of composite zone

—20— Line of equal thickness of uppermost confining units--
Hachures indicate declining thickness. Interval 20 feet.
Datum is sea level

● Well log used for control

▼ Well log used for control--Uppermost confined aquifers are absent

Figure 6. Thickness of uppermost confining units and extent of surficial aquifer, southern Wadena County and parts of surrounding counties, Minnesota.

comprise the deposits. Consequently, glacial deposits can be either an aquifer or a confining unit. Field tests were not conducted for this investigation to determine the hydraulic properties of aquifers and confining units. Reported values of hydraulic conductivity, transmissivity, specific yield, and storage coefficient are shown in table 2.

Hydrology

Ground water generally moves from high morainal areas toward major streams, which flow across topographically lower outwash plains. The regional direction of flow in the surficial aquifer is toward the Leaf and Crow Wing Rivers and, to a lesser extent, toward the Wing, Partridge, Red Eye, and Long Prairie Rivers (fig. 7). Locally, flow is also toward smaller streams and lakes. The regional direction of flow in the uppermost confined aquifers is to the east, southeast, and southwest toward the Crow Wing River in the eastern part of the study area and toward the Leaf River in the western part (fig. 8). A steep hydraulic gradient (40 to 60 ft/mi) exists in the northwestern part of the study area near the boundaries of the Leaf and Red Eye River valleys. Potentiometric surface maps (figs. 7 and 8) indicate that the Crow Wing and Leaf Rivers are major discharge areas for the surficial and uppermost confined aquifers.

Recharge to the surficial aquifer occurs by infiltration of precipitation to the saturated zone (areal recharge). Helgesen (1977) considered an areal recharge rate of about 5 in./yr to be representative of long-term conditions for the area between the Redeye and Crow Wing Rivers and the area east of the Crow Wing River. Ground-water recharge rates in the study area for 1998 and 1999 were estimated from monthly water-level measurements for 17 observation wells completed in the surficial aquifer, based on the method of hydrograph analysis described by Rasmussen and Andreasen (1959). The method assumes that all water-level rises in a well result from areal recharge. A specific yield value of 0.20 was assumed in the areal recharge calculations. Estimated areal recharge ranged from 6.0 to 23.0 in. during 1998, and averaged 13.9 in. Estimated areal recharge ranged from 6.2 to 17.3 in. during 1999, and averaged 11.5 in./yr. These recharge rates generally are greater than those reported by previous investigations (table 2). The areal recharge rates estimated from hydrographs for wells located near the Leaf River were greater than for other areas. Estimated areal recharge rates near the Leaf River during 1998–99 ranged from 10.6 to 23.0 in./yr, with an average of 15.5 in./yr. Estimated areal recharge rates for other areas generally ranged from 6 to 12 in./yr.

Sources of water to the uppermost confined aquifers are leakage of water through overlying till and clay and ground-water flow from aquifers adjoining the northeastern, northwestern, and southwestern study area boundaries. Delin (1987 and 1988) suggested that leakage through overlying till in west-central Minnesota ranges from 3 to 6 in./yr, based on hydrograph and ground-water-flow model analysis (table 2). Leakage rates through till computed using Darcy's Law, however, were much lower, 0.06–1.60 in./yr (Delin, 1988).

Discharge from the surficial aquifer is: (1) by withdrawals from irrigation, municipal, commercial, and domestic wells; (2) by ground-water evapotranspiration in areas where the water table is within about 5 ft of land surface; and (3) to streams. Water in the uppermost confined aquifers flows toward the river valleys, where it discharges to the overlying surficial aquifer. Discharge from the uppermost confined aquifers also is by withdrawals from irrigation, municipal, golf course and landscaping, and domestic wells.

Water levels in the aquifers fluctuate seasonally in response to seasonal variations in recharge and discharge (fig. 9). Ground-water levels commonly rise in spring, when areal recharge is greatest because of snowmelt, spring rain, and minimal evapotranspiration losses. Ground-water levels generally decline in summer because discharge by evapotranspiration discharges to streams, and withdrawals by wells exceed recharge. Net recharge to the aquifers also occurs in the fall of most years, due to rainfall and low evapotranspiration rates.

The available hydrologic data in and near the study area indicate that the ground-water levels fluctuate in response to seasonal variations in recharge and discharge around mean water levels that remain relatively constant in time. The ground-water system is in a dynamic equilibrium, or steady-state condition, in which discharges from the system are balanced by recharge to the system. Ground-water levels may rise or decline for a period of a few years in response to periods of above-normal or below-normal precipitation, but long-term declines in levels have not occurred in the study area. Winter water levels from a given year approximate long-term steady-state conditions.

Ground-Water Withdrawals

Ground water is the primary source of water for irrigation, municipal, commercial, and domestic uses in the study area. Glacial-deposit aquifers are the source of water for all municipal supply wells in the study area. There were 11 municipal water-supply wells and 199 irrigation wells that withdrew water during 1997–98 (table 3). Nine of the 11 municipal wells are completed in the uppermost confined aquifers. Most permits for irrigation have been issued since

Table 2. Reported values of hydraulic properties and fluxes, southern Wadena County and parts of surrounding counties, Minnesota

[in./yr, inches per year; ft, feet; ft/d, feet per day; ft^2/d, feet squared per day; gpd/ft, gallons per day per foot; >, greater than. Number in parentheses refers to number of aquifer tests conducted]

Hydraulic property or flux	Area value(s) applies to	Method used to determine value(s)	Single or mean value	Range of values
		Horizontal hydraulic conductivity (ft/d) [gpd/ft^2]		
Glacial-deposit aquifers				
Freeze and Cherry (1979)	Not specified	Reported values		10^1–10^4
Surficial aquifers				
Lindholm (1970)	Wadena area	Aquifer-tests (3)		193–321 [1,440–2,400]
Helgesen (1977)	T134N,R32W, section 7	Aquifer test	320	
Myette (1984)	Staples Irrigation Center (located about 5 miles northwest of Staples)	Aquifer test	325	
Confined aquifers				
Delin (1988)	West-central Minnesota	Aquifer tests and specific capacities		10–750
Lindholm (1970)	Wadena area	Aquifer test	341 [2,550]	
Glacial-deposit confining units				
Norris (1962)	South Dakota	Reported values	$9.4x10^{-3}$	$4.0x10^{-5}$–$6.7x10^{-2}$
Delin (1988)	West-central Minnesota	Slug tests (8)	$1.4x10^{-1}$	
Stark and others (1991)	North-central Minnesota	Ground-water-flow model analysis		0.1–1.0
		Transmissivity (ft^2/d) [gpd/ft]		
Surficial aquifers				
Lindholm and others (1972)	Crow Wing River Watershed	Aquifer tests and specific capacities		1,337–13,369 [10,000–100,000]
Lindholm and others (1972)	Verndale area	Aquifer tests and specific capacities	>4,011[>30,000]	
Lindholm (1970)	Wadena area	Aquifer test (3)		8,690–10,963 [65,000–82,000]
Lindholm (1970)	Wadena area	Aquifer test, laboratory analyses, and published data		2,005–16,043 [15,000–120,000]
Helgesen (1977)	T134N,R32W, section 7	Aquifer test	10,700	
Myette (1984)	Staples Irrigation Center (located about 5 miles northwest of Staples)	Aquifer test	9,800	
Confined aquifers				
Lindholm and others (1972)	Crow Wing River Watershed	Specific capacities		134–1,337 [1,000 - 10,000]
Lindholm (1970)	Wadena area	Aquifer test	15,642 [117,000]	
		Vertical hydraulic conductivity (ft/d) [gpd/ft^2]		
Glacial-deposit confining units				
Freeze and Cherry (1979)	Not specified	Reported values		10^{-6}–1
Delin (1988)	West-central Minnesota	Aquifer tests (4)	$4.0x10^{-1}$	$8.6x10^{-6}$–1.8
Miller (1982)	Northwestern Minnesota	Aquifer test	$1.8x10^{-2}$	
		Specific yield		
Heath (1983)	Not specified	Reported values		0.10–0.30
Lindholm and others (1972)	Verndale area	Aquifer tests	0.15	
Lindholm (1970)	Wadena area	Aquifer test (3)		0.11–0.18
Helgesen (1977)	T134N,R32W, section 7	Aquifer test	0.18	

Table 2. Reported values of hydraulic properties and fluxes, southern Wadena County and parts of surrounding counties, Minnesota (Continued)

[in./yr, inches per year; ft, feet; ft/d, feet per day; ft^2/d, feet squared per day; gpd/ft, gallons per day per foot; >, greater than. Number in parentheses refers to number of aquifer tests conducted]

Hydraulic property or flux	Area value(s) applies to	Method used to determine value(s)	Single or mean value	Range of values
Myette (1984)	Staples Irrigation Center (located about 5 miles northwest of Staples)	Aquifer test	0.185	
		Storage coefficient		
Glacial-deposit confined aquifers				
Lindholm (1970)	Wadena area	Aquifer test	$1.4x10^{-2}$	
Freeze and Cherry (1979)	Not specified	Reported values		$5.0x10^{-5}$–$5.0x10^{-3}$
Glacial-deposit confining units				
Lindgren and Landon (2000)	Southwestern Minnesota	Ground-water-flow model analysis		$1.0x10^{-5}$–$5.0x10^{-4}$
		Areal recharge to surficial aquifers (in./yr)		
Lindholm (1970)	Wadena area	Hydrograph analysis		4.8–12.0
Helgesen (1977)	Central Minnesota	Hydrograph analysis	5.1	
Lindgren and Landon (2000)	Southwestern Minnesota	Hydrograph analysis		2.9–8.2
		Recharge to confined aquifers by leakage through till (in./yr)		
Delin (1986)	Western Minnesota	Computed using Darcy's Law		0.4–3.4
Delin (1988)	West-central Minnesota	Computed using Darcy's Law		0.06–1.60
Delin (1987 and 1988)	West-central Minnesota	Hydrograph analysis and ground-water-flow model analysis		3.0–6.0

1960. Fifty-six percent (111) of the irrigation wells are completed in the surficial aquifer. Water was pumped for irrigation purposes from 47 dug pits, which are equivalent to wells completed in the surficial aquifer. The locations for which irrigation permits have been issued are largely within the areas of surficial outwash. Some irrigation wells are completed in the uppermost confined aquifers in T133N, R35W, where the uppermost confining units are present at land surface and the surficial aquifer is absent.

Vertical Hydraulic Connection between aquifers

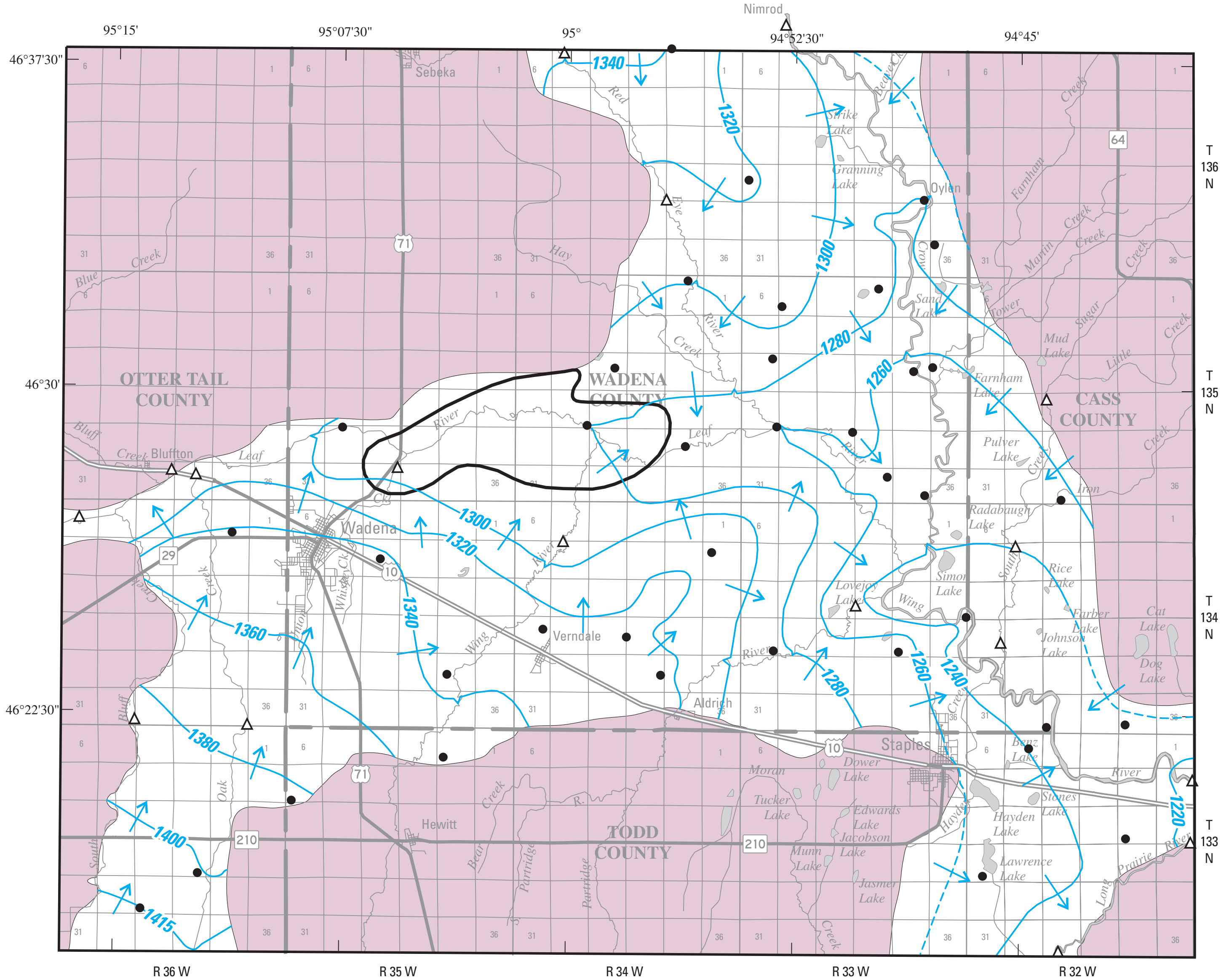
The vertical hydraulic connection between the surficial and uppermost confined aquifers is dependent on the thicknesses and vertical hydraulic conductivities of the uppermost confining units that separate the aquifers. The primary area of hydraulic connection between the aquifers, with presumably the greatest amount of leakage, is in the central part of the study area near the Leaf River where the uppermost confining units are comparatively thin and discontinuous. In this area, the surficial and uppermost confined aquifers cannot be clearly separated and for the purposes of this report are considered a single aquifer (composite zone, fig. 6) The composite zone is probably in hydraulic connection with adjacent uppermost confined aquifers.

The uppermost confining units separating the surficial and uppermost confined aquifers consist of sandy clay and are generally from 20 to 80 ft thick outside the boundaries of the composite zone (fig. 6). Thicknesses of less than 20 ft occur west of Wadena, north of Verndale, and near the Crow Wing River. The greatest potential for hydraulic connection and leakage between the aquifers is where the uppermost confining units are less than 20 ft thick.

Water levels in wells completed in the surficial and uppermost confined aquifers indicate that hydraulic heads in the aquifers are similar in most of the study area. The vertical hydraulic gradient is generally downward at the USGS well sites with nested wells, but of small magnitude (less than 0.4 ft of hydraulic head difference), indicating minimal leakage between the aquifers. Near the major streams, however, water levels in nested wells indicate relatively strong upward vertical gradients. The average 1998–99 hydraulic head differences were as much as 10.8 ft near the Leaf River, 4.2 ft near the Crow Wing River, 3.9 ft near the Wing River, 2.3 ft. near the Red Eye River, and 1.7 ft near the Partridge River.

Stream-Aquifer Leakage

Stream-discharge measurements indicated that the Crow Wing River in the study area may have both gaining and losing reaches, but is a gaining stream overall (table 1). The measured gains and losses for the Crow Wing River, other than for reach SW1-SW2 in November 1999, were less than the



Base from U.S. Geological survey digital data 1:100,000, 1972
US Albers Equal Area Projection
standard parallels 29°30' and 45°30', central meridian -95°

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

Extent of surficial aquifer

Area where surficial aquifer is absent

Boundary of composite zone

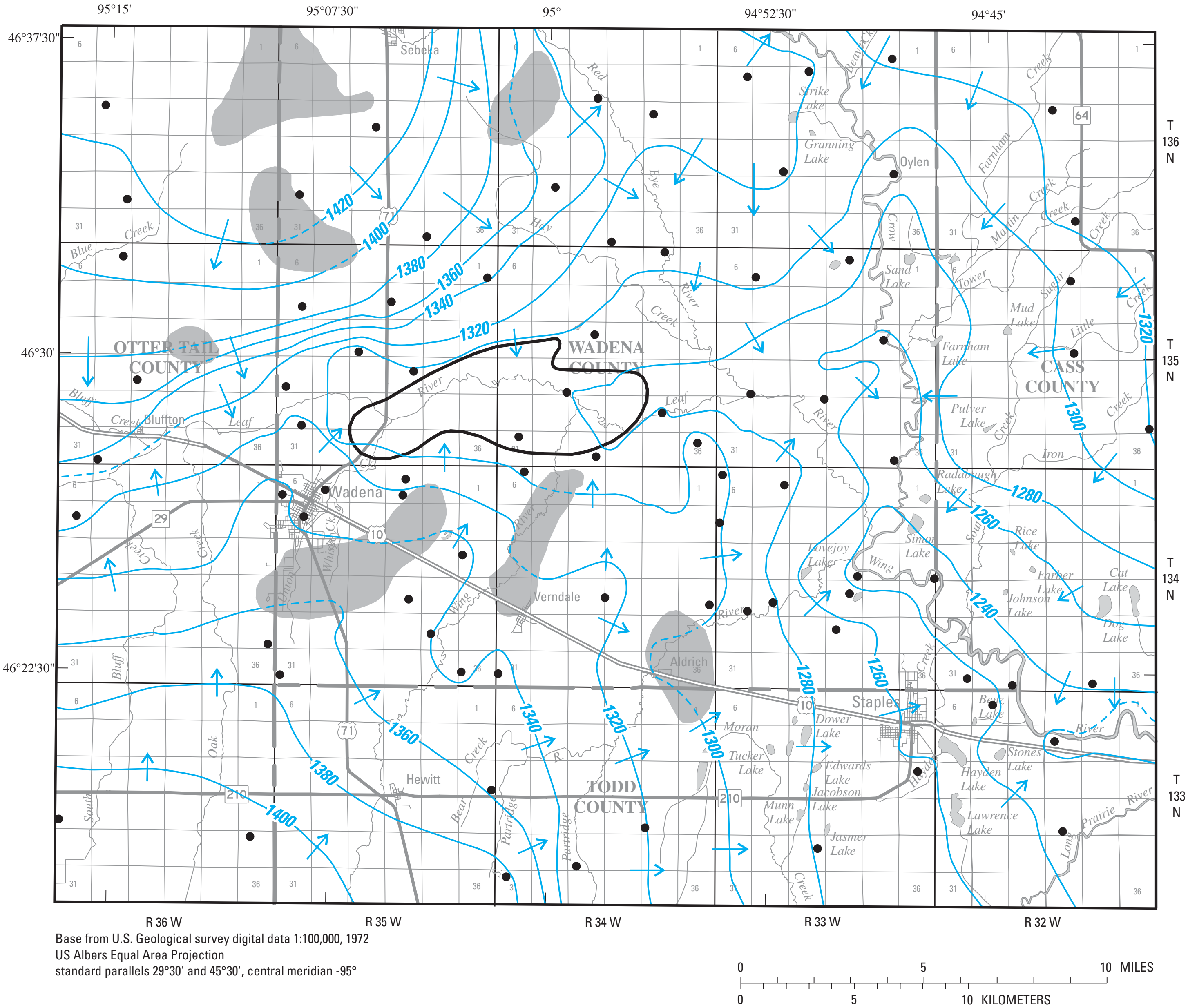
—1300— Measured potentiometric contour--Shows altitude at which level would have stood in tightly cased wells open to the surficial aquifer. Dashed where inferred. Interval varies. Datum is sea level

Generalized direction of ground-water flow

Well used for control

Stream-stage measurement site used for control

Figure 7. Altitude of potentiometric surface of surficial aquifer, December 1998, and extent of surficial aquifer, southern Wadena County and parts of surrounding counties, Minnesota.



EXPLANATION

Large area where uppermost confined aquifers are absent

Boundary of composite zone

—1300— Measured potentiometric contour--Shows altitude at which level would have stood in tightly cased wells open to the uppermost confined aquifer. Dashed where inferred. Interval 20 feet. Datum is sea level

Generalized direction of ground-water flow

Well used for control

Figure 8. Altitude of potentiometric surface of uppermost confined aquifers, December 1998, southern Wadena County and parts of surrounding counties, Minnesota.

magnitude of the estimated measurement uncertainty of 5–8 percent. The discharge measurements for the Leaf, Wing, and Partridge Rivers indicated that these rivers are all gaining streams for all measured reaches. The measured gains for these stream reaches were appreciably greater than the estimated measurement uncertainty of 5–8 percent, except for reach SW9-SW10 of the Leaf River. The discharge measurements for the Red Eye River indicated that the river is a gaining stream overall, but possibly with a losing reach near its confluence with the Leaf River. The measured loss in streamflow in August 1998 is minimally greater than the estimated measurement uncertainty of 5 percent.

The measured streamflows during November 1999 were much greater than in August 1998 (table 1). The anomalously high measured gain in streamflow for reach SW1-SW2 of the Crow Wing River during November 1999 probably is due to wet conditions that developed as a result of rainfall during the time of the measurements and may include a component of overland runoff. The lower streamflows measured during August 1998 are probably more representative of base-flow conditions, and therefore stream-aquifer leakage.

Theoretical Maximum Well Yields in Uppermost Confined Aquifers

The theoretical maximum well yields for the uppermost confined aquifers range from less than 175 gal/min to greater than 3,000 gal/min (fig. 10). The distribution of theoretical maximum well yields is derived from aquifer thickness, a uniform horizontal hydraulic conductivity of 150 ft/d, and available drawdown. The value of 150 ft/d was derived from numerical ground-water-flow model analysis and represents an average, regional value. The comparatively high value reported by Lindholm (1970) (table 2) is probably due to a high degree of vertical hydraulic connection between the surficial and uppermost confined aquifer at the aquifer-test site. Areal variations in the magnitude of theoretical maximum well yields shown on figure 10 are caused predominantly by areal variations in aquifer thickness (fig. 4). The areas of greatest theoretical maximum well yields coincide with areas of greatest aquifer thickness and transmissivity. High-capacity wells generally are located in these areas.

No aquifer or well fully satisfies the assumptions inherent in the method used to estimate theoretical maximum well yields. Local variations in aquifer hydraulic properties, recharge, proximity of the well to other pumping wells, effects of hydrologic boundaries (for example, rivers), well diameter and efficiency, and duration of pumping will cause differences from the values shown on figure 10. The theoretical maximum well yields for the uppermost confined aquifers are intended to show only general conditions and relative differences in water-yielding capability. The map cannot be used for accurate estimation of well yields at a given location. Determination of site-specific well yields requires hydraulic testing such as aquifer tests.

SIMULATION OF GROUND-WATER FLOW

A conceptual model is a qualitative description of the known characteristics and functioning of the glacial-deposit aquifers. It was formulated from knowledge of the hydrogeologic setting, aquifer characteristics, distribution and amount of recharge and discharge, and aquifer boundaries. A numerical model of ground-water flow was constructed based on this conceptual model using the MODFLOW code developed by McDonald and Harbaugh (1988).

Numerical Model Description

The study area was subdivided into rectangular finite-difference grid cells within which the properties of the hydrogeologic unit represented are assumed to be uniform. The center of a grid cell is referred to as a node and represents the location for which the hydraulic head is computed by the model. The uniformly-spaced finite-difference grid has 96 rows and 120 columns (fig. 11). The dimensions of each grid cell are one-quarter mile (1,320 ft) along rows and columns. Notation of the form (11, 24), where the first number in parentheses indicates the row and the second number indicates the column, is used to refer to the location of an individual cell within the grid. The area modeled was extended away from the area of extensive irrigation in southern Wadena County by sufficient distances to minimize boundary effects.

The ground-water system was subdivided vertically into three layers, corresponding to generally horizontal hydrogeologic units. The altitudes of the layer tops and layer bottoms were specified for each model cell for the three layers. The thickness of a cell representing a hydrogeologic unit is incorporated in the transmissivity term for the cell. Simulation of leakage of water between model layers is dependent on the thicknesses and vertical hydraulic conductivities of the adjacent layers. A detailed discussion of leakage between model layers can be found in McDonald and Harbaugh (1988).

The hydrogeologic units represented in the ground-water-flow model are, in descending order: (1) the surficial aquifer (layer 1), (2) the confining units underlying the surficial aquifer (layer 2), and (3) the uppermost confined aquifers (layer 3). Cells in model layers 1 and 3 generally were assigned the hydrogeologic properties of sand and gravel. Cells in model layer 2 were assigned the

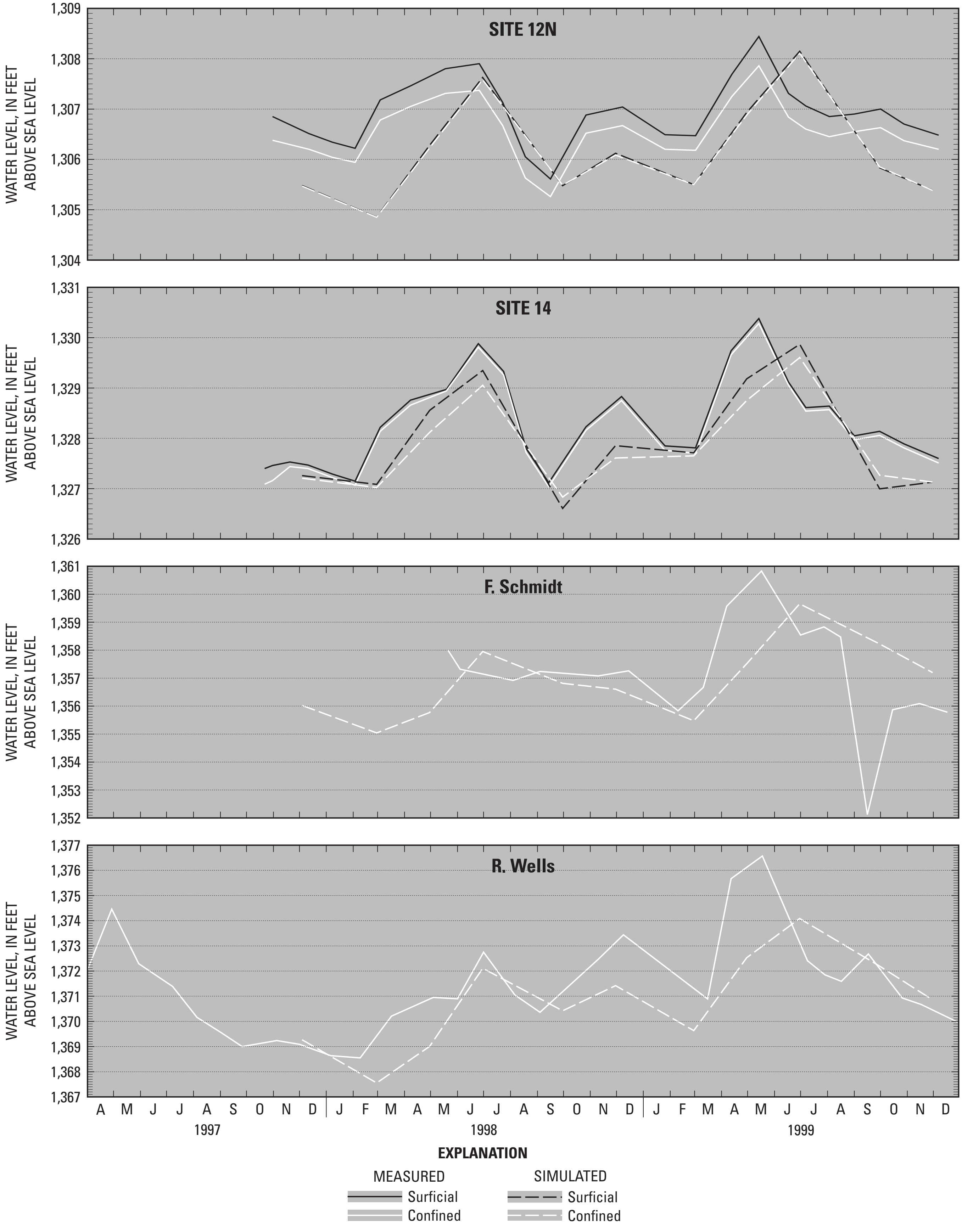
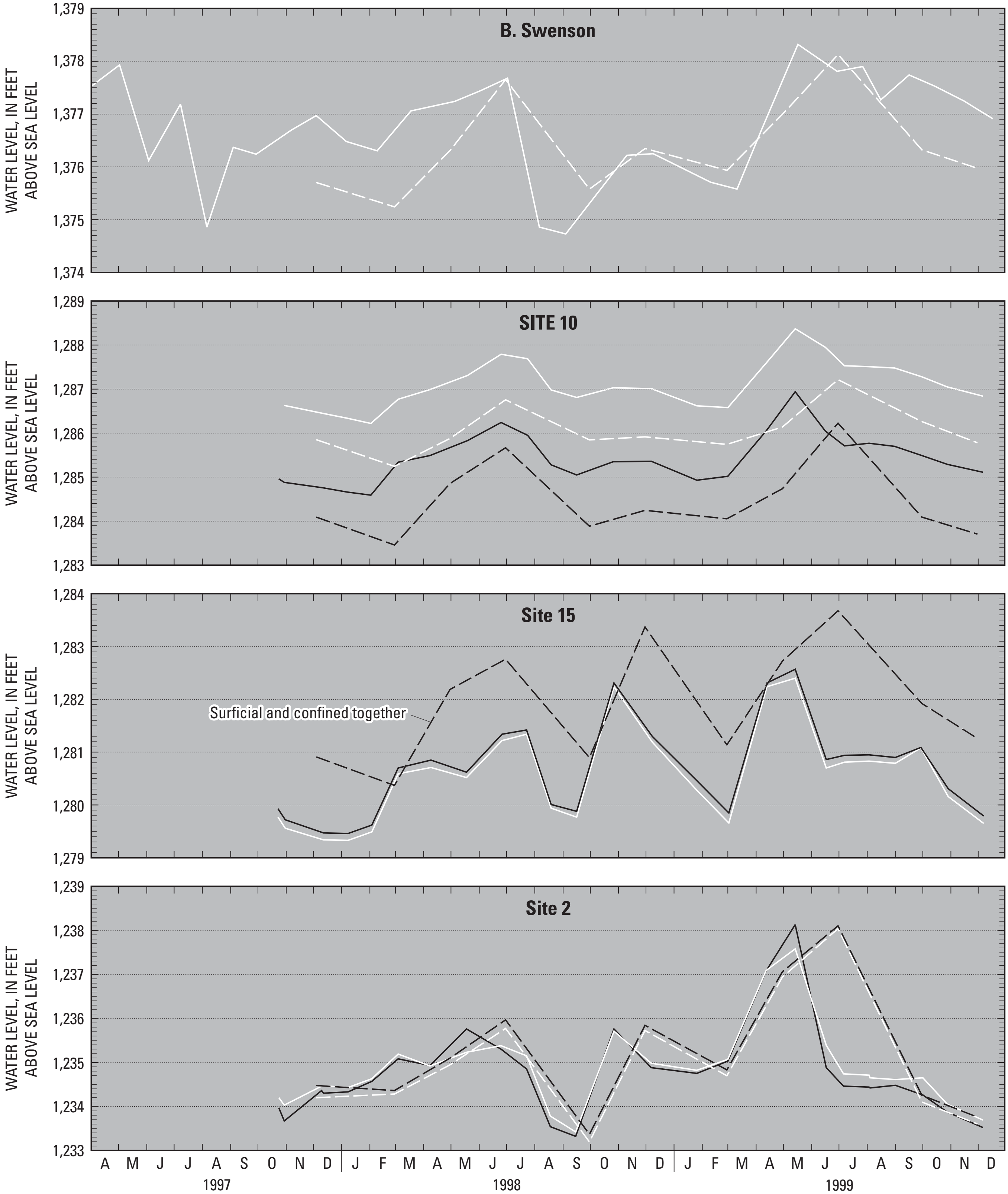


Figure 9. Measured and simulated hydraulic heads for selected observation wells completed in surficial and uppermost



confined aquifers, transient simulation 1998-99, southern Wadena County and parts of surrounding counties, Minnesota.

hydrogeologic properties of clay and till.

The transmissivities associated with the model cells for layer 1 vary as the saturated thicknesses vary. The transmissivities assigned to the model cells for layer 2 and layer 3 are constant in time.

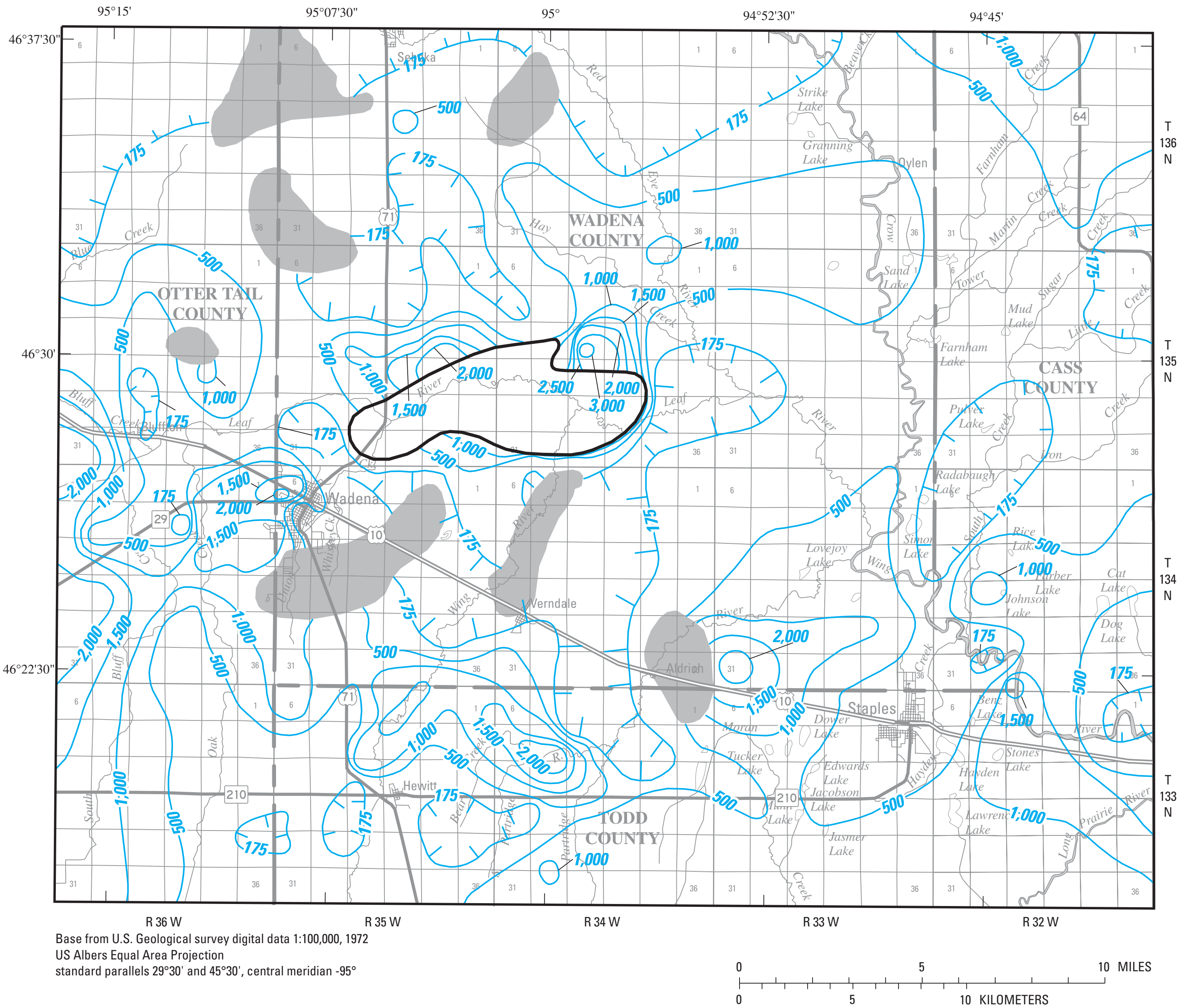
Ideally, all model boundaries should be located at the physical limits of the aquifer system or at other hydrologic boundaries, such as a major river. Practical considerations, such as limitations concerning the size of the area modeled, may necessitate the use of arbitrarily imposed model boundaries where the natural hydrologic boundaries lie outside the model area. The boundaries for model layer 1 are located at the physical limits of the aquifer, except for the north-central, southwestern, and southeastern boundaries (fig. 12a). Ground-water flow was not simulated across the boundaries. No ground-water flow is simulated across the north-central boundary because the predominant flow directions are toward the Crow Wing and Red Eye Rivers, approximately parallel to the boundary. Similarly, no ground-water flow is simulated across the southwestern boundary because the predominant flow direction is toward Oak Creek, approximately parallel to the boundary. The southeastern boundary is partially defined by the Long Prairie River, which serves as a discharge area (sink) for the surficial aquifer. No ground-water flow is simulated across the portions of the southeastern boundary west of the Long Prairie River and between the Long Prairie and Crow Wing Rivers because the predominant flow is approximately parallel to these boundaries. The boundaries for model layer 2 were imposed to coincide with the boundaries for model layer 1 (fig. 12b). Because flow in confining units is predominantly vertical, no ground-water flow across boundaries was simulated for model layer 2. The boundaries for model layer 3 coincide with the boundaries of the study area (fig. 12c). Ground-water flow near the boundaries is approximately parallel to the boundaries, except for the northwestern, northeastern, and southwestern boundaries; therefore, no ground-water flow across the boundaries was simulated. Hydraulic heads were specified (constant-head boundary condition) for the northwestern, northeastern, and southwestern boundary cells, based on measured water levels in those areas. These boundaries are far enough away from the areas of primary interest (irrigation areas in southern Wadena County) to minimize boundary effects on model-computed hydraulic heads and flows in the areas of primary interest.

A specified-flux boundary was used to represent areal recharge to

Table 3. Ground-water withdrawals during 1997-98 in southern Wadena County and parts of surrounding counties, Minnesota
[Mgal, million gallons; --, no ground-water withdrawals. Ground-water withdrawals were obtained from the Mnnesota Department of Natural Resources]

Aquifer and well type	Number of wells	Withdrawals	
		1997 (Mgal)	1998 (Mgal)
Surficial aquifer			
Irrigation wells	111	833.48	1441.76
Municipal wells	2	19.48	19.41
Commercial wells	2	--	10.51
Subtotal	115	852.96	1471.68
Dug pits	47	329.76	431.28
Total	162	1182.72	1902.96
Uppermost confined aquifers			
Irrigation wells	88	899.80	1437.69
Municipal wells	9	428.61	456.39
Other wells[1]	3	25.87	31.69
Total	100	1354.28	1925.77

[1]Golf course and landscaping wells



EXPLANATION

Large area where uppermost confined aquifers are absent

Boundary of composite zone

—500— Line of equal theoretical maximum yield assuming an efficient fully penetrating well and available drawdown defined as the difference between static water level in a well and bottom of uppermost confined aquifer penetrated. Hachures indicate yield less than 175 or 500 gallons per minute. Interval, in gallons per minute, varies

Figure 10. Theoretical maximum yield of wells completed in uppermost confined aquifers, southern Wadena County and parts of surrounding counties, Minnesota.

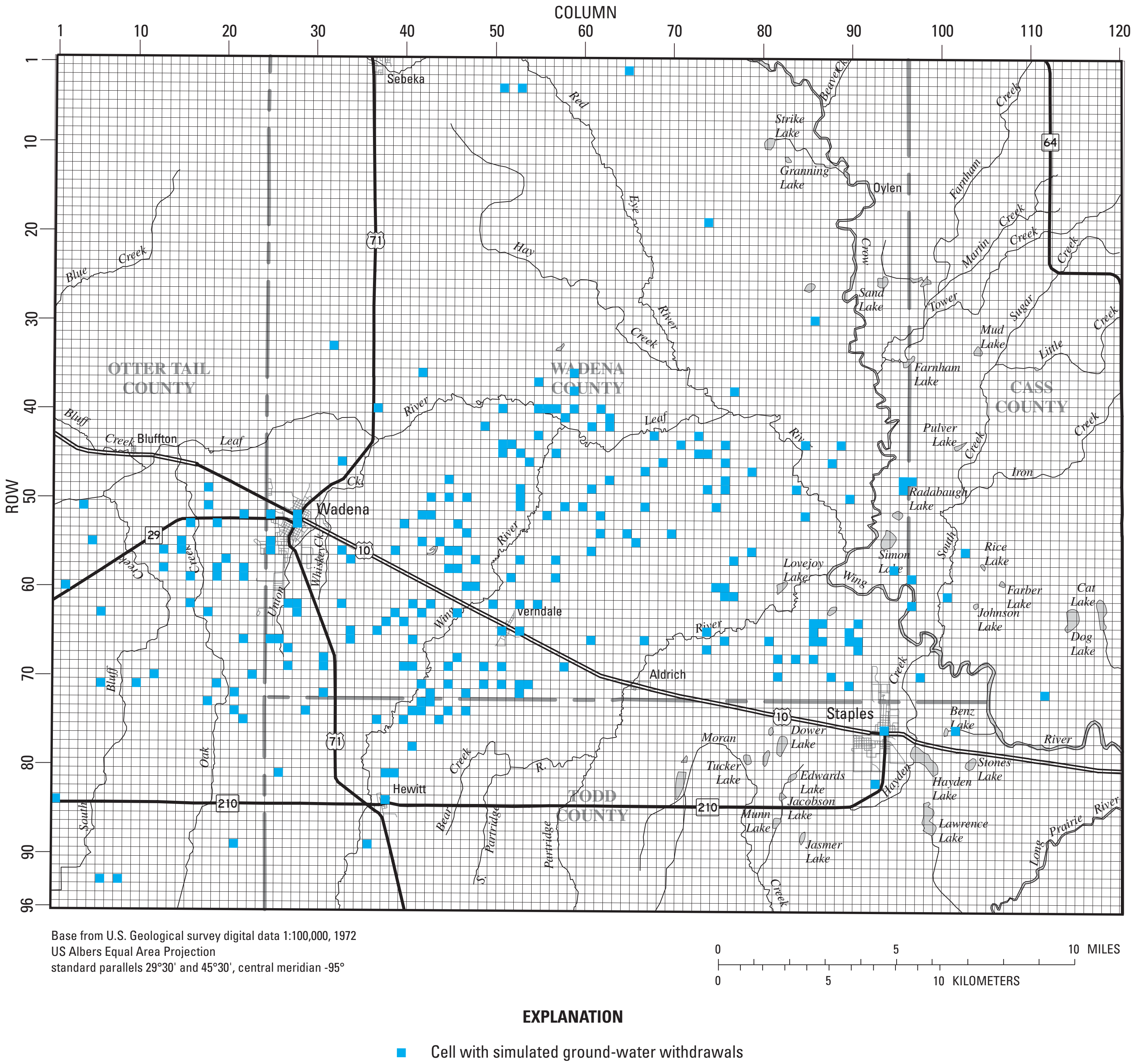


Figure 11. Grid for finite-difference ground-water-flow model and model cells with simulated ground-water withdrawals, southern Wadena County and parts of surrounding counties, Minnesota.

layer 1 and leakage through overlying clay and till (confining units) to layer 3 in areas where the surficial aquifer is absent. Areal recharge to layer 1 represents the net difference between precipitation and surface runoff and evapotranspiration losses occurring above the water table. Leakage to layer 3 represents the amount of water reaching the uppermost confined aquifers by movement through the overlying confining units in areas where the surficial aquifer is absent. Areal recharge or leakage was applied to the highest active cell in each vertical column of cells. In areas where the surficial aquifer is present, the amount of leakage to the uppermost confined aquifers through the confining units is computed by the model.

Stream-aquifer leakage was simulated with head-dependent flux nodes (McDonald and Harbaugh, 1988, Chapter 6). The streams simulated were the Crow Wing, Leaf, Long Prairie, Red Eye, Wing, and Partridge Rivers, South Bluff Creek, and Oak Creek. The streams were divided into reaches, each of which is completely contained in a single cell. Stream-aquifer leakage through a reach of streambed is dependent on: (1) the vertical hydraulic conductivity, thickness, and area (length times width) of the streambed; and (2) the difference between stream stage and hydraulic head in the aquifer.

The length of the streambed in each river cell was measured on USGS 7.5-minute-quadrangle topographic maps. The average widths of the streambeds were estimated at stream-stage and discharge measurement sites within the model area. The lower limit of the streambeds is poorly defined, thus the thickness of the streambeds was assumed to be 1 ft, which is similar to other numerical ground-water-flow models (Yager, 1993; Lindgren and Landon, 2000). The initial values for vertical hydraulic conductivity of the streambeds were: (1) 10 ft/d for the Leaf and Red Eye Rivers; (2) 1.0 ft/d for the Crow Wing, Long Prairie, Wing, and Partridge Rivers; and (3) 0.1 ft/d for South Bluff and Oak Creeks, based on the observed texture of the riverbed material. Published values for vertical hydraulic conductivity of riverbed material for streams in glacial terrain commonly range from 0.1 to 10 ft/d (Norris and Fidler, 1969; Jorgensen and Ackroyd, 1973; Prince and others, 1987; Delin, 1990; and Lindgren and Landon, 2000). Stream stage for each river cell between measured stream-stage sites was interpolated based on the length of the stream reach in the cell.

Discharge by ground-water evapotranspiration occurs from layer 1. The model simulates evapotranspiration from the saturated zone only. The initial maximum ground-water evapotranspiration rate specified in the model was 26.5 in./yr, which corresponds to the estimated average annual lake-evaporation rate in the model area. The assumption was made that evaporation from lakes was a reasonable estimate of the maximum ground-water evapotranspiration rate that occurs when the water table is at the land surface. Evaporation from lakes can be estimated from pan-evaporation data using a pan coefficient (Baker and others,1979). The ground-water evapotranspiration rate in the model decreases linearly with depth below land surface and becomes zero at the extinction depth. The extinction depth corresponds to a depth below land surface minimally greater than the rooting depth of the plants present. The plausible range for evapotranspiration extinction depth was assumed to be from 5 to 10 ft, based on plant root-zone depths, with an average value of 7 ft. A root-zone depth of 5 ft was considered applicable by Helgesen (1977). The altitude of the land surface for each cell was determined from USGS 7.5-minute-quadrangle topographic maps.

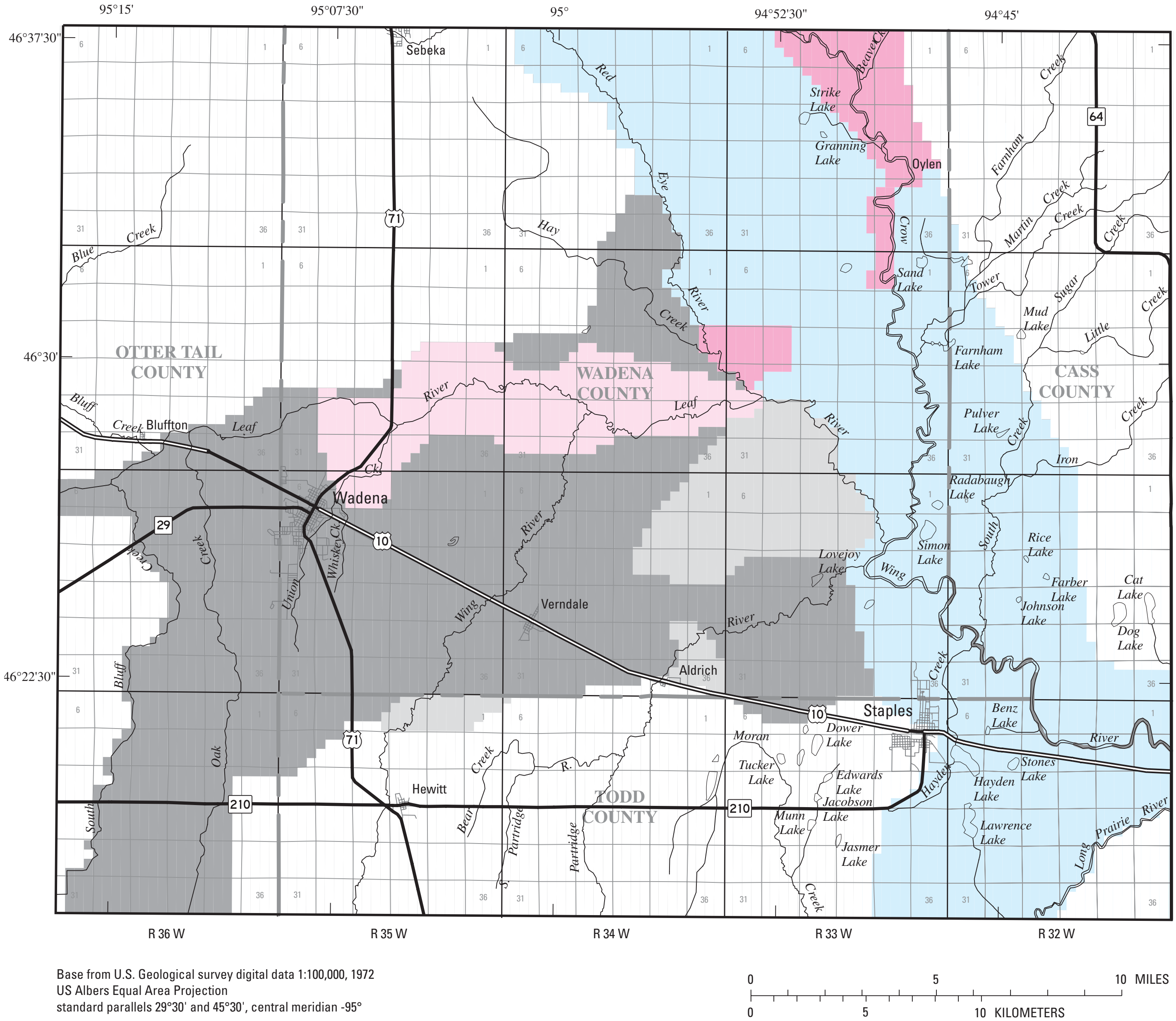
The initial values of hydraulic properties represented in the model are listed in table 4. Initial values for hydraulic conductivity for each hydrogeologic unit were based on the reported results of aquifer tests conducted in the study area and published values in the literature. Different horizontal hydraulic conductivity values were assigned to each model layer and areally to zones of differing geologic materials based on well and test-hole logs. Layer 1 was divided into 3 horizontal hydraulic conductivity zones. The western part was assigned a horizontal hydraulic conductivity 200 ft/d. The area near the Leaf River was assigned a horizontal hydraulic conductivity of 300 ft/d. The eastern area was assigned a horizontal hydraulic conductivity of 150 ft/d, with smaller areas near the northern reach of the Crow Wing River assigned a horizontal hydraulic conductivity of 10 ft/d. Layer 2 was assigned a horizontal hydraulic conductivity of 1.0 ft/d, except for the area near the Leaf River where only thin, discontinuous clay layers are present. This area was assigned a horizontal hydraulic conductivity of 200 ft/d, the same as for the uppermost confined aquifers. Layer 3 was assigned a horizontal hydraulic conductivity of 150 ft/d in areas where overlain by the uppermost confining units at land surface. The areas where the uppermost buried aquifers are absent were assigned a horizontal hydraulic conductivity of 1.0 ft/d, representative of clay and till.

Initial values for vertical hydraulic conductivity for model layers 1 and 3 were one-tenth the corresponding values for horizontal hydraulic conductivity. For layer 2, and for areas of layer 3 where the uppermost confined aquifers are absent, an initial vertical hydraulic conductivity of 0.001 ft/d was used.

The initial values for areal recharge were 9 in./yr for most of layer 1 and 12 in./yr for the area near the Leaf River, based on rates estimated for this investigation and those reported by Lindholm (1970). The initial value for recharge to layer 3 by leakage through overlying till in areas not overlain by the surficial aquifer was 2 in./yr, based on reported values (table 2).

Numerical Model Calibration

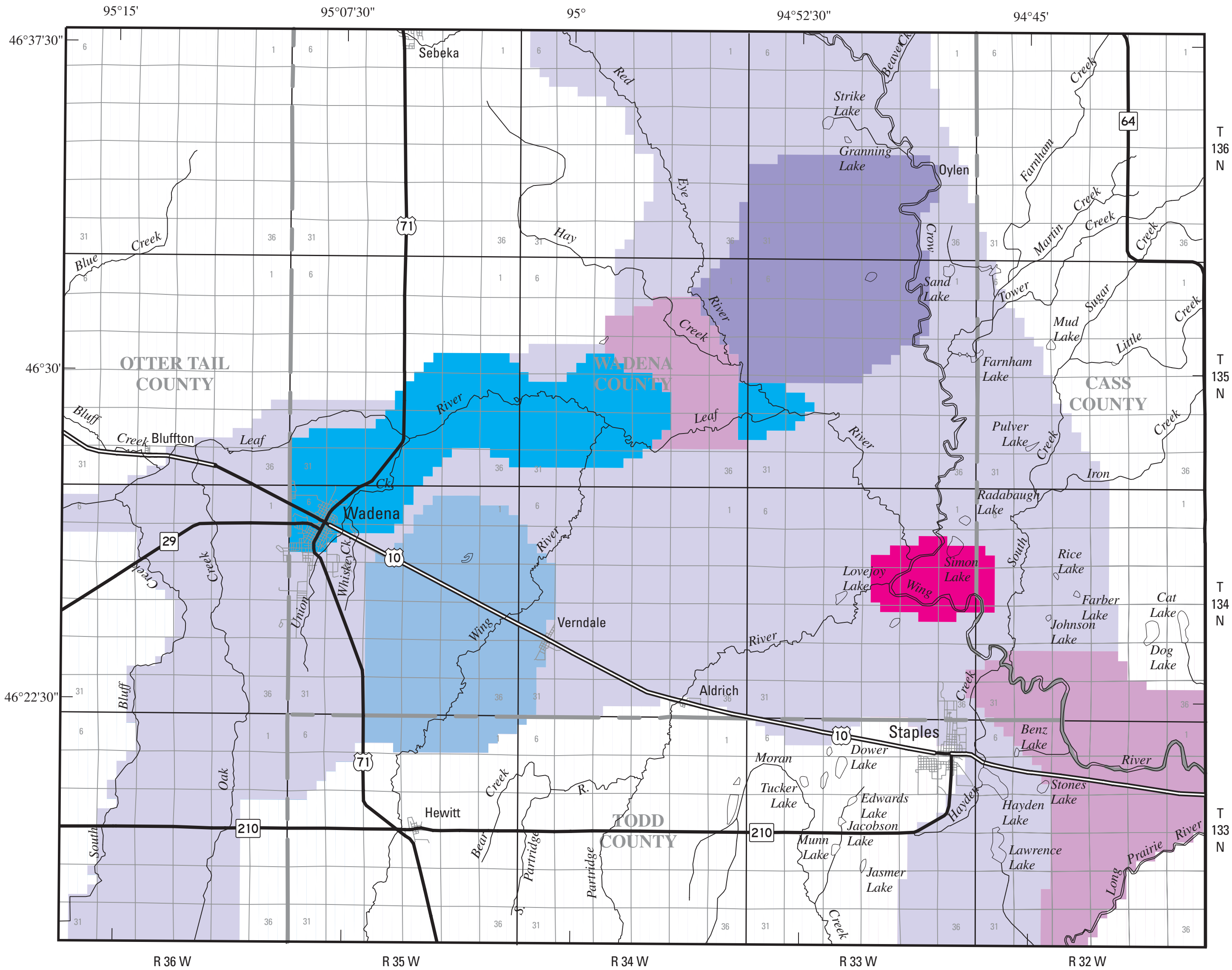
Model calibration is a process in which initial estimates of aquifer properties and boundary conditions are adjusted until simulated hydraulic heads and fluxes acceptably match measured water levels and fluxes. Calibration and evaluation of the ground-water-flow model were conducted for steady-state (equilibrium) conditions and for transient conditions. No storage terms are included in the steady-state simulation. Transient simulations incorporate the stor-



EXPLANATION

- Inactive cells
- Horizontal hydraulic conductivity of 5 feet per day
- Horizontal hydraulic conductivity of 100 feet per day
- Horizontal hydraulic conductivity of 150 feet per day
- Horizontal hydraulic conductivity of 200 feet per day
- Horizontal hydraulic conductivity of 350 feet per day

Figure 12a. Simulated boundary conditions and horizontal hydraulic conductivity zones for ground-water-flow model layer 1, southern Wadena County and parts of surrounding counties, Minnesota.



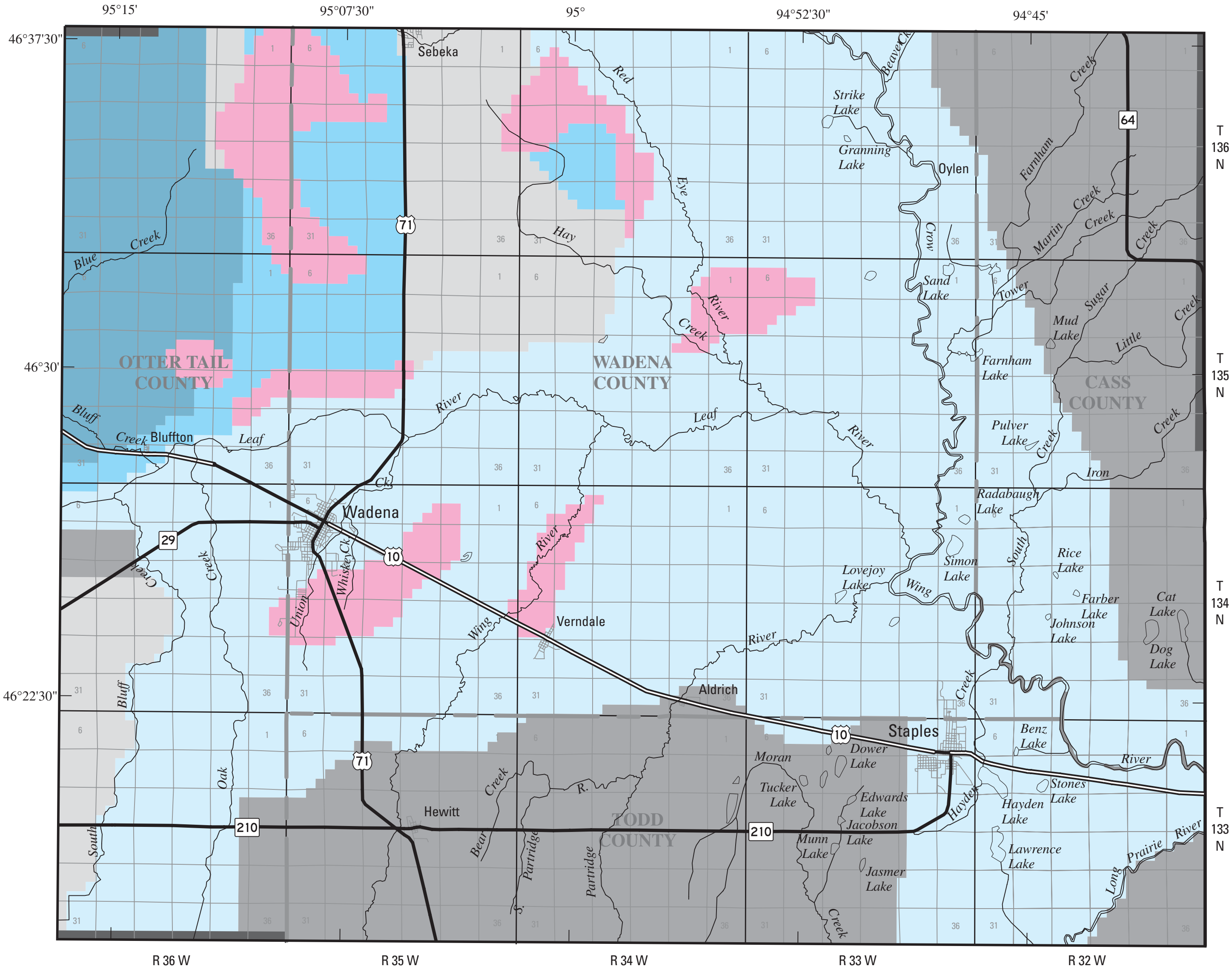
Base from U.S. Geological survey digital data 1:100,000, 1972
US Albers Equal Area Projection
standard parallels 29°30' and 45°30', central meridian -95°

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

- Inactive cells
- Horizontal and vertical hydraulic conductivities of 1 and 0.0025 feet per day, respectively
- Horizontal and vertical hydraulic conductivities of 1 and 0.0075 feet per day, respectively
- Horizontal and vertical hydraulic conductivities of 1 and 0.05 feet per day, respectively
- Horizontal and vertical hydraulic conductivities of 1 and 0.1 feet per day, respectively
- Horizontal and vertical hydraulic conductivities of 5 and 0.25 feet per day, respectively
- Horizontal and vertical hydraulic conductivities of 200 and 20 feet per day, respectively

Figure 12b. Simulated boundary conditions and horizontal and vertical hydraulic conductivity zones for ground-water-flow model layer 2, southern Wadena County and parts of surrounding counties, Minnesota.



Base from U.S. Geological survey digital data 1:100,000, 1972
US Albers Equal Area Projection
standard parallels 29°30' and 45°30', central meridian -95°

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

- Horizontal hydraulic conductivity of 1-5 feet per day
- Horizontal hydraulic conductivity of 50 feet per day
- Horizontal hydraulic conductivity of 100 feet per day
- Horizontal hydraulic conductivity of 150 feet per day
- Horizontal hydraulic conductivity of 200 feet per day
- Horizontal hydraulic conductivity of 250 feet per day
- Constant-head boundary cell

Figure 12c. Simulated boundary conditions and horizontal hydraulic conductivity zones for ground-water-flow model layer 3, southern Wadena County and parts of surrounding counties, Minnesota.

Table 4. Initial and final calibration values of hydraulic properties and fluxes simulated in numerical ground-water-flow model, southern Wadena County, and parts of surrounding counties, Minnesota
[in./yr, inches per year; ft/d, feet per day; ft, feet]

Hydraulic property for fluxes and hydrogeologic unit	Inital value	Final calibration
Horizontal hydraulic conductivity (ft/d)		
Surficial aquifer (layer 1)		
Western area	200	200
Leaf River area	300	350
Eastern area	10, 150	5, 100, 150
Uppermost confining units (layer 2)		
Main body	1	1, 5
Discontinuous confining units area	200	200, 1
Uppermost confined aquifers (layer 3)		
Surficial aquifer present	150	150
Surficial aquifer absent	200	5 - 250
Uppermost confined aquifers absent	1	1, 5
Vertical hydraulic conductivity (ft/d)		
Surficial aquifer (layer 1)		
Western area	20	20
Leaf River area	30	35
Eastern area	1, 15	0.25, 0.01, 15
Uppermost confining units (layer 2)		
Main body	0.001	0.0025 - 0.25
Discontinuous confining units area	20	20
Uppermost confined aquifers (layer 3)		
Surficial aquifer present	15	15
Surficial aquifer absent	20	0.0005 - 25
Uppermost confined aquifers absent	0.001	0.0005
Specific yield for surficial aquifer	0.15	0.20
Storage coefficient		
Uppermost confining units (layer 2)	0.0001	0.0001
Uppermost confined aquifers (layer 3)	0.001	0.0005 - 0.025
Areal recharge to surficial aquifer (in./yr)(steady-state simulation)	6	7
Main body	9	10
Leaf River area	12	12
Recharge to uppermost confined aquifers by leakage where not overlain by surficial aquifer (in./yr) (steady-state simulation) (layer 3)		
Northwest area	2	1.6
South-central area	2	0.0, 0.9
Southwest area	2	0.9
Eastern areas	2	0.9
Uppermost confined aquifers absent areas	0	0
Ground-water evapotranspiration rate (in./yr)	26.5	26.5
Ground-water evapotranspiration extinction depth (ft)	7	5

age properties of the aquifers and are time dependent. Changes in storage in the aquifers occur when the amount of water entering the aquifers and the amount of water leaving the aquifers are not equal.

Steady-State Simulation

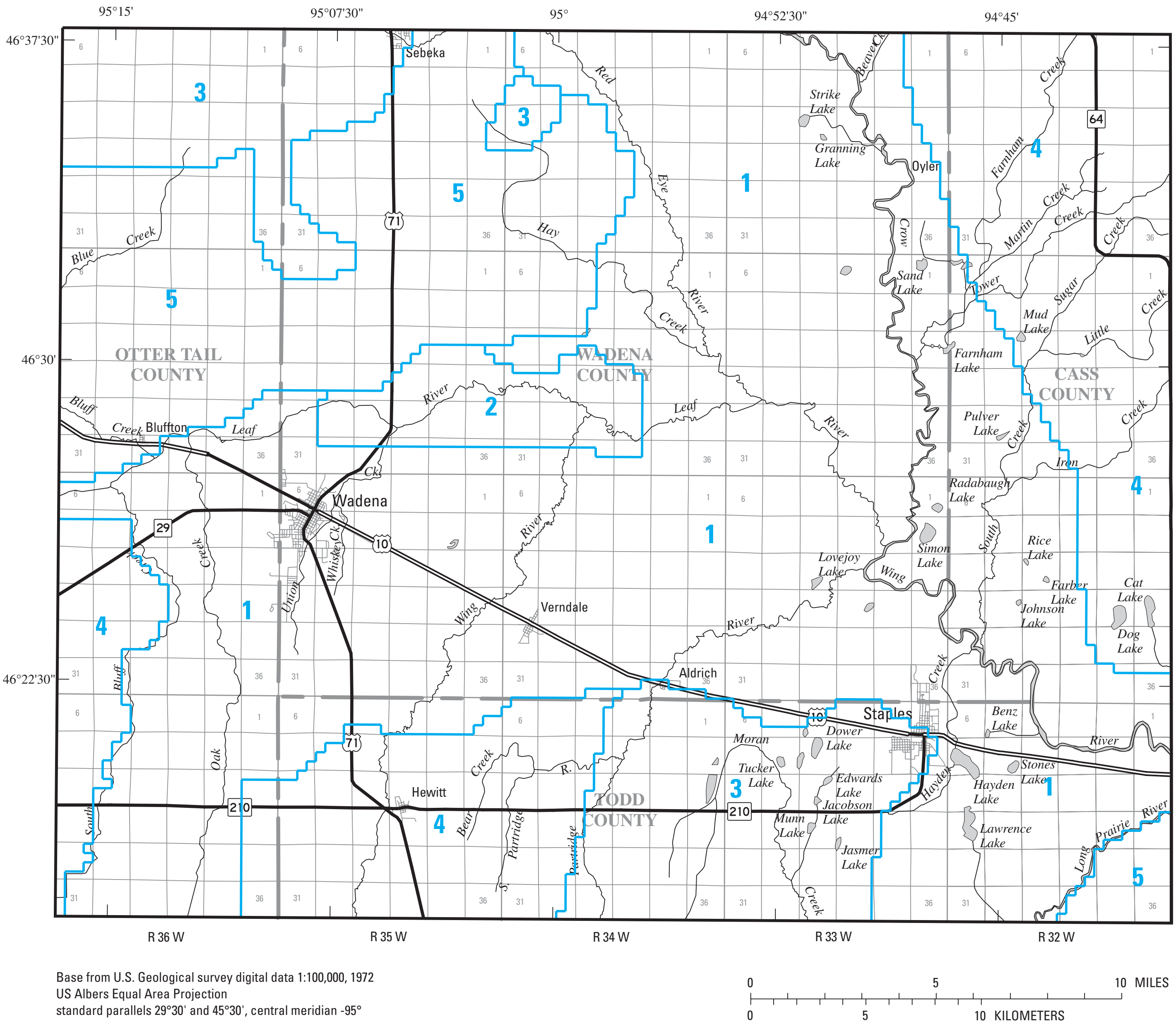
Water levels measured in 126 observation wells during December 1998 and streamflows measured at 24–28 sites during August 1998 and November 1999 (used to estimate stream-aquifer leakage) were used to calibrate the model under approximate steady-state conditions. Average ground-water withdrawals by high-capacity water-supply wells from the surficial and uppermost confined aquifers during 1997 and 1998 were simulated. Total annual ground-water withdrawals from layer 1 and layer 3 for the steady-state simulation were 6.45 and 6.95 ft^3/s, respectively. The model was calibrated by varying the simulated values of: (1) hydraulic properties of the hydrogeologic units (horizontal and vertical hydraulic conductivity), (2) areal recharge to layer 1 and leakage to layer 3 where layer 1 is absent, (3) ground-water evapotranspiration rate and extinction depth, and (4) streambed vertical hydraulic conductivity. The final calibration values are listed in table 4 and shown in figures 12 and 13. The match between measured and simulated hydraulic heads and stream-aquifer leakage was improved by: (1) adjusting horizontal hydraulic conductivity values and zones (figs. 12a–12c), (2) adjusting vertical hydraulic conductivity values and zones (fig. 12b), (3) increasing the areal recharge rate to most of layer 1 to 10 in./yr (fig. 13, areal recharge zone 1), (4) decreasing leakage rates to layer 3 where not overlain by the surficial aquifer from 2 in./yr to 0 to 1.6 in./yr (fig. 13, leakage zones 3–5), and (5) decreasing the ground-water evapotranspiration extinction depth to 5 ft (table 4). The above changes are considered acceptable because they are all within ranges of values measured for this investigation or reported by previous investigations (table 2). The initially uniform rate of simulated leakage to layer 3 where not overlain by the surficial aquifer (2 in./yr) did not accurately simulate measured hydraulic heads in the aquifers. During calibration, the leakage rates were varied within reported ranges for different parts of the study area. The distribution of leakage rates that best matched measured hydraulic heads is shown in figure 13.

The final simulated steady-state hydraulic heads were within 5.5 ft of measured water levels at all but 7 of the 38 wells completed in the surficial aquifer for which December 1998 water-level data were available. The largest difference between measured and simulated hydraulic heads was 8.2 ft. The difference was less than 3.0 ft at 23 of the wells and less than 1.0 ft at 13 of the wells. The final simulated hydraulic heads were within 5.0 ft of measured water levels at all but 19 of the 86 wells completed in the uppermost confined aquifers for which December 1998 water-level data were available. The largest difference between measured and simulated hydraulic heads was 14.3 ft. The difference was less than 3.0 ft at 39 of the wells and less than 1.0 ft at 23 of the wells. The differences between simulated and measured hydraulic heads at 2 wells completed in the uppermost confining units were less than 1.0 ft.

The mean absolute difference between simulated and measured hydraulic heads for the 126 wells, computed as the sum of the absolute values of the differences divided by the number of wells, is 1.92 ft. The mean absolute difference between simulated and measured hydraulic heads at wells completed in the surficial and uppermost confined aquifers is 2.1 ft and 1.8 ft, respectively. The mean algebraic difference between simulated and measured hydraulic heads for the 126 wells, computed as the algebraic sum of the differences divided by the number of wells, is -0.13 ft, indicating the positive differences were approximately balanced by the negative differences. The mean algebraic difference between simulated and measured hydraulic heads at wells completed in the surficial and uppermost confined aquifers is -0.6 ft and 0.2 ft, respectively. The simulated potentiometric surfaces for the surficial and uppermost confined aquifers, shown in figures 14a and 14b, respectively, are consistent with the measured water levels and the model reasonably simulates directions of ground-water flow in the aquifers.

Comparison of stream-aquifer leakage estimated from measured streamflows during August 1998 and November 1999 and simulated stream-aquifer leakage was also used to evaluate how well the model simulates the ground-water system (table 1). Uncertainty of the stream-discharge measurements was plus or minus 5–8 percent. Estimates of stream-aquifer leakage likely are less than the measurement uncertainty for the measurements on the Crow Wing River; therefore the match between the measured and simulated stream-aquifer leakage is uncertain. Estimates of stream-aquifer leakage, however, are greater than the measurement uncertainty for the Leaf, Wing, Partridge, and Red Eye Rivers and comparisons between measured and simulated stream-aquifer leakage can be made. For these streams, the model reasonably represented the magnitude and direction of stream-aquifer leakage. For the Wing, Partridge, and Red Eye Rivers and two of the four reaches of the Leaf River, the simulated stream-aquifer leakage was within the range of the measured stream-aquifer leakage (table 1). For reach SW7-SW8 of the Leaf River, the simulated stream-aquifer leakage is less than the measured values, but is of the same order of magnitude (table 1).

A water budget is an accounting of inflow to, outflow from, and storage change in the aquifers. For steady state, inflow (sources) to the aquifers equals outflow (discharges) from the aquifers (table 5). Areal recharge to the surficial aquifer accounts for 86.9 percent of the water to the aquifers, and leakage through the confining units to the uppermost confined aquifers where the surficial aquifer is absent contributes 6.9 percent (table 5). The remaining 6.2 percent is by flow into the uppermost confined



Base from U.S. Geological survey digital data 1:100,000, 1972
US Albers Equal Area Projection
standard parallels 29°30' and 45°30', central meridian -95°

EXPLANATION

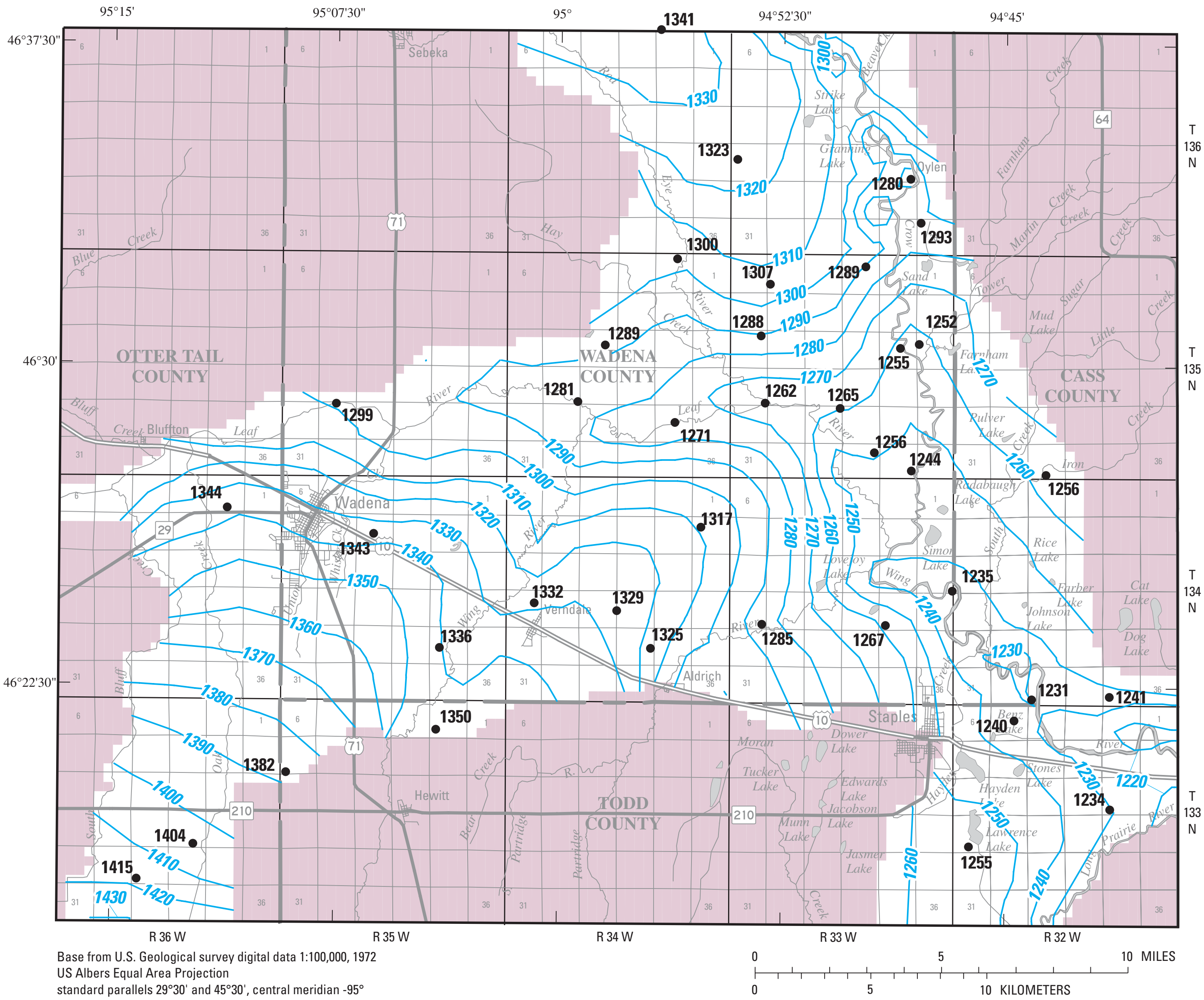
Simulated areal recharge zones

- **1** Areal recharge to model layer 1 (surficial aquifer) equals 10 inches per year
- **2** Areal recharge to model layer 1 (surficial aquifer) equal 12 inches per year

Simulated leakage zones

- **3** Leakage through till to model layer 3 (uppermost confined aquifer) equals 0.0 inches per year
- **4** Leakage through till to model layer 3 (uppermost confined aquifer) equals 0.9 inches per year
- **5** Leakage through till to model layer 3 (uppermost confined aquifer) equals 1.6 inches per year

Figure 13. Simulated areal recharge and leakage zones for ground-water-flow model, southern Wadena County and parts of surrounding counties, Minnesota.



EXPLANATION

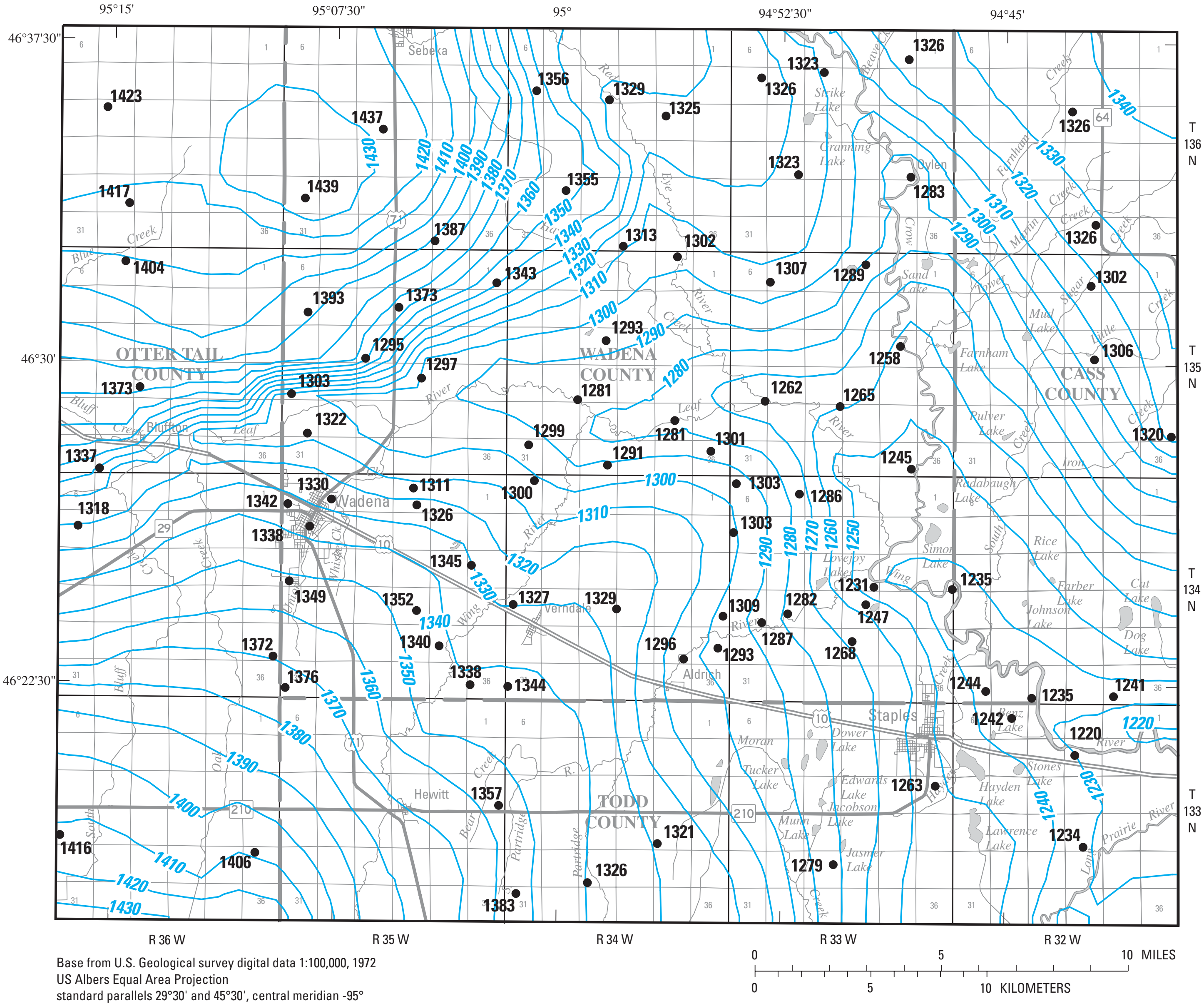
Extent of surficial aquifer

Area where surficial aquifer is absent

1360 — Simulated potentiometric contour--Interval 10 feet. Datum is sea level

1325 — Observation well completed in surficial aquifer--Number is measured water-level altitude

Figure 14a. Measured water-level altitude in the surficial aquifer, December 1998, simulated altitude of potentiometric surface for model layer 1, steady-state conditions, and extent of surficial aquifer, southern Wadena County and parts of surrounding counties, Minnesota.



EXPLANATION

—1380— Simulated potentiometric contour--Interval 10 feet. Datum is sea level

•1329 Observation well completed in uppermost confined aquifer--Number is measured water-level altitude

Figure 14b. Measured water-level altitude in the uppermost confined aquifers, December 1998, and simulated altitude of potentiometric surface for model layer 3, steady-state conditions, southern Wadena County and parts of surrounding counties, Minnesota.

aquifers at the study area boundaries (constant-head boundaries) (5.0 percent) and by leakage from streams into the surficial aquifer (1.2 percent). Most of the flow into the uppermost confined aquifers at the study area boundaries occurs through the southwestern boundary (61.2 percent), with minimal flow through the northwestern boundary.

The largest discharges from the aquifers are leakage from the surficial aquifer to streams (54.5 percent) and ground-water evapotranspiration (41.4 percent) (table 5). Net discharge from the aquifer to streams of 179.41 ft^3/s represents 54.5 percent of the areal recharge to the surficial aquifer. Pumpage constitutes 4.1 percent of the discharges from the aquifers, with the withdrawals being approximately equally divided between the surficial (layer 1) and uppermost confined aquifers (layer 3).

Water flows vertically through the uppermost confining units separating the surficial and uppermost confined aquifers in both downward and upward directions. The model simulation indicates a net flow upward of 32.16 ft^3/s from layer 3 to layer 1 through layer 2 (table 5). This net flow upward is balanced by leakage and flow through constant-head boundaries to layer 3.

The calibration steady-state simulation is considered to be reasonable because: (1) hydraulic conductivity values of the aquifers are known within a relatively small range of measured or reported values; (2) reasonable estimates of the major dis-

Table 5. Simulated water budget for the steady-state model, southern Wadena County and parts of surrounding counties, Minnesota

[Numbers in parentheses are percentages of total sources or of total discharges; --, not applicable]

Budget component	Source (cubic feet per second)	Discharge (cubic feet per second)
Areal recharge to surficial aquifer (layer 1)	285.96 (86.9)	--
Leakage through confining units to uppermost confined aquifers where surficial aquifer is absent (layer 3)	22.75 (6.9)	--
Flow into uppermost confined aquifers at study area boundaries (constant-head boundaries) (layer 3)		
Southwestern boundary	10.04 (3.1)	--
Northeastern boundary	6.31 (1.9)	--
Northwestern boundary	0.05 (0.0)	--
Subtotal	16.4 (5.0)	--
Leakage from streams to surficial aquifer (layer 1)	4.04 (1.2)	--
Pumpage		
Layer 1	--	6.45 (2.0)
Layer 3	--	6.95 (2.1)
Subtotal	--	13.4 (4.1)
Ground-water evapotranspiration (layer 1)	--	136.34 (41.4)
Leakage from surficial aquifer to streams (layer 1)	--	179.41 (54.5)
Total	329.15 (100.0)	329.15 (100.0)
Leakage between model layers		
Layer 1	102.27	69.85
Layer 2		
Layer 1	69.85	102.27
Layer 3	95.77	63.61
Subtotal	165.62	165.88
Layer 3	63.61	95.77
Total	331.50	331.50

charges from the aquifers in the study area–ground-water discharge to streams and ground-water withdrawals by wells–are available; and (3) the simulation results reasonably represented the correct magnitude and direction of leakage between the streams and the surficial aquifer.

Transient Simulation

The model was calibrated under transient conditions using seasonally variable ground-water withdrawals, areal recharge and leakage rates, ground-water evapotranspiration rates, and stream stages and the resulting fluctuations in hydraulic heads in the aquifers during December 1997 through November 1999. Reported monthly ground-water withdrawals by high-capacity wells within the model area were used in the transient simulation. Hydraulic conductivity values for the hydrogeologic units were the same as for the steady-state simulation (table 4). The initial value of specific yield for layer 1 was 0.15, based on an aquifer test previously conducted in the study area (Lindholm, 1970). The initial storage coefficient specified for layer 3 was 0.001, based on aquifer tests previously conducted in the study area (Lindholm, 1970) (table 4). The initial value of storage coefficient assigned to layer 2 was 0.0001, based on recorded values in the literature (table 4).

To simulate transient conditions during December 1997 through November 1999, five stress periods were specified each year. The stress periods specified were winter (December-February), spring (March-April), early summer (May-June), late summer (July-September), and fall (October-November). Simulated ground-water withdrawals during 1999 for the specified stress periods ranged from 1.59 ft^3/s for winter to 29.55 ft^3/s for late summer. The withdrawal rates for each stress period during 1998 were similar to the 1999 rates. The starting heads used in the transient simulation were the simulated hydraulic heads from the calibration steady-state simulation.

The initial values for simulated areal recharge rates to layer 1 and leakage to layer 3 for each stress period are shown in table 6. The initial values for areal recharge for each stress period were derived to account for spring snowmelt and seasonal ground-water evapotranspiration rates. Areal recharge rates for the spring, early summer, and fall 1998 stress periods were calculated as the product of the average water-level rises in observation wells during the respective stress periods and a specific yield of 0.20. Areal recharge rates for the winter, late summer, and fall 1999 stress periods were assigned a value of zero to reflect no net areal recharge to ground water, as indicated by most hydrographs. The initial values for leakage to layer 3 were assigned to each stress period based on the distribution of assigned areal recharge rates for the stress periods (table 6). Leakage rates for the winter, late summer, and fall 1999 stress periods were assigned a value of zero, with the highest leakage rate being assigned to the early summer stress periods.

Ground-water evapotranspiration rates also vary seasonally (table 6). The initial values for maximum ground-water evapotranspiration rates, by stress period, were based on seasonal ratios of evapotranspiration to pan evaporation published by the Southwest Agricultural Experiment Station, University of Minnesota, in southwestern Minnesota (Baker and others, 1979). The seasonal ratios incorporate: (1) differences between the pan (used to measure pan evaporation) and soil and plants, and how much solar energy they absorb; and (2) variations in available soil water. The ratio varies from about 0.15 in the spring and fall to about 0.90 in July and provides a more accurate estimate of seasonal ground-water evapotranspiration rates than pan-evapotranspiration rates alone. The maximum ground-water evapotranspiration rates were calculated as the reported pan-evaporation rate at Staples during a stress period, multiplied by 0.3 for the early summer stress periods or by 0.8 for the late summer stress periods.

In addition to areal recharge and ground-water evapotranspiration, seasonal variations in the constant heads specified at the model boundaries and in stream stages were simulated. The seasonal variations in the constant heads were derived from the hydraulic heads measured in the same observation wells used for the steady-state simulation. Seasonal variations in stream stages were derived from monthly stage measurements at 11 sites during the investigation.

The model was calibrated to transient conditions by adjusting specific yield, storage coefficient values, stress-period areal recharge, and stress period ground-water evapotranspiration rates until the simulated hydraulic heads acceptably matched water levels measured in wells during December 1997 through November 1999. Monthly water-level measurements were available for 81 observation wells during December 1997 through November 1999. The match between simulated and measured hydraulic heads was improved by: (1) increasing the specific yield of layer 1 from 0.15 to 0.20, (2) decreasing the storage coefficient in the southwestern part of layer 3, and (3) increasing the storage coefficient in the central part of layer 3 (table 4, fig. 15). The match was also improved by: (1) increasing areal recharge to layer 1 for recharge zone 2 during the spring, early summer, and fall 1998 stress periods, (2) decreasing leakage to layer 3 for recharge zone 4 during the spring, early summer, and fall 1998 stress periods, (3) decreasing leakage to layer 3 for recharge zone 5 during

Table 6. Initial and final calibration values of areal recharge, leakage, and ground-water evapotranspiration for transient simulation, southern Wadena County and parts of surrounding counties, Minnesota

[All values in inches per year]

Stress period	Recharge										Maximum ground-water evapotranspiration	
	Areal recharge to surficial aquifer				Leakage through confining unit to uppermost confined aquifers where surficial aquifer is absent							
	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5			
	Initial value	Final calibration value	Initial value	Final calibration value	Initial value	Final calibration value	Initial value	Final calibration value	Initial value	Final calibration value	Initial value	Final calibration value
Winter 1998	0	0	0	0	0	0	0	0	0	0	0	0
Spring 1998	26.9	26.9	26.9	35.9	0	0	4.8	1.8	4.8	3.5	0	0
Early summer 1998	35.9	35.9	35.9	47.9	0	0	6.4	3.6	6.4	5.5	27.7	27.7
Late summer 1998	0	0	0	0	0	0	0	0	0	0	69.6	78.3
Fall 1998	18.0	18.0	18.0	26.9	0	0	3.0	0.9	3.0	3.0	0	0
Winter 1999	0	0	0	0	0	0	0	0	0	0	0	0
Spring 1999	26.9	26.9	26.9	35.9	0	0	4.8	3.6	4.8	3.5	0	0
Early summer 1999	35.9	35.9	35.9	47.9	0	0	6.4	3.6	6.4	5.5	26.0	26.0
Late summer 1999	0	0	0	0	0	0	0	0	0	0	59.3	66.7
Fall 1999	0	0	0	0	0	0	0	0	0	0	0	0

the spring and early summer stress periods, and (4) increasing the ground-water evapotranspiration rate during the late summer stress period (table 6).

The transient simulation for December 1997 through November 1999 acceptably reproduces measured seasonal fluctuations in hydraulic heads in the surficial and uppermost confined aquifers (fig. 9). The ability of the transient simulation to approximate seasonal fluctuations in hydraulic heads during December 1997 through November 1999 indicates that the simulation reasonably represents hydraulic properties of the hydrogeologic units and fluxes in the ground-water system during the calibration period. The specified boundary conditions are considered appropriate, areal recharge and leakage to the aquifers are within reasonable expected ranges, and ground-water withdrawals are known. Table 4 gives the values for the hydraulic properties of the hydrogeologic units resulting in the best fit between measured and simulated hydraulic heads for the transient simulation. The values given represent the best estimates for the hydraulic properties of the hydrogeologic units in the study area, based on reported values and the results of the model calibration.

The simulated transient water budget for 1999 is shown in table 7. Principal sources of water to the aquifers were areal recharge to the surficial aquifer during the spring and early summer stress periods and release from storage during the winter, late summer, and fall stress periods. Areal recharge to the surficial aquifer dominates the water budget during the spring and early summer stress periods, constituting 87.6 and 93.1 percent of the sources of water for these stress periods, respectively. The amount and percentage of water released from storage is greatest during the winter, late summer, and fall stress periods because no areal recharge or leakage occurs to the aquifers. The effects of ground-water withdrawals, ground-water evapotranspiration (late summer stress period), and stream-aquifer leakage are, therefore, magnified during these stress periods. The water released from storage is derived predominantly from the surficial aquifer (from 68.4 to 77.2 percent). From 21.9 to 30.7 percent of the water released from storage is derived from the uppermost confined aquifers. During stress periods with areal recharge, a greater proportion of the water withdrawn by wells is supplied by the areal recharge and less release of water from storage is required.

The principal discharges from the aquifers are: (1) leakage from the surficial aquifer to streams during the fall and winter stress periods, (2) addition to storage during the spring and early summer stress periods, and (3) ground-water evapotranspiration during the late summer stress period (table 7). Ground-water withdrawals are greatest during the early summer and late summer stress periods, constituting 1.6 and 5.6 percent of the total discharges, respectively, during these stress periods. Areal recharge and leakage to the uppermost confined aquifers is greater than the sum of the discharges from the aquifers (other than addition to storage) during the spring and early summer stress periods. A portion of the areal recharge and leakage to the uppermost confined aquifers is therefore returned to storage in the aquifers. The amount and percentage of addition to storage during the spring and early summer stress periods is much greater than during the other stress periods because areal recharge and leakage to the uppermost confined aquifers occurs during these stress periods. Approximately 73 percent of the addition to storage occurs in the surficial aquifer.

The net stream-aquifer leakage during each stress period in 1999 was from the surficial aquifer to the streams for the model area as a whole (table 7). The net gains to streams during the winter, late summer, and fall stress periods are similar, but the gains during the spring and early summer stress periods are much greater than during the other stress periods. The stress periods with large gains to streams correspond with the stress periods when areal recharge occurs. These results indicate that the magnitude of simulated gains to streams is in direct relation to the amount of areal recharge.

EFFECTS OF GROUND-WATER WITHDRAWALS

The ground-water flow model was used as a tool to evaluate ground-water availability in the study area by assessing the potential effects of hypothetical conditions on ground-water levels and streamflow. The hypothetical simulations test the effects of: (1) historical withdrawals, (2) anticipated increases in ground-water withdrawals (pumping), (3) anticipated increases in withdrawals during a drought, (4) greater than anticipated increases in withdrawals, and (5) greater than anticipated increases in withdrawals during a drought. Table 8 is a summary of the hypothetical steady-state model simulations and corresponding responses. Steady-state simulations represent average, equilibrium conditions and no times are associated with the responses. Two-year transient simulations also were done for some of the hypothetical conditions.

Historical Withdrawals

Simulation 1 (table 8) was designed to evaluate the effects of historical withdrawals on water levels and streamflow. This was achieved by removing pumping from the steady-state simulation and simulating average recharge; results thus were pre-

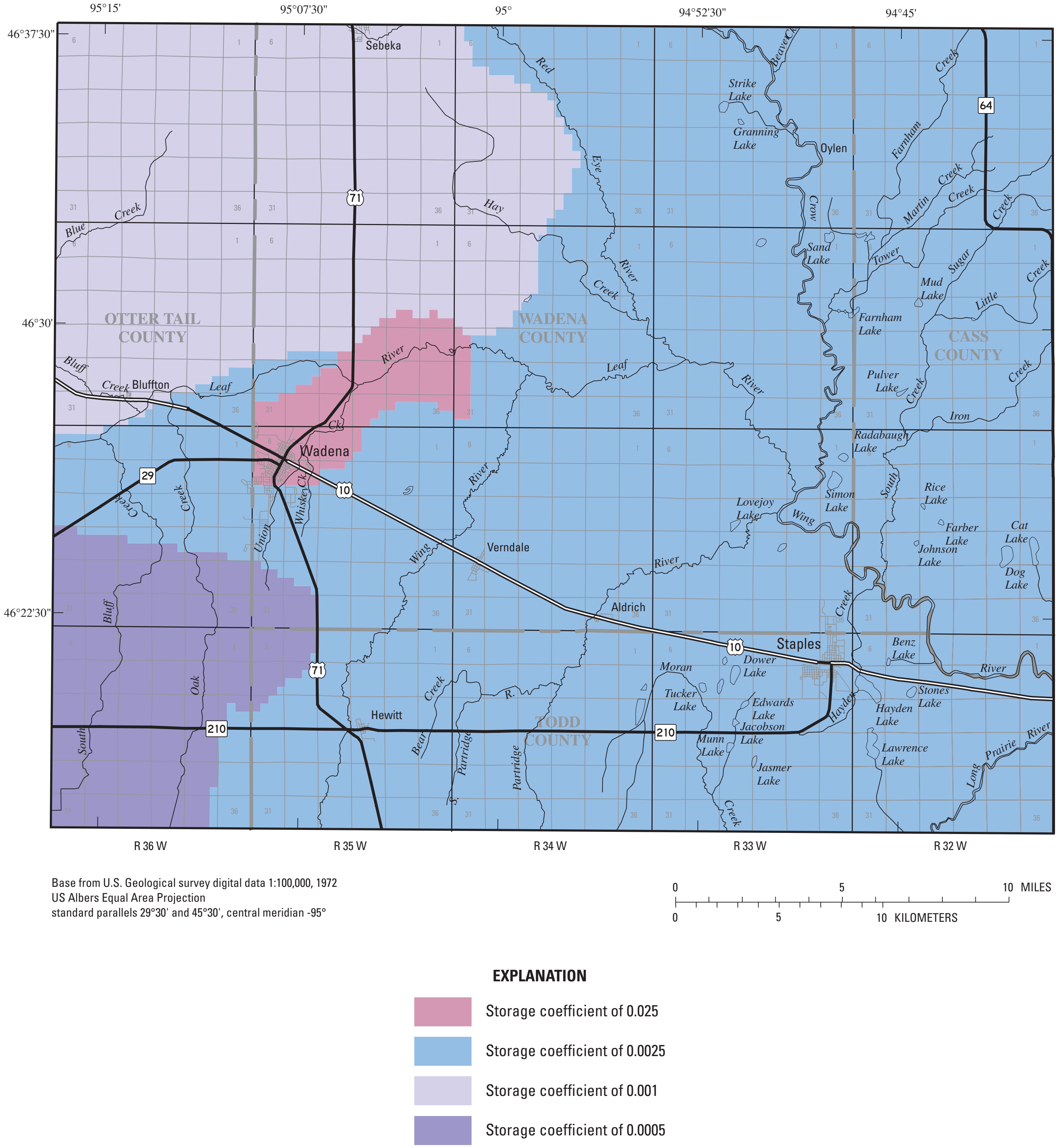


Figure 15. Storage coefficient zones for ground-water-flow model layer 3, southern Wadena County and parts of surrounding counties, Minnesota.

Table 7. Simulated water budget, by stress period, for 1999 for transient simulation, southern Wadena County and parts of surrounding counties, Minnesota

[Numbers in parentheses are percentages of total sources or of total dischargesby stress period]

Budget component	Sources of water by stress period (cubic feet per second)				
	Winter (December-February)	Spring (March-April)	Early summer (May-June)	Late summer (July-September)	Fall (October-November)
Recharge (from precipitation) to surficial aquifer (layer 1)	0	774.12 (87.6)	1033.07 (93.1)	0	0
Leakage through confining unit to uppermost confined aquifers (layer 3)	0	93.00 (10.5)	65.67 (5.9)	0	0
Flow into uppermost confined aquifers at study area boundaries (constant-head) (layer 3)	15.40 (8.4)	16.55 (1.9)	6.15 (0.6)	16.58 (3.1)	13.84 (6.4)
Leakage from streams to surficial aquifer (layer 1)	0.54 (0.3)	0.15 (0.0)	0	7.92 (1.5)	0.33 (0.2)
Release from storage					
Layer 1	120.44 (65.8)	0	3.79 (0.35)	389.89 (73.7)	138.19 (63.9)
Layer 2	1.48 (0.8)	0	0.02 (0.0)	4.15 (0.8)	1.82 (0.8)
Layer 3	45.33 (24.7)	0.02 (0.0)	0.56 (0.05)	110.81 (20.9)	62.12 (28.7)
Subtotal	167.25 (91.3)	0.02 (0.0)	4.37 (0.4)	504.85 (95.4)	202.13 (93.4)
Total	183.19 (100.0)	883.84 (100.0)	1109.26 (100.0)	529.35 (100.0)	216.30 (100.0)
	Discharges of water, by stress period (cubic feet per second)				
Pumpage					
Layer 1	0.11 (0.1)	0.11 (0.0)	9.19 (0.8)	17.26 (3.3)	0.14 (0.1)
Layer 3	1.48 (0.8)	1.64 (0.2)	8.63 (0.8)	12.29 (2.3)	1.58 (0.7)
Subtotal	1.59 (0.9)	1.75 (0.2)	17.82 (1.6)	29.55 (5.6)	1.72 (0.8)
Ground water evapotranspiration (layer 1)	0	0	247.88 (22.3)	349.32 (66.0)	0
Flow out of uppermost confined aquifers at study area boundaries (constant-head boundaries) (layer 3)	0	0	1.32 (0.1)	0.53 (0.1)	0.18 (0.1)
Leakage from surficial aquifers to streams (layer 1)	164.41 (89.7)	242.67 (27.5)	294.61 (26.6)	149.33 (28.2)	186.91 (86.4)
Addition to storage					
Layer 1	13.91 (7.6)	465.97 (52.7)	398.71 (35.95)	0	24.01 (11.1)
Layer 2	0.08 (0.05)	4.97 (0.55)	4.88 (0.45)	0.00	0.12 (0.1)
Layer 3	3.2 (1.75)	168.49 (19.05)	143.97 (13.0)	0.63 (0.1)	3.35 (1.5)
Subtotal	17.19 (9.4)	639.43 (72.3)	547.56 (49.4)	0.63 (0.1)	27.48 (12.7)
Total	183.19 (100.0)	883.85 (100.0)	1109.19 (100.0)	529.36 (100.0)	216.29 (100.0)
Difference: sources - discharges	0.00	-0.01	0.07	-0.01	0.01

sumed to approximate predevelopment conditions. By comparing results of Simulation 1 with the steady-state (1998-99) calibration, effects of historical withdrawals can be estimated. A majority of ground-water pumpage in the area is from irrigation wells that were installed after about 1970. Prior to this time the only appreciable ground water pumpage was from a relatively few municipal, industrial, and commercial wells. Consequently, Simulation 1 is designed to estimate water level and streamflow changes that have occurred in the aquifer system since about 1970.

Model results indicate that historical withdrawals have lowered water levels regionally in the surficial and uppermost confined aquifers an average of 0.31 and 0.42 ft, respectively (figs. 16a and 16b). Declines in the surficial aquifer have been greatest near Wadena (4.0 ft) and Staples (2.5 ft). Maximum declines in the uppermost confined aquifers in Wadena and Staples have been 4.0 and 4.5 ft, respectively, and as much as 4.5 ft elsewhere in the vicinity of other high capacity wells. Model results also indicate that ground-water discharge to rivers has been reduced by less than one percent compared to predevelopment conditions.

Anticipated Increases in Withdrawals

Simulation 2 (table 8) was designed to evaluate the steady-state effects of anticipated increases in withdrawals on water levels and streamflow. Ground-water withdrawals for irrigation in southern Wadena County are expected to increase by 20 percent over the next 10 to 20 years

Table 8. Summary of steady-state results of hypothetical model Simulations 1-5, southern Wadena County and parts of surrounding counties, Minnesota.

[Increased withdrawal rates are in comparison to 1998-99 steady-state calibration rates; ET, evapotranspiration]

Simulation	Conditions of simulation	Model results
1	Historical withdrawals Pumping removed to determine the effects of historical pumpage Average precipitation.	Water levels decline an average of 0.31 ft in the surficial aquifer and 0.42 ft in the uppermost confined aquifers. Declines are greatest (4.0 ft or greater) near Wadena and Staples in both aquifers. Ground-water discharge to streams is reduced less than one percent since predevelopment.
2	Anticipated increases in withdrawals (20 percent increase for 88 irrigation wells and 40 percent increase for 5 Wadena municipal wells in uppermost confined aquifers). Average recharge.	Water levels decline an average of 0.03 ft in the surficial aquifer and 0.08 ft in the uppermost confined aquifers. Maximum declines of 0.3 ft in the surficial aquifer and 0.9 ft in the uppermost confined aquifers occur near Wadena. Ground-water discharge to streams is reduced by 0.6 percent of 1998-99 conditions.
3	Anticipated increases in withdrawals with drought conditions (33 percent increase for 160 irrigation, commercial, and dug-pit wells in the surficial aquifer; 53 percent for 88 irrigation wells, 50 percent for 5 Wadena municipal wells; and 10 percent for other municipal wells in uppermost confined aquifers). Average recharge reduced by 25 percent. ET rates increased 17 percent. Stream stage lowered 1.0 ft. Boundary heads lowered 3.0 ft.	Water levels decline an average of 2.13 ft in the surficial aquifer and 5.87 ft in the uppermost confined aquifers. Declines in the surficial aquifer of about 6 ft occur in Wadena and between the Leaf, Red Eye, and Partridge Rivers. Declines in the uppermost confined aquifers are similar to those in the surficial aquifer in general, but exceed 20 ft north of the Leaf River. Ground water discharge to streams is reduced by 23 percent of 1998-99 conditions.
4	Greater than anticipated increases in withdrawals (20 percent increase for 160 irrigation, commercial, and dug-pit wells in the surficial aquifer; 50 percent for 88 irrigation wells; and 40 percent for 5 Wadena municipal wells in uppermost confined aquifers). Average recharge.	Water levels decline an average of 0.09 ft in the surficial aquifer and 0.13 ft in the uppermost confined aquifers. Ground-water discharge to streams is reduced by 1.4 percent of 1998-99 conditions.
5	Greater than anticipated increases in withdrawals with drought conditions (53 percent increase for 160 irrigation, commercial, and dug-pit wells in the surficial aquifer; 83 percent for 88 irrigation wells; and 50 percent for 5 Wadena municipal wells in uppermost confined aquifers). Average recharge reduced by 25 percent. ET rates increased 17 percent. Stream stage lowered 1 foot. Boundary heads lowered 3 ft.	Water levels decline an average of 2.25 and 6 ft in the surficial and uppermost confined aquifers, respectively. Ground-water discharge to streams is reduced by 25 percent of 1998-99 conditions.

(Malinda Dexter, Wadena Soil and Water Conservation District, oral commun., 2000). The increased withdrawals are all expected to be from wells completed in the uppermost confined aquifers and in areas of existing irrigation development (Don Sirucek, Minnesota Department of Agriculture, oral commun., 2000). Ground-water withdrawals for municipal supplies for Wadena are expected to increase by a maximum of 2 percent per year (Gary Peters, City of Wadena, oral commun., 2000).

These anticipated increases were simulated with the model by increasing withdrawals from the 88 irrigation wells completed in the uppermost confined aquifers by 20 percent above 1998-99 withdrawals. Withdrawals from the five Wadena municipal wells completed in the uppermost confined aquifers were also increased by 40 percent. Average steady-state recharge conditions were simulated. A transient simulation was also used to investigate the effects of the anticipated increases in withdrawals over a hypothetical 2-year period. Changes made to the transient simulation inputs were analogous to those for the steady-state simulation.

Results of the steady-state simulation indicate that the anticipated increases in withdrawals will have a minor effect on ground-water levels and streamflow in the area. Water levels may decline an average of 0.03 ft regionally in the surficial aquifer with maximum declines of 0.3 ft near Wadena. In the uppermost confined aquifers, water levels may decline an average of 0.08 ft regionally with maximum declines of 0.9 ft near Wadena. The anticipated increases in withdrawals would cause decreases in ground-water discharge to streams of about 0.6 percent (1.1 ft^3/s) of 1998-99 steady-state conditions, as well as small decreases in ground-water evapotranspiration. Results of the transient simulation similarly indicate that water levels will be minimally affected by the anticipated increases in pumping. The maximum increase in seasonal water-level decline for the uppermost confined aquifers would be 1.34 ft.

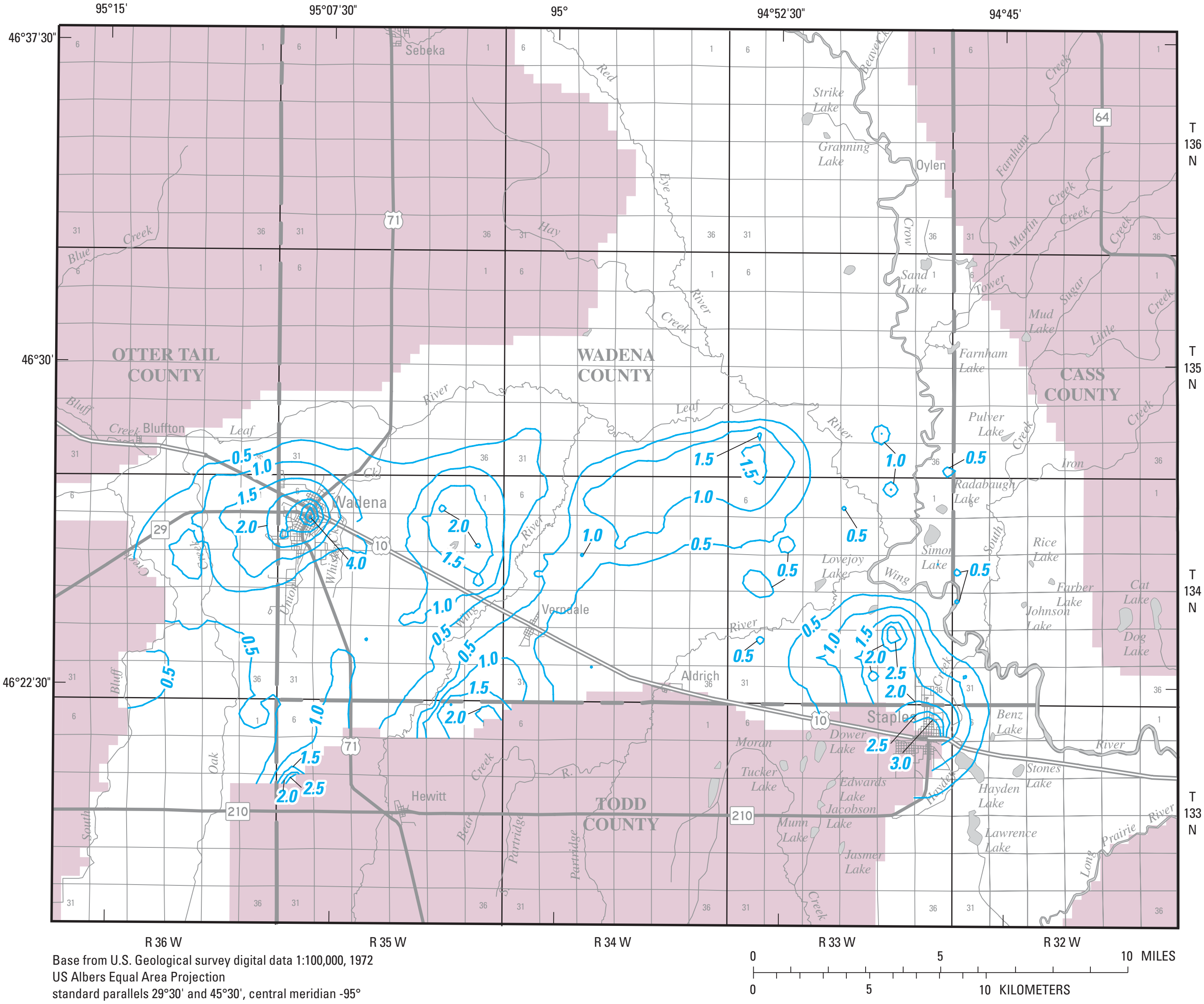
Anticipated Increases in Withdrawals During a Drought

Simulation 3 (table 8) was designed to evaluate the steady-state effects of anticipated increases in withdrawals on water levels and streamflow during a typical drought. The drought was simulated by making the following changes to the model compared to the 1998-99 steady-state rates: (1) increasing withdrawals from the 113 irrigation and commercial wells and 47 dug pits in the surficial aquifer by 33 percent, (2) increasing irrigation well withdrawals from the uppermost confined aquifers by 53 percent, (3) increasing withdrawals from the 5 Wadena municipal wells in the uppermost confined aquifers by 50 percent, (4) increasing withdrawals from the other municipal wells in the uppermost confined aquifers by 10 percent, (5) increasing maximum evapotranspiration rates by 17 percent (based on pan evaporation rates at Staples during 1967-99), and (6) reducing average recharge by 25 percent. In addition to the above changes, the stage of all rivers were lowered 1.0 ft and hydraulic heads at the boundaries were lowered 3.0 ft, to coincide with the lowest levels measured during this investigation. A transient simulation was also used to investigate the effects of the anticipated increases in withdrawals during a 2-year drought. Changes made to the transient simulation inputs were analogous to those for the steady-state simulation.

The normal (1961-90) annual precipitation at Wadena is 26.24 in. Assuming recharge correlates directly with precipitation, the 25 percent reduction in recharge used in Simulation 3 corresponds to 20 in. of annual precipitation. A drought of this severity has occurred during 8 years since 1905 (U.S. Department of Commerce, 1999).

Results of the steady-state simulation indicate that the anticipated increases in withdrawals during a drought may lower water levels 2 to 4 ft regionally in much of both the surficial and uppermost confined aquifers (figs. 17a and 17b). Water-level declines in the surficial aquifer of about 6 ft may occur in Wadena and in the central part of the aquifer south of the Leaf River (fig. 17a). Simulated declines in the uppermost confined aquifers for much of T133N, R35W range from 6 to 8 ft due to withdrawals from irrigation wells (fig. 17b). Declines in the uppermost confined aquifers north of the Leaf River may be 15 to 30 ft due to the comparatively low hydraulic conductivities of these aquifers and low recharge rates through the overlying confining units. Simulated declines in all aquifers as a result of the anticipated increased withdrawals and hypothetical drought are not great enough to cause most wells to go dry. Ground-water discharge to rivers would be reduced by 23 percent (42 ft^3/s) compared to 1998-99 steady-state conditions as a result of the anticipated increases in withdrawals during a drought (table 8). Although 42 ft^3/s is large compared to 1.1 ft^3/s (0.6 percent) from Simulation 2 (without a drought), it still represents less than 5 percent of total streamflow in the area.

Results of the transient simulation indicate that the anticipated increases in withdrawals during a drought would generally increase seasonal declines in the surficial and uppermost confined aquifers less than 1 and 2 ft, respectively. Maximum increases in seasonal water level declines for the aquifers were 1.54 and 6.89 ft, respectively. The maximum declines



EXPLANATION

Extent of surficial aquifer

Area where surficial aquifer is absent

—1.5— Line of equal simulated drawdown--Interval 0.5 feet

Figure 16a. Extent of surficial aquifer and simulated drawdowns for model layer 1, representing the surficial aquifer, due to historical ground-water withdrawals, steady-state simulation, southern Wadena County and parts of surrounding counties, Minnesota.

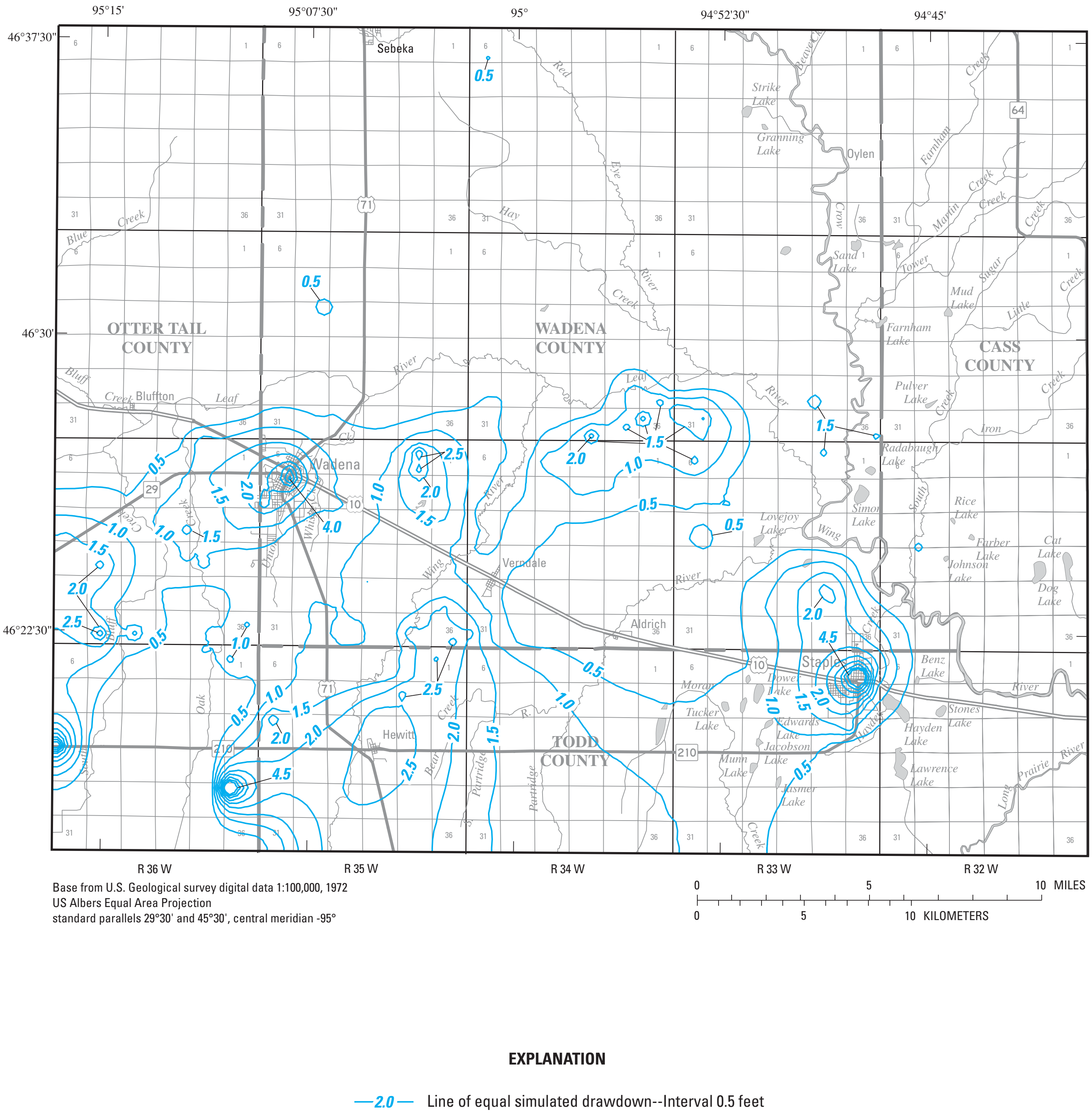
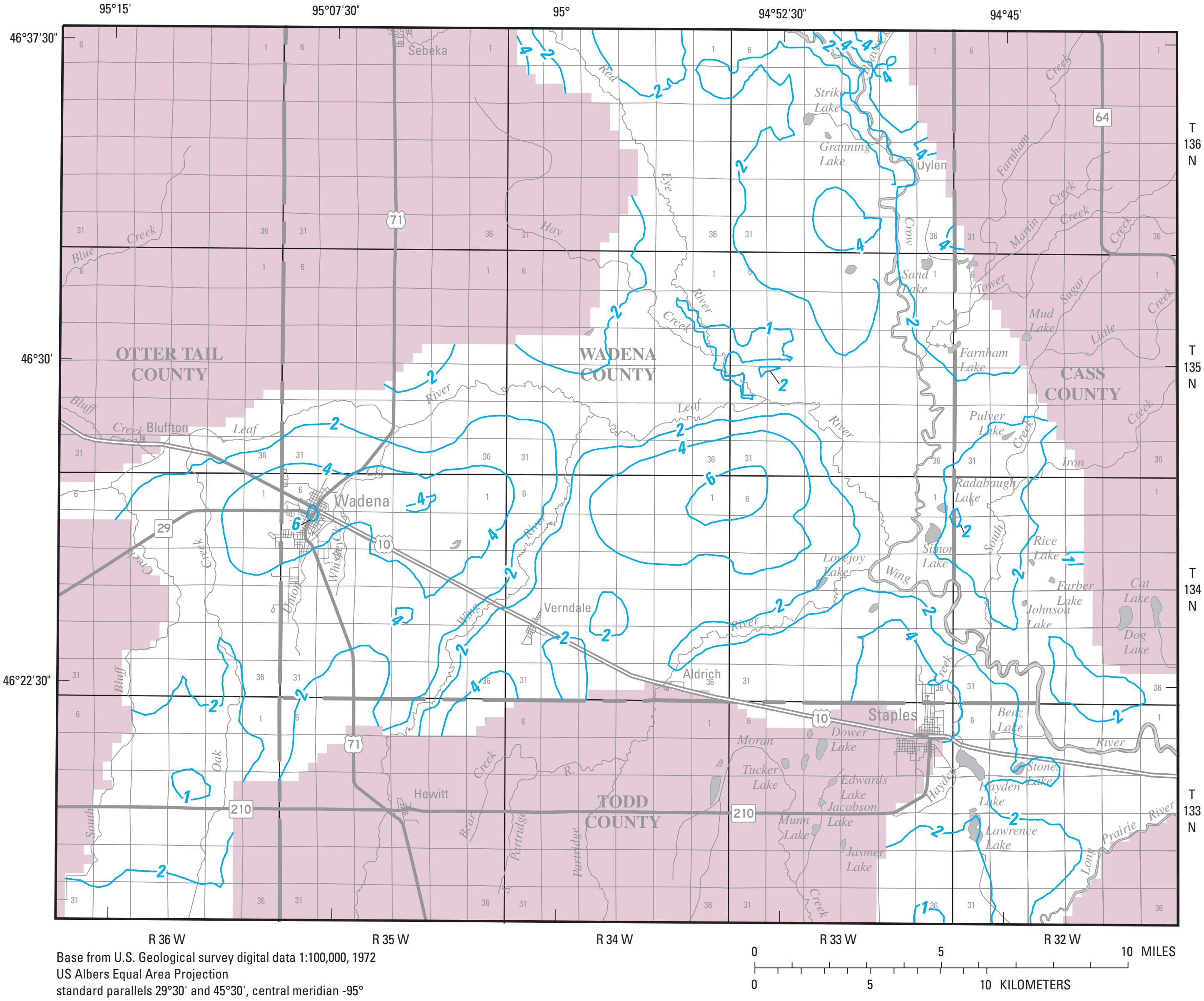


Figure 16b. Simulated drawdowns for model layer 3, representing the uppermost confined aquifers, due to historical ground-water withdrawals, steady-state simulation, southern Wadena County and parts of surrounding counties, Minnesota.



Base from U.S. Geological survey digital data 1:100,000, 1972
US Albers Equal Area Projection
standard parallels 29°30' and 45°30', central meridian -95°

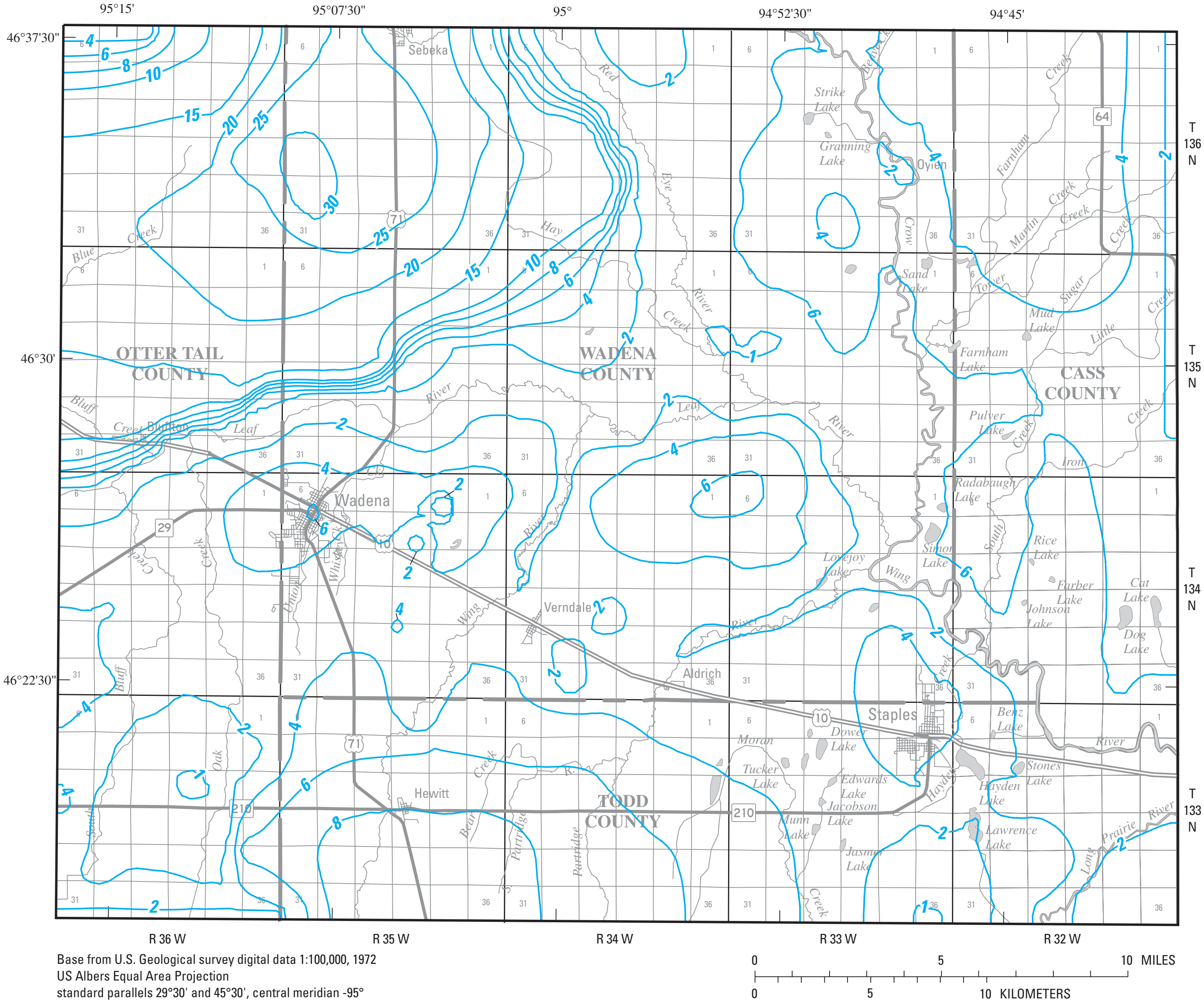
EXPLANATION

Extent of surficial aquifer

Area where surficial aquifer is absent

—2— Line of equal simulated drawdown--Interval is variable, in feet

Figure 17a. Extent of surficial aquifer and simulated drawdowns for model layer 1, representing the surficial aquifer, due to anticipated increased ground-water withdrawals and drought conditions, steady-state simulation, southern Wadena County and parts of surrounding counties, Minnesota.



EXPLANATION

—*1*— Line of equal simulated drawdown--Interval is variable, in feet

Figure 17b. Simulated drawdowns for model layer 3, representing the uppermost confined aquifers due to anticipated increased ground-water withdrawals and drought conditions, steady-state simulation, southern Wadena County and parts of surrounding counties, Minnesota.

occurred during the late summer each year. The long-term (net) decline in water level for the 2-year simulation at any one location was 0.3 ft or less, indicating that water levels did not fully recover from seasonal withdrawals during the drought. Streamflow reductions were least during the spring and early summer and were greatest during the late summer.

Greater Than Anticipated Increases in Withdrawals

Simulation 4 (table 8) was designed to evaluate the steady-state effects of greater than anticipated increases in withdrawals on water levels and streamflow. This was simulated by making the following changes to the model compared to the 1998-99 steady-state rates: (1) increasing withdrawals from the 113 irrigation and commercial wells and 47 dug pits in the surficial aquifer by 20 percent, (2) increasing irrigation well withdrawals from the uppermost confined aquifers by 50 percent, and (3) increasing withdrawals from the 5 Wadena municipal wells in the uppermost confined aquifers by 40 percent. Average steady-state recharge was assumed for the simulation.

Model results indicate that greater than anticipated increases in withdrawals will have minimal effects on ground-water levels and streamflow in the area. In the surficial aquifer, water levels may decline an average of 0.09 ft regionally, with maximum declines of 0.5 ft near Wadena, southwest of Verndale, and south of the Leaf River near its confluence with the Red Eye River. In the uppermost confined aquifers, model results indicate that water levels may decline an average of 0.13 ft regionally, with maximum declines of 0.8 to 2.1 ft near Wadena and near a few irrigation wells in the southwestern part of the study area, southwest of Verndale, and south of the Leaf River near its confluence with the Red Eye River. Declines in the northern, eastern, and south-central parts of the study area were less than 0.4 ft due to lack of wells completed in the uppermost confined aquifers. Model results indicate that greater than anticipated increases in withdrawals would cause decreases in ground-water discharge to streams of about 1.4 percent (2.5 ft^3/s) of 1998-99 steady-state conditions.

Greater Than Anticipated Increases in Withdrawals During a Drought

Simulation 5 (table 8) was designed to evaluate the steady-state effects of greater than anticipated increases in withdrawals on water levels and streamflow during a typical drought. For this simulation, the conditions of greater than anticipated increases in withdrawals described in the previous section were superimposed on the conditions of the hypothetical drought described previously.

Simulated results of greater than anticipated increases in withdrawals during a drought were very similar to those based only upon effects of the hypothetical drought (figs. 17a and 17b), only magnified slightly. Model results indicate that water-level declines in the surficial aquifer of as much as 6.4 ft may occur in Wadena and in the central part of the aquifer south of the Leaf River. Simulated declines in the uppermost confined aquifers for much of T133N, R35W range from 8 to 10 ft due to withdrawals from irrigation wells. Declines in the uppermost confined aquifers north of the Leaf River may be as much as 30.6 ft. Ground-water discharge to streams would be reduced by 25 percent (44 ft^3/s) compared to 1998-99 steady-state conditions as a result of the greater than anticipated increases in withdrawals during a drought.

MODEL LIMITATIONS AND ACCURACY OF RESULTS

A numerical ground-water-flow model is a practical tool for simulating the response of the stream-aquifer system to anticipated climatic conditions and development patterns. However, the model necessarily is a simplification of a complex flow system. Accuracy of the simulations is limited by accuracy of the data used to describe the properties of the aquifers and confining units, areal recharge rates, ground-water withdrawal rates, streambed hydraulic conductivities, and boundary conditions. Quantitative field data for these variables would greatly enhance model accuracy and, therefore, the simulated responses to anticipated increases in withdrawals and drought. In addition, a different combination of input could produce the same result.

Caution should be used in making ground-water management decisions based on the model simulations described in this report. Actual water-level declines in wells will differ from computed values and declines in or near individual high-capacity wells generally will be greater. Steady-state simulations do not consider water from storage, which may appreciably affect short-term changes in water levels. Pumping from wells in a confined aquifer results in a reduced confining-bed porosity and a corresponding reduction in drainage of water from the confining bed. Consequently, less water is available for withdrawal and water-level declines increase after an aquifer has been stressed for an extended period of time.

Use of the calibrated model as a management tool is based on the premise that if historical conditions in the aquifer can be simulated accurately, then future hydrologic conditions of similar magnitude can also be simulated. The duration of the hypothetical simulation period should be the same as or less than the duration of the calibration period, which is the case for the transient simulations. In addition, the rate of simulated recharge to or discharge from the aquifer should be similar to those used in the calibration simulations. This premise holds true for the simulation of anticipated increases in withdrawals and average recharge (Simulation 2). However, for the simulations of greater than anticipated increases in withdrawals or drought conditions (Simulations 3-5), the recharge and withdrawal rates are much different than for the calibration simulations. Therefore, the results of Simulations 3-5 should be viewed with caution and regarded only as plausible indicators of the response of ground-water levels and streamflow to the hypothetical stresses.

SUMMARY

Although numerous wells and test holes have been completed in the uppermost confined aquifers in the Wadena area, little is known about the continuity or the hydraulic response of the aquifers to ground-water withdrawals. Water managers of the Minnesota Department of Natural Resources and the Wadena Soil and Water Conservation District are concerned about the increase of ground-water withdrawals from high-capacity wells completed in these aquifers. To address these concerns, and to evaluate the ground-water resources in the uppermost confined aquifers in southern Wadena County, an investigation was conducted during 1997–2000 by the U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources and the Wadena Soil and Water Conservation District.

The hydrogeologic units of primary interest in the study area are the surficial aquifer, the uppermost confining units, and the uppermost confined aquifers. The surficial aquifer underlies all but portions of the eastern, western, and south-central parts of the study area, and is as much as 70 ft thick. The uppermost buried sand and gravel lenses of appreciable thickness in a vertical section at a location constitutes the uppermost confined aquifers. Thickness of the uppermost confined aquifers in the study area is as much as 72 ft. The thickness of the aquifers is greatest in the south-central and west-central parts of the study area, with thicknesses greater than 50 ft. Depth to the top of the uppermost confined aquifers ranges from 23 to 132 ft. The thickness of the uppermost confining units ranges from 4 to 132 ft, but generally is less than 50 ft thick where the surficial aquifer is present.

The regional direction of flow in the uppermost confined aquifers is to the east, southeast, and southwest toward the Crow Wing River in the eastern part of the study area and toward the Leaf River in the western part. Recharge to the surficial aquifer occurs by infiltration of precipitation to the saturated zone (areal recharge). Estimated areal recharge to the surficial aquifer averaged 13.9 in./yr during 1998, and 11.5 in./yr during 1999, based on hydrograph analysis. Sources of water to the uppermost confined aquifers are leakage of water through overlying till and clay and ground-water flow from adjoining aquifers outside the study area. Discharge from the surficial aquifer is by withdrawals from wells, by ground-water evapotranspiration, and to streams. Discharge from the uppermost confined aquifers is by withdrawals from wells and to the surficial aquifer in river valleys. The theoretical maximum well yields for the uppermost confined aquifers range from less that 175 gal/min to greater than 2,000 gal/min and are greatest in areas of greatest aquifer thickness and transmissivity.

A numerical model of ground-water flow was constructed based on knowledge of the hydrogeologic setting, aquifer characteristics, distribution and amount of recharge and discharge, and aquifer boundaries. The simulated water budget for the calibrated steady-state simulation indicated that areal recharge to the surficial aquifer accounts for 86.9 percent of the sources of water to the aquifers, with leakage to the uppermost confined aquifers where the surficial aquifer is absent contributing 6.9 percent. The largest discharges from the aquifers are leakage from the surficial aquifer to streams (54.5 percent) and ground-water evapotranspiration (41.4 percent). The simulated transient water budget for 1999 indicated that the principal sources of water to the aquifers were areal recharge to the surficial aquifer during the spring and early summer stress periods and release from storage during the winter, late summer, and fall stress periods. The principal discharges were stream-aquifer leakage during the fall and winter stress periods, addition to storage during the spring and early summer stress periods, and ground-water evapotranspiration during the late summer stress period.

The calibrated ground-water flow model was used as a tool to evaluate ground-water availability in the study area by assessing the potential effects of hypothetical conditions on ground-water levels and streamflow. Model results indicate that historical withdrawals have lowered water levels regionally in the surficial and uppermost confined aquifers an average of 0.31 and 0.42 ft, respectively. Declines in the surficial aquifer have been greatest near Wadena (4.0 ft) and Staples (2.5 ft). Model results also indicate that ground water discharge to rivers has been reduced by less than one percent compared to predevelopment conditions.

Model results indicate that the anticipated increases in withdrawals will have a minor effect on ground-water lev-

els and streamflow in the area. Water levels may decline an average of 0.03 ft regionally in the surficial aquifer with maximum declines of 0.3 ft near Wadena. In the uppermost confined aquifers, water levels may decline an average of 0.08 ft regionally with maximum declines of 0.9 ft near Wadena. The anticipated increases in withdrawals would cause decreases in ground-water discharge to streams of about 0.6 percent (1.1 ft^3/s) of 1998-99 conditions, as well as small decreases in ground water evapotranspiration. Results of the transient simulation similarly indicate that water levels will be minimally affected by the anticipated increases in pumping. The maximum increase in seasonal water-level decline for the uppermost confined aquifers would be 1.34 ft.

Model results indicate that the anticipated increases in withdrawals during a drought may lower water levels 2 to 4 ft regionally in much of both the surficial and uppermost confined aquifers. Water-level declines in the surficial aquifer of about 6 ft may occur in Wadena and in the central part of the aquifer south of the Leaf River. Simulated declines in all aquifers as a result of the anticipated increased withdrawals and hypothetical drought are not great enough to cause most wells to go dry. Ground water discharge to rivers would be reduced by 23 percent (42 ft^3/s) compared to 1998-99 steady-state conditions. Results of the transient simulation indicate that the anticipated increases in withdrawals during a drought would increase seasonal declines in the surficial and uppermost confined aquifers less than 1 and 2 ft, respectively.

Model results indicate that greater than anticipated increases in withdrawals during periods of average recharge will have minimal effects on ground-water levels and streamflow in the area. In the uppermost confined aquifers, for example, water levels may decline an average of 0.13 ft regionally, with maximum declines of 0.8 to 2.1 ft near Wadena and Verndale. Greater than anticipated increases in withdrawals would cause decreases in ground-water discharge to streams of about 1.4 percent (2.5 ft^3/s) of 1998-99 steady-state conditions. Greater than anticipated increases in withdrawals during a drought may cause and average decline of 6 ft in the uppermost confined aquifers and a reduction in ground-water discharge to streams of about 25 percent.

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GLOSSARY

Alluvial deposits: Gravel, sand, silt, and clay deposited in channels and floodplains of modern streams.

Aquifer: Formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Areal recharge: Recharge to the aquifer by infiltration of precipitation to the saturated zone.

Base flow: Sustained streamflow, consisting mainly of ground-water discharge to a stream.

Confined aquifer: Aquifer bounded above by a confining unit. An aquifer containing confined ground water. Synonymous with buried aquifer.

Confining unit: Body of materials with low vertical permeability stratigraphically adjacent to one or more aquifers.

Drawdown: Vertical distance between the static (nonpumping) hydraulic head and hydraulic head caused by pumping.

Evapotranspiration: Water discharge to the atmosphere by evaporation from water surfaces and moist soil and by plant transpiration.

Gaining stream: Stream or reach of a stream whose flow is being increased by inflow of ground water.

Ground water: The part of subsurface water that is in the saturated zone.

Ground-water evapotranspiration: Water discharged to the atmosphere from ground water by direct evaporation from the water table where it is at or near land surface and transpiration from vegetation where the water table is above the root zone or within reach of roots through capillary action; does not include evapotranspiration losses occurring above the water table.

Head, hydraulic: The height, above a standard datum, of the surface of a column of water that can be supported by the static pressure at a given point.

Hydraulic conductivity: Capacity of porous material to transmit water under pressure. The rate of flow of water passing through a unit section or area under a unit hydraulic gradient.

Hydraulic gradient: The change in hydraulic head per unit distance of flow in a given direction. Synonymous with potentiometric gradient.

Losing stream: Stream or reach of a stream whose flow is being decreased by leakage to ground water.

Nested wells: Two or more wells at the same location completed at different depths below land surface.

Outwash: Washed, sorted, and stratified drift deposited by water from melting glacier ice.

Permeability: Measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient.

Potentiometric surface: A surface that represents the static head of water in an aquifer, assuming no appreciable variation of head with depth in the aquifer. It is defined by the levels to which water will rise in tightly cased wells from a given point in an aquifer.

Saturated zone: The zone in which all voids are ideally filled with water. The water table is the upper limit of this zone. Water in the saturated zone is under pressure equal to or greater than atmospheric.

Specific capacity: The rate of discharge of water from a well divided by the drawdown of water level within the well.

Specific yield: The ratio of the volume of water that aquifer material will yield by gravity drainage to the volume of the aquifer material.

Steady state: Equilibrium conditions whereby hydraulic heads and the volume of water in storage do not change substantially with time.

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, it is the same as specific yield.

Stream-aquifer leakage: Movement of water between a stream and the underlying aquifer, not restricted to either direction of flow.

Surficial aquifer: The saturated zone between the water table and the first underlying confining unit. Synonymous with unconfined aquifer.

Till: Unsorted, unstratified drift deposited directly by glacier ice.

Transmissivity: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unconfined aquifer: The saturated zone between the water table and the first underlying confining unit. Synonymous with surficial aquifer.

Water table: The surface in an unconfined ground-water body at which the water pressure is atmospheric. Generally, that is the potentiometric surface of the upper part of the zone of saturation.