Hydrology of the Lower Dakota Aquifer

Groundwater availability in northwest Iowa

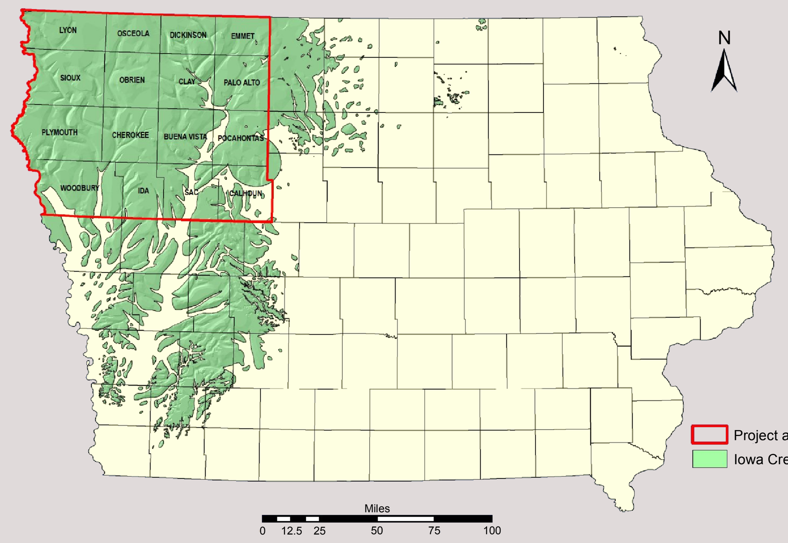
Northwest Iowa is often described as “fair” in terms of groundwater availability, quantity, and quality. This area has fewer options for potable groundwater than some other parts of Iowa. The Lower Dakota Aquifer is the primary source of groundwater because of its relatively shallow depth and generally good yields. The aquifer is composed of the contiguous sandstones of two members of the Dakota Formation. The Woodbury Member includes thinly bedded and well sorted shales and very fine- to fine-grained sandstones, and the underlying Nishnabotna Member consists of thickly bedded and poorly-sorted fine- to very course-grained sandstones. The water quality from the aquifer is fair to poor throughout most of the area. The bedrock aquifers underlying the Lower Dakota Aquifer contain water with very high total dissolved solids, making them unsuited for human or livestock use in this part of the state.

Alluvial aquifers are the youngest and shallowest aquifers in northwest Iowa and are used extensively along the Floyd, Rock, Little Sioux, Big Sioux, and Missouri rivers. Buried valley aquifers occur along ancient river valleys carved into bedrock. These aquifers are composed of sand and gravel that are buried by younger impermeable glacial tills. The ancient valleys usually show no expression on the modern landscape. These aquifers are highly productive in some parts of northwest Iowa. Glacial drift aquifers are pockets of sand and gravel surrounded by glacial till. Their configurations are irregular and locations are unpredictable.

While not as productive, these aquifers are sufficient for many private and small public water supplies. The "salt and pepper" sands, named for their white quartz grains and dark volcanic glass fragments, occur within or just below the base of the glacial tills in western Iowa. Locally, these deposits may produce moderate yields. These sands were derived from Rocky Mountain sources and deposited in western Iowa by eastward-flowing rivers before the Missouri River existed in its present form and location. The sands occur on some uplands where they are often buried beneath 50 to 300 feet of glacial deposits.

The circular Manson Impact Structure, in parts of Calhoun and Pocahontas counties, is a Cretaceous meteorite crater that contains a massive disruption of the normal bedrock sequence. Near the center of the crater, fractured Precambrian granite yields the only soft groundwater found in Iowa. Finding groundwater within the buried feature can be difficult. Test holes are needed to search for water within the impact structure, and once water is found, the supply may not last long since the rocks are no longer connected to the aquifers surrounding the structure.

Northwest Iowa has substantial thickness of loess, glacial drift, and in some areas shale overlying the bedrock aquifers, thus protecting them from surface contamination. The major contamination issue in the area is the vulnerability of surficial aquifers to contamination from the land surface.



Area of occurrence and significant use of the Dakota Aquifer in western Iowa (modified from Iowa’s Groundwater Basics by Jean Prior et al., 2003, Iowa Department of Natural Resources, Iowa Geological Survey Educational Series 6, 83 pages).

While Iowa is probably not facing an immediate water shortage, increased demand for groundwater by agriculture, industries, and municipalities have raised concerns for the future of the resource. The last comprehensive water plan for Iowa was compleated in 1978, so we do not have current information or resources available at the state level to answer basic questions regarding how much water can be withdrawn from Iowa’s aquifers on a sustainable basis.

Following a proposal in 2007 from the Iowa Geological and Water Survey (IGWS) for funding to characterize the availability, quality, use, and sustainability of Iowa’s water resources, the Iowa legislature approved funding to support the first year of a multi-year evaluation of Iowa’s major aquifers. The Dakota Aquifer is the first aquifer to be studied under the auspices of the 2008 Water Resources Management program. An intensive one-year investigation of the aquifer was conducted to provide a quantitative assessment of groundwater availability and to construct a groundwater flow model that can be used for planning future water resource development. A series of maps were made to define the geometry and geologic and hydrologic properties of the Lower Dakota Aquifer and surrounding strata. These maps were then used to construct and calibrate a groundwater flow model for the aquifer.

The groundwater flow model

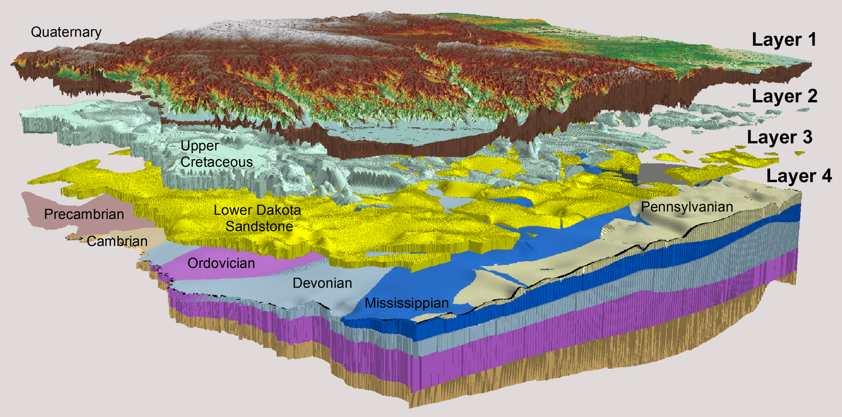
A conceptual model represents our best understanding of the three-dimensional geology and hydrogeology of the Lower Dakota Aquifer and surrounding strata. The model does not necessarily use formations or stratigraphic units, but relies on variations in lithology and hydraulic parameters to represent groundwater flow conditions. The aquifer was modeled using four layers.

Layer 4 is the base of the model. It represents the Paleozoic and Precambrian units that are found beneath the lower Dakota sandstone. Depending on lithology, the units represent either no-flow boundaries or flow-through boundaries (upward). This unit is referred to as the sub-Cretaceous.

The Lower Dakota Aquifer is represented by **Layer 3**. It is confined above by various Cretaceous shale units. The aquifer pinches out to the east and south. These boundaries are assumed to be no-flow boundaries. The discontinuous nature of the aquifer to the east and south would violate the continuity of flow if it were included in the active model. Flow-through boundaries are assumed to be along the north, west, and a small southeast corner of Buena Vista County.

Layer 2 includes the shale-dominated upper Cretaceous strata, and **Layer 1** is the Quaternary units. Both are primarily confining units. The exception to these two confining units is in the Sioux City area, where shallow alluvium of the Missouri River directly overlies the aquifer. This is represented by a higher hydraulic conductivity in Layers 1 and 2 in areas overlain by alluvium.

Due to the relatively thick glacial till and shale units, the net recharge value used in the model represents the amount of precipitation that enters Layer 2, the Cretaceous bedrock, from Layer 1, the Quaternary units.



Conceptual model of the 16-county Dakota Aquifer study area in western Iowa as viewed from the southwest.

To simulate pre-development conditions, the static water level from the first recorded well in a community was used. It was assumed that observation well data outside major pumping centers represented pre-development conditions. The observed static water levels used in steady-state calibration may slightly underestimate the actual pre-development values due to historical pumping.

Drawdown in static water levels since pre-development has been caused by pumping. Areas with the greatest drawdown are the result of the distribution of wells, pumping rates, and aquifer properties.

The vertical hydraulic gradient between layers 3 and 4 is assumed to be downward under predevelopment conditions. Under transient or pumping conditions this gradient has the potential to reverse and become upward. The amount of drawdown created by pumping stress is the determining factor.

In order to not violate the law of continuity of flow, only those regions where the Lower Dakota sandstone is continuous are modeled. The continuous sandstone is designated as active, and the non-continuous area is designated as inactive in the model. A minimum thickness of 1 meter was used in the model.

Monthly pumping data obtained from the IDNR water-use database were used to calibrate the transient conditions from January 2001 to December 2006. Quarterly water level data collected by the United States Geological Survey for the IDNR Watershed Monitoring and Assessment Section were also used for calibration.

The aquifer parameters used in the model were based on the results of twenty-five aquifer tests and, during model development, approximately 1,900 private wells were added to the model as pumping wells.

The groundwater model is described in detail in *Water Resources Investigation Report No. 1A, Groundwater Availability Modeling of the Lower Dakota Aquifer in Northwest Iowa*, which is available from the IGWS in hard copy or downloadable PDF format at www.igsb.uiowa.edu/gsbpubs/.

Model design

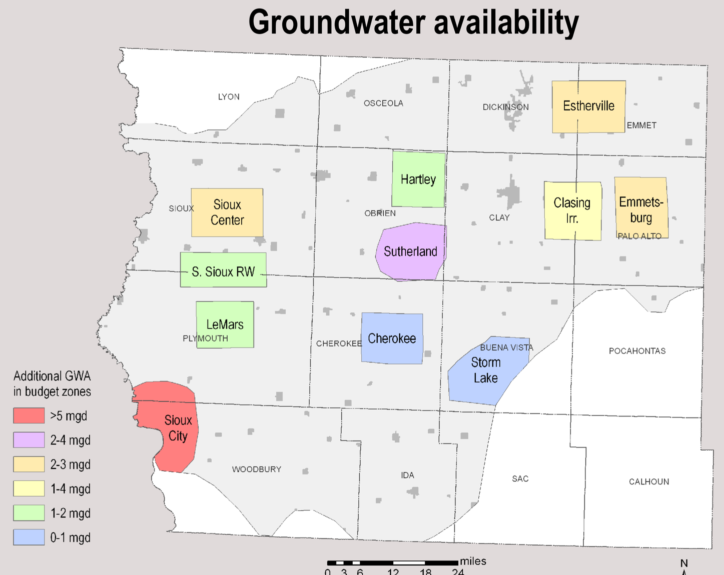
A numerical model of the Lower Dakota Aquifer was developed to evaluate groundwater sustainability utilizing current usage and several future usage scenarios. The future scenarios involved a low-, medium-, and high-water use and an irrigation usage expansion.

The concept of zone budgeting was used within high usage areas to evaluate the local water budget. Eleven zones were used to allow a better indication of the current water balance in high usage areas, and to show the ability of the aquifer to sustain these withdrawals. The zones were also used to evaluate how much water is available in these areas for future development.

An important component of the model was a network of about 60 wells, used to evaluate water levels. Eleven observation wells which had time series data were used for the transient model development. Other tasks performed to develop an understanding of the hydrology of the study area included collection, compilation, and analysis of available geologic and hydrologic data and collection, compilation, and estimation of the major points of groundwater withdrawals.

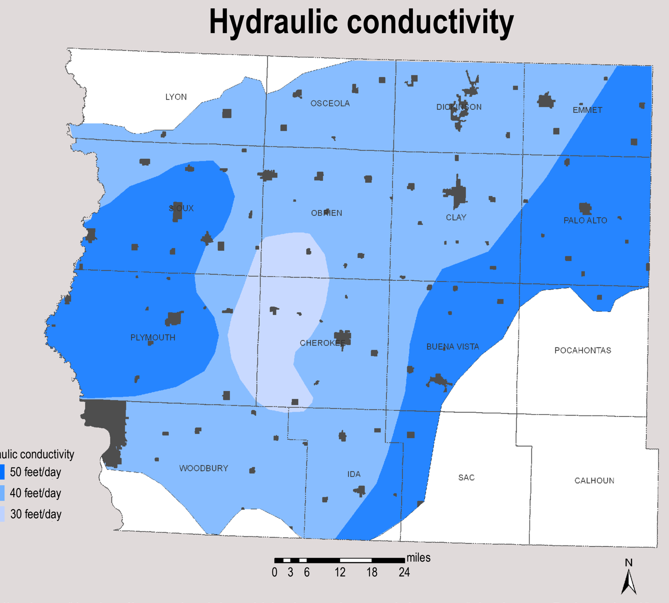
The model was created using Visual MODFLOW 4.2. The hydrologic processes examined in the model include net recharge, hydraulic conductivity, specific storage, flow-through boundaries, no-flow boundaries, well discharge, river boundary, and groundwater upwelling.

Groundwater availability



Groundwater availability (GWA) map based on zone budget analyses and predictive modeling.

Hydraulic conductivity



Distribution of hydraulic conductivity within the active model area of the Lower Dakota Aquifer.

The modeling approach involved the following components:

1. Calibrating a pre-development steady-state model using water level data from historic records and wells approximately 10 miles from major pumping centers.

2. Calibrating a transient model using water-use data from 2001 through 2006. Simulated water levels were compared to observed time-series water level measurements.

3. The calibrated model was used to predict additional drawdowns through 2028 for low, medium, and high usage simulations. Another simulation was run to predict the additional drawdown for a 2-year drought using 161 new irrigation permits.

The hydraulic properties of the aquifer were shown to vary considerably in both the lateral and vertical direction, and were obtained for modeling primarily from aquifer pump test analyses. Based on aquifer test results, the hydraulic conductivity of the aquifer ranges from 22 to 81 feet/day, with an arithmetic mean of 47 feet/day. Transmissivity values range from 2,700 to 12,000 feet^2/day and are controlled primarily by aquifer thickness. The storage coefficient of the aquifer ranges from 1.8 x 10^{-5} to 2 x 10^{-3}, with an arithmetic mean of 3.3 x 10^{-4}.

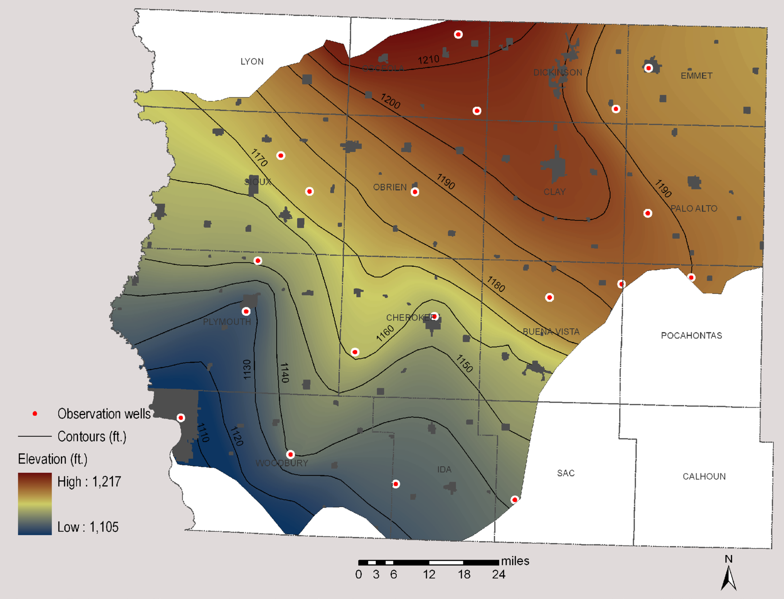
Due to the relatively thick confining units, the rate of recharge to the aquifer is very small. Calibrated recharge rates varied from 0.05 to 0.15 inches/year over most of the study area. A calibrated recharge rate of 3 inches/year was used in the Sioux City area due to overlying Missouri River alluvium and thin or absent confining units in the area.

Lower Dakota Aquifer test results used to determine aquifer parameters for groundwater flow modeling.

Well Name	Well Number	W Number	Aquifer Thickness (feet)	Transmissivity (ft2/day)	Hydraulic Conductivity (ft/day)	Storage Coefficient	Method
Osceola RW North Subsystem$_1$	D-S	27140	130	2800	22		Cooper/Jacobs
Osceola County RW$_1$		27191	130	10,500	81		Cooper/Jacobs
IGS-USGS$_1$	D-8	24734	130	5,600	43		Cooper/Jacobs
Southern Sioux County RWS$_1$	D-1	25487	157	8,290	53	3.2 x 10^{-4}	Hantush
Southern Sioux County RWS$_1$	D-2	42553	157	6,950	44		Theis Recovery
Southern Sioux County RWS$_1$	D-3	57869	175	8,800	50		Cooper/Jacobs
City of Emmetsburg$_1$	#6	33749	75	5020	67		Theis Recovery
City of Remsen$_1$	#9	57863	108	2800	26		Cooper/Jacobs
City of Orange City$_1$	#3	41179	125	3050	24		Theis Step Test
Verasun Energy Hartley Site$_2$	#1	65429	175	6,700	38	1.0 x 10^{-3}	Cooper/Jacobs
			175	7,750	44	1.0 x 10^{-4}	Cooper/Jacobs
			175	7,830	45	2.0 x 10^{-4}	Theis
			175	8,320	48	2.0 x 10^{-4}	Theis
			175	9,740	56	2.0 x 10^{-4}	Theis
Loren Hansen$_3$	#1	24520	80	3877	48	6.0 x 10^{-4}	Theis
Larry Ritz$_3$		25186	140	7620	54	3.5 x 10^{-5}	Theis
Rheinhold Hibbing Observation$_3$	#2	34581	162	12032	74	2.0 x 10^{-4}	Theis
Rheinhold Hibbing$_3$	D-39; #5	25899	162	5348	33	2.0 x 10^{-3}	Theis
South Sioux County RWD$_3$	79-1	28389	155	7353	47	8.0 x 10^{-4}	Theis
Southern Sioux County RWS$_3$	79-2	25509	155	5882	38	3.0 x 10^{-4}	Theis
Green Plains Renewable Energy$_2$	#2	64846	172	6,380	37	1.8 x 10^{-4}	Hantush
Sioux Center Land Development	#1	63799	87	3900	45	1.0 x 10^{-4}	Recovery
City ofLeMars	#11	62831	128	7200	56	3.4 x 10^{-4}	Theis
City of LeMars	#12	62832	128	6800	53	1.8 x 10^{-5}	Cooper/Jacobs
Donald Hosteng$_3$	#2	24560	125	4545	36	8.0 x 10^{-4}	Theis

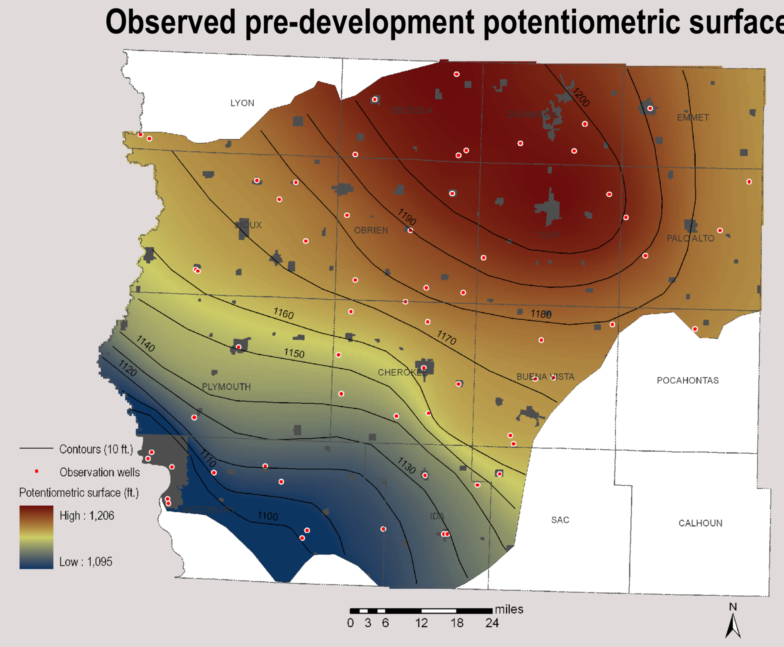
$_1$ Data Provided by Dewild Grant Reckert and Associates
$_2$ Data Provided by Layne Christiansen
$_3$ Munter, Ludvigson, Bunker, 1983

Potentiometric surface 2000 to 2002



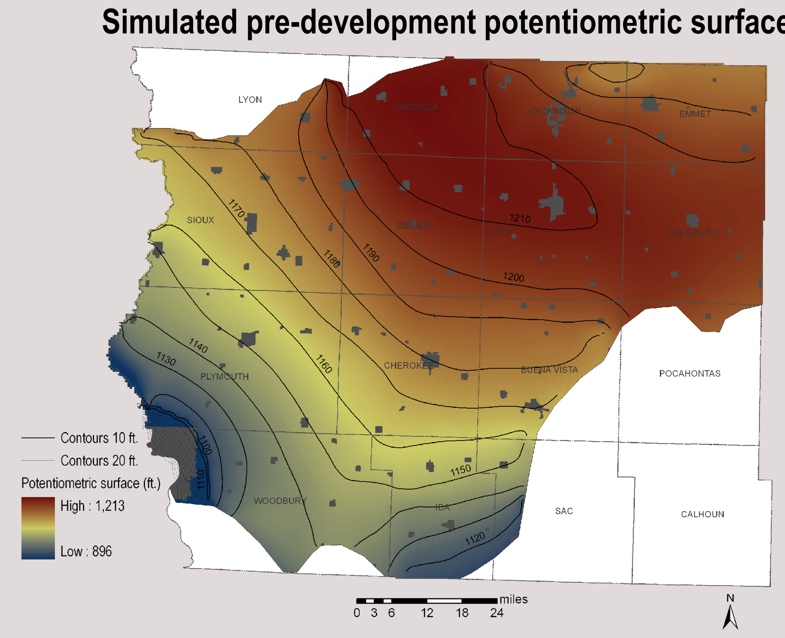
Lower Dakota Aquifer potentiometric surface based on water level data collected from 2000 to 2002.

Observed pre-development potentiometric surface



Observed potentiometric surface for estimated pre-development steady-state conditions.

Simulated pre-development potentiometric surface



Simulated potentiometric surface for estimated pre-development steady-state conditions.

Making maps with GIS

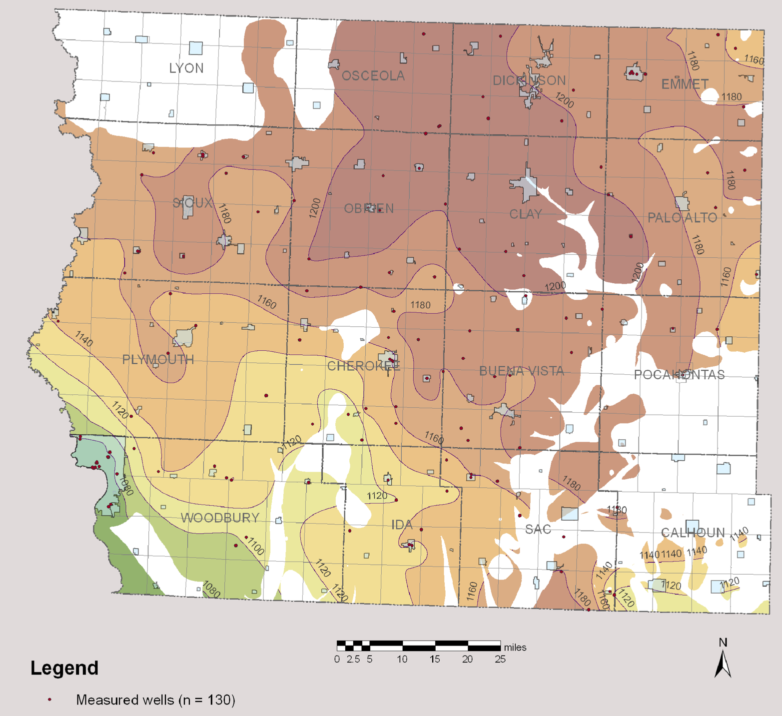
Geographic Information System (GIS) software stores geographically indexed information in layers and allows users to analyze spatial relationships and map them. The information can be represented in two dimensions as points, lines, polygons, and grid cells, or in three dimensions as triangular irregular network (TIN) data with x, y, and z values and a series of edges connecting these points to form triangles. Like grids, TINs are used to represent continuous surfaces such as a landscape, but unlike grids, TINs have a vertical component such as thickness or elevation. GIS software tools allow the user to create three-dimensional layers and perform mathematical calculations on them.

After reviewing all data sources for well information, 130 wells within the study area were selected as a basis for producing hydrogeologic maps. For wells with multiple static water levels, the water levels were averaged for use in constructing a potentiometric surface. An average hydraulic conductivity (K) value of 48 feet/day, and an average well function (W[u]) value of 270 were assumed for the Nishnabotna Member sandstones based on previously collected and currently reviewed pumping test data. The well point locations for the averaged constituents were then converted to a grid using a topo to raster tool. The grid was then clipped using the appropriate bedrock coverage and outline of the sixteen counties in northwest Iowa as a boundary condition, and the grid was contoured using a raster surface contour tool. The maps that were generated by the groundwater flow model compared well with the hydrogeologic maps that were based on observed water levels and empirical data.

The following first and second tier maps were constructed with desktop GIS software using data from wells completed in the Lower Dakota Aquifer. The map layers can be related to one another employing a few simple hydrologic equations using data from geologic field observations and pumping tests. The map layers were made sequentially by using earlier constructed layers to calculate succeeding layers.

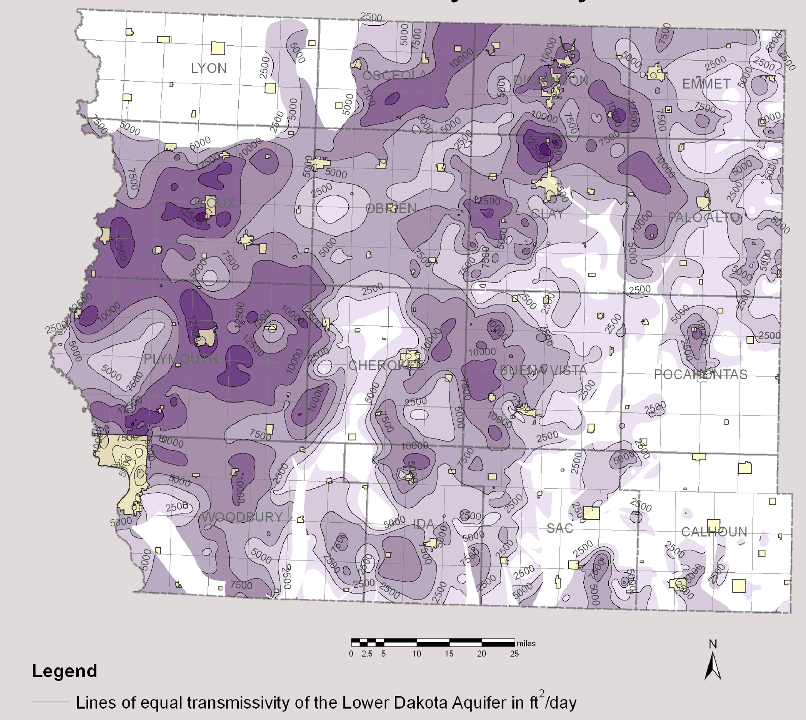
The methods and data sources used for the groundwater resource evaluation are described in detail in *Water Resources Investigation Report No. 1B, Groundwater Resource Evaluation of the Lower Dakota Aquifer in Northwest Iowa*, which is available from the IGWS in hard copy or downloadable PDF format at www.igsb.uiowa.edu/gsbpubs/. The hydrologic maps are available as PDFs from the IGWS website at www.igsb.uiowa.edu. For those with desktop GIS software, the map layers, known as coverages or themes, are accessible from the Natural Resources GIS Library at www.igsb.uiowa.edu/nrgislibx/.

Potentiometric surface 1912 to 1996



A potentiometric surface is an imaginary surface formed by measuring the level to which water will rise in wells of a particular aquifer. In a confined aquifer, like the Lower Dakota, this surface is above the top of the aquifer, whereas in an unconfined aquifer, it is the same as the water table. This map was made by contouring mean static water levels collected from 1912 to 1996 from wells completed in the aquifer. Since the static water levels span a large range of time, the potentiometric surface is representative of average water levels during the time of collection. For areas where water use has remained relatively constant, the map is probably representative of current water levels. For areas where water use has increased significantly, current water levels may be lower than those represented by the map. Since water moves from higher to lower elevations or pressure areas, lateral water movement in the aquifer is from the uplands in the north-central part of the study area to the Missouri and Big Sioux river valleys in the southwest and bedrock valleys toward the south and east.

Transmissivity in ft²/day

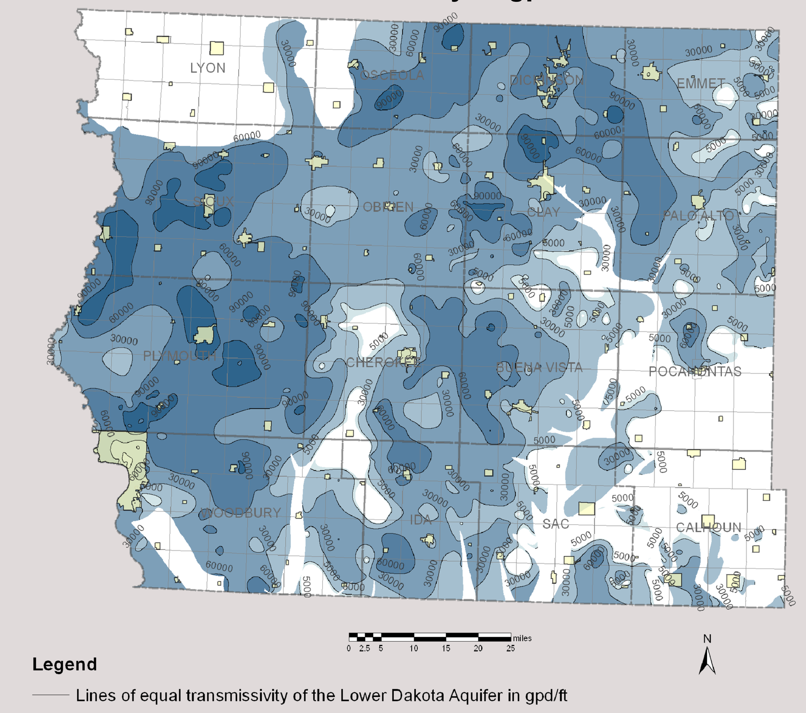


Transmissivity (T) is a measure of how much water an aquifer can transmit horizontally to a pumping well.

T = Kb, where K = hydraulic conductivity and b = aquifer thickness.

K is a measure of the rate of flow of water through a cross-sectional area of the aquifer and is expressed in units of length/time. Units of T are length^2/time, since units of b are length and units of K are length/time. This map was made by multiplying the Lower Dakota Aquifer’s thickness by the aquifer’s average hydraulic conductivity of 48 feet/day. Assuming that K is constant, the transmissivity is greatest where the aquifer is thickest.

Transmissivity in gpd/ft

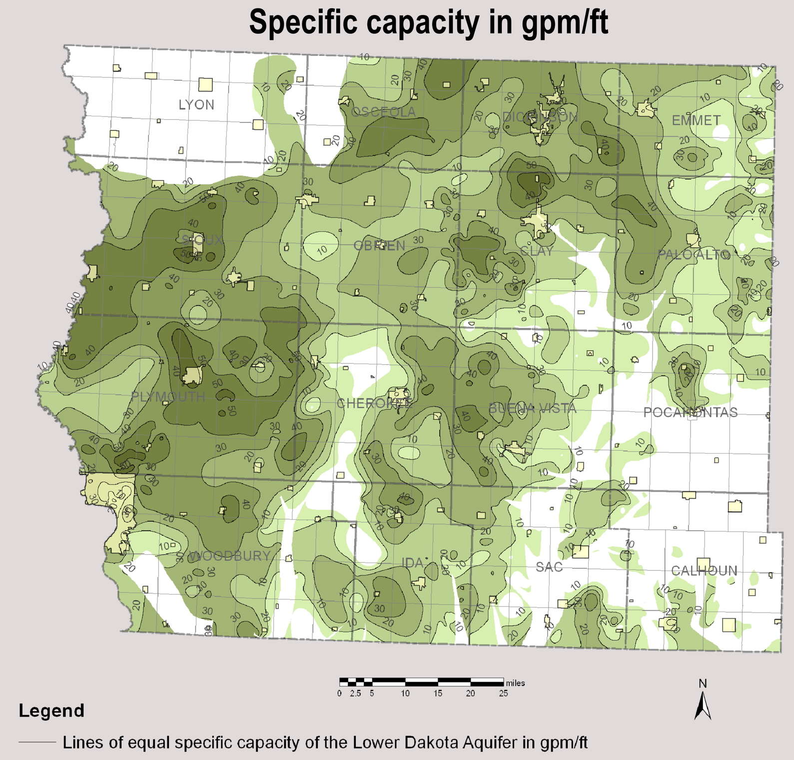


Transmissivity can also be expressed as [volume/time]/length, or gallons/day/foot, since one cubic foot contains 7.481 gallons of water. For example, an aquifer with a K of 10 feet/day that has a saturated thickness of 25 feet would have a transmissivity as follows:

T = Kb, or T = 10 x 25, so T = 250 feet^2/day, or 250 x 7.481 = 1,870 gpd/ft.

For a confined aquifer, transmissivity remains constant, as the saturated thickness remains constant. For an unconfined aquifer, the aquifer thickness is from the base of the aquifer, or the top of the aquitard, to the water table. Since the water table can fluctuate, the transmissivity of an unconfined aquifer can change. This map was made by multiplying the previous transmissivity map layer by 7.481.

Specific capacity in gpm/ft

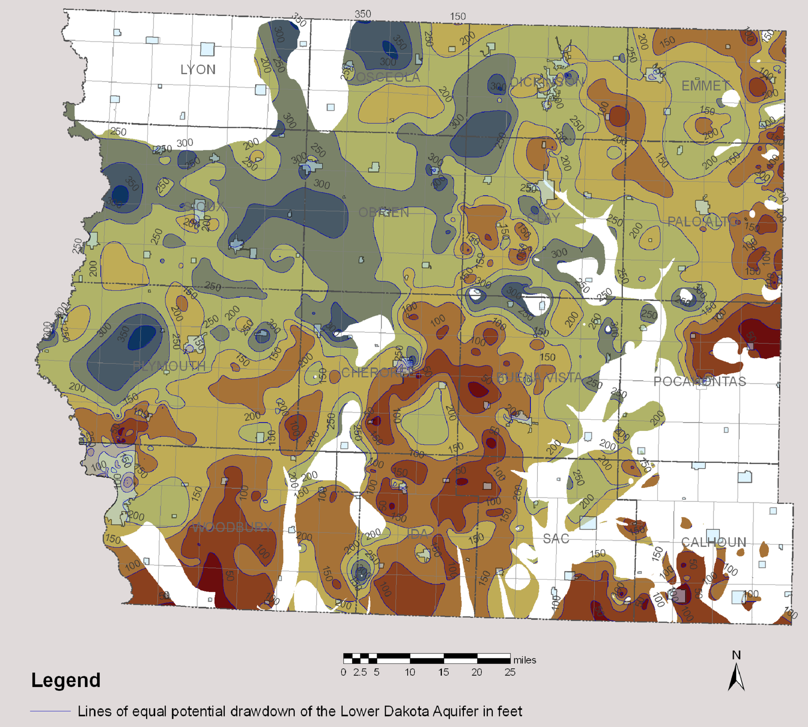


Specific capacity (C) is a measure of well performance, usually in gpm per foot. Specific capacity can be used to provide the design pumping rate or maximum yield for a well. It can also be used to identify potential well, pump, or aquifer problems, and accordingly to develop a proper well maintenance schedule.

$C = Q/\Delta h$,

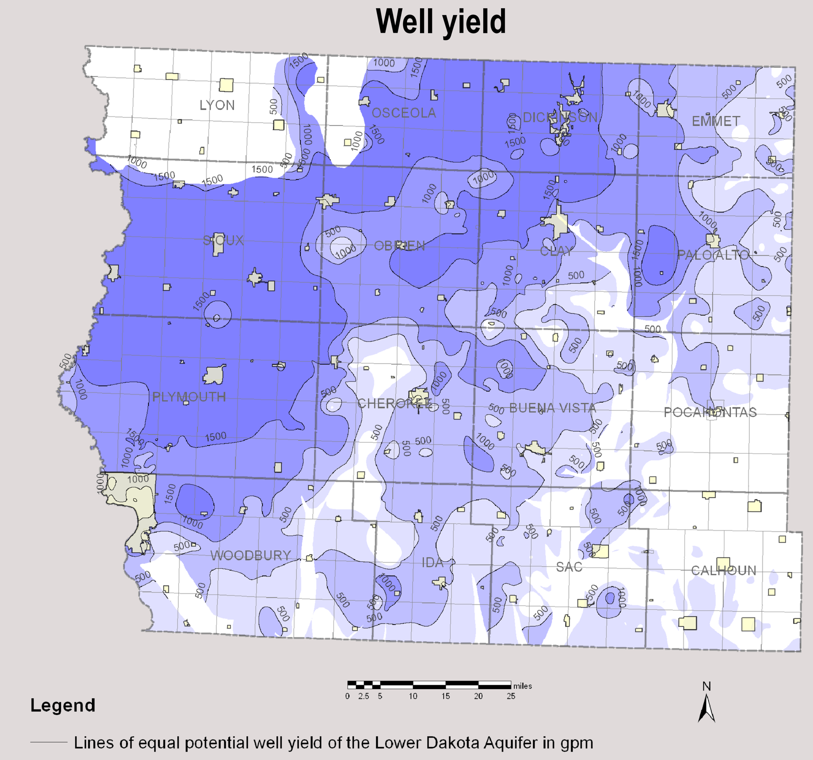
where Q = well pumping rate or yield and Δh = well drawdown (the drop in water level in the well when it is pumped). Well function, $W(u) = r^2S/4Tt$, where r is radial flow, S is storativity, T is transmissivity, and t is time. T = well function x Q/Δh, so C = T/well function. Since the average well function for the aquifer is 270, this map was made by dividing the transmissivity map layer (in ft^2/day) by 270. Assuming that W(u) is constant the specific capacity is greatest where T is greatest.

Drawdown



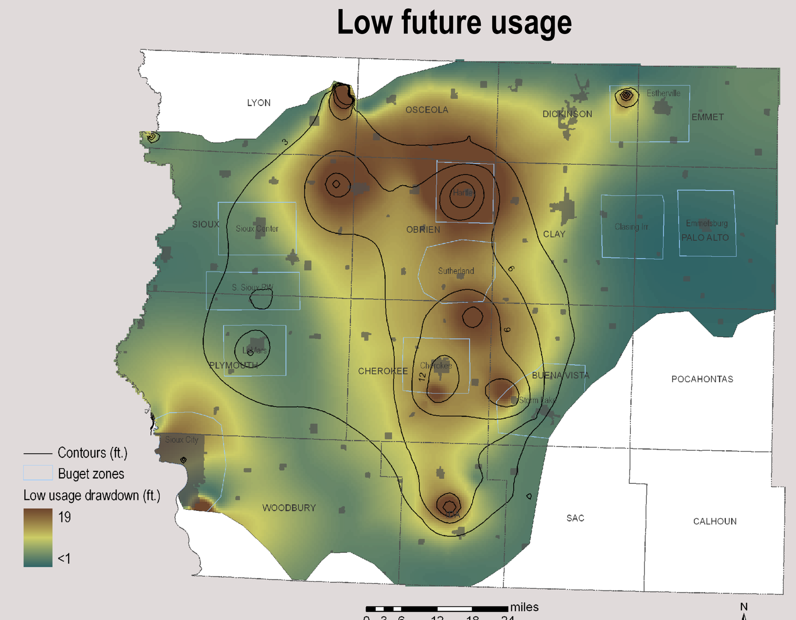
Drawdown (Δh) is the drop in the water level in a well when it is pumped, measured in feet or meters. Typically, drawdown increases with the length of pumping time, producing a cone of depression. Well yield (Q) or the amount of water that can be pumped is limited by the amount of drawdown produced. Since specific capacity (C) = Q/Δh, Q = C x Δh, so well yields can be determined from specific capacity (C) and drawdown. This map was made by subtracting the elevation of the top of the aquifer from the elevation of the aquifer’s potentiometric surface. The amount of drawdown that occurs in a well is determined by an aquifer’s ability to replace water that is being pumped. If there is a lot of water in an aquifer that can move freely to a well, the drawdown will be low. If water cannot move through the aquifer quickly, the drawdown will be high and unsustainable. To assure that withdrawals from an aquifer will be sustainable, a margin of safety can be added by using only a portion of the total potential drawdown to calculate potential well yields.

Well yield



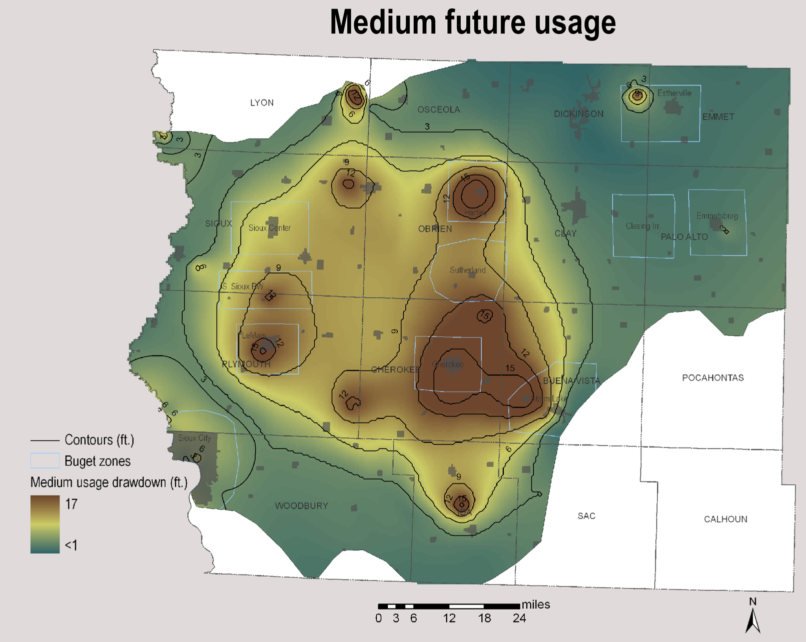
Well yield (Q) is a measure of how quickly and how much water can be withdrawn from an aquifer over a period of time and is usually expressed in gpm. A sustainable well yield is that which can be maintained during periods of extended drought. Since specific capacity (C) = Q/Δh, Q = C x Δh, so well yields can be determined from specific capacity (C) and drawdown (Δh). Actual well yields may vary due to well loss, or the inability of the well to produce at 100% efficiency. This map was made by multiplying the specific capacity map layer by 50% of potential drawdown, then multiplying by a 50% well efficiency. Generally, yields are greatest in areas where the aquifer is thickest. This map and the groundwater availability map should be used with caution. The actual availability for a specific water use permit should be modeled at the local scale to evaluate the potential for long term interference with existing well owners. This is especially true when completing a well within one of the eleven groundwater budget zones.

Low future usage



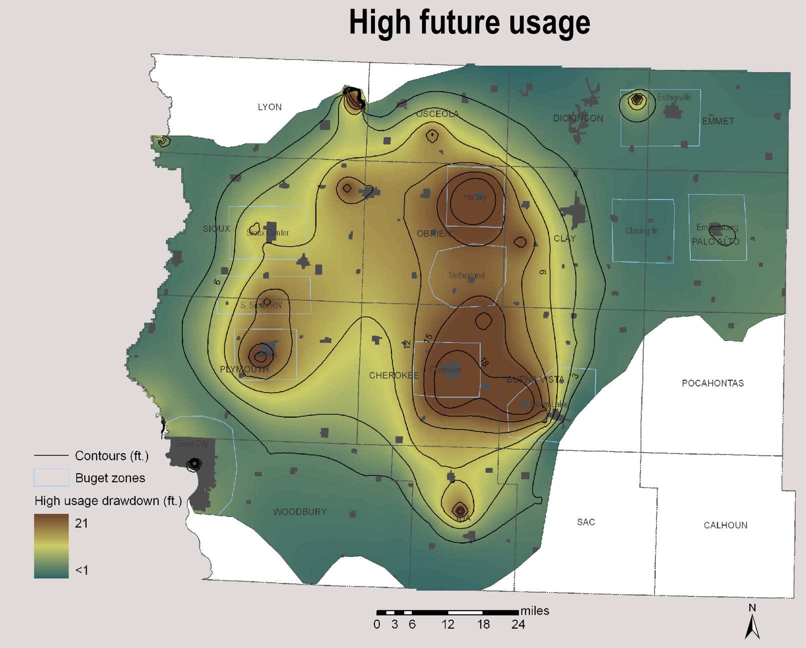
The additional modeled drawdown from 2008 to 2028, based on low future usage, assumes a stagnant population growth. This limits the future usage of the aquifer to the 2001 to 2006 values plus the new water-use permits that have not gone on-line. For simplicity, the average daily water-use pumping rates were used throughout the year. Additional ethanol permits are proposed in Ida, Cherokee, and Sioux counties with an average daily usage at each of 1.6 million gallons per day (mgd). Irrigation permits are assumed to remain unchanged. The most significant areas of drawdown occur in the Cherokee, Storm Lake, and Hartley (new ethanol plant) budget zones and near the proposed ethanol plants in Ida, Cherokee, and Sioux counties. Based on the simulated time series graphs, additional drawdown appears to stabilize after 6 years, which suggests that the aquifer can handle the increase in water use caused by the new permits and the three proposed ethanol permits.

Medium future usage



The additional modeled drawdown from the aquifer from 2008 to 2028, based on medium future usage, assumes a 25% increase in pumping rates from the low usage scenario. Additional ethanol plants are predicted in Sioux and Plymouth counties, with an average daily usage at each of 1.6 mgd. Irrigation permits are assumed to remain unchanged. Additional drawdown is observed near the proposed ethanol plants in Clay and Osceola counties, and also near Storm Lake, Cherokee, and the Hartley ethanol plant. The Hartley, Storm Lake, and Cherokee areas show the largest amount of additional drawdown. Based on the 25% increase in pumping rates, all the zones except Cherokee and Storm Lake appear to have additional water use expansion capacity. The Storm Lake and Cherokee areas show significant drawdown when pumping rates are increased by 25%. These drawdowns begin to stabilize after 18 to 20 years, suggesting that these areas may be approaching their sustainable groundwater withdrawal rates.

High future usage



The additional modeled drawdown from 2008 to 2028, based on high future usage, assumes a 50% increase in pumping rates from the aquifer from the low usage scenario. Additional ethanol plants are predicted in Clay and Osceola counties, with an average daily usage at each of 1.6 mgd. Irrigation permits are assumed to remain unchanged. The Hartley, Storm Lake, and Cherokee areas show significant additional drawdown that ranges from 15 to 18 feet. Drawdowns in the Le Mars, Sioux Center, and South Sioux Rural Water District zones range from 6 to 15 feet. Additional drawdowns stabilize after 18 years of pumping except in the Cherokee and Storm Lake zones. Le Mars and South Sioux Rural Water District appear to be approaching their sustainable pumping rates using the high future use simulation. Future water use permits should be evaluated using a local scale model within the regional MODFLOW model.

Summary and Conclusions

A series of maps, based on well data, were constructed and used to define the geometry of the Lower Dakota Aquifer and the three other major geologic packages used for modeling. Sixty wells were used to evaluate water levels and eleven observation wells with time series data were used for the transient model development. Other tasks performed to develop an understanding of the hydrology of the study area included collection, compilation, and analysis of available geologic and hydrologic data and estimation of the major points of groundwater withdrawals in the area. With this information a four layer numerical groundwater flow model of the aquifer was developed using Visual MODFLOW version 4.2. Hydrologic processes examined in the model include net recharge, hydraulic conductivity, specific storage, flow-through boundaries, no-flow boundaries, well discharge, river boundaries, and groundwater upwelling. The hydraulic properties of the aquifer vary considerably both laterally and vertically and were obtained for modeling primarily from aquifer pump tests. The hydraulic conductivity of the aquifer ranges from 22 to 81 ft/day, with a mean of 47 ft/day. Transmissivity ranges from 2,700 to 12,000 ft^2/day and is controlled primarily by aquifer thickness. The storage coefficient of the aquifer ranges from 1.8 x 10^{-5} to 2 x 10^{-3}, with a mean of 3.3 x 10^{-4}. Recharge to most of the aquifer is through relatively thick confining beds that include Cenozoic (Pleistocene) glacial till and upper Cretaceous shale units. Due to the relatively thick confining units, the rate of recharge is very small, ranging from 0.05 to 0.15 inches/year over most of the study area. A recharge rate of 3 inches/year was used in the Sioux City area due to the overlying alluvium and thin or absent confining units. The calibrated model provided good correlation for both steady-state and transient conditions. Root mean square errors of 14.8 and 9.4 ft were relatively small errors over an area of 8,100 mi^2. Simulated water level changes are most sensitive to recharge in the steady-state model, and to pumping rates in the transient model. The aquifer has tremendous development capacity. Potential yields to wells completed in the aquifer exceed 500 gpm throughout much of the study area, and yields of greater than 1,500 gpm are possible in much of the western and north-central portions of the area. Greater yields may be possible if more than 50% of potential drawdown is acceptable. The current summertime usage was estimated to be approximately 31.6 mgd. This withdrawal is well below the development potential for the aquifer. The actual volume of groundwater available for development depends on location. However, both the Storm Lake and Cherokee areas are producing water at or near the sustainability threshold of the Lower Dakota Aquifer.