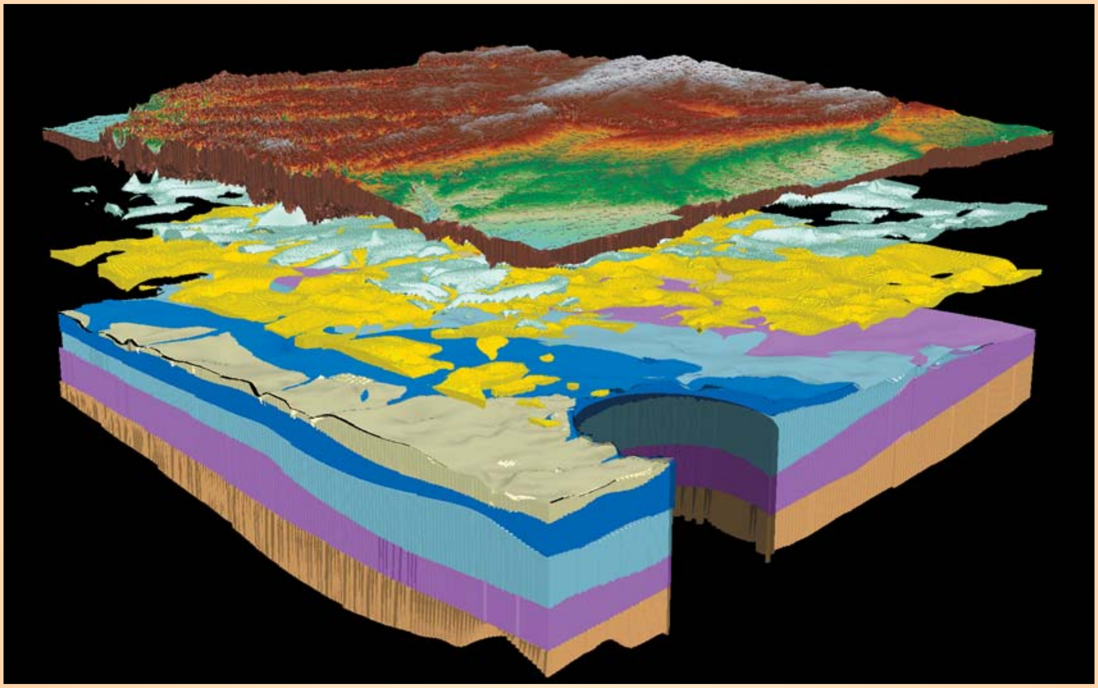
Groundwater Availability Modeling of the Lower Dakota Aquifer in Northwest Iowa

Iowa Geological and Water Survey
Water Resources Investigation Report No. 1A



Iowa Department of Natural Resources
Richard Leopold, Director
October 2008

COVER

Geologic conceptual model of the 16-county
study area in northwest Iowa as viewed
from the southeast.

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Water Resources Investigation Report No. 1A

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EXECUTIVE SUMMARY

The 2007 Iowa General Assembly, recognizing the increased demand for water to support the growth of industries and municipalities, approved funding for the first year of a multi-year evaluation and modeling of Iowa's major aquifers by the Iowa Department of Natural Resources. The task of conducting this evaluation and modeling was assigned to the Iowa Geological and Water Survey (IGWS). The first aquifer to be studied was the Lower Dakota aquifer in a sixteen county area of northwest Iowa.

The geology of the northwest Iowa study area is characterized by a sequence of unconsolidated upper Cenozoic (less than about 5 million years) deposits, overlying Mesozoic Cretaceous (about 100 million years) sandstones, shales, and limestones, Paleozoic (520 million to 280 million years) sandstones, shales, and limestones, and Precambrian (2.8 billion to 1.1 billion years) quartzites, granites, and related rocks. The major sources of groundwater in this area are the sandstones in the Cretaceous Dakota Formation.

Most of the water-producing sandstones in the Dakota Formation are found in the basal Nishnabotna Member, although scattered sandstones in the overlying Woodbury Member also yield significant amounts of groundwater. For this study, IGWS geologists defined the Lower Dakota aquifer as the water-bearing sandstone and conglomerate units of the Nishnabotna Member and the directly adjacent, and hydrologically contiguous sandstone bodies in the overlying Woodbury Member. An intensive one-year study of the geology and hydrogeology was undertaken to provide a more quantitative assessment of the aquifer, and to construct a groundwater flow model that can be used as a planning tool for future water resource development.

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

Recharge to most of the Lower Dakota 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 in the lower Dakota is very small. Calibrated recharge rates varied from 0.15 inches per year to 0.05 inches per year over most of the study area. A calibrated recharge rate of 3 inches per year was used in the Sioux City area due to thin or absent confining units.

A numerical groundwater flow model of the Lower Dakota aquifer was developed using four hydrogeologic layers. The model was created using Visual MODFLOW version 4.2. Hydrologic processes include net recharge, hydraulic conductivity, specific storage, flow through boundaries, no flow boundaries, well discharge, river boundary, and groundwater upwelling.

The calibrated model provides a good correlation for both steady-state and transient conditions. Root mean square errors of 14.8 and 9.4 feet were calculated for the steady-state and transient flow models. Simulated water level changes are most sensitive to recharge in the steady-state model, and pumping rates in the transient model.

The Lower Dakota aquifer has tremendous development capacity. The current summer time usage is approximately 31.6 million gallons per day, and winter usage is approximately 20.2 million gallons per day. This is well below the development potential for the aquifer. The actual volume of groundwater available for development depends on location. Based on water balance and predictive model simulations, both the Storm Lake and Cherokee areas are at or near the sustainability threshold.

INTRODUCTION

Recently, concerns about the availability of groundwater in Iowa have come to light because of increasing demand for large quantities of water from the biofuel industries and suggestions that climate trends indicate that the state might experience drought conditions in the near future. In addition, recent tightening of water quality standards mandated for municipal water supplies combined with the deterioration of surface water quality in Iowa has pushed many cities to look for new sources of water. Although Iowa is not facing an immediate water shortage, Iowa's comprehensive water plan hasn't been updated since 1985. The water plan summarizes what is known about Iowa's water resources and includes suggestions for addressing problems. A revised water plan would update our understanding of Iowa's aquifers, examining trends over time in water levels, current levels of use, and most importantly, projections for future water use in the state. Much has changed in the last 20 years, including the pattern of demand on water supplies. An updated plan is needed to avoid water shortages, crises and conflicts between water users in the future. The key is to update the plan regularly to account for new water uses as they emerge and changes in our knowledge of the resource.

In 2007 state legislators provided appropriations to begin the process of characterizing Iowa's aquifers. The Dakota aquifer (Figure. 1) in western Iowa was chosen to be the first of the bedrock aquifers to be investigated. The Dakota is used by agriculture, industry, and rural and public water supplies in much of western Iowa. Because of the discontinuous nature of the Dakota aquifer in southwest Iowa the first year's study was restricted to northwest Iowa (Figure 1) where the aquifer could be modeled more accurately.

The purpose of this study was to provide a quantitative assessment of groundwater resources in the Dakota aquifer in northwest Iowa, including development of a groundwater flow model to guide future development and utilization of the aquifer. The study included the following tasks:

- Collecting, compiling, and analyzing available geologic and hydrologic data;
- Collecting, compiling, and estimating the location and amounts of groundwater withdrawals within the study area;
- Constructing and calibrating a groundwater flow model for the Lower Dakota aquifer;
- Simulating future water-use scenarios and the overall groundwater availability within the aquifer;
- Documenting the data used and the model simulations.

This report describes the hydrogeology of the Cretaceous aquifer system, specifically the Lower Dakota aquifer in northwest Iowa. It summarizes and documents the geologic framework and layers, as well as the construction and calibration of a groundwater flow model. The model was then used to predict the potential effects of future water-use scenarios for low, moderate, and high water withdrawals. Aquifer test data, water-use data, and water balance results are included in the Appendices.

Study Area

The focus of the study of the Dakota aquifer was the 16 counties in northwest Iowa, shown in Figures 1 and 2. The western boundary of the study area borders the states of South Dakota and Nebraska. The northern boundary borders the state of Minnesota. The eastern and southern boundaries were based on geologic and hydrogeologic constraints, and represent the approximate lateral extent of continuous lower Dakota sandstone.

PHYSIOGRAPHY AND CLIMATE

The 16-county study area encompasses approximately 9,340 square miles, with land surface elevations ranging from 1,047 feet in the

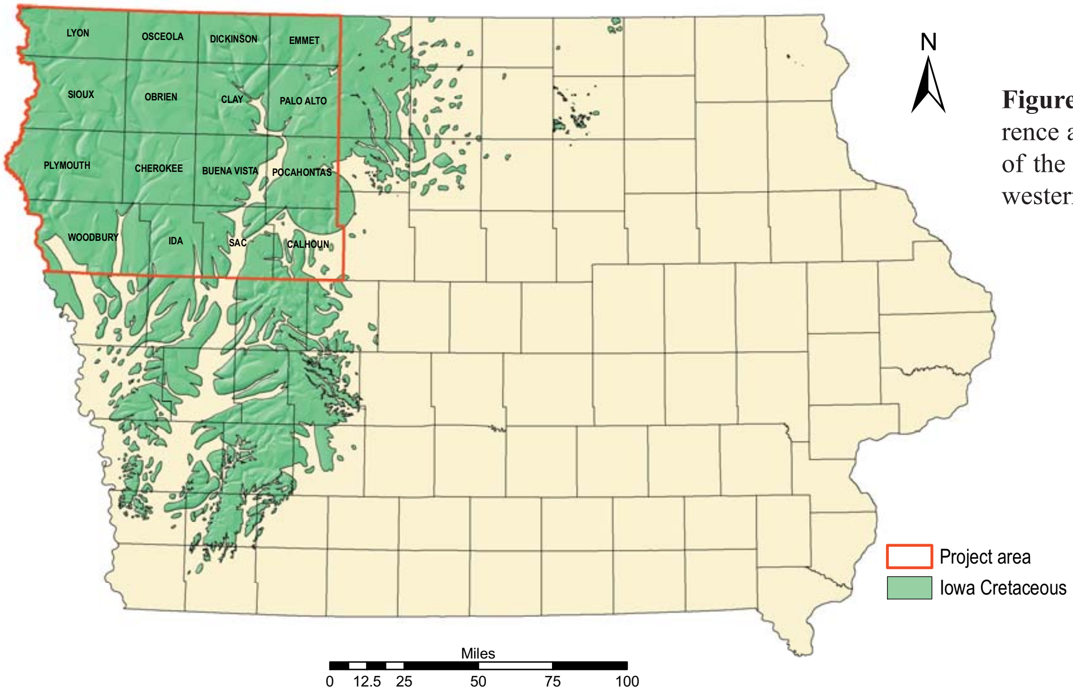


Figure 1. Area of occurrence and significant use of the Dakota aquifer in western Iowa.

southwest to 1,670 feet in the north-central portion of the study area, averaging 1,336 feet above sea level. (Figure 3). The land surface consists primarily of gently rolling to nearly flat plains of the Northwest Iowa Plains and Southern Iowa Drift Plain (Figure 4). The southwest quadrant of the study area includes the northern end of the high relief Loess Hills region and the moderately high relief Southern Iowa Drift Plains. The eastern portion of the study area includes the moderately low relief Des Moines Lobe region and the southwest-most area includes the extremely flat Missouri River Alluvial Plain (Figure 4).

The climate of northwest Iowa is classified as sub-humid. Average monthly temperatures at Spencer in Clay County range from 14.6° F in January to 72.8° F in July, although temperature extremes range from a record low of -38° F in January 1912 to a record high of 113° F in July 1936 (Midwest Regional Climate Center, 2008).

Based on data compiled by the Spatial Climate Analysis Service at Oregon State University (2000), the average annual precipitation in the study area ranges from less than 28 inches per year in Lyon and Sioux Counties (Figure 5) to 32 to 34 inches per year in Calhoun County.

Northwest Iowa has historically experienced moderate to severe droughts. Table 1 shows the annual precipitation amounts for a select number of cities in Northwest Iowa (Midwestern Regional Climate Center, 2008). The record minimum precipitation amounts range from 11.90 inches at Cherokee to 15.41 inches at Sheldon (see Figure 2 for location of cities). The year 1958 was one of the driest years on record, with 5 of the 11 record minimum annual precipitation records occurring in that year. The historical maximum precipitation amounts range from 39.74 inches at Sioux Center to 51.34 inches at Ida Grove.

GEOLOGY OF THE 16-COUNTY STUDY AREA

For the purpose of this investigation, the rocks in the region have been grouped into four major geologic assemblages (from the top down): Quaternary materials, upper Cretaceous, Lower Dakota aquifer, and sub-Cretaceous rocks (Figure

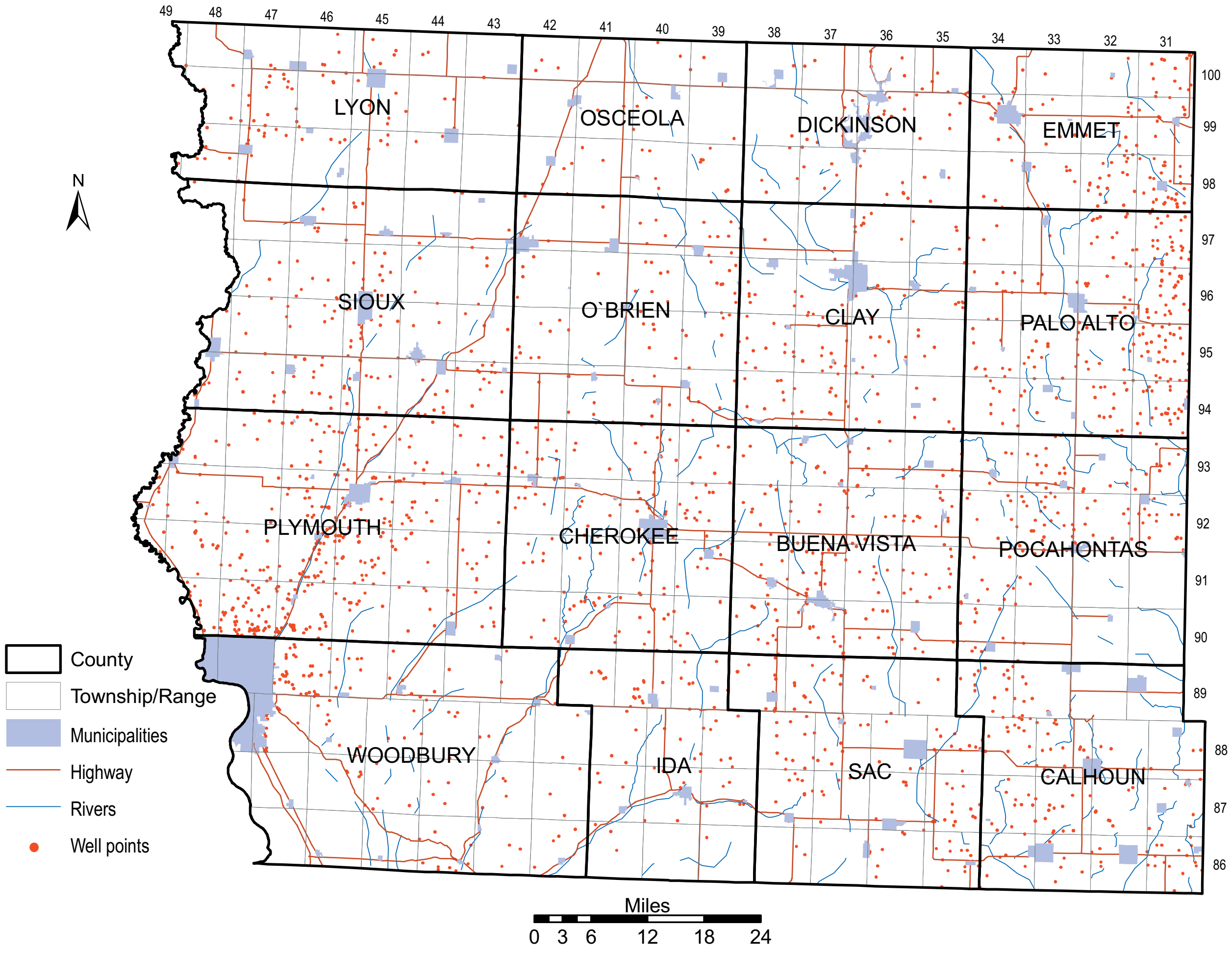


Figure 2. Location map of the northwest Iowa study area showing major towns, highway, rivers, and location of wells that provided geologic information for this study.

6). These mapping packages and their hydrostratigraphic components will be discussed in greater detail in the following sections;

- **QUATERNARY GEOLOGY**

- **GENERAL CRETACEOUS STRATIGRAPHY**
  INCLUDING UPPER CRETACEOUS AND LOWER DAKOTA AQUIFER

- **SUB-CRETACEOUS GEOLOGY OF NORTHWEST IOWA**
  INCLUDING PENNSYLVANIAN, MISSISSIPPIAN, DEVONIAN - UPPER ORDOVICIAN, ST. PETER - CAMBRIAN AND PRECAMBRIAN

Geologic Maps in this Report

The geologic maps used in this report were produced using well and exposure data from the Iowa Geological and Water Survey's on-line Geosam database application. This database includes almost 65,000 records, predominantly information derived from water wells drilled throughout Iowa. Geosam contains a wide variety of information in each record, including depth to the various geologic units in the state. Geospatial analyses of this data utilizing software such as ESRI's ArcGIS, Iowa Geological and Water Survey geologists were able to produce a variety of useful and informative map products.

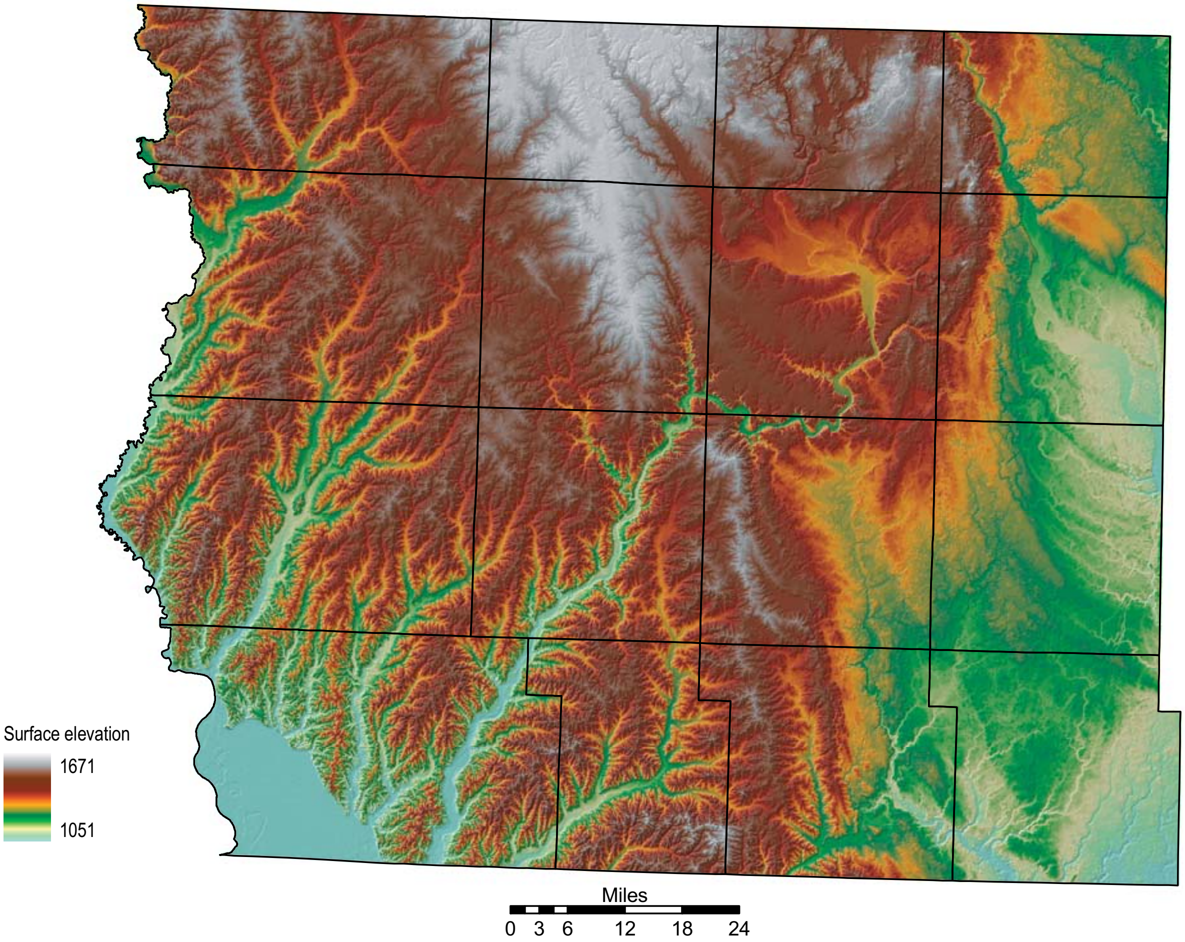


Figure 3. Map showing surficial relief in the 16-county study area.

Trend surface analysis is a process of generating a rectangular collection of grid cells of x and y coordinates defined as a raster, and for three-dimensional images z coordinates may be included. Each cell contains a single value, so the amount of detail that can be represented for the surface is limited to the size of the raster cells. This is one of the oldest mathematical techniques used by geologists and hydrologists to assess resources and reserves of defined geologic units of economic value. Generalized maps are produced by utilizing observed distributions of standardized data, represented at a number of sample points, and then drawing contour lines (i.e. lines of equal value across a surface) to show different levels of representation (e.g. elevation and thickness in this study). Such maps will show the broad regional trends and local variations in the distribution, in part at least overcoming irregularities in the distribution of sample points.

The stratigraphic synthesis of the Dakota aquifer consisted of generating a series of raster elevation surfaces and the resultant differences to create the thicknesses of the stratigraphic units that are of hydrologic significance for regional modeling. A total of 7,453 well points with associated x, y, and z values are irregularly distributed across the study area. Of these, 2,383 well points are partial to complete penetration of the Cretaceous, and 330 of these wells penetrate into the underlying sub-Cretaceous units. In combination with the Digital Elevation Model of the Iowa

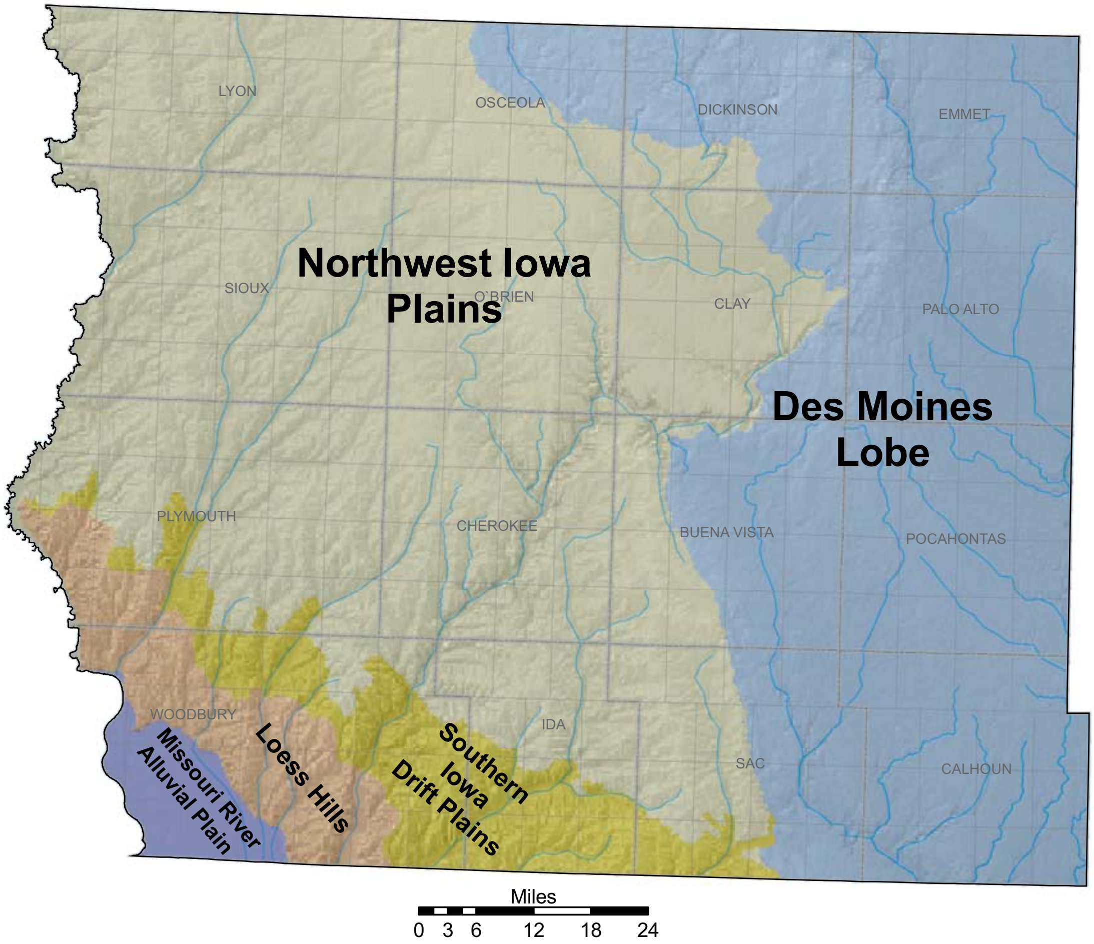


Figure 4. Landform regions in northwest Iowa (Prior, 1976) combined with topographic relief.

land surface, contour maps digitized from previous studies (Burkart, 1982 and 1984, Anderson and others, 1992, and Munter et al., 1983), and elevations of various horizons identified within the wells utilized for this study, rasters of various surfaces were generated using ArcGIS 9.2 software. These surfaces include 1) elevation of the bedrock surface (Figure 9), 2) elevation of the top of the Lower Dakota aquifer (Figure 17) elevation of the sub-Cretaceous surface (Figure 12). Combinations of these rasters were then used to create maps displaying the thickness of various units, including Quaternary thickness (Figure 8), the Lower Dakota aquifer thickness (Figure 18), and the thickness of Cretaceous strata above the Lower Dakota aquifer (Figure 19). Characterizations of the hydrogeologic properties that define the mapped units were utilized in the construction of these maps (e.g. sandstone/siltstone vs. shale; carbonates vs. sandstone/shale). The Quaternary was not evaluated at this time.

QUATERNARY GEOLOGY

The unconsolidated materials that overlie Cretaceous rocks in the northwest Iowa study area are grouped together as Quaternary materials for the northwest Iowa Lower Dakota aquifer study project. This grouping includes youngest to oldest: Holocene (modern) river deposits, Pleistocene loess (wind-blown silt), Pleistocene glacial materials (including glacial till and related deposits),

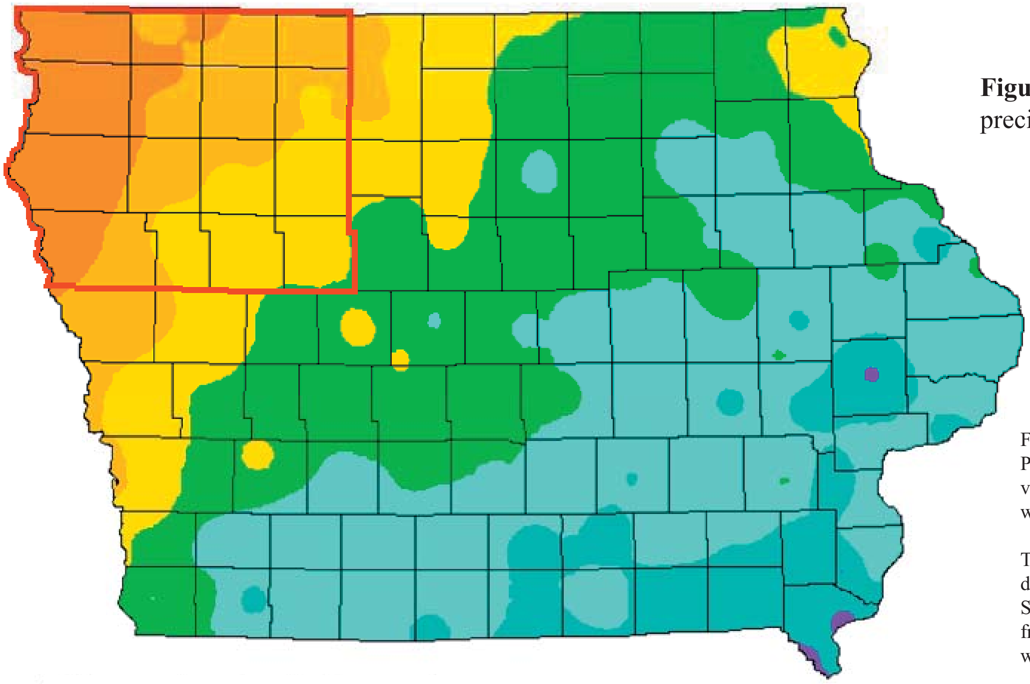


Figure 5. Average annual precipitation in Iowa.

For information on the PRISM modeling system, visit the SCAS web site at www.ocs.orst.edu/prism

The latest PRISM digital data sets created by the SCAS can be obtained from the Climate Source at www.climatesource.com

This is a map of annual precipitation averaged over the period 1961-1990. Station observations were collected from the NOAA Cooperative and USDA-NRCS Sno-Tel networks, plus other state and local networks. The PRISM modeling system was used to create the gridded estimates from which this map was made. The size of each grid pixel is approximately 4x4 km. Support was provided by the NRCS Water and Climate Center.

Legend (in inches)

🟧 Under 28
🟧 28 – 30
🟨 30 – 32
🟩 32 – 34
🟦 34 – 36
🟦 36 – 38
🟪 Above 38

16-county study area

buried bedrock valley fill materials, and Tertiary "Salt and Pepper" sands (Figure 7). Although the hydrologic characteristics of these units vary greatly, their distributions and thicknesses are difficult to map with the limited available well data. Most of these unconsolidated materials are treated as a single unit for the groundwater modeling (Figure 8), with porosity, permeability, and other characteristics estimated for the entire package. Only the alluvial deposits of the Missouri River are considered as a unique package in the model.

Holocene (Modern) Alluvium

Numerous modern rivers and streams cross the northwest Iowa study area. These include the Big Sioux, Rock, Floyd, Little Sioux, Raccoon, and Des Moines rivers and many smaller streams. The Missouri River, which bounds the southwest edge of the study area, has a major effect on the Lower Dakota aquifer and will be considered separately. Alluvial materials deposited in the beds and floodplains of these modern rivers, known as the DeForest Formation, include gravel, sand, silt, and clay, but are dominated by the finer-grained materials (silt and clay) derived by the erosion of soils developed in loess and till parent materials.

Missouri River Alluvium

The most significant alluvial unit affecting the hydrology of the Lower Dakota aquifer is found in the Missouri River Valley in the southwest

Table 1. Annual precipitation at major cities in the study area.

Location	Minimum inches (Year)	Maximum inches (Year)
Spencer	14.41 (1958)	42.51 (1951)
Sioux Center	14.17 (1958)	39.74 (1983)
Le Mars	13.02 (1956)	42.35 (1951)
Sioux City Airport	14.33 (1976)	41.10 (1903)
Cherokee	11.90 (1958)	42.86 (1938)
Storm Lake	13.90 (1976)	45.94 (1951)
Emmetsburg	15.20 (1958)	45.15 (1993)
Sheldon	15.41 (1958)	46.02 (1951)
Ida Grove	14.21 (1976)	51.34 (1951)
Estherville	15.10 (1897)	45.04 (1993)

corner of the study area. The current channel of the Missouri River was probably established at some time during the Pleistocene Pre-Illinoian Episode (500,000 – 2.2 million years ago), at some time after the glacial filling of the Fremont Channel (Figure 9), but demonstrably by the Illinoian Episode (130,000 – 300,000 years ago). The river carried large quantities of glacial melt water and sediment during the Illinoian and Wisconsin Episodes, and it has drained large areas of North and South Dakota, Montana, and Colorado east of the Rocky Mountains since the end of continental glaciation. In the study area the Missouri River is incised over 200 feet into the bedrock, completely cutting out portions of the Lower Dakota aquifer (see Figure 18). The alluvium fills the Missouri River valley to depths of over 200 feet, is completely water saturated, and serves as a major recharge source for the Lower Dakota aquifer in the southwest corner of the study area

Loess

Loess is wind-blown silt and fine sand, originally derived from rock materials by the abrasive actions of continental glacial ice, transported south by the glacier, freed from the ice as it melted. This material was initially deposited on the floodplains of rivers that carried the glacial melt water, then blown out of the river valleys and onto the landscape by prevailing winds. Loess in the study area was deposited during the Pleistocene Epoch, most during the final three episodes of glacial activity. These loess sequences are known as (oldest to youngest) the Loveland, Pisgah, and Peoria formations. Loess is generally very porous and permeable, allowing water to move through it fairly quickly.

The Peoria Formation is the youngest, thickest, and most widespread of the loess units in the study area. The Peoria Formation, composed of both a silt and fine sand facies, was deposited between about 25,000 and 12,000 years ago, during the advance and retreat of the most recent Wisconsin glacier, the ice advance that created the Des Moines Lobe. The Peoria Formation constitutes the majority of the loess in the study area and is the surficial geologic unit in most of the counties in the western 2/3 of the study area.

The two older loess units, the Pisgah and Loveland formations, are much thinner than the Peoria. The Loveland Formation, the basal loess unit in the study area, includes silt and fine sand deposited between about 165,000-125,000 years ago during the advance and retreat of the Illinoian glaciers. The Pisgah Formation (known as the Roxana Formation in eastern Iowa) was de-

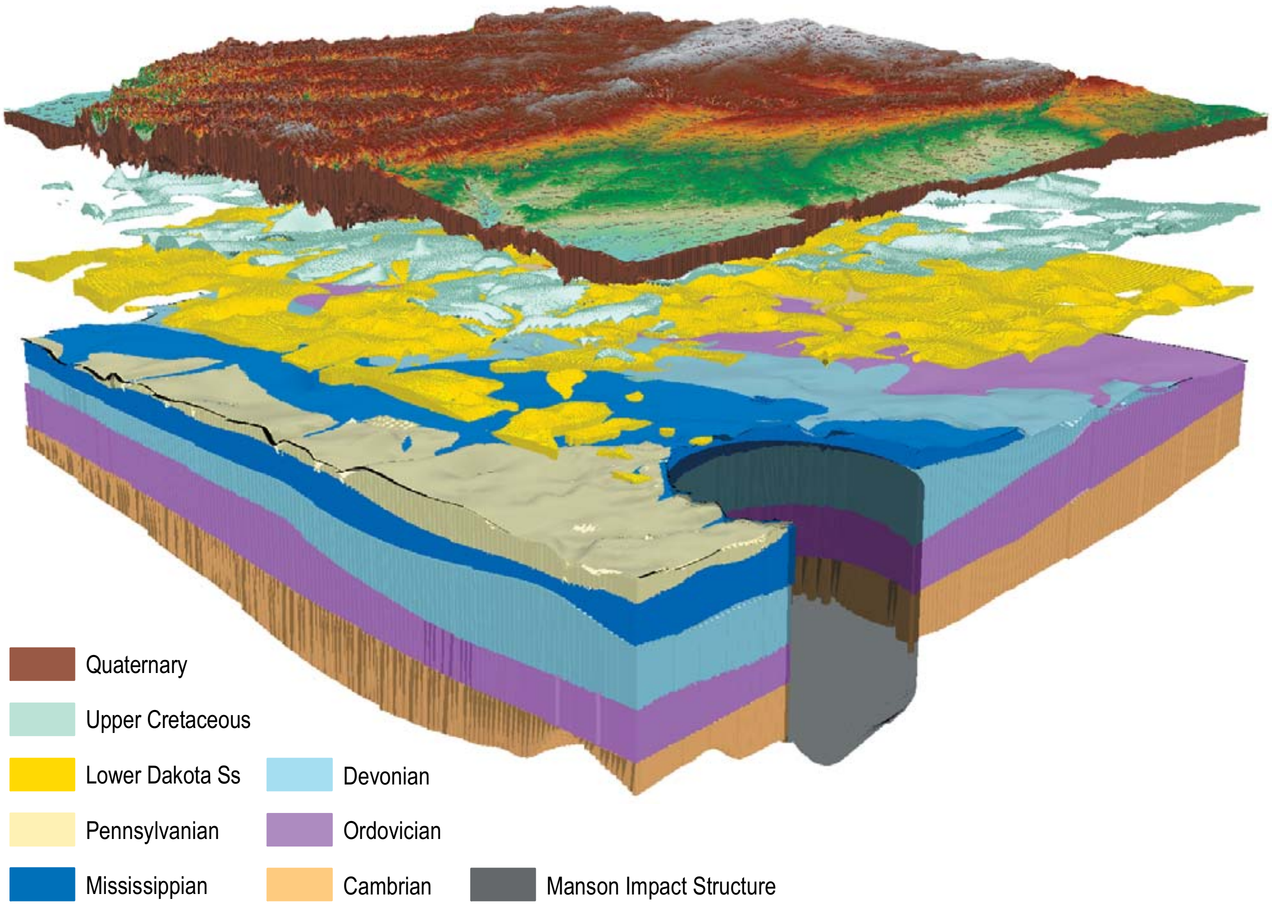


Figure 6. Geologic unit groupings for Lower Dakota aquifer study. Geologic conceptual model of the 16-county study area as viewed from the southeast.

posited between about 53,000 and 25,000 years ago during the advance and retreat of the first two continental glaciers during the Wisconsin Episode. The Pisgah Formation was formerly known as the basal Wisconsin loess or basal Wisconsin sediment. It contains primary eolian silt and sand as well as reworked eolian materials and associated colluvial and slope materials. The Pisgah loess is the thinnest of the three major loess packages.

Glacial Materials

Glacial deposits in the study area include glacial till, moraine materials, glacial lake deposits, and outwash materials deposited by advancing and retreating continental ice. Glacial till in Iowa is composed of nearly equal amounts of sand, silt, and clay with a lesser volume of pebbles, cobbles, and boulders. Till can be deposited beneath the glacial ice (subglacial) or left behind by melting out of the retreating glacial ice (supraglacial). Till is generally very impervious to the movement of water, however it may contain very permeable water-bearing pockets or channels of sand and gravel deposited by streams flowing within the ice or other glacial phenomenon. Weathering can increase the porosity and permeability of till, and fractures or joints that form in the material provide passageways for the movement of water.

Glacial moraines are piles of glacial materials that build up along the edges of the ice sheet during times when the glacier is neither advancing nor

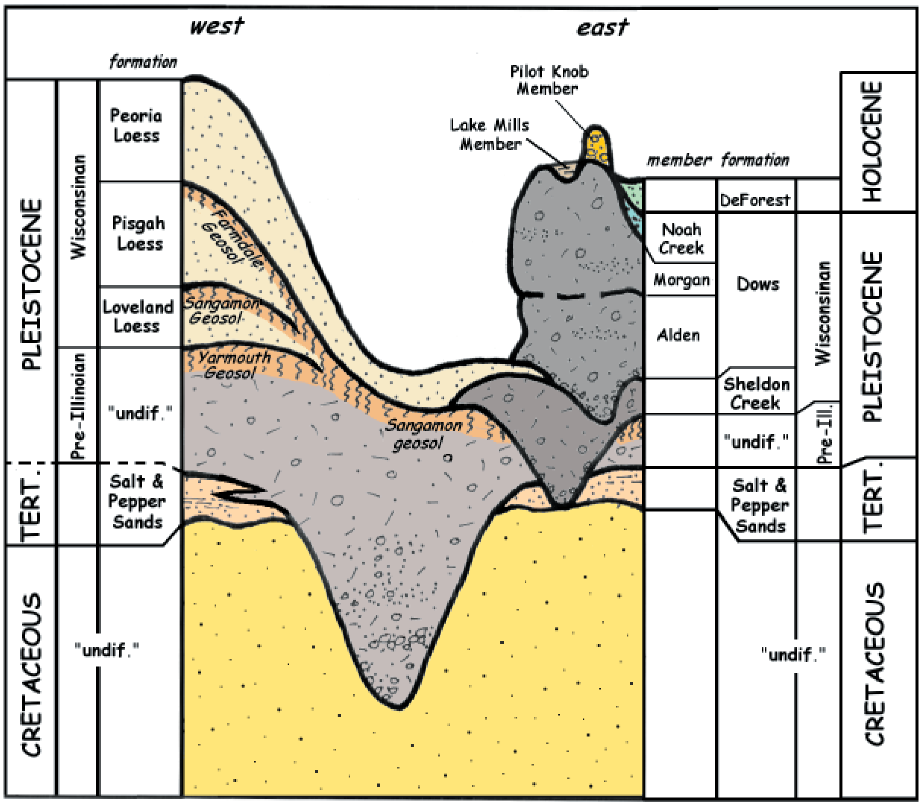


Figure 7. Generalized post-Cretaceous stratigraphy across study area from west to east.

retreating across the landscape. Moraines contain a variety of glacial materials, but frequently include abundant sand and gravel resources. These materials make moraines good media for the storage and movement of water.

Glacial lakes form when ice or moraine deposits constrict glacial streams or when large blocks of ice melt leaving depressions on the landscape. The sediment that accumulates in these lakes is usually fine-grained (clays and silts) but thin, discontinuous sand lenses may also be deposited. These materials have low porosity and permeability and usually retard the movement of water.

Glacial outwash is generally coarse sand and gravel that was transported on or along a glacier by streams and is typically deposited beyond the glacial margin, often far down valley. These materials were frequently deposited by flash floods when glacial lakes emptied catastrophically. These materials are usually fairly well sorted and can store or transmit water readily under certain conditions.

Glacial materials were deposited by at least ten (and probably more) ice advances through the northwest Iowa study area. At least seven Pre-Illinoian glacial tills (deposited between about 2.2 million and 500,000 years ago) have been identified in southwest Iowa and adjacent areas of Nebraska (Boellstorff, 1978). These glaciers, and possibly others that have not yet been identified, almost surely passed through the study area. Additionally, three glacial ice sheets are known to have moved through the eastern portions of the study area during the Wisconsin Epoch. These include two glacial advances that created the Tazewell Lobe between about 20,000 and 30,000 years ago and one additional glacial advance that formed the Des Moines Lobe between about 15,000 and 12,000 years ago.

The glacial materials in the study area are best

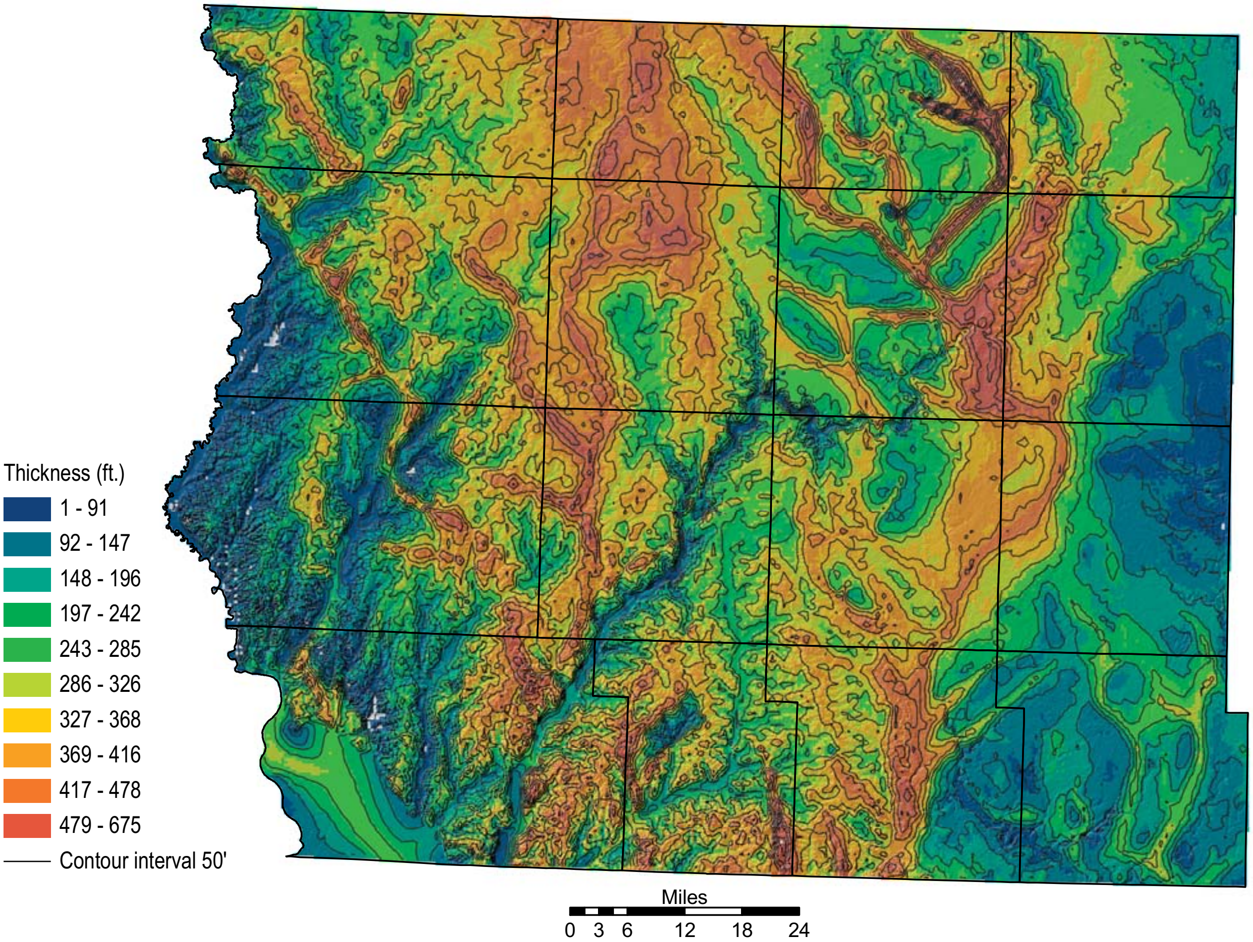


Figure 8. Isopach (thickness) map of unconsolidated Quaternary materials in northwest Iowa. These materials include glacial till, alluvium, loess, and various inter-till and sub-till sediments. Although most of these materials are of Quaternary age, it is likely that some sediments may be of Pliocene (or possibly Miocene) age.

known in eastern Iowa where they are not buried beneath loess. The oldest (Pre-Illinoian) glacial deposits have not yet been differentiated in the region, but may include several of the till advances informally named by Boellstorff (1978) and generally correlated with the Wolf Creek and Alburnett formations defined by Hallberg (1980) in east-central Iowa. Additional till units may also be present. Deposits from the earliest two Wisconsinan glacial advances are currently not differentiated and are combined under the name Sheldon Creek Formation. The most recent Wisconsin glacial deposits are included in the Dows Formation (Figure 7), composed of members including the Alden (basal till), Morgan (superglacial till), Lake Mills (lake deposits) and Pilot Knob (moraine, esker, and kame deposits), with associated alluvial and outwash deposits known as the Noah Creek Formation (Bettis et al., 1996).

Buried Bedrock Valleys

Rivers carrying water from melting glaciers flowed throughout the region on numerous occasions in the geologic past. The largest of these rivers were able to cut channels deep into the underlying bedrock (Figure 9). One of the largest known bedrock valleys in Iowa, the Fremont Channel, crosses the northwest Iowa study area. This channel formed during one of the earliest

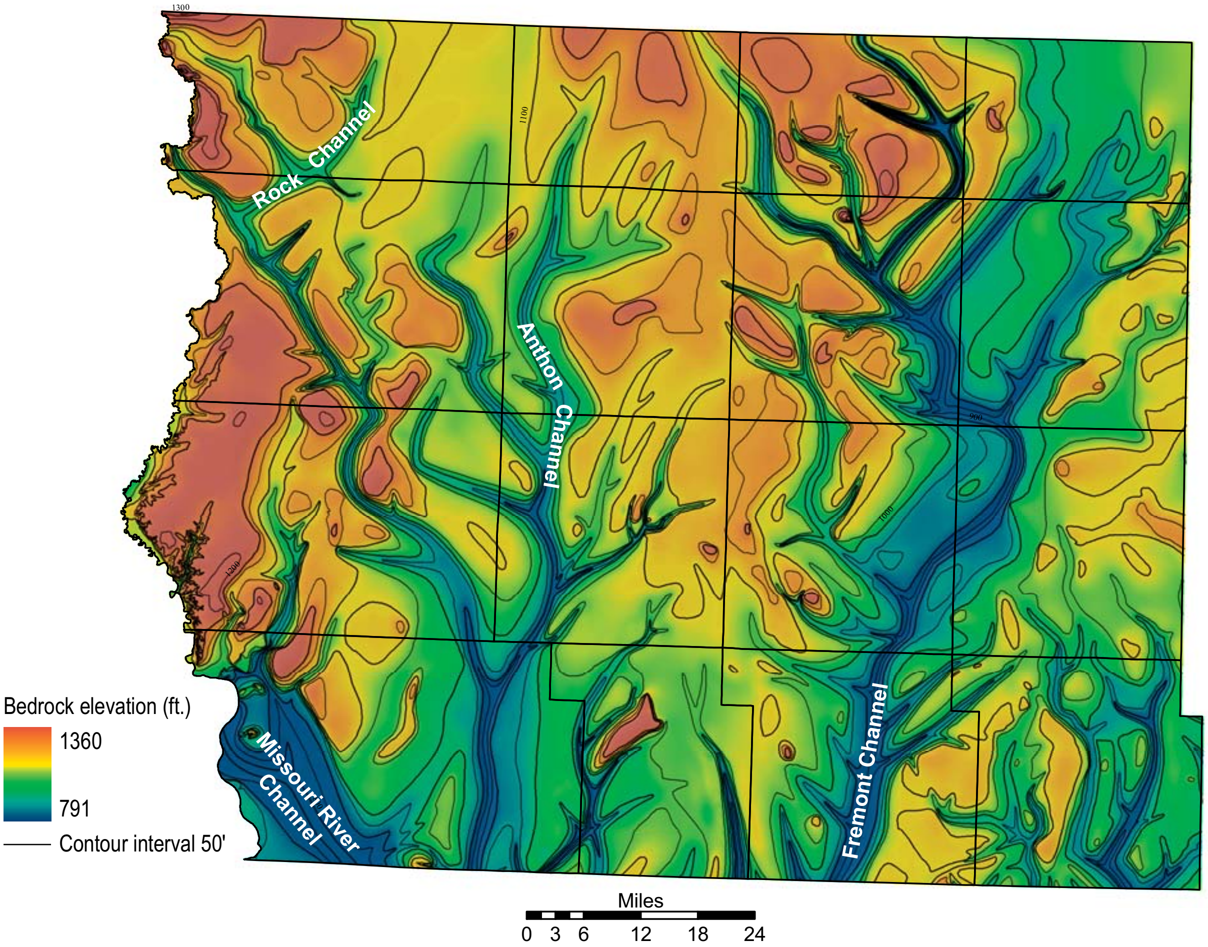


Figure 9. Elevation of the bedrock surface in the northwest Iowa study area. Bedrock channels appear as dark green and blue linear features.

of the Pre-Illinoian glacial ice advances, about 2 million years ago. The Fremont Channel, sometimes referred to as the ancestral Missouri River, is incised more deeply into the bedrock surface than the current Missouri River. These bedrock valleys may be filled with their original alluvial sand, gravel, and related materials or these materials may have been scooped out of their valleys by subsequent glacial ice advances and the valley filled with glacial drift deposits. The thickest known sequence of Quaternary materials in Iowa, in excess of 650 feet, is found in and above the Fremont Channel. In areas where these channels contain sand and gravel they may be used as aquifers.

Salt and Pepper Sands

A sequence of unconsolidated sands and associated silts are found below the Pleistocene glacial sediments in many localities within the northwest Iowa study area. These sands are informally called the "Salt and Pepper" sands (a name first applied by Iowa well drillers) because the constituent quartz and volcanic glass grains give the unit a distinctive white and black appearance. These sands are very similar to the Tertiary Ogallala Formation of Nebraska, and they are currently interpreted as an eastern extension of this unit. The Salt and Pepper sands have been observed in some drill holes to lie above the oldest (latest Ter-

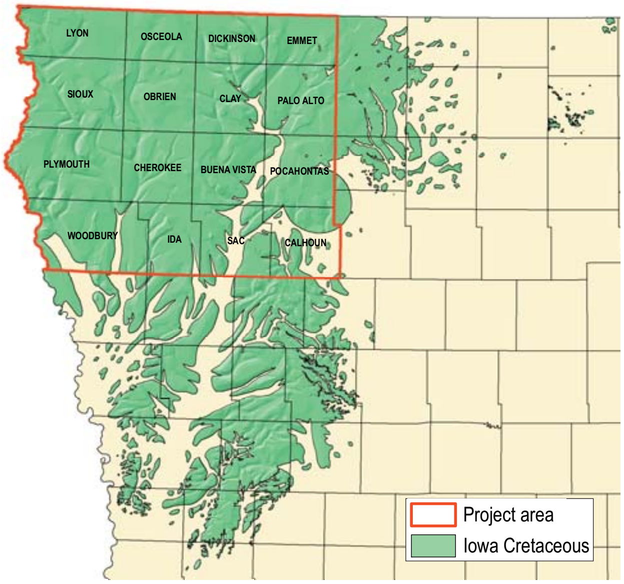


Figure 10. Distribution of Cretaceous strata in Iowa. Sixteen-county study area is outlined in red.

tiary) glacial tills. The "Salt and Pepper" sands and silts in the northwest Iowa study area reach a maximum thickness of about 30 feet and serve as water supplies to a limited number of individual households.

GENERAL CRETACEOUS STRATIGRAPHY

Cretaceous rocks are recognized across much of western Iowa, with scattered outliers identified eastward in northern Iowa (Figure 10). These strata encompass water-bearing sandstones that have been previously termed the Dakota aquifer. Numerous water wells have been developed within these sandstones, primarily in the sixteen county study area of northwestern Iowa (outlined in Figure 10). Generally, only minor production has been developed in these sandstones in areas elsewhere in the state where Cretaceous strata are markedly thinner. Much of the study area in northwestern Iowa is underlain by Cretaceous bedrock (Figure 11), although it is buried beneath a relatively thick cover of Quaternary sediments over most of the region (see Quaternary isopach map, Figure 8). As such, much of what is currently known of the Cretaceous strata in the area was derived from subsurface well and core samples (see well locations, Figure 2). Supplementing this information, a number of surface exposures of Cretaceous rocks are known in northwest Iowa, primarily in the Sioux City area and in the drainage of the Big Sioux River, with additional exposures noted in adjoining areas of northeast Nebraska and southeast South Dakota. Cretaceous strata are primarily represented by the Dakota Formation across most of the area, but younger Cretaceous strata are identified in some areas (see Figure 11; Ft. Benton Group, Niobrara Fm., and the Manson Impact Structure). Earlier studies of Cretaceous stratigraphy in Iowa provide additional information (Tester, 1931; Brenner et al., 1981, 2000; Munter et al., 1983; Witzke et al., 1983; Witzke and Ludvigson, 1994, 1996; Koeberl and Anderson, 1996). Correlation and age of the various Cretaceous strata have been facilitated by study of nonmarine palynomorphs (Ravn and Witzke, 1994, 1995; Witzke and Ludvigson, 1996) in the Dakota Formation, and foraminifera, ammonites, bivalves, and coccoliths in the marine succession.

Dakota Formation

The Dakota Formation is the most widespread Cretaceous stratigraphic unit in northwest Iowa. The name derives from exposures in the Missouri River Valley in Dakota County, Nebraska, across the river from Sioux City, Iowa. The Sioux City area (Figure 14) comprises the classic type area of the formation (Witzke and Ludvigson, 1994). The Dakota Formation is characterized by a succession of poorly consolidated sandstone (generally best developed in the lower part of the formation) and mudstone (shaly strata), which typically dominates the upper portion. Where covered by younger Cretaceous strata, the Dakota Formation reaches maximum thicknesses to about 500 feet in northwestern Iowa. However, its thickness is highly variable due to relief on the underlying sub-Cretaceous surface (Figure 12) and significant sub-Quaternary erosional truncation of Da-

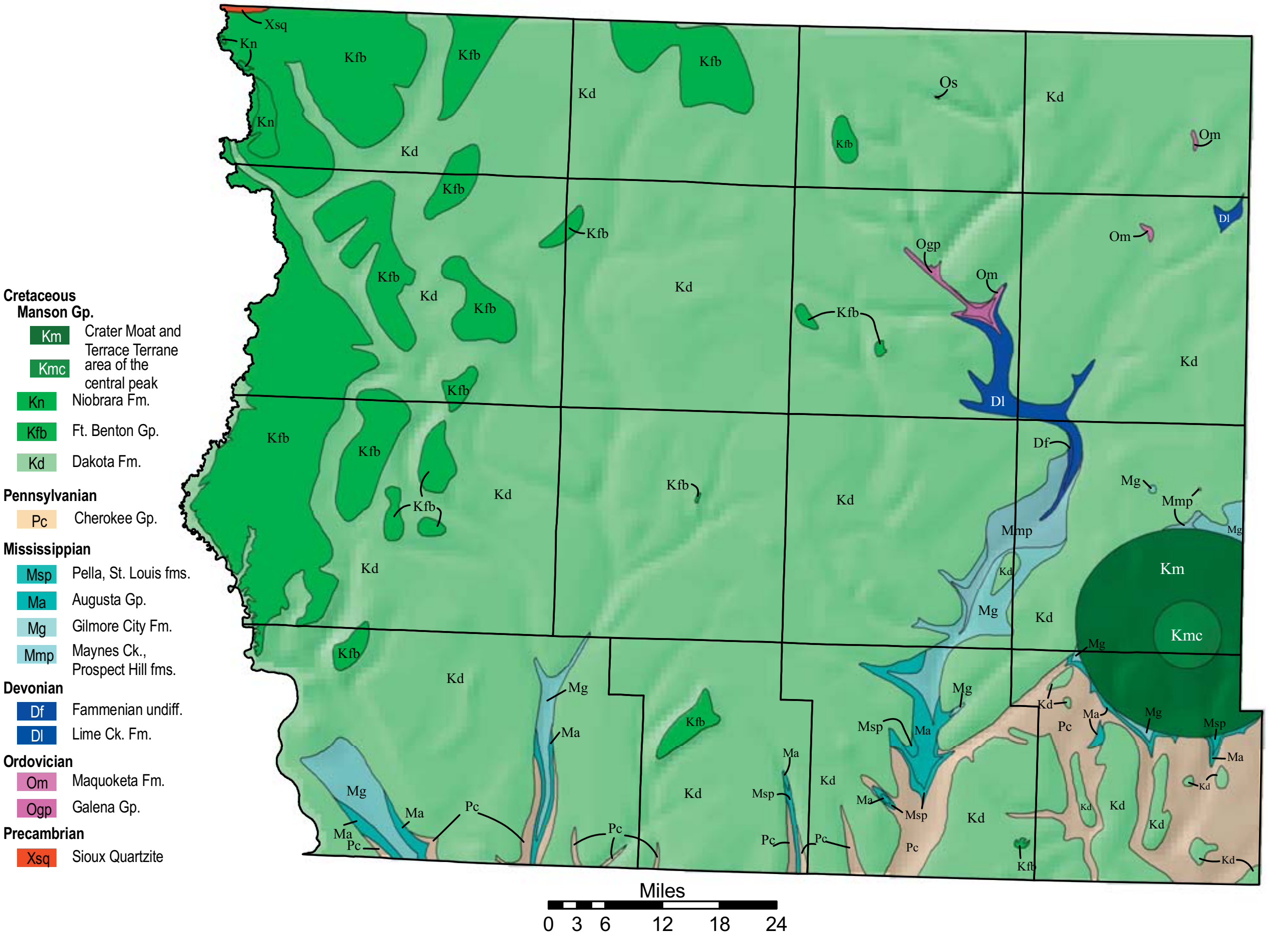


Figure 11. Bedrock geology of the northwest Iowa study area. Bedrock topography shown as shaded background.

kota strata across much of the area (see Figure 9). Where the Dakota Formation forms the bedrock surface in northwest Iowa, it ranges from less than 50 feet to about 450 feet in thickness.

The Dakota Formation is stratigraphically subdivided into two lithologically distinct members across most of its extent in Iowa, a lower Nishnabotna Member and an upper Woodbury Member (see Munter et al., 1983; Witzke and Ludvigson, 1994; see Figures 13, 14, 15, and 16). These member names derive from lower Dakota exposures along the Nishnabotna River Valley in southwest Iowa and from upper Dakota exposures in Woodbury County, northwest Iowa, respectively. The Nishnabotna Member is dominated by poorly consolidated sandstone strata across most of its extent, but discontinuous mudstone units locally occur and comprise about 15% of the member regionally. As discussed later, in a few small areas the Nishnabotna Member appears to be dominated locally by mudstone. However, over most of the study area quartz sandstones overwhelmingly dominate the member. The sandstones vary between very fine- and very coarse-grained lithologies, and some of the sandstone beds contain quartz granules and pebbles (primarily in the lower part of the member). Quartz and chert gravels locally occur within the lower Nishnabotna Member in the region (Figures 13A). The Nishnabotna Member forms a body of continuous sandstone across much of northwest Iowa (Figure 16), and its sheet-like geometry of porous

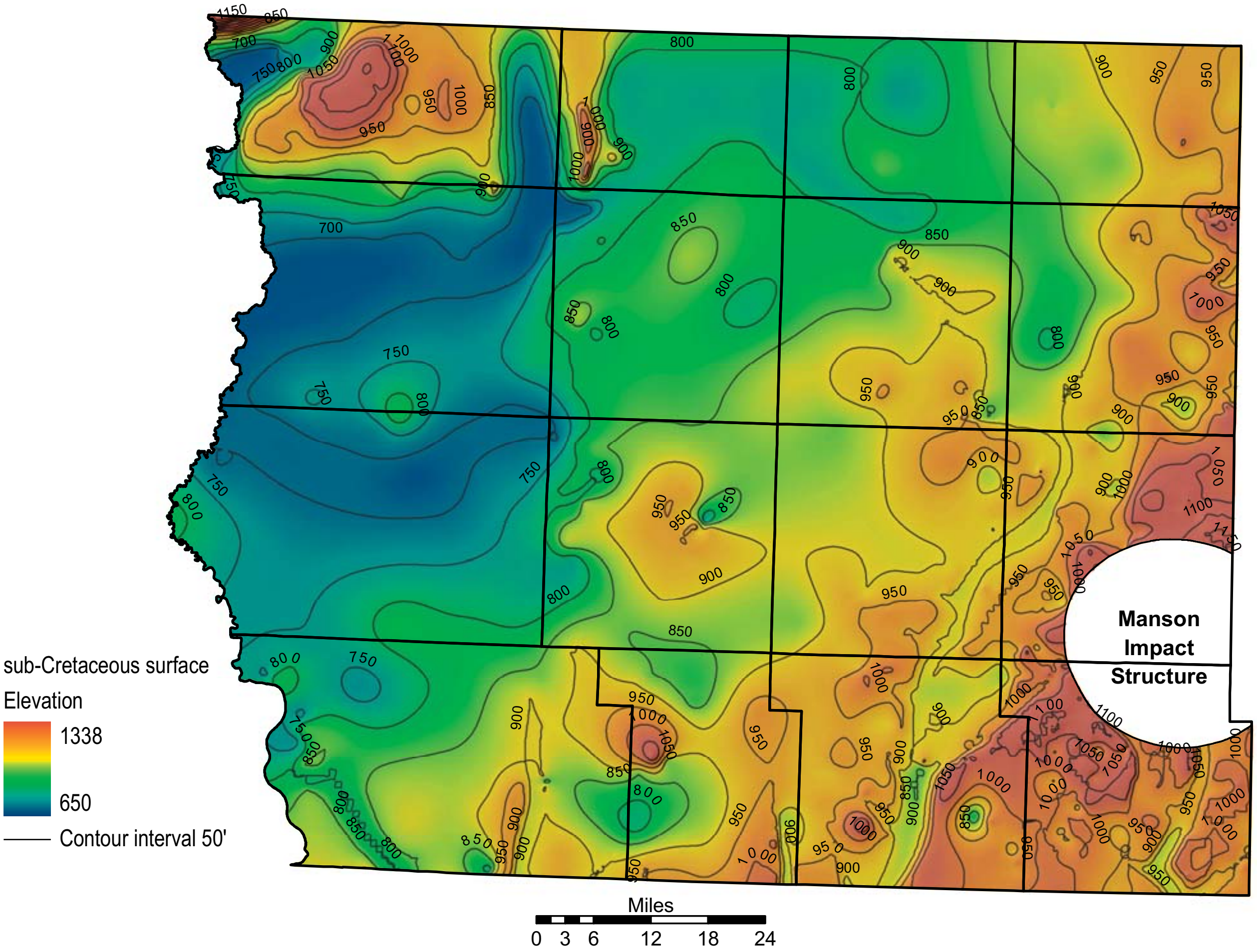
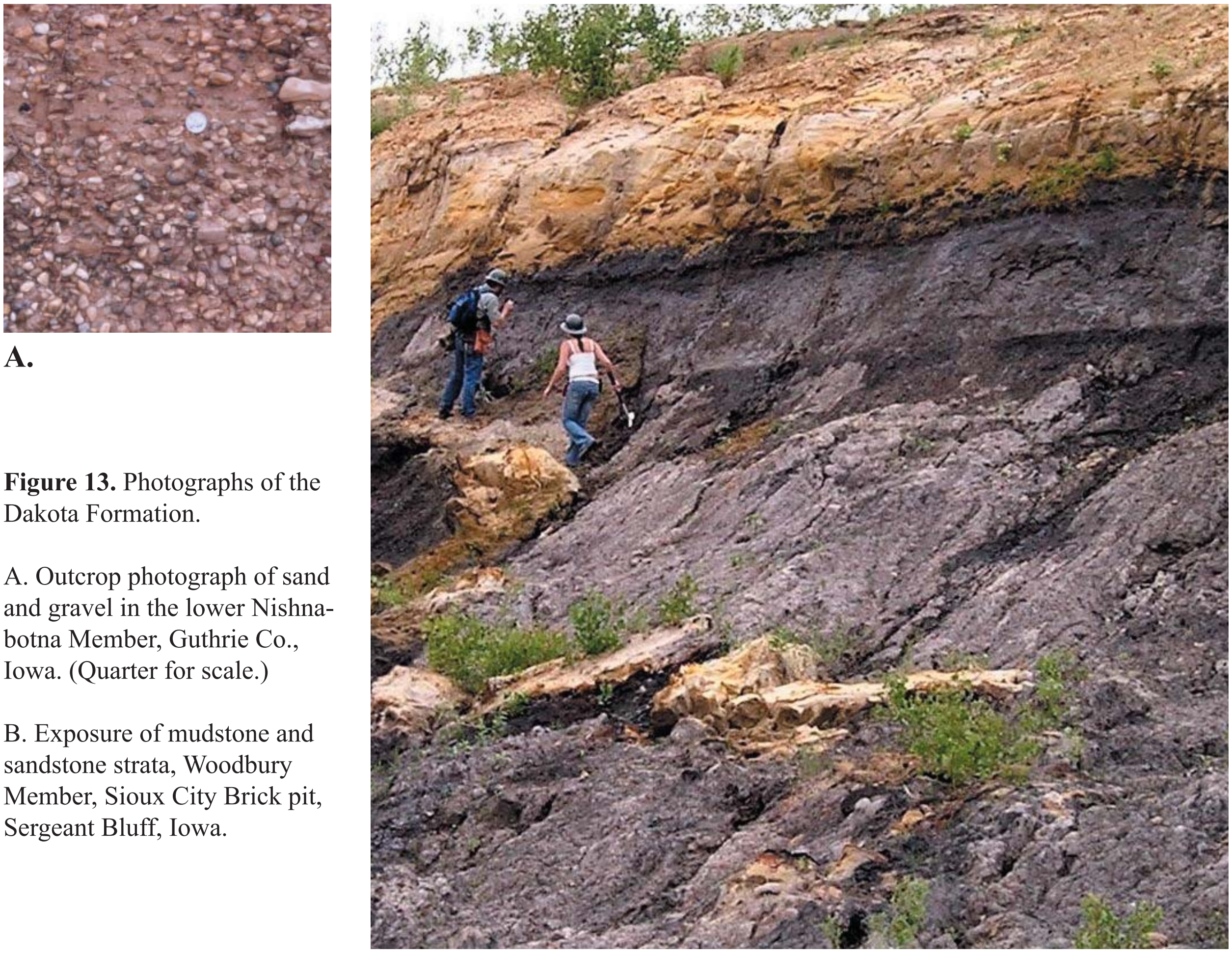


Figure 12. Elevation of the sub-Cretaceous surface in northwest Iowa. Where Cretaceous strata are erosionally removed (see geologic map, Fig. 11), the contours are drawn at the bedrock surface (Paleozoic or Precambrian).

and permeable sandstone defines this interval as the primary and most productive portion of the Dakota aquifer in Iowa. The member ranges from 0 to over 300 feet in thickness in northwest Iowa, reaching its maximum thicknesses in parts of Woodbury and Plymouth counties. In general, the Nishnabotna Member is thickest within a broad southwestward-trending topographic low developed across the eroded sub-Cretaceous surface (Figure 12), and it is overstepped by upper Dakota strata eastward onto the elevated Paleozoic bedrock surface and northwestward onto elevated areas of Precambrian bedrock (Figure 16).

The Woodbury Member spans the upper portion of the Dakota Formation above the Nishnabotna sandstones (Figures 13B). This upper interval is highly variable lithologically, but it is generally dominated by gray- and red-mottled mudstones at most localities, commonly with some subsidiary sandstone or siltstone beds. However, the Woodbury Member locally contains thick but discontinuous sandstone channel bodies. The Woodbury sandstones are generally very fine- to fine-grained, and regionally they comprise less than 20 to 30% of the Woodbury interval. Because of the local prominence of sandstone bodies within the member, especially in the lower part of the member, it is locally difficult to separate these sandstones from those of the Nishnabotna Member. The local continuity of Woodbury and



A.

B.

Figure 13. Photographs of the Dakota Formation.

A. Outcrop photograph of sand and gravel in the lower Nishnabotna Member, Guthrie Co., Iowa. (Quarter for scale.)

B. Exposure of mudstone and sandstone strata, Woodbury Member, Sioux City Brick pit, Sergeant Bluff, Iowa.

Nishnabotna sandstones poses special problems for defining the geometry of the Lower Dakota aquifer in the region, as discussed later in this report. The mudstones of the Woodbury Member are silty to varying degrees, and silt laminae and siltstone interbeds are locally significant. Many of the mudstones, especially in the lower half of the member, display pedogenic fabrics (soil structures) developed in subtropical environments (especially wetland settings). These pedogenically-modified mudstones typically show red-mottled or vertical plinthic structures commonly bearing abundant small sphaerosiderite pellets (small spherical siderite concretions < 1 to 2 mm in diameter). Black to dark gray lignites and carbonaceous shales locally occur at a number of stratigraphic positions within the Woodbury succession (Figure 14), but lignites are very rare to absent in the Nishnabotna Member. The Woodbury Member locally contains iron oxide, siderite, pyrite, and limestone concretions. The Woodbury Member is erosionally truncated across much of northwest Iowa, where it forms the Cretaceous bedrock surface. It reaches maximum thickness of 150 to 230 feet in the area, where covered by younger Cretaceous strata. Woodbury strata overstep the Nishnabotna edge to directly overlie Precambrian and Paleozoic rocks in portions of the study area, including parts of Lyon, Osceola, Emmet, Palo Alto, Pocahontas, and Calhoun counties.

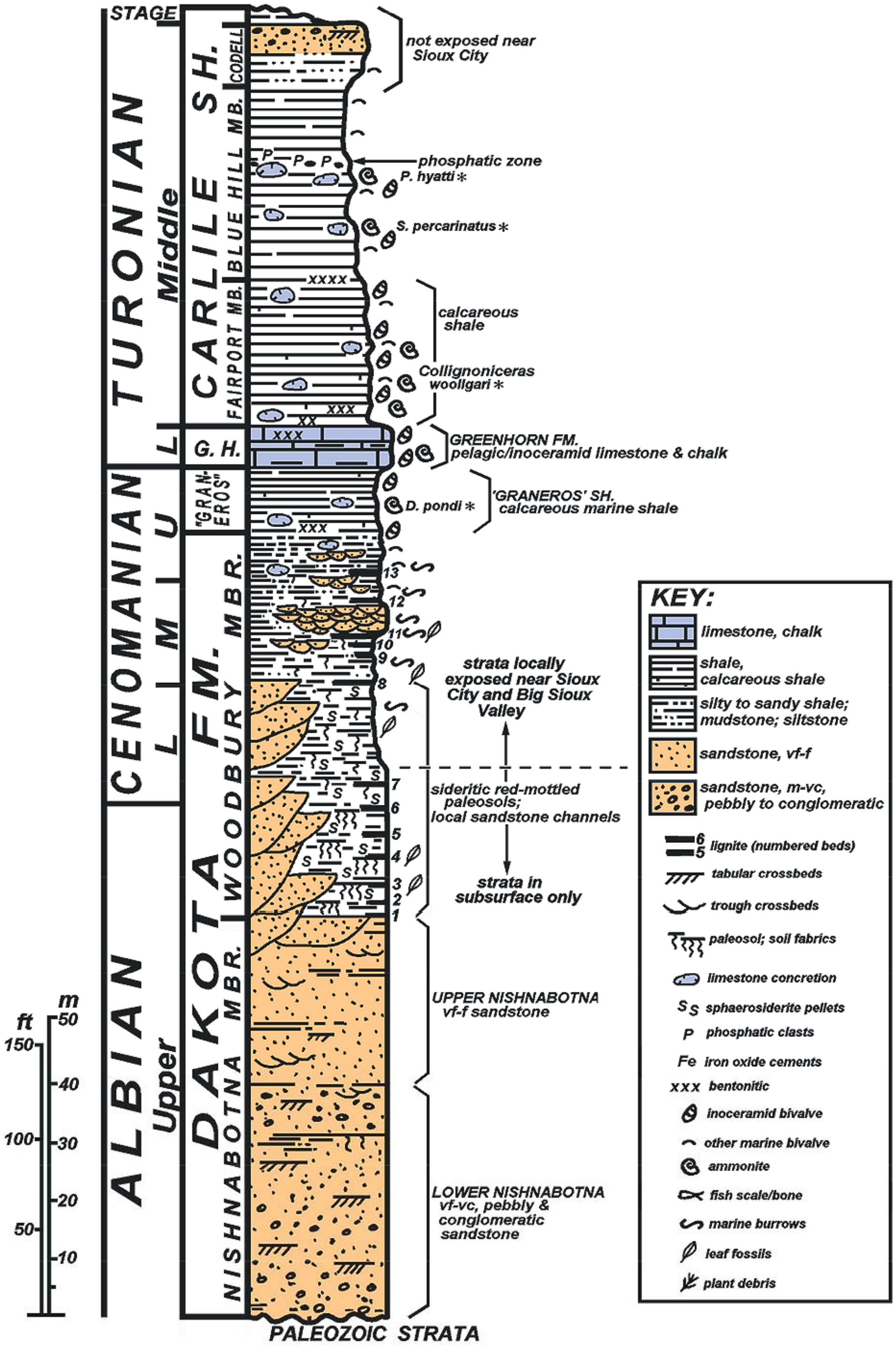


Figure 14. General Cretaceous stratigraphy in the area of Sioux City and the Big Sioux River Valley, northwest Iowa. Niobrara strata are not shown. Strata identified in outcrop (surface exposure) in the area are marked above the dashed line. The highest parts of the Carlile succession (Codell Member) are not identified in the study area (but are recognized westward in South Dakota). General positions of key ammonite fossils in the marine succession are marked by asterisks (*).

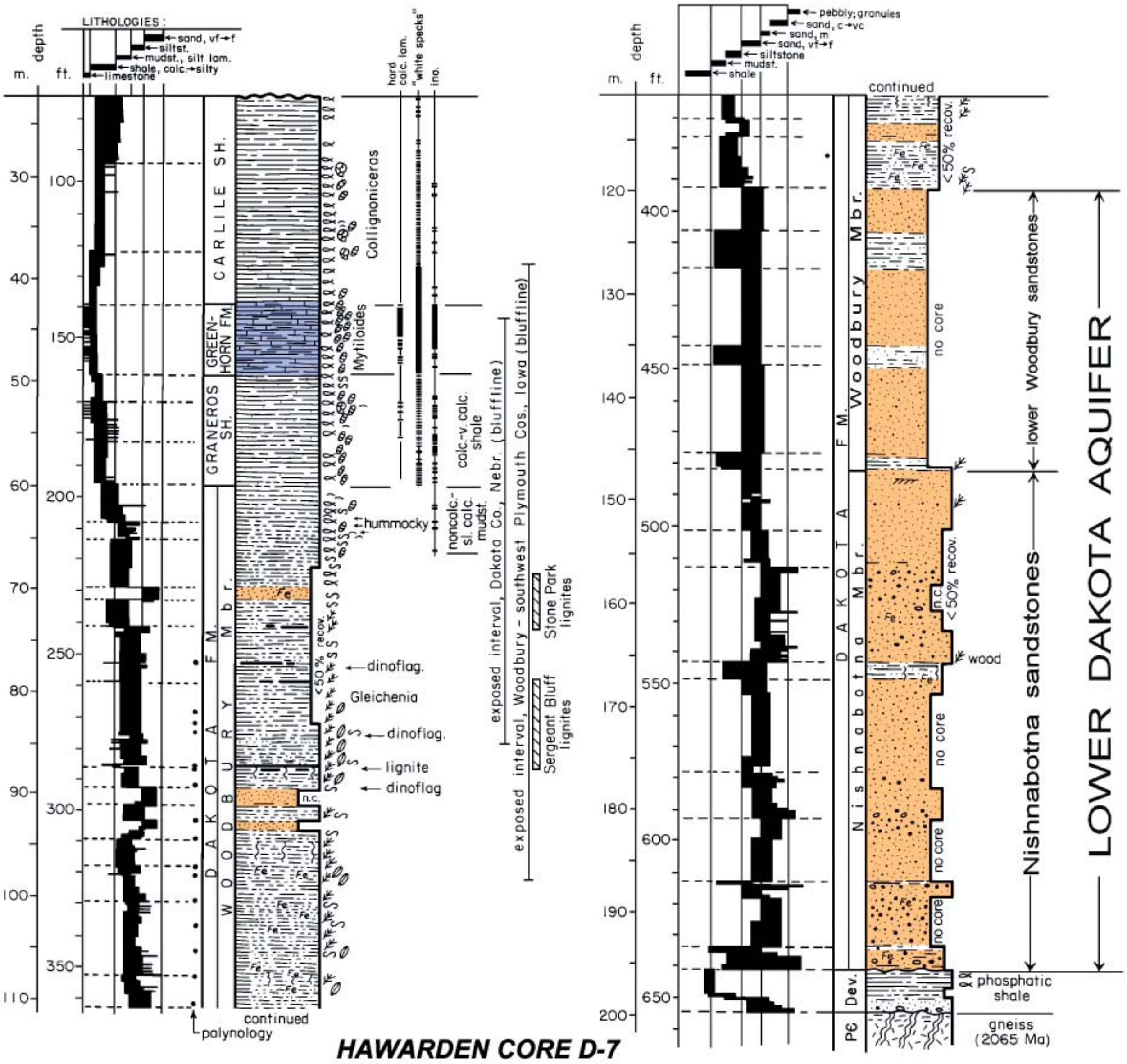


Figure 15. Graphic lithologic log and stratigraphy of the Hawarden Core (D-7), Sioux Co., Iowa (NE NE NE sec. 5, T95N, R47W); Adapted from Witzke and Ludvigson (1994). See Figure 14 for key to lithologic and fossil symbols. abbreviations: sh. – shale; mudst. – mudstone; fm. – formation; mbr. – member; n.c. – no core; recov. – core recovery; v. – very; sl. – slightly; calc. – calcareous; f – fine; m – medium; c – coarse; lam. – laminae; dinoflag. – dinoflagellates; Ino. – inoceramid bivalves; Dev. – Devonian; P€ - Precambrian; Ma – mega annum (millions of years ago).

Based on the palynology (the study of fossil spores and pollen) of Dakota strata in western Iowa and eastern Nebraska (Ravn and Witzke, 1994, 1995; Witzke and Ludvigson, 1996; and unpublished studies of Ravn and Witzke), the Dakota Formation can be correlated with mid Cretaceous strata of the Western Interior region (Great Plains and Rocky Mountain areas). The Nishnabotna Member is an upper Albian unit, and the Woodbury Member ranges from upper

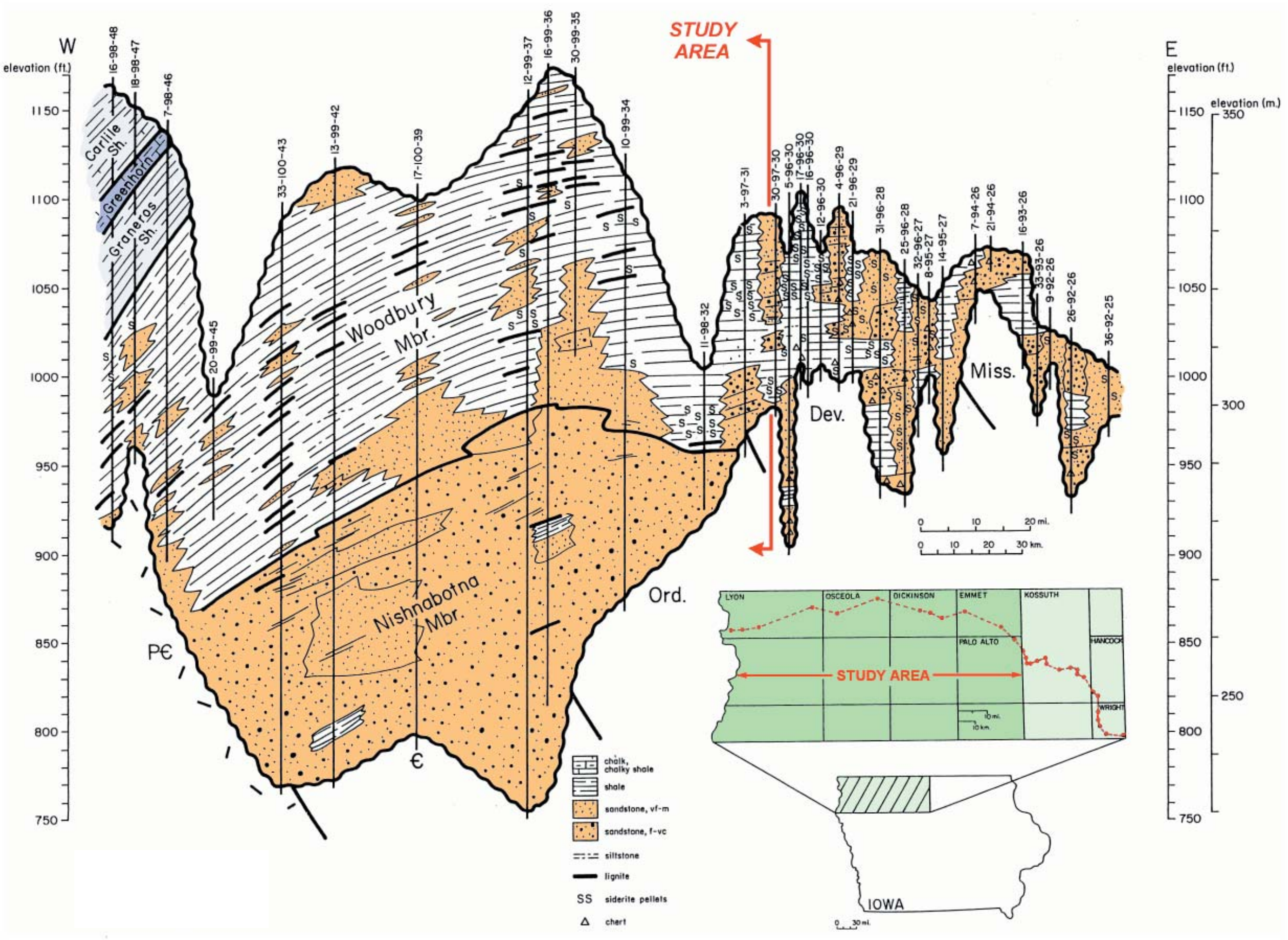


Figure 16. Stratigraphic cross section of Cretaceous strata across the northern part of the study area showing the Dakota Formation Nishnabotna and Woodbury members, adapted from Witzke and Ludvigson (1994). Well locations noted by section – Township – Range. sub-Cretaceous units abbreviated as Follows: P€ - Precambrian; € - Cambrian; Ord. – Ordovician; Dev. – Devonian; Miss. – Mississippian.

Albian to upper Cenomanian in age (Figure 14). Sediments of the Nishnabotna Member were aggraded in large rivers (mostly braided river systems) that drained westward across Iowa into the nearby Western Interior Seaway. Most sandstone and mudstone strata of the Nishnabotna Member represent fluvial and floodbasin deposits, but estuarine sediments are locally recognized in the lower part of the member (Witzke and Ludvigson, 1996, 1998). The Woodbury Member was also deposited primarily in aggrading large rivers (mostly meanderbelt systems) with extensive floodbasins and overbank deposits. Numerous fluctuations in base levels within these systems are recorded by alternating episodes of channel aggradation and incision, accompanied by periods of extensive soil development across the floodbasins. Such fluctuations are also recorded by the development of estuarine facies (tidally-influenced salt-water embayments) at multiple stratigraphic positions within the Woodbury succession. Woodbury deposition shows a general upward increase in marine influence (estuaries), culminating in deposition of nearshore marine shales in the uppermost Dakota and overlying "Graneros" Shale as the Western Interior Seaway deepened and encroached eastward across the region.

Upper Cretaceous Marine Strata

Cretaceous marine strata, primarily shale, conformably overlie the Dakota Formation in areas of northwest Iowa, especially in the western part. Most of these strata are included within the Fort Benton Group, an interval comprising, in ascending order, the "Graneros" Shale, Greenhorn Formation, and Carlile Shale (Figure 14). This interval reaches maximum thicknesses of about 200 feet in the study area. Outliers of the Niobrara Formation have recently been recognized in western Lyon County, and Cretaceous-aged rocks of the Manson Impact Structure are found in the southeastern part of the study area (Figure 11). Biostratigraphic correlation of these Upper Cretaceous units indicates the following ages: "Graneros" (upper Cenomanian), Greenhorn (lower Turonian), Carlile (middle Turonian), Niobrara (lower Campanian), and Manson Structure (upper Campanian).

The so-called "Graneros" Shale comprises an interval of gray calcareous shale (variably silty) that lies conformably on the Woodbury Member. Although the term "Graneros" has been applied to these strata for many decades, the term actually has been used inappropriately in western Iowa as this interval is lithologically dissimilar and does not correlate with the type Graneros Shale of Colorado. Pending further stratigraphic study this interval will be informally labeled the "Graneros" Shale (in quotes), although it seems desirable to give this interval a new stratigraphic name to avoid confusion with the actual Graneros Shale of the Western Interior. This interval in Iowa ranges between about 30 and 50 feet in thickness. It can be distinguished from underlying shaley strata of the Woodbury Member by its calcareous character (including calcareous mm-scale "white specks") and by the absence of sandstone interbeds (Figure 15). It locally contains limestone concretions and silty skeletal limestone lenses, and it has yielded marine fossils of foraminifera, bivalves (especially inoceramids), ammonites, fish, and marine reptile bones.

The Greenhorn Formation of northwest Iowa is a relatively thin (20-25 feet thick) interval of marly to argillaceous limestone and chalk (pelagic limestone). These strata are primarily composed of microscopic coccoliths (calcareous nannofossils) and foraminifera, and some limestone beds contain abundant shells of inoceramid bivalves. The Greenhorn is less argillaceous than the bounding shale units above and below, and the microporous and fractured character of some of the Greenhorn limestone beds enables it to be locally used as a low-yield aquifer in areas of western Plymouth and Sioux counties. The Greenhorn Formation has yielded marine fossils of coccoliths, foraminifera, inoceramid bivalves, ammonites, fish, and marine reptile bones.

The Carlile Shale is a gray shale interval, variably silty, reaching maximum thicknesses to about 150 feet in the area. The lower part of the Carlile includes a mixture of gray calcareous and noncalcareous shale; this calcareous interval (which includes "white specks") is sometimes referred to the Fairport Member (Figure 14). The upper strata of the Carlile in Iowa are generally noncalcareous gray shales sometimes referred to the Blue Hill Member. Limestone concretions are present at a number of stratigraphic positions within the Carlile Shale interval, and a zone of phosphatic concretions is locally noted in the upper part (Figure 14). The Carlile has yielded marine fossils including foraminifera, inoceramid and other bivalves, ammonites, and fish bone/scale.

The Niobrara Formation is now recognized in the subsurface of a small area of western Lyon County (Figure 11). The Niobrara is a well known and widespread chalk-dominated formation in parts of Nebraska, South Dakota, and Kansas, but its eastward occurrence in Iowa does not include the characteristic chalks and marls seen further to the west. The Niobrara in Iowa is dominated by gray silty calcareous shale, which resembles lithologies seen in the "Graneros" and lower Carlile of the area. The high stratigraphic position of these shales within the Cretaceous marine succession suggested possible correlation with the Niobrara Formation (and not the Carlile as previously thought). These suspicions were confirmed when diagnostic Niobrara microfossils (coccoliths) were recovered from well cuttings in Lyon County as part of a bedrock mapping program in that area (Ludvigson et al., 1997). Based on the biostratigraphy, a notable unconformity separates the Niobrara strata from the underlying Carlile Shale.

A large asteroid struck the area now located near the Pocahontas-Calhoun county line (see Figure 11) during the Late Cretaceous about 74 million years ago, forming the Manson Impact Structure. Explosive processes created a large impact crater that was quickly and catastrophically filled with a complex variety of materials (the Manson Group) derived from the area, including broken and brecciated Cretaceous, Paleozoic, and Precambrian rocks, significantly altered to melted in some crater-filling units (Koeberl and Anderson, 1996). The uppermost fill material across most of the crater is characterized by a shaley diamicton or breccia dominated by Cretaceous shale lithologies (and secondary Paleozoic rocks). The Manson Group crater-filling materials are not in direct hydrologic continuity with the Dakota aquifer and are excluded from further consideration in this report. Nevertheless, it should be noted that our understanding of groundwater resources in the area of the Manson Impact Structure is poorly known, and this general lack of knowledge of groundwater systems within the structure is of growing concern to the residents and businesses of that area.

Compilation and Synthesis of Cretaceous Units

The new compilation and synthesis of all available bedrock stratigraphic information in northwest Iowa was necessary to define the physical container for the Dakota aquifer. Accurately located well penetrations and surface exposures of bedrock strata in the area provided the primary basis to geographically and topographically constrain the bedrock surface and stratigraphy. An earlier compilation of bedrock and groundwater information provided the first major synthesis of the stratigraphy and Dakota aquifer in northwest Iowa (Munter et al., 1983). Additional data was compiled during 1996-1997 to create a new bedrock geologic map for northwest Iowa (Witzke et al., 1997). However, the previous bedrock compilations did not adequately define the Dakota aquifer (and which was not a mapping unit for the 1997 map), nor did they include additional information for hundreds of newly available and unstudied well penetrations in the area which became available since 1982 and 1997. These additional wells were incorporated into the new synthesis presented in this report.

All available well records for northwest Iowa (which can be accessed at the Iowa Geological Survey's GEOSAM website) were reexamined or newly studied for this project. This process included: 1) reevaluation of all existing strip logs (which includes lithologic descriptions of well cuttings with stratigraphic interpretations), 2) creation of new strip logs by Survey geologists for many previously unstudied well samples (locations were prioritized to maximize new information, especially deep well penetrations); and 3) examination of all available drillers' logs, many of which lacked well samples. Drillers' logs proved to be of highly variable quality, and an estimate of the reliability of each record was individually evaluated. Available lithologic and stratigraphic information for each well was recorded including: 1) depth intervals of Dakota sandstone units, subdivided according to grain size (very fine- to medium grained and coarse-grained), 2) depths intervals of Cretaceous shale units, 3) depth intervals of Cretaceous limestone, 4) depth intervals of Cretaceous siltstone, 5) depth of formational and member contacts, 6) depth of sub-Cretaceous units, 7) miscellaneous comments. Because of varying uncertainty associated with many drillers' logs, separate categories were used to denote information of a less reliable nature (but which proved to have utility for the regional synthesis in delimiting lithologic and geographic patterns when used in conjunction with more reliable data sources). These various data and information were compiled in an Excel spreadsheet [available on the IGWS web site] which when coupled with geographic location and surface elevation, could be imported for use in various GIS software applications. In particular, 3-D graphic portrayals of this data using ESRI ArcGIS 9.2 software were produced so that the array of well information could be manipulated to help the authors visualize, interpret, and delimit important lithologic and stratigraphic intervals and surfaces through numerous iterations and trials.

The chief goal of this subsurface data compilation was to delimit for each well site, where possible, the upper and lower surfaces of the relatively thick interval of continuous sandstone in the lower to middle Dakota Formation which forms the primary and most productive portion of the Dakota aquifer (hereafter referred to as the Lower Dakota aquifer). This approach attempts to honor all available well and outcrop data for the study area. Those well sites that penetrated the entire Dakota Formation into underlying Paleozoic or Precambrian rocks served as the principal data points used to create the first-order estimate of the top and bottom of the Lower Dakota aquifer. All wells that penetrated the sub-Cretaceous surface, including those that occur within bedrock channels from which Cretaceous rocks have been eroded, were included in this data set. Because the Nishnabotna Member, which forms the container for the bulk of the Lower Dakota aquifer, is known to contain thin and discontinuous mudstone units, thin mudstone units less than 5 feet thick which occur within an otherwise sandstone-dominated succession were also included within the Lower Dakota aquifer. However, mudstone units greater than 10 feet thick which occur above the lower Dakota sandstone succession were used to delimit the upper boundary of Lower Dakota aquifer. The stratigraphic placement of the Nishnabotna-Woodbury Member contact was not used to define the aquifer boundaries in this synthesis of the stratigraphic package that includes the Lower Dakota aquifer. This was done in order to include sandstone units of the lower Woodbury interval that appear to be in direct hydrologic connection with the main sandstone aquifer body contained within the Nishnabotna Member (e.g., see distribution of lower Woodbury sandstones portrayed in Figure 16).

As described above, these principal data points (which penetrated the sub-Dakota surface) were used to construct preliminary estimates of the surfaces that would be used to define the top and bottom of the Lower Dakota aquifer. This first-order surface provided a basis for comparing other less complete (shallower) well penetrations. Additional well data from well borings that reached into sandstone units of the Dakota Formation but did penetrate through the formation to the sub-Cretaceous surface were used next to further refine the upper boundary of the Lower Dakota aquifer. Because it was not known immediately whether the sandstones contained within this set of well data were actually part of the Lower Dakota aquifer or merely isolated sandstone bodies within the Woodbury Member, several different conditions were considered in order to use this supplementary data. 1) If a very fine- to medium-grained sandstone unit was underlain by a mudstone unit greater than 10 feet thick, it was excluded from the Lower Dakota aquifer (such sandstones likely would be isolated bodies within the Woodbury Member). 2) If the top of the lowest sandstone unit within an individual well log lay below or within ± 50 feet of the previously-generated first-order surface, the top of the Lower Dakota aquifer was modified to include this new well point. 3) All coarse-grained sandstone intervals were automatically included within the Lower Dakota aquifer (except where underlain by mudstone units greater than 20 feet thick), as all known coarse sandstones are restricted to the Nishnabotna Member in the study area (the member that provides the bulk of the container for the Lower Dakota aquifer). Using these criteria, a second-order iteration of the upper Dakota surface was generated.

Well sites where the lowest interval penetrated was dominated by mudstone or shale greater than 10 feet thick, with or without minor sandstone interbeds, needed to be excluded from the Lower

Dakota aquifer. In these cases, the top of Lower Dakota aquifer could be no higher than the base of the well penetration at each site. Using this criterion, shale-dominated basal well sections occurred below the previously generated second-order iteration of the top of the Lower Dakota aquifer were identified. In those cases where such basal mudstone/shale intervals occurred below this surface, the elevation of the top of the aquifer needed to be modified to be no higher than the base of that particular well. This modification produced the third iteration of the top of the Lower Dakota aquifer. In some areas where much of the Dakota Formation is dominated by mudstones, particularly parts of Sioux, northwest Plymouth, Lyon, and Osceola counties, this procedure significantly lowered the top of the aquifer. This modification further indicated that the Nishnabotna Member, which was previously assumed to be dominated by sandstone throughout its extent, can be replaced laterally by mudstone-dominated intervals in some areas. This discovery was vitally important in accurately defining and modeling the Lower Dakota aquifer.

The remaining set of well data included a number of well points represented exclusively by drillers' logs where the quality of lithologic information remained uncertain or of questionable character. Unfortunately, cuttings samples were unavailable for these well sites, and further confirmation was not possible. This lower-quality data were included under separate categories in our Excel spreadsheet of well information in the study area. This information included well intervals considered as "possible" (although not definitive) Cretaceous sandstone or mudstone/shale and "possible" sub-Cretaceous rocks. Information from these drillers' logs was generally insufficient to adequately distinguish Cretaceous mudstone/shale and sandstone from similar lithologies in parts of the Quaternary or Paleozoic stratigraphic succession. In particular, distinguishing Pennsylvanian mudstone/shale and sandstone from Dakota mudstone and sandstone in areas of Sac and Calhoun counties based on drillers' logs alone was difficult. In other cases, it was not possible to distinguish certain basal Quaternary sands or tills from Dakota sandstone or mudstone units because of inadequate descriptions on certain drillers' logs. This set of less reliable and uncertain well data was visually checked against the previously generated surfaces using 3-D GIS graphic portrayals. Over most of the area, no changes in the original surfaces were apparent using this supplementary and less reliable set of well data. However, in a few small areas where deeper well penetrations (below the third-order top of the Lower Dakota aquifer) included no mention of sand or sandstone (but included mention of "gray clay") by the driller, the aquifer surface was modified (lowered) to honor this information if there were nearby wells that included more reliable information that thicker lower Dakota mudstones occurred in the area. This produced the fourth and final iteration of our interpretation of the top of the Lower Dakota aquifer (Figure 17). This surface in conjunction with the sub-Cretaceous surface (Figure 12) was used to calculate and create an isopach (thickness) map (Figure 18) of the lower Dakota sandstone-dominated interval that contains the Lower Dakota aquifer.

Definition of the Lower Dakota Aquifer

The well information synthesized for this study has provided a clearer idea of what comprises the stratigraphic container for the Dakota aquifer. An earlier study by the Iowa Geological Survey during the early 1980s was the first to recognize the stratigraphic basis for understanding and defining the Dakota aquifer. As summarized by Munter and others, (1983, p. 19), that study was the first to recognize the relationship between the stratigraphy and water yields within the aquifer:

> "The term Dakota aquifer, as used in this report, refers to sandstone beds within the Dakota Formation that yield significant quantities of water to wells. Wells drilled only into the Woodbury Member are significantly less productive than wells completed in the Nishnabotna Member because of the limited vertical and lateral extent of the sandstone deposits within the Woodbury.

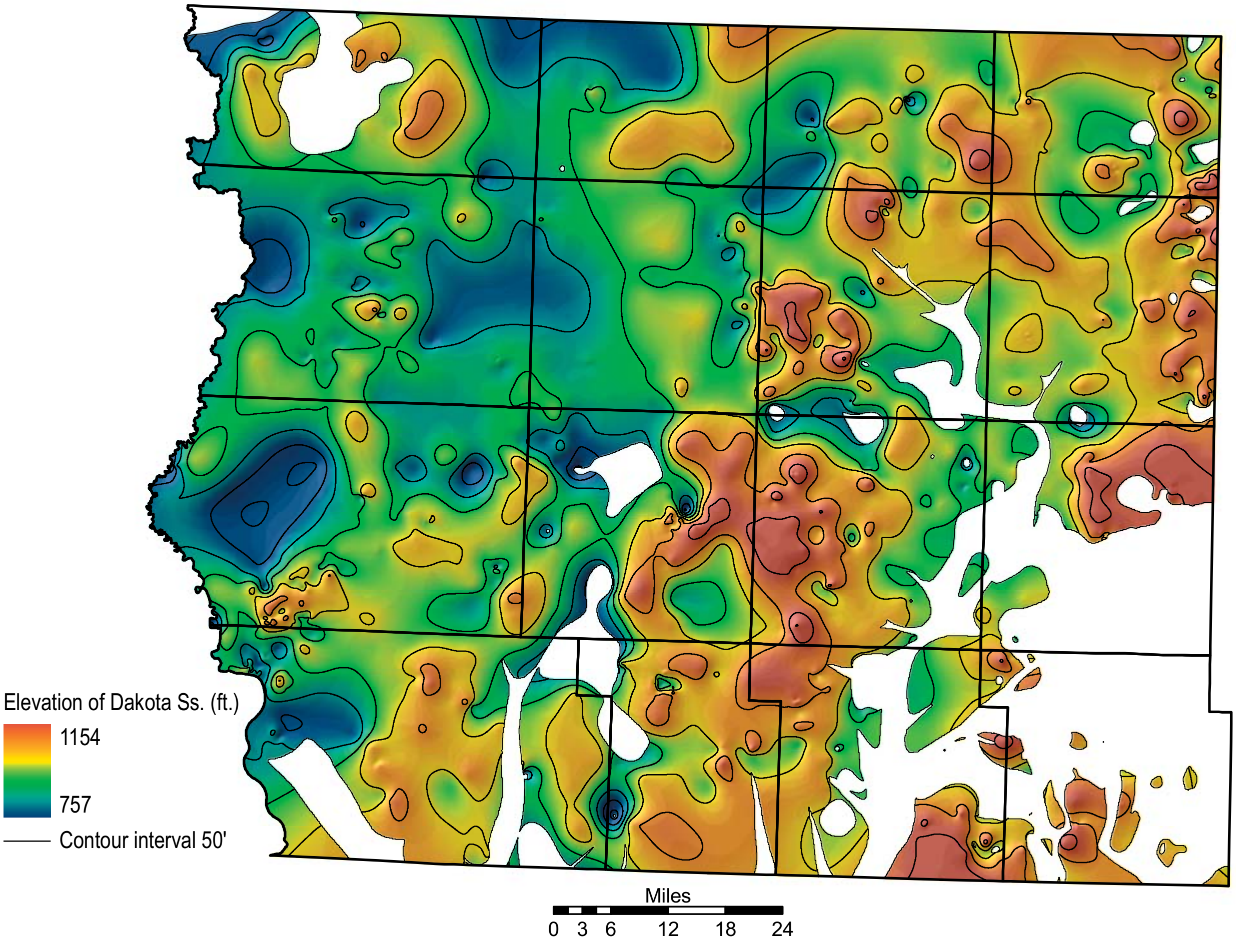


Figure 17. Elevation of the top of the Lower Dakota aquifer used to generate Figure 18.

> Wells penetrating a significant thickness of the Nishnabotna Member, commonly have very high yields (800-1000 gpm) because of the thick and extensive nature of the sandstone units."

These observations significantly changed the earlier conception of a homogeneous Dakota aquifer. Stratigraphic position within the Dakota Formation proved to be vitally important in the development of high-capacity wells. The important results of the Munter and others, (1983) study were used in the design of the current study, with our primary focus on defining the stratigraphic package that hosts the lower highly productive part of the aquifer. However, unlike the earlier Munter and others, (1983) summary, the lower aquifer was not simply restricted to the Nishnabotna Member. Instead, the current study has recognized that the stratigraphic container of the lower aquifer also locally includes contiguous sandstone bodies of the lower Woodbury Member and locally excludes strata of the Nishnabotna Member where they are dominated by mudstone. Although the general coincidence of the Nishnabotna Member with the lower aquifer holds true across much of the study area, it is not a one-for-one correspondence.

As noted earlier, the container for the Lower Dakota aquifer is now defined to include the body of contiguous sandstone that encompasses portions of the Nishnabotna and lower Woodbury

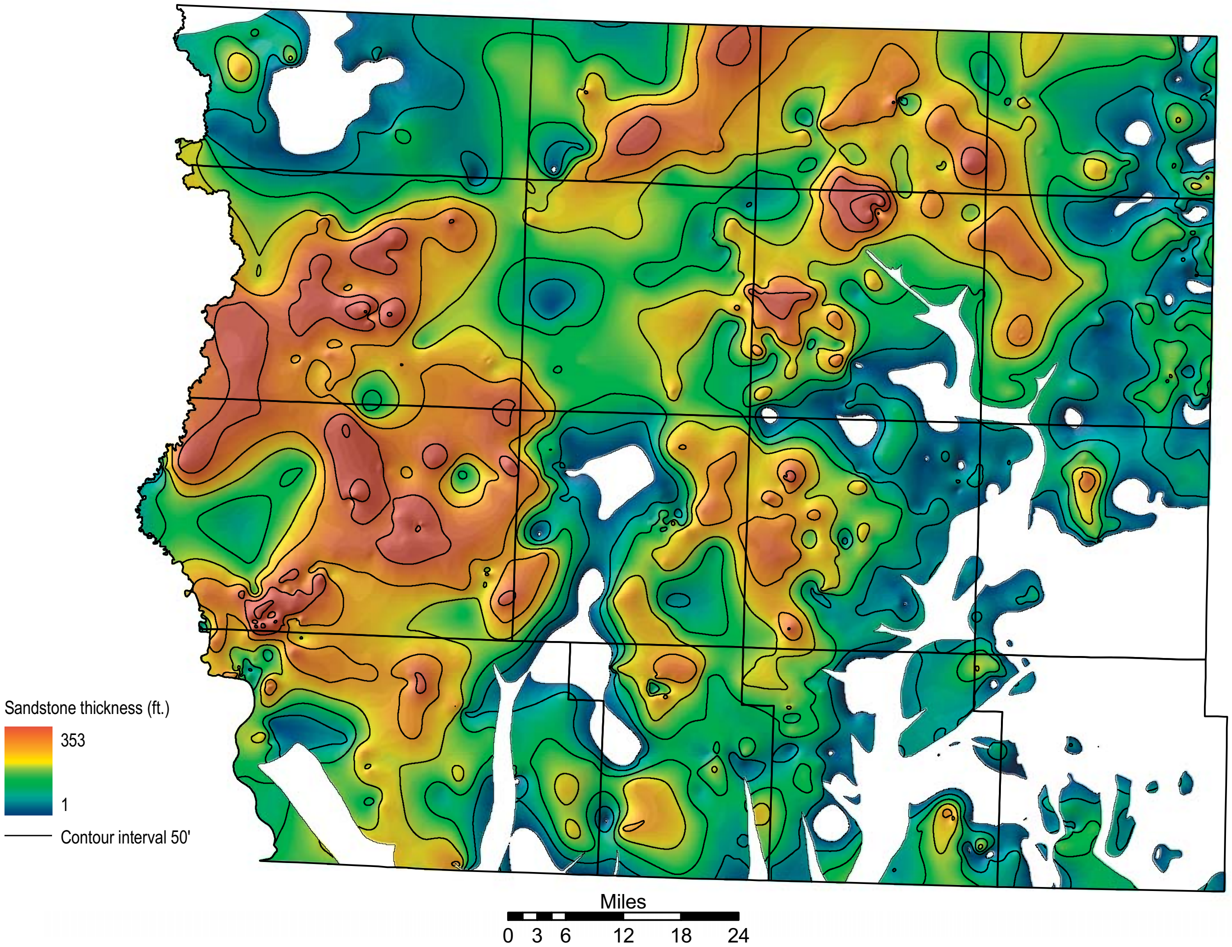


Figure 18. Isopach (thickness) map of the Lower Dakota aquifer in northwest Iowa.

members regionally. Thereby, its upper surface is not a regional stratigraphic datum, but it forms a highly irregular surface regionally (Figure 17), defined by the complex arrangement of contiguous sandstone and mudstone lithofacies within the Dakota Formation. The Lower Dakota aquifer is confined over much of its extent by mudstone and shale strata of the Woodbury Member (which thickens in some areas to include the overlying marine shales). In areas where the Woodbury Member is erosionally removed, the Lower Dakota aquifer is largely confined by Quaternary glacial tills.

The Dakota aquifer has also been used historically as a term to include water-bearing sandstone bodies within the Woodbury Member. Many of these sandstone bodies are not directly connected to the Lower Dakota aquifer, but are physically separated from it by intervening mudstone strata. Likewise, the lateral extent of these upper Dakota sandstone bodies is limited, and most appear to be less than a mile or two in cross-sectional dimensions. However, these sandstone bodies may extend as elongate channel bodies within the surrounding mudstone succession, and some could conceivably extend over one or two counties. Based on regional paleotransport directions of sandstones within the Dakota Formation, such channel bodies would be predicted to trend in a southwesterly direction. As noted by Munter and others, (1983), these sandstones are much less productive than the lower aquifer. Nevertheless,

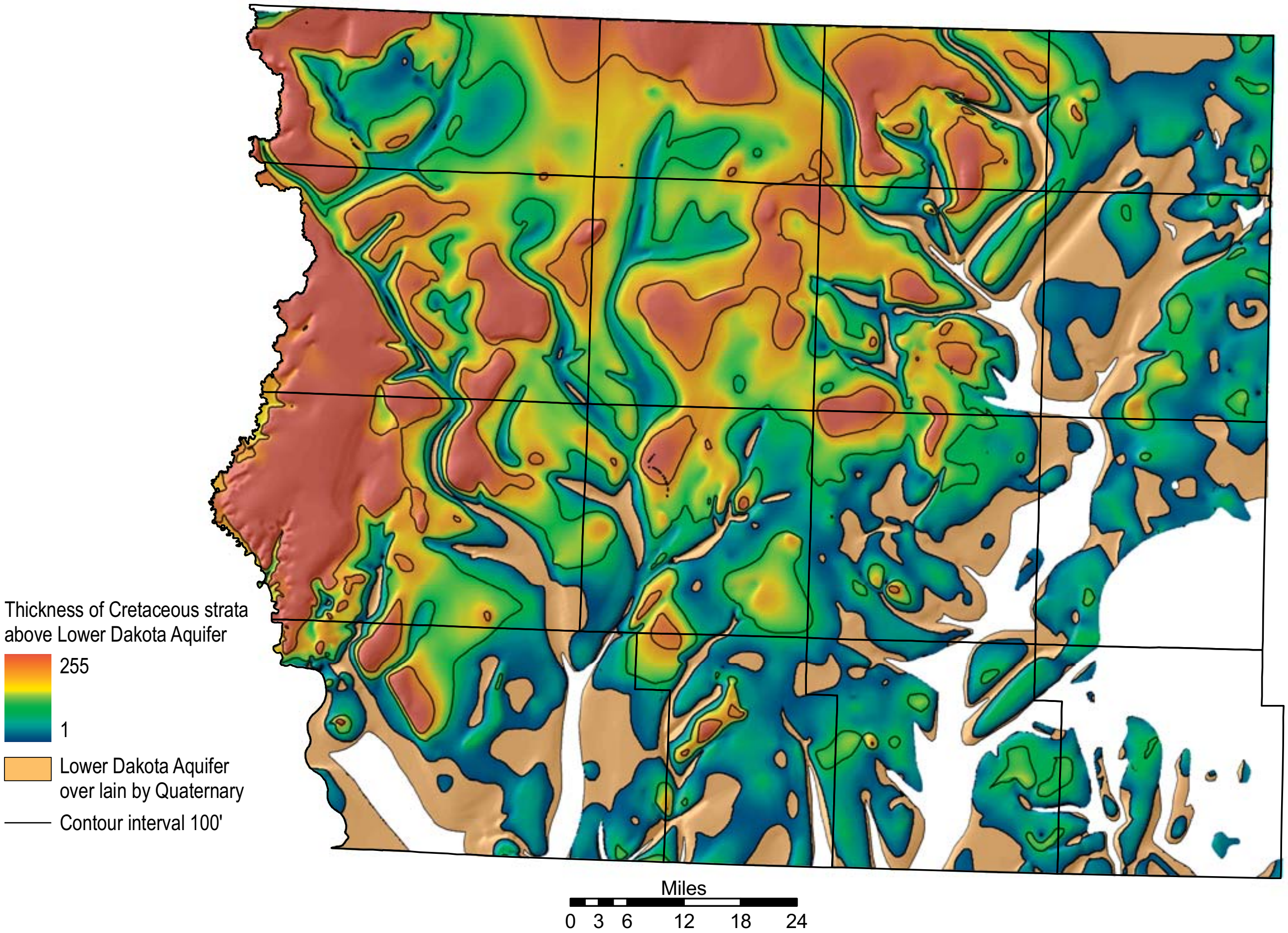


Figure 19. Isopach (thickness) map of Cretaceous strata above the Lower Dakota aquifer in northwest Iowa. This interval is dominated by shale and mudstone, but locally includes sandstone units in part (Woodbury Member).

these upper Dakota sandstone bodies are locally important sources of water, particularly for the development of smaller production wells for domestic or farm use. Unlike the lower aquifer, the distribution of subsurface data in most of northwest Iowa is insufficient to accurately predict the stratigraphic and geographic distribution of sandstone bodies within the upper Dakota. Nevertheless, virtually all known well sections of the Woodbury Member greater than about 100 feet in thickness contain sandstone units varying between about 5 and 75 feet in thickness. Because of the local economic importance of these upper Dakota sandstones bodies, an isopach map of the Cretaceous interval above the Lower Dakota aquifer was prepared (Figure 19). Since the probability of finding one of these sandstone bodies should be highest at localities where the Woodbury Member is thickest, this supplemental isopach map (Figure 19) is potentially useful in a regional context for maximizing the possibilities of encountering isolated sandstone bodies in the upper Dakota in the absence of other well data.

Because there is no direct hydrologic connection between these isolated sandstone bodies of the Woodbury Member and the Lower Dakota aquifer, it was not immediately clear whether or not to include these sandstones within a broadly based and expanded concept of the Dakota aquifer. Certainly, these isolated sandstone bodies were historically included within the same generalized Dakota aquifer that also includes the in-

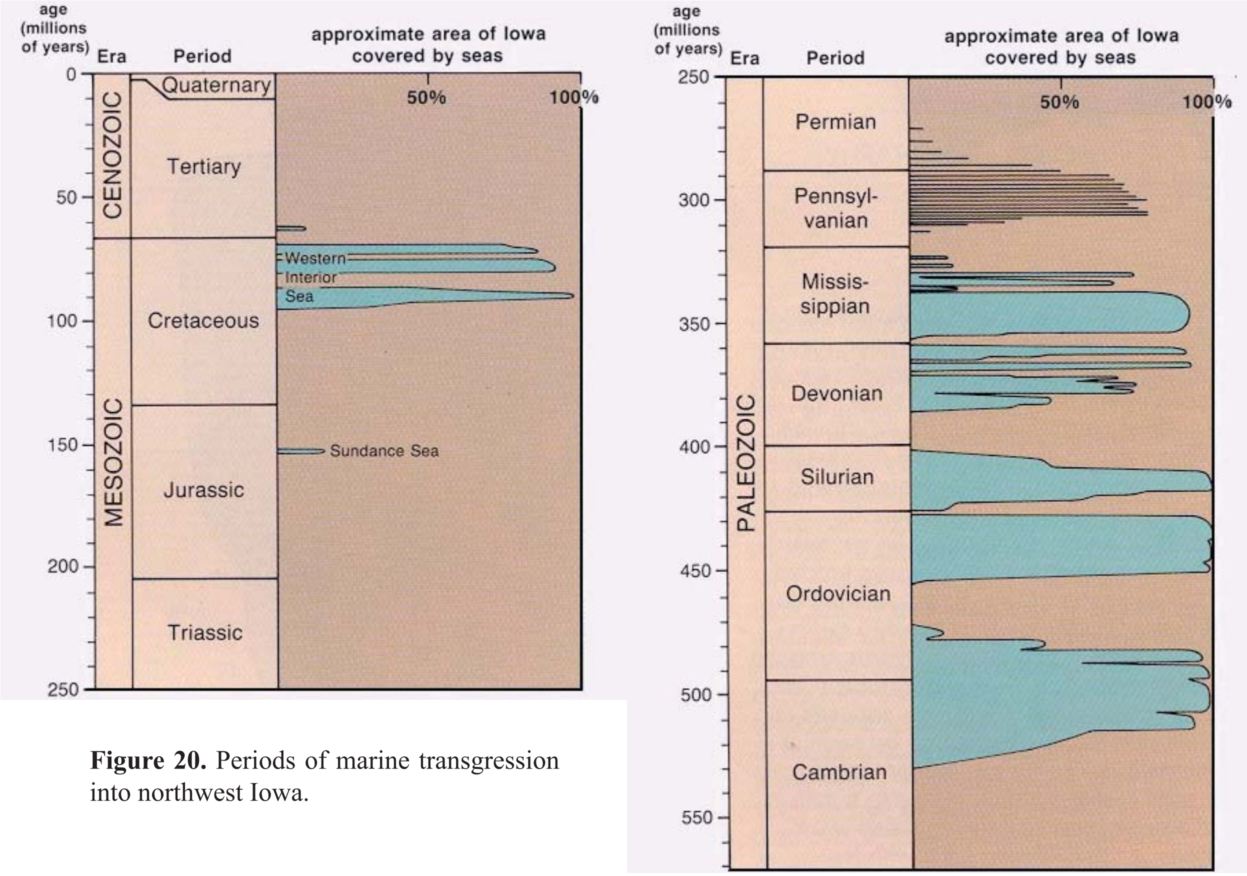


Figure 20. Periods of marine transgression into northwest Iowa.

terval here termed the Lower Dakota aquifer. But there is no stratigraphic evidence that these sandstone bodies share any direct hydrogeologic relationship with the Lower Dakota aquifer, or, for that matter, it is unknown if the various discontinuous sandstone bodies within the Woodbury Member share any hydrogeologic relationships with each other. Further studies of individual Woodbury sandstone bodies are needed to evaluate and define regional hydrogeologic parameters within the Woodbury Member. Until such studies are undertaken, isolated water-bearing sandstone bodies within Woodbury Member are informally included within a largely undefined "Upper Dakota aquifer."

SUB-CRETACEOUS GEOLOGY OF NORTHWEST IOWA

Introduction

The rock units that lie beneath Cretaceous strata in northwest Iowa range from Precambrian to Pennsylvanian in age. Geologic mapping associated with this project has combined these pre-Cretaceous units into nine map units, from oldest to youngest, 1) Precambrian, 2) Cambrian undifferentiated, 3) the Cambrian Jordan Sandstone and the Ordovician Prairie du Chien Group and St. Peter Sandstone, 4) Ordovician Decorah and Platteville formations, 5) Ordovician Galena Group and Maquoketa Formation, 6) Devonian, 7) Devonian Hawarden Formation, 8) Mississippian, and 9) Pennsylvanian. These deposi-

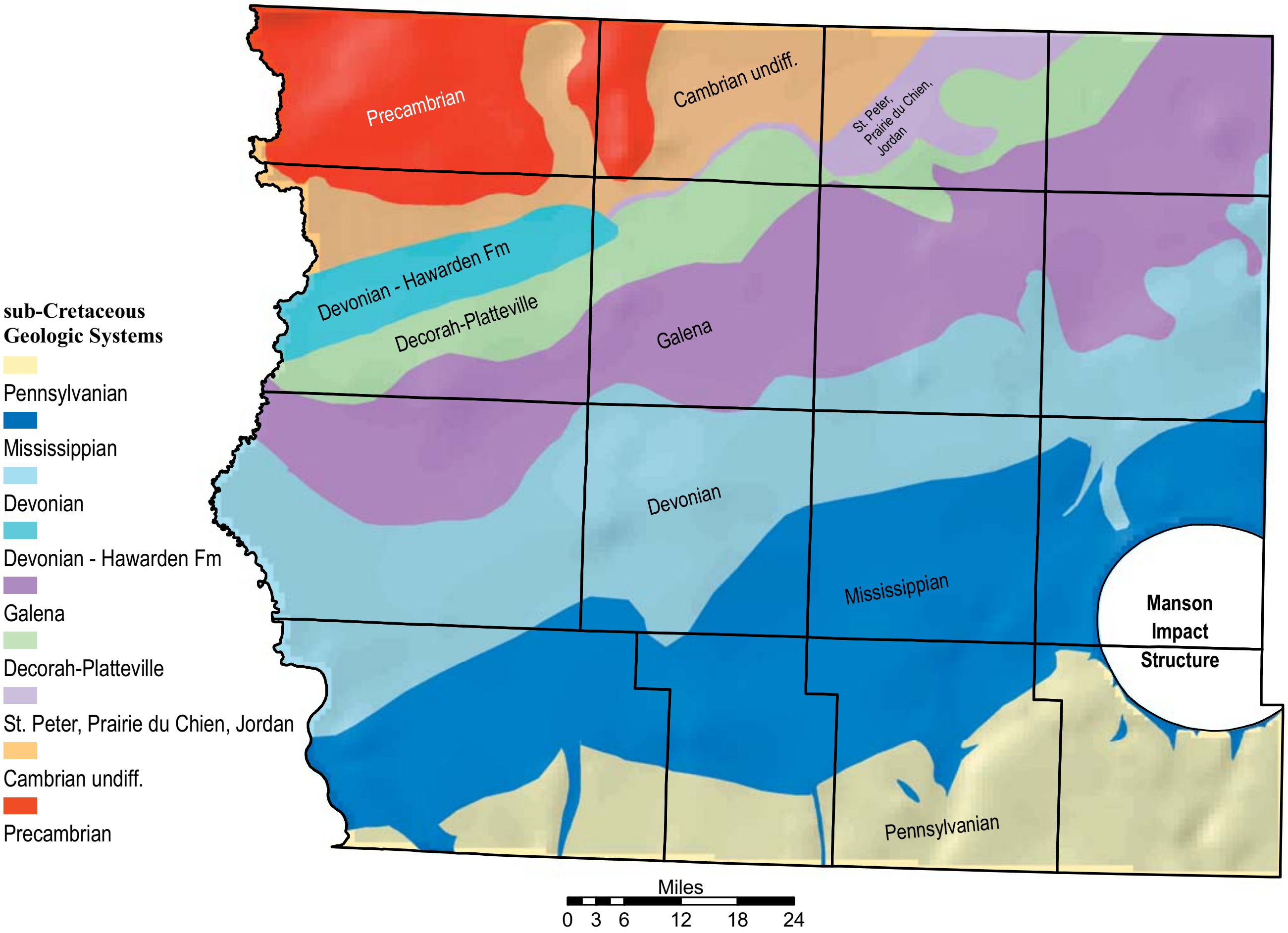


Figure 21. Map of the geology of the sub-Cretaceous surface in the northwest Iowa study area.

tional packages also represent periods of marine transgressions into Iowa (Figure 20), and each of these units is erosionally beveled to the northwest beneath the Cretaceous, and each Paleozoic unit (Cambrian through Pennsylvanian) becomes truncated in that direction (Figure 21). These mapping units were chosen for several reasons; they share hydrologic relationships with overlying Cretaceous strata, they form identifiable lithologic packages, and they are of mappable scale. Munter and others, (1983, p. 7) first summarized the general sub-Cretaceous stratigraphy in northwest Iowa. Witzke and others, (1997) produced a bedrock geologic map of the study area that shows Precambrian and Paleozoic units forming the bedrock surface in areas where Cretaceous rocks have been erosionally removed.

The sub-Cretaceous units are known to form additional bedrock aquifers in northwest Iowa that are in direct hydrologic connection with the Lower Dakota aquifer. Some of these sub-Cretaceous aquifers are currently being used as groundwater sources in areas of northwest Iowa, especially from the Galena, Devonian, and Mississippian. The exact hydrologic relationships between the sub-Cretaceous units and Lower Dakota aquifer are not yet clarified. However, probable head relationships and flow directions between the various sub-Cretaceous and Cretaceous aquifers were proposed by Munter and others, (1983), who interpreted primarily downward recharge and flow from the Lower Dakota aquifer into the sub-Cretaceous aquifers over most of the study area. However, they also interpreted a region of upward discharge and flow from the Ordovician Galena aquifer into the Cretaceous aquifer.

Precambrian

The oldest rocks underlying Cretaceous strata were emplaced during the Precambrian and were combined as one mapping unit for this study. These rocks include layered mafic intrusive rocks of the Otter Creek Mafic Complex (with ages calculated between 2.0 and 2.7 billion years, these are Iowa's oldest known rocks), Penokean granitic plutonic rocks, rhyolitic volcanic ash, and lava flows of the Hull Rhyolite, and the Sioux Quartzite. The Sioux Quartzite is extremely resistant to erosion and has survived the millennia with minimal erosion, while hundreds of feet of Precambrian rocks were eroded from the surrounding area by normal geologic processes over the billion year period before deposition on the next map unit. This left the quartzite capping a high-relief feature called the Sioux Ridge. When Paleozoic and Cretaceous seas flooded the area, shorelines and embayments developed around the ridge. Of the Precambrian rock units, only the Sioux Quartzite has been used as a source of water, but its water is restricted to fractures and its use is limited.

Cambrian Undifferentiated

The Cambrian undifferentiated mapping unit includes the entire Cambrian stratigraphic package in northwest Iowa except for the Jordan Sandstone (Figure 21). The interval includes several sequences of sandstone, shale, and dolomite that can be grouped into one or two hydrologic units in the area. The basal Cambrian Mount Simon Sandstone aquifer is overlain by the low porosity shales and dolomites of the Bonneterre Formation. Above this, a sandstone-dominated Wonewoc Formation is identified in the northern part of the study area, but is absent in the southern part. The Wonewoc likely forms a sandstone aquifer in the northern area. Overlying Cambrian strata of the Lone Rock and St. Lawrence formations are characterized by dolomite, shale, and siltstone strata that form a major aquitard in the area. The interval of the Lone Rock Formation has also been referred to the Davis Formation in the area (e.g., McCormick, 2005).

Jordan-Prairie du Chien-St. Peter (Cambro-Ordovician Aquifer)

The uppermost Cambrian unit, the Jordan Formation, is included with the Ordovician Prairie du Chien Group and St. Peter Sandstone as a mapping unit in the northwest Iowa study area and throughout Iowa where it forms the Cambro-Ordovician aquifer. As the name implies, all three units yield water and are in hydrologic communication, acting as one continuous aquifer. Both the Jordan and the St. Peter are dominated by sandstones although rare dolomite beds occur in the Jordan and rare, thin shales in the St. Peter. The Prairie du Chien Group is dominated by dolomite, commonly porous and fractured, sandy, or cherty in part. A prolonged period of erosion separated deposition of the Prairie du Chien Group and St. Peter Sandstone, and significant erosional beveling of strata beneath the St. Peter increases northwestward in the study area. In areas of Plymouth, Sioux, O'Brien, and Osceola counties, the St. Peter Sandstone lies directly on Cambrian strata.

Decorah-Platteville

The rocks of the Upper Ordovician Decorah and Platteville formations form a unit that serves as an aquitard separating the Cambro-Ordovician aquifer from the Galena aquifer (Figure 22). The Decorah Formation forms a thick shale succession in the study area, and the Platteville Formation is characterized by dense to shaley dolomite. The unit also includes a thin Glenwood Shale (basal part of the mapping unit).

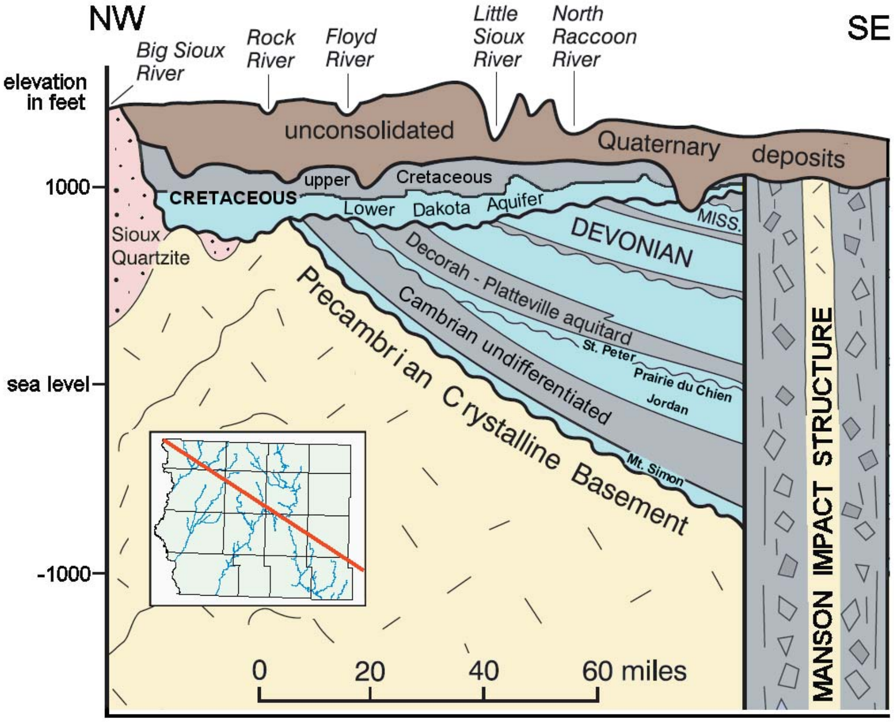


Figure 22. Stratigraphic section displaying the stratigraphic units in the northwest Iowa study area (adapted from Prior et al., 2003). Dips of geologic units are greatly vertically exaggerated. Red line on inset map show line of stratigraphic cross-section.

Galena-Maquoketa

The Upper Ordovician Galena-Maquoketa mapping unit forms the sub-Cretaceous surface across a large portion of the northern study area (Figure 21). Although the Decorah Shale forms the basal part of the Galena Group (Figure 22), it is excluded in this mapping unit, and the Galena Group interval mapped here includes only the thicker dolomite-dominated interval above the Decorah (including the Dunleith, Wise Lake, and Dubuque formations). A thin sliver of the lower Maquoketa Formation forms the sub-Cretaceous surface north of the Devonian edge in the northeastern study area (Munter et al., 1983, p. 6), but the Maquoketa thickens southward beneath the Devonian cover. The Galena-Maquoketa interval is dominated by dolomite and cherty dolomite throughout the map area, and no significant shales are identified. The basal Galena includes sandy dolomite in the study area, locally with thin sandstones (Witzke, 1980; McCormick, 2005). The Galena and Maquoketa dolomites are porous and fractured, and the interval forms a carbonate aquifer in the region.

Devonian

Devonian strata form the sub-Cretaceous surface in an east-west trending swath across the central portion of the study area (Figure 21). These strata primarily belong to the Upper Devonian Lime Creek Formation with a thin local cap of Upper Devonian shale (a Famennian shale unit commonly referred to the “Maple Mill Shale”). A significant period of erosion (more than 30 million years) preceded Devonian deposition across Iowa, which produced pronounced northwestward erosional beveling of Galena and Maquoketa strata beneath the Devonian in the study area. Over most of the area, Devonian strata overlie the Lower Maquoketa Formation, but in areas of Plymouth, O’Brien, and Cherokee counties. Devonian strata directly overlie the Galena Group. The Lime Creek Formation is characterized by a thick succession of dolomite strata, locally including minor limestone or chert. The basal part of the Lime Creek interval commonly includes shale interbeds in the eastern study area, but basal shales are mostly absent to the west. Lime Creek dolomite strata are variably dense to vuggy and, where fracture permeability is developed, these strata comprise a locally productive Devonian aquifer in the study area. This aquifer is separated from the underlying Galena-Maquoketa aquifer by a shaley aquitard interval in the basal Lime Creek to the east (Figure 22), but the basal shales disappear to the west where the Devonian and Galena-Maquoketa carbonate aquifers are apparently in direct connection (as seen in core in the Big Sioux drainage; McCormick, 2005).

The top of the Devonian succession is commonly marked by a thin Famennian shale unit ("Maple Mill Shale") that serves as an aquitard separating Devonian and Mississippian aquifers over much of the southern study area. However, this shale is locally absent in the study area (due to sub-Mississippian erosion), and in places the Devonian and Mississippian aquifers are apparently in direct connection. As noted, the Lime Creek Formation directly overlies Ordovician strata over most of the study area. However, an older Devonian unit, the Cedar Valley Group, occurs beneath the Lime Creek in the southeastern study area (primarily in the deeper subsurface of Calhoun County). This marks the northwestern boundary of the Cedar Valley Group in Iowa, where it is overlapped by Lime Creek strata to the northwest. Cedar Valley strata in Calhoun County are dominated by dolomite and sandy dolomite with minor anhydrite (the Cedar Valley Group is a widespread unit elsewhere in Iowa and surrounding states).

Hawarden Formation

A unique sub-Cretaceous Devonian stratigraphic unit, here termed the Hawarden Formation, has been identified in several well penetrations in Sioux and western O'Brien counties (GEOSAM database, W-27270, W-25941, W-11197, W-53532), but this unit is unknown outside of northwestern Iowa. It was first recognized in the Hawarden core (see Figure 15), where the unit forms a thin interval characterized by medium brown to gray phosphatic and organic shale with a basal sandstone unit. The shales are silty with minor fine sand, and much of the shale interval displays varve-like phosphatic laminae. Thin siltstone intercalations are noted. The core interval from the 641-654 feet in the Hawarden core (W-27270, core D-7, NE NE NE sec. 5, T95N, R47W, Sioux Co., Iowa; reposited at the Iowa Geological and Water Survey) is here designated the type section of the Hawarden Formation (Dakota Project well drilled 1977; also see Munter et al., 1983). At the time this well was drilled the age and correlation of the shale as well as a similar brown organic shale seen in well cuttings in another Dakota Project well (W-25941, D-44, Boyden, 679-681 ft) were unknown, and samples from both wells were processed in 1979 for possible recovery of microfossils (phosphatic microfossils and spores). Typical marine microfossils (especially conodonts) were absent in the shales, but abundant fish remains (scales, spines, teeth, bone) and abundant spores (analyzed by R. Ravn) were recovered (Storrs, 1987). Ravn (see summary in Storrs, 1987) identified a number of spores that indicated a "Middle to early Late Devonian age," "probably Givetian or Frasnian." The fish fossils are consistent with this correlation.

The sub-Cretaceous Devonian interval immediately to the south of the Hawarden Formation (Figure 21) is marked at its base by dolomite strata of the Upper Devonian (upper Frasnian) Lime Creek Formation. Because the Hawarden Formation occupies the same basal Devonian position as the Lime Creek Formation in the area, it seems likely that two units are correlative. However, the Hawarden and Lime Creek formations are lithologically and depositionally dissimilar. The organic shales and sandy strata of the Hawarden Formation are strikingly different from the vuggy and fossiliferous basal Lime Creek dolomite strata found a short distance to the south. The absence of definitive marine fossils in the Hawarden shales, and the abundance of nonmarine spores and probable nonmarine fish fossils (Storrs, 1987), indicate that the unit was not deposited in a normal marine environment. The fish fauna and varve-like laminae in the unit along with its geographic placement suggest deposition of the Hawarden shales in lacustrine (lake) or estuarine settings located onshore from the margins of the Lime Creek seaway. The basal sandstone of the Hawarden Formation may represent a fluvial (river) sand facies, or, alternatively, it could be a reworked Cambrian sandstone interval.

The Hawarden Formation is known to variably overlie Cambrian strata and Precambrian crystalline basement rocks (as in the Hawarden core). It likely overlies Ordovician strata of the St. Peter and Decorah-Platteville along its southern margin, as schematically shown on Figure 22. The formation is shale dominated and is interpreted to form an aquitard interval below the Lower Dakota aquifer.

Mississippian

The entire Mississippian System forms a single mapping unit in the study area, and Mississippian strata mark the sub-Cretaceous surface across a large portion of the southern study area (Figure 21). Although Mississippian strata are mainly confined to the subsurface in the study area, an area of bedrock exposure is noted in eastern Pocahontas County (includes limestone quarries in the Gilmore City area). The Mississippian is dominated by a succession of limestone, dolomite, and cherty dolomite strata, but minor siltstone, shale, and sandstone is noted. The Mississippian interval is generally considered to comprise a single bedrock aquifer in Iowa, although a shaley aquitard (upper Keokuk-Warsaw) may separate the Mississippian succession into two hydrologic units. Further hydrogeologic study is needed. The Mississippian aquifer provides groundwater for domestic and municipal use in the study area. It is confined below by a shaley aquitard at the top of the Devonian (Figure 22) and the base of the Mississippian, but this aquitard is locally absent in portions of the study area where the Devonian and Mississippian aquifers are likely in direct hydrologic connection. In the southernmost portion of the study area, the Mississippian aquifer is confined above by shaley Pennsylvanian strata.

The basal Mississippian Prospect Hill Formation, dominated by argillaceous siltstone, is included in the basal aquitard (with the underlying Famennian shale). A thin limestone and dolomite unit, the Chapin Formation, caps the Prospect Hill in the southeastern study area. However, the Prospect Hill and Chapin formations are absent in the southwestern portion of the study, where the Maynes Creek Formation lies directly on Devonian strata. The bulk of the Mississippian succession in the study area is characterized by a thick interval of carbonate strata, including cherty dolomites of the Maynes Creek Formation, limestones and dolomites of the Gilmore City Formation, and dolomites (part cherty) of the Keokuk Formation. This fractured to porous carbonate interval comprises the most productive portion of the Mississippian aquifer. Shales and shaley dolomite strata occur above this interval in the upper Keokuk and Warsaw formations. The uppermost Mississippian strata are assigned to the “St. Louis Formation,” marked by a variable succession of limestone and dolomite, with minor shale and sandstone. This interval overlies an erosional surface developed on underlying Keokuk and Warsaw strata. The “St. Louis” interval locally contributes water to the Mississippian aquifer.

Pennsylvanian

An erosional period of about 20 million years preceded Pennsylvanian deposition in the study area. Pennsylvanian strata form the sub-Cretaceous surface, and locally the bedrock surface, in the southernmost portion of the study area. These strata belong to the Cherokee Group of Middle Pennsylvanian age. The Cherokee Group is dominated by dark shales and mudstones that comprise a major aquitard in the region. Minor coal and limestone beds are identified in many sections. Sandstone channels and beds commonly occur within the Cherokee succession, and these sandstones are locally used as a source of groundwater. Where the Cherokee Group includes significant sandstone, and where well logs are of questionable quality, it can be difficult separating

Pennsylvanian from Dakota sandstones. In some instances, it seems likely that Pennsylvanian and Dakota sandstones are in local hydrologic connection. The Pennsylvanian succession in the area includes estuarine, nearshore, and open-marine depositional facies, as well as nonmarine fluvial (river) and paludal (swamp) facies and soil horizons. The complex succession of rocks in the Cherokee Group resulted from repeated cyclic rises and falls of sea level during deposition (subdivided into genetic units termed cyclothems).

Structural and Stratigraphic Configuration of Sub-Cretaceous Rocks

All Paleozoic sedimentary rocks units dip slightly to the SSE and strike ENE across northwest Iowa (see Figure 22). This structural configuration reflects proximity to the broad Transcontinental Arch (also known as the "Continental Backbone") which spans the North American continental interior from New Mexico to Ontario and whose southern margin occupies the northwestern part of the study area. The ENE-trending strike of Paleozoic units in northwest Iowa parallels the trend of the Transcontinental Arch, and reflects original depositional strike and stratal onlap along the arch. In particular, the Sioux Ridge, which formed the highest topographic feature on the trend of the Transcontinental Arch throughout the Paleozoic was likely never completely covered by Paleozoic strata. During marine transgressions, Paleozoic shorelines advanced across the region onto the margins of the Sioux Ridge, which apparently remained partially emergent as an island even during sea-level highstands. Because the Transcontinental Arch and the Sioux Ridge formed a topographically elevated region with respect to the remainder of Iowa, Paleozoic units generally onlap to the northwest across the study area. Northwestward stratigraphic onlapping and overstepping is particularly evident in the basal Devonian and basal Mississippian stratigraphy in the study area. Likewise, the degree of erosional truncation of large-scale stratigraphic sequences (megasequences of Sloss, 1963) expands towards the northwest, with sub-St. Peter and sub-Devonian erosion being particularly noteworthy in the area.

The general southeastward thickening of Paleozoic strata across northwest Iowa also reflects the presence of increased structural subsidence in that direction during long episodes of deposition. Patterns of Paleozoic subsidence in the Iowa area show shifting loci, but a general pattern of southward or southeastward thickening across northwest Iowa is maintained throughout the Paleozoic. These shifting patterns of subsidence include 1) the Hollandale Embayment in the Cambrian-Lower Ordovician, 2) the East-Central Iowa and North Kansas basins in the Upper Ordovician and Silurian, 3) the Iowa and Massena basins in the Devonian and Mississippian, and 4) the Forest City Basin in the Pennsylvanian (see summary Bunker et al., 1988). Because of the regional dip of Paleozoic strata in northwest Iowa, general flow of water in confined bedrock aquifers is primarily to the south. However, complex head relationships in some areas produce local upward discharge from Paleozoic aquifers into the overlying Lower Dakota aquifer.

There is a significant change in regional structural configuration of Cretaceous strata as reflected by the general westward dip and stratigraphic thickening of Cretaceous units across western Iowa and eastern Nebraska and South Dakota (see Figure 22). This change was created by increasing westward subsidence into the Western Interior Basin during the Cretaceous across the central United States. Subsequent Cenozoic structural modifications in the region resulted in eastward erosional truncation of Cretaceous strata, likely resulting from a reversal in regional stream gradients associated with Laramide (Rocky Mountain) uplift to the west.

GEOLOGIC DATA AND RESOURCES USED IN THIS REPORT

IGWS Geosam Database

Geosam is the Iowa Geological and Water Survey's (IGWS) on-line geologic site and sample database (http://gsbdata.igsb.uiowa.edu/geosam/).

It provides location information for a wide variety of geologic data and is the access point to the Iowa Geological Survey Rock Library and its millions of samples of Iowa's geologic materials. Geosam includes information on many of the wells drilled in Iowa and geologic exposures, as well as Rock Library locations of related geologic samples. Geosam is the most recent in a series of Geological Survey information databases that began with paper files over 100 years ago, which evolved into an electronic file with the invention of computers, then into an on-line electronic database with the implementation of the internet. The Geosam (a contraction of "geologic samples") database was launched on the Survey's web site in 2000, and has been continuously evolving ever since, to meet the needs of the many users. The database is accessed hundreds of thousands of times every year by Survey geologists, environmental and engineering companies, well drillers, government agencies, and many other users. This information is available to anyone, at no charge, via the internet and the IGWS homepage (www.igsb.uiowa.edu).

Geosam information, related by a unique site identification number (w-number), includes the owner name, county name, location (i.e. township, range, and section), well depth, and site type. The database can be searched by location, county name, owner name, USGS 7.5' topographic quadrangle name, or any combination of these, or by w-number. For some sites, geology, water production, well casing, and a graphic representation of the site may be available. Additionally, drillers' logs, geophysical logs, and other information is available in some Geosam records.

Water Well Sample Data

The IGWS has been repositing well rock chip samples collected on a voluntary basis by Iowa well drillers since the 1930s. The Survey provides drillers with sample bags and forms on which they document important well information, and the drillers collect a sample of the materials in which they are drilling at 5-foot intervals. The samples are returned to the IGWS, assigned Geosam W-numbers, processed, and shelved for future study. Sample information and status are continuously updated in Geosam. Samples are later retrieved by IGWS geologists, microscopically studied, and documented on detailed strip logs that describe, lithologies, mineralization, key fossils, and other rock characteristics and identify unit stratigraphy. These logs are scanned and added to Geosam. Drillers' logs are also scanned and added to Geosam. Today the collection of samples by drillers remains primarily a voluntary program, with sample collection mandated only for municipal water wells, oil, gas, or metallic mineral exploration wells, and large capacity irrigation and other permitted wells. The completion of a driller's log describing the details of the well is mandated for all wells drilled in Iowa.

For this study, IGWS, geologists accessed Geosam information from water wells drilled in the study area. Key, unstudied wells in the area were identified, and their samples were logged by geologists, providing additional information for the study. These well data provided information for identifying important geologic units, their depth, composition, and characteristics.

Drillers' Logs Data

For many wells in the study area no samples were saved by drillers. For some of these wells, the drillers' logs provided important information, although the quantity and quality of these data are variable. These logs provide information on well location depth and descriptions of the geologic materials encountered as well as well construction information and limited water production data.

IGWS Drill Cores

In the late 1980s the Iowa Geological Survey conducted a research drilling program in the northwest Iowa area. A total of 53 test wells were drilled including 4 cores. Drill cores are continuous cylinders of rock, providing much more geologic information than the chips of rocks collected at 5 foot intervals during normal drilling operations. These drill cores provided critical information for the interpretation of the geologic units in this report.

Exposures

For over 100 years geologists have been examining exposures of geological materials in Iowa. Quaternary materials cover virtually all of the study area, with older rock exposures very rare. No exposures of Cretaceous rocks exist in ten of the sixteen counties in the study area (Munter et al., 1983). IGWS geologists have examined nearly all of the rock exposures in the study area, as well as exposures of related rocks in other areas of Iowa and adjacent states. These rock exposures provided important information about the geology of the study.

Previous Geologic Investigations

As with all geological studies, this investigation was constructed on a foundation of information provided by earlier workers. The 1983 investigation of the hydrology and stratigraphy of the area by Munter and others (1983) and related work by Burkart (1982 and 1984) provided critical information on which to base this investigation. Subsequent work by many geologists, especially Witzke and Ludvigson (see References), have advanced our understanding of the study area. For this study, new data were examined and integrated with previous information using new digital software to produce a series of maps and a new database for understanding the Lower Dakota aquifer.

HYDROGEOLOGY

Hydrostratigraphic Units

Four hydrostratigraphic units were recognized for the modeling of the Lower Dakota aquifer. They include the Quaternary materials, the upper Cretaceous strata (including all Cretaceous strata above the Lower Dakota aquifer), the Lower Dakota aquifer, and all sub-Cretaceous units.

Quaternary Units

The upper most hydrostratigraphic unit used in the study was the Quaternary deposits, ranging in thickness from 0 to about 400 feet. The Quaternary deposits constitute a confining unit above the shale-dominated upper Cretaceous strata. The lone exception to this is the Sioux City area, where Quaternary alluvial sand and gravel in the Missouri River Valley directly overlie the lower Dakota sandstone in many places. With this exception, the Quaternary deposits were defined as a continuous confining unit. The horizontal hydraulic conductivity and the storativity were assumed to be the same as the upper Cretaceous strata package.

Upper Cretaceous Strata

As discussed earlier, Cretaceous shales and sandstones overlie the entire region except for isolated areas near windows in areas of bedrock incision (see Figure 10). The lateral extent and thickness of these units creates a regional confined or leaky confined aquifer system. Field tests, conducted on Cretaceous Pierre shale in South Dakota, estimated horizontal hydraulic conductivities at 2.83 x 10^{-6} feet/day (Neuzil, Bredehoeft, and Wolff, 1984). Hydraulic conductivity values based on model calibration of South Dakota Cretaceous shales were 8.50 x 10^{-5} feet/day (Konikow and Neuzil, 2007). Additional field studies in Virginia obtained similar results for hydraulic conductivities in shale confining units (Konikow and Neuzil, 2007). For the purposes of our conceptual model, the Cretaceous shale was assumed to have a uniform horizontal hydraulic conductivity of 3.28 x 10^{-3} feet/day and a vertical hydraulic conductivity of 3.28 x 10^{-4} feet/day. This higher hydraulic conductivity is the result of the many sandstone units that are interbedded within these shales. Many are used locally as aquifers by domestic as well as public water supplies. They are not included within the model because these units are not laterally or vertically continuous across the study area.

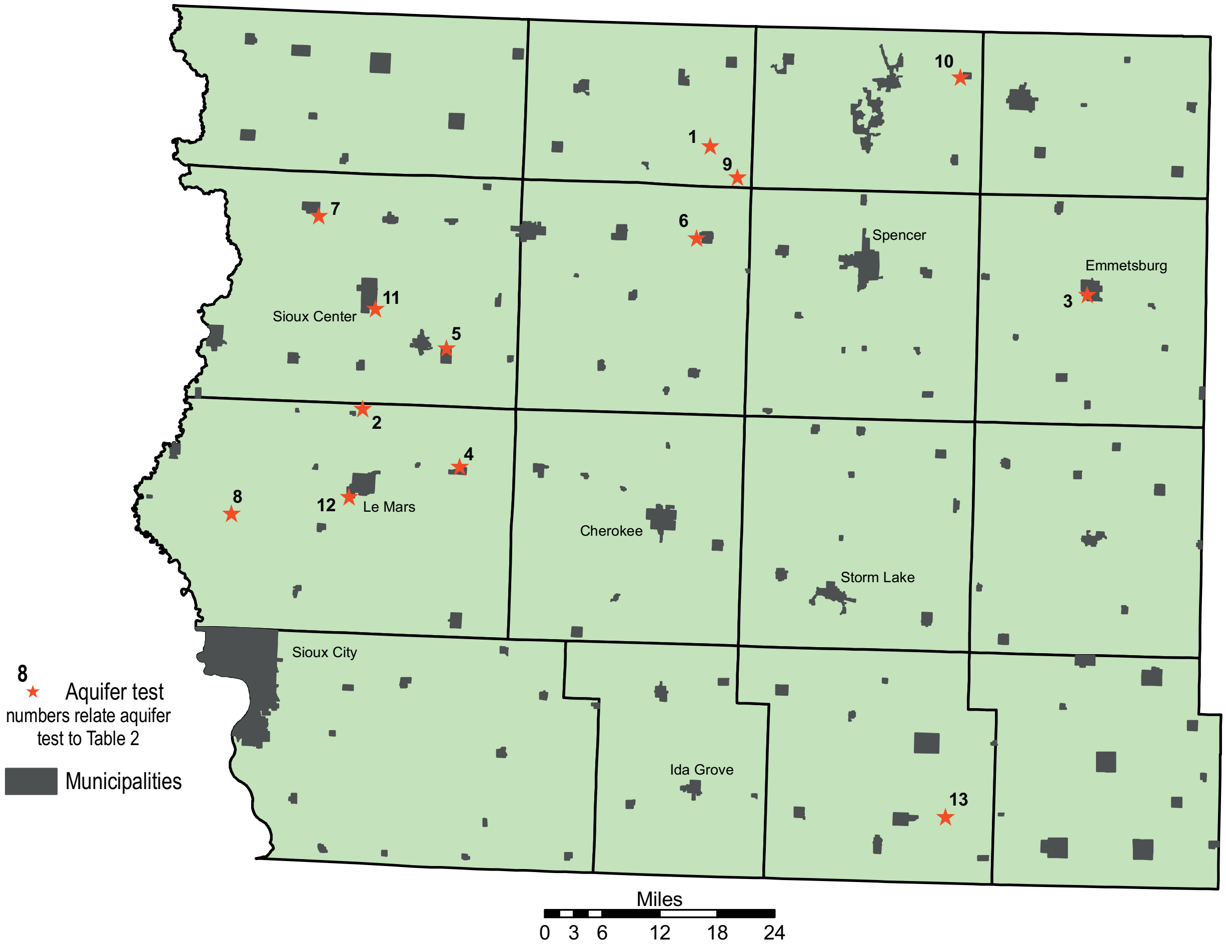


Figure 23. Location of aquifer tests conducted in the Lower Dakota aquifer. Map locations referenced in Table 2.

Lower Dakota Aquifer

The Lower Dakota aquifer is defined as the contiguous body of sandstone that lies at the base of the Dakota Formation. The hydraulic properties of the Lower Dakota aquifer vary both laterally and vertically. The aquifer consists of fine to coarse sandstone, as well as isolated conglomerate units. Most of the sandstone and conglomerate is poorly cemented, and wells installed in the Lower Dakota aquifer require well screen.

The most reliable hydraulic properties are those obtained from controlled aquifer tests with known pumping rate, pumping duration, accurate well locations, and accurate water level measurements. A total of twenty-five pump tests were conducted in the Lower Dakota aquifer by various consultants, well drillers, and communities. The distribution of these tests is shown in Figure 23. A majority of the aquifer tests were conducted in high usage areas in Plymouth and Sioux counties. Table 2 lists each test, the method of analyses, transmissivity values, aquifer thickness, hydraulic conductivity values, storativity values, and who collected the data. The raw data and graphs can be found in Appendix A.

Table 2. Aquifer test results for the Lower Dakota aquifer.

Map Location	Well	W Number	Aquifer Thickness (feet)	Transmissivity (ft2/day)	Hydraulic Conductivity (ft/day)	Storage Coefficient	Method
1. Osceola RW May City[1]	DS-1	27140	130	2800	22		Cooper/Jacobs
		27191	130	10,500	81		Cooper/Jacobs
		24734	130	5,600	43		Cooper/Jacobs
2. S. Sioux RW Maurice[1]	D-1	25487	157	8,290	53	3.2×10^{-4}	Hantush
2. S. Sioux RW Maurice[1]	D-2	42553	157	6,950	44		Theis Recovery
2. S. Sioux RW Maurice[1]	D-3	57869	175	8,800	50		Cooper/Jacobs
3. Emmetsburg[1]	#6	33749	75	5020	67		Theis Recovery
4. Remsen[1]	#9	57863	108	2800	26		Cooper/Jacobs
5. Orange City[1]	#3	41179	125	3050	24		Theis Step Test
6. Hartley [2]	#1	65429	175	6,700	38	1×10^{-3}	Cooper/Jacobs
(Verasun Ethanol)			175	7,750	44	1×10^{-4}	Cooper/Jacobs
			175	7,830	45	2×10^{-4}	Theis
			175	8,320	48	2×10^{-4}	Theis
			175	9,740	56	2×10^{-4}	Theis
7. W-24520 Sioux County[3]	Rock Valley	24520	80	3877	48	6×10^{-4}	Theis
8. W25186 Plymouth County[3]		25186	140	7620	54	3.5×10^{-5}	Theis
9. Hibbing #2 Osceola County[3]		34581	162	12032	74	2×10^{-4}	Theis
9. Hibbing #5 Osceola County[3]		25899	162	5348	33	2×10^{-3}	Theis
2. S. Sioux RW 79-1[3]		28389	155	7353	47	8×10^{-4}	Theis
2. S. Sioux RW 79-2[3]		25509	155	5882	38	3×10^{-4}	Theis
10. Superior Ethanol[2]		64846	172	6,380	37	1.8×10^{-4}	Hantush
11. Sioux Center Land Dev.	#1	63799	87	3900	45	1×10^{-4}	Recovery
12. LeMars	#11	62831	128	7200	56	3.4×10^{-4}	Theis
12. LeMars	#12	62832	128	6800	53	1.8×10^{-5}	Cooper/Jacobs
13. W24560 Sac County[3]		24560	125	4545	36	8×10^{-4}	Theis
footnotes							
1	Data Provided by Dewild Grant Reckert and Associates						
2	Data Provided by Layne Christiansen						
3	Munter, Ludvigson, Bunker, 1983						

Table 3. Hydrologic properties of sub-Cretaceous strata.

Stratigraphic Unit	Primary Lithology	Specific Storage m^{-1}	Horizontal Conductivity ft/day
Pre-Cambrian	Igneous/Metamorphic	0.00001	0.003
Cambrian	Shale/Siltstone	0.00001	0.003
St. Peter	Sandstone	0.00001	40.000
Jordan	Sandstone	0.00001	40.000
Prairie du Chien	Carbonate	0.00001	40.000
Decorah-Plattville	Shale/Siltstone	0.00001	0.003
Galena/Ordovician	Carbonate	0.00001	5.000
Devonian-Hawarden	shale	0.00001	0.003
Devonian	Carbonate	0.00001	5.000
Mississippian	Carbonate	0.00001	2.000
Pennsylvanian	Shale	0.00001	0.003

Based on aquifer test results, the transmissivity of the Lower Dakota aquifer ranged from 2.7 x 10^3 ft^2/day in Remsen to 1.2 x 10^4 ft^2/day near the Hibbing farm, in Osceola County about 4 miles southeast of May City. The arithmetic mean is 6.8 x 10^3 ft^2/day. Much of the variability in the transmissivity is related to sandstone thickness, which varies from 80 feet in parts of Sioux County to 175 feet in O'Brien County.

Hydraulic conductivity can be calculated by dividing the transmissivity by the sandstone thickness. Hydraulic conductivity is considered an intrinsic aquifer parameter, which means that it is independent of the thickness of the formation. Hydraulic conductivity is also the input variable used in Visual MODFLOW. The arithmetic mean of the hydraulic conductivity was 47 feet/day, and the geometric mean was 45 feet/day. The range in hydraulic conductivity was 22 to 81 feet/day, with both test results obtained near May City. The standard deviation of the hydraulic conductivity was 16.2. This relatively low standard deviation value is an indication of the uniformity of the hydraulic conductivity in the Lower Dakota aquifer.

Similar hydraulic conductivity values were found in the Dakota aquifer in Kansas. Based on twenty-two aquifer tests conducted in the Dakota aquifer in Kansas, hydraulic conductivity values ranged from 3.6 to 88 feet/day, with a geometric mean value of 12.4 feet/day (Dakota aquifer Program, Kansas Geological Survey)

Another important aquifer parameter measured during an aquifer test is the dimensionless storage coefficient. The storage coefficient or storativity, is equal to the volume of water released from a vertical column of the aquifer per unit surface area of the aquifer and unit decline in water level. Based on aquifer test data, the storage coefficient of the Lower Dakota aquifer sandstone ranged from 1.8 x 10^{-5} near Le Mars, to 2 x 10^{-3} in southeast Osceola County. The arithmetic mean storage coefficient was 3.3 x 10^{-4}.

Sub-Cretaceous Units

The stratigraphic units below the Lower Dakota aquifer create either a lower confining boundary or a source of upward leakage into the aquifer depending on the hydraulic conductivity of the rock. The determining factor in the hydraulic conductivity of the sub-Cretaceous units is the lithology. Figure 21 shows the distribution of the stratigraphic units below the lower Dakota sandstone based on limited borehole data. Hydraulic conductivity and specific storage values were assigned to each of the stratigraphic units as shown in Table 3. The evaluation of the hydraulic properties of each unit was based on data from other parts of Iowa where the stratigraphic units are used as local and regional aquifers, or they act as confining units.

Recharge

Recharge to most of the Lower Dakota aquifer occurs through relatively thick glacial till (over 90% of Quaternary is glacial till) and shale units. Because the vertical hydraulic conductivity of both glacial till and shale is very low, the rate of recharge into the Lower Dakota is also assumed to be very small. The term recharge as defined in this report is simply the leakage into the lower Dakota sandstone from the overlying shale and glacial till. Even though the recharge or leakage is relatively small, the long-term sustainability of the aquifer is directly dependent on the recharge value. The following equation represents the water balance formula for a confined aquifer:

$$Q(t) = R(t) - O(t) + dS/dt$$

Where

Q = Volume of pumpage over time
R = Recharge over time
O = Outflow-Inflow over time
dS/dt = Change in storage over time

The thick confining units above the Lower Dakota aquifer create extremely slow vertical groundwater velocities. The following equation represents the vertical groundwater velocity:

$$V_v = -K_v\, dh/dL$$

Where

V_v = vertical groundwater velocity
K_v = vertical hydraulic conductivity
dh/dL = vertical hydraulic gradient

If we use representative values from our study area (Burkart, 1984) and insert them into the equation we get the following:

$$V_v = (3.28 \text{ X } 10^{-4} \text{ ft/day})\ (0.5 \text{ ft/ft}) = 1.6 \text{ X } 10^{-4} \text{ feet/day}$$

Since it takes a relatively long time for precipitation to travel to most of the lower Dakota sandstone, droughts or climatic cycles have very little influence on the recharge or leakage into the aquifer. The primary influence of a drought on the Lower Dakota aquifer is the large increase in water demand, which significantly increases pumping rates. It is the increase in pumping rates that is the primary cause for lower head values in the system. Groundwater availability modeling conducted for the Trinity/Woodbine confined aquifer in Texas indicated that water levels were primarily controlled by the amount of pumping, not the lack of precipitation (Harden, Griffin, and Nicot, 2007).

Methods of Estimating Recharge

Recharge to most of the Lower Dakota aquifer is through relatively thick confining beds that include Wisconsinan glacial till, Pre-Illinoian Glacial till, and various Cretaceous shale units. Recharge values in the Dakota aquifer were estimated by Burkart (1984) using average vertical gradients and published vertical hydraulic conductivity measurements. Using an average vertical gradient of 0.5 ft/ft, and published vertical hydraulic conductivity values that range from 0.0013 to 0.000013 feet per day, he estimated recharge values into the Dakota sandstone that ranged from 0.03 to 3 inches per year.

Estimates of vertical hydraulic conductivity in Pre-Illinoian glacial till have been made by Simpkins and Parkin (1993), where they measured vertical hydraulic conductivity values beneath Wisconsinan till in central Iowa. Unoxidized Pre-Illinoian till was found to have a vertical hydraulic conductivity value of $8.5 \text{ x } 10^{-6}$ feet/day (Simpkins and Parkin, 1993). If we assume the same vertical gradient as Burkart (1984) of 0.5 ft/ft, recharge can be estimated at 0.02 inches per year.

Estimates of vertical hydraulic conductivity in marine shales have also been made by Robson and Stewart (1990), where they measured hydraulic conductivity values in the Mesaverde Group shales in Colorado. Based on slug test results, they reported a geometric mean vertical hydraulic conductivity value of $8.5 \text{ x } 10^{-5}$ feet/day. If we assume the same vertical gradient as Burkart (1984) of 0.5 ft/ft, recharge can be estimated at 0.2 inches per year.

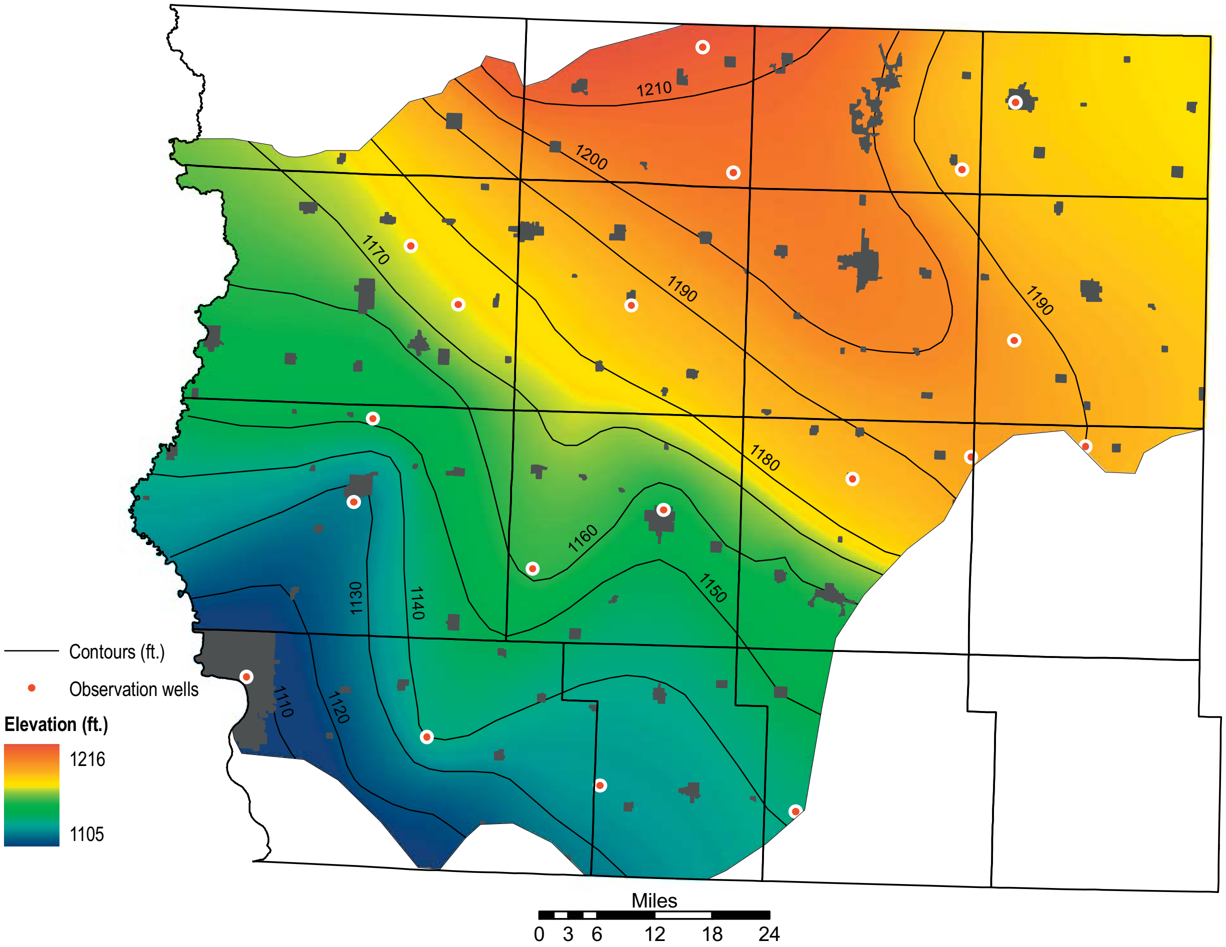


Figure 24. Lower Dakota aquifer potentiometric surface using data from 2000 to 2002.

Groundwater Flow Direction

The Lower Dakota aquifer is a confined aquifer throughout most of Northwest Iowa except for a small area near Sioux City where it is hydraulically connected to the Missouri River alluvium. Groundwater elevation contours or potentiometric surface in the Lower Dakota aquifer was estimated using water level measurements collected from 2000 to 2002. The potentiometric surface is shown in Figure 24. Regional groundwater flow is generally from north to south. A groundwater divide exists in Clay and western Dickinson Counties. On the western side of this divide groundwater flows in a southwesterly direction. On the eastern side of the divide the flow direction is toward the east and southeast.

Vertical gradients were measured at ten locations using nested wells. Water level differences and vertical gradients are shown on Table 4. One well nest W-25898 measured a downward vertical gradient of -0.02 ft/ft from the Upper Cretaceous shale to the Lower Dakota aquifer. Well nests W-24736, W-25321, W-25526, W-25529, W-25591, W-25735 all measured downward vertical gradients that ranged from -0.01 to -0.14 ft/ft from the Lower Dakota aquifer to the Paleozoic units. One well nest W-25736 measured an upward gradient of +0.08 ft/ft from the Paleozoic units into the Lower Dakota aquifer near the city of Le Mars. The upward vertical gradient may be related to the pumping stress on the Lower Dakota aquifer from the city of Le Mars well field, which results in an upwelling

Table 4. Vertical Hydraulic Gradients (from Munter and others, 1983).

W-Number	County	Date	Water Level Difference (ft)	Hydraulic Gradient (ft/ft)	Hydrogeologic Units
25898/25899	Osceola	6/17/1980	-5	-0.02	Upper Cret./Lower Dakota
24736	Ida	3/6/1980	-11	-0.06	Mississippian/Lower Dakota
25114	Cherokee	8/4/1980	0	0.00	Devonian/Lower Dakota
25321	Sioux	8/6/1980	-9	-0.14	Ordovician/Lower Dakota
25526	Buena Vista	8/4/1980	-2	-0.01	Mississippian/Lower Dakota
25529	Cherokee	8/6/1980	-3	-0.03	Mississippian/Lower Dakota
25591	Woodbury	8/7/1980	-4	-0.02	Devonian/Lower Dakota
25735	Woodbury	8/7/1980	-4	-0.05	Mississippian/Lower Dakota
25736	Plymouth	5/5/1980	+6	0.08	Ordovician/Lower Dakota
Munter et al. (1983)					

of groundwater from the Ordovician carbonates into the Lower Dakota aquifer.

CONCEPTUAL GROUNDWATER MODEL

A conceptual model represents our best understanding of the three-dimensional geology and hydrogeology. A conceptual model does not necessarily use formations or stratigraphic units, but relies primarily on variations in lithology and hydraulic parameters to represent groundwater flow conditions. The following items represent the basic elements of the conceptual model of Lower Dakota aquifer:

- The Lower Dakota aquifer can be modeled using four layers. Figure 25 gives a graphical representation of each of these layers.

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

- Above the sub-Cretaceous is the lower Dakota sandstone aquifer. The Lower Dakota aquifer is represented by Layer 3 and is confined above by various Cretaceous shale units. The Lower Dakota 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.

- Above the Lower Dakota aquifer are the shale-dominated upper Cretaceous strata (Layer 2) and the Quaternary units (Layer 1), which are primarily confining units. The exception to these two confining units is in the Sioux City area, where shallow alluvium of the Missouri River Valley is in direct contact with the Lower Dakota aquifer in many places. This is represented by a higher hydraulic conductivity in Layers 1 and 2.

- Due to the relatively thick glacial till and shale units, the recharge value used in the model represents the amount of groundwater

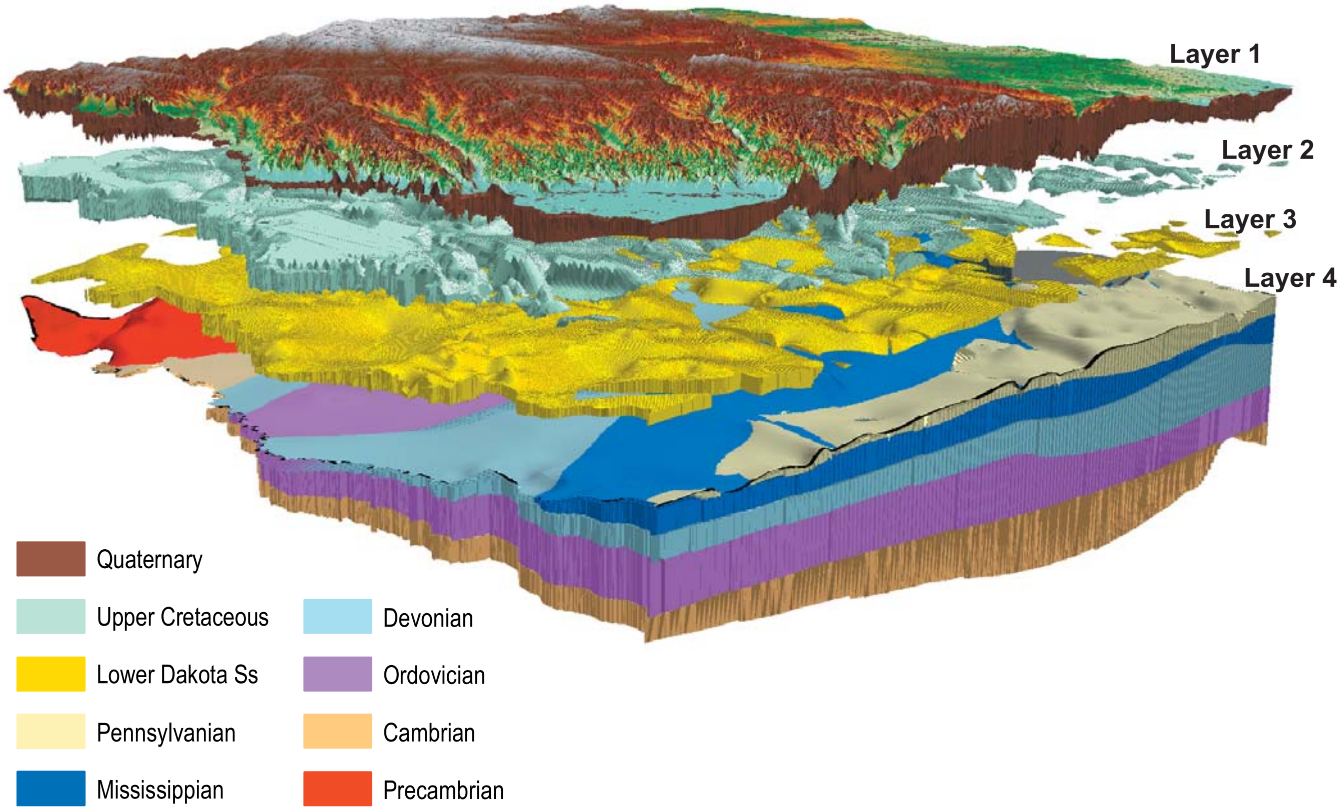


Figure 25. Geologic conceptual model of the 16-county study area as viewed from the southwest.

that enters the Cretaceous bedrock (Layer 2) from the Quaternary units (Layer 1). This is also referred to as net recharge.

- To simulate predevelopment conditions, the static water level from the first recorded well in a community was used. It was also 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 predevelopment head due to historical pumping.

- Drawdown in static water levels since predevelopment 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 at the Lower Dakota aquifer/sub-Cretaceous boundary is assumed to be downward under predevelopment conditions. Under transient or pumping conditions this gradient has the potential to reverse and become an upward gradient. The amount of drawdown created by pumping stress is the determining factor.

- The aquifer parameters used in the model were based on the results of twenty-five aquifer tests.

- In order to not violate the law of continuity of flow, only those regions where the lower Dakota sandstone is continuous is modeled. The continuous sandstone is designated as active, and the non-continuous area is designated as inactive in the model.

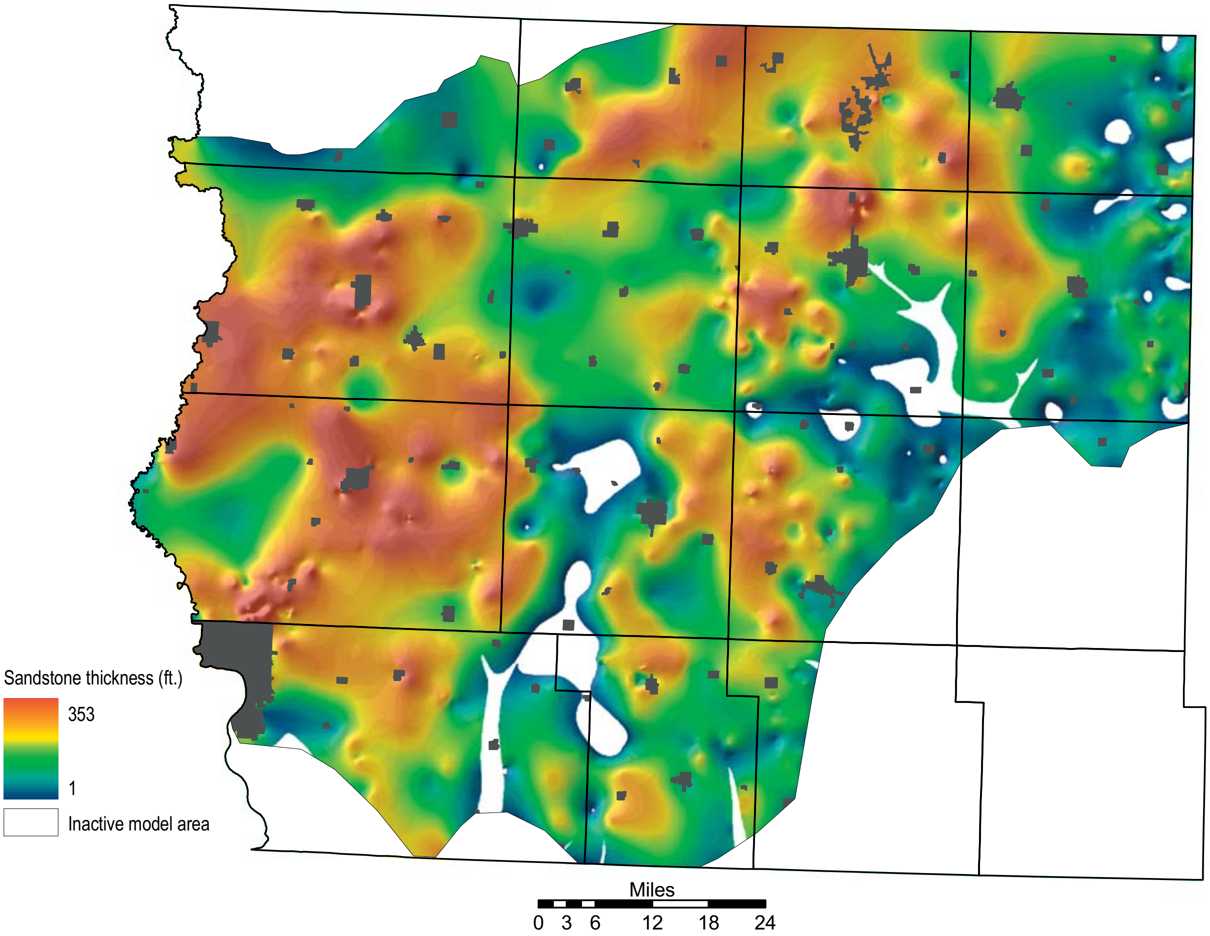


Figure 26. Active model area of the Lower Dakota aquifer.

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 used in the calibration process.
- Approximately 1,900 private wells were added to the model as pumping wells.

MODEL DESIGN

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

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

Code and Software

Groundwater flow in the Lower Dakota aquifer was simulated using Visual MODFLOW Version 4.2 (Waterloo Hydrogeologic, Inc. 2006). The preconditioned conjugate-gradient method was used to solve the linear and non-linear flow conditions (Hill, 1990). MODFLOW is a widely used finite difference groundwater modeling program originally developed by the United States Geological Survey.

Model Parameters

The following model parameters were included in Visual MODFLOW:

- The model consists of four layers as described in the conceptual model.
- The top surface for each of the four layers was entered using 1,600 by 1,300 meter grids. The top of Layer 1 was the ground-surface elevation. The top surfaces for Layers 2, 3, and 4 were derived from geologic data as described in Section 7.0.
- Layer 1 consists of unconsolidated Quaternary sediments, and includes loess, alluvium, glacial till, and buried sand and gravel deposits. Because the various glacial till units represent the majority of the Quaternary thickness, and dominate the vertical movement of groundwater to the Lower Dakota aquifer, the aquifer parameters assigned to this unit are those typical of unoxidized glacial tills. The one exception is the Sioux City area that has alluvial sand and gravel deposits in hydraulic connection with the Lower Dakota aquifer in some areas.
- In Layer 2 there are many lenses of sandstone found within the upper Cretaceous shale unit, but since they are not hydraulically connected to the lower Dakota sandstone they were ignored. The upper Cretaceous shale was modeled as one continuous confining unit.
- The horizontal hydraulic conductivity of Layers 1 and 2 were assigned a value of 3×10^{-3} feet/day. This hydraulic conductivity value is typical for unoxidized glacial till and shale. The vertical hydraulic conductivities were 3×10^{-4} feet/day. The region around Sioux City, Iowa was assigned a higher value of 5 feet/day to represent the thin or discontinuous confining layer in that area.
- Layer 3, the Lower Dakota aquifer, is discontinuous in the lateral direction. To represent this discontinuity, model cells were de-activated within Visual MODFLOW. The thickness map of the Lower Dakota aquifer was generated and used to deactivate model cells. The final active portion of the model is shown in Figures 26 and 27.
- Figure 28 represents the horizontal hydraulic conductivity values in the Lower Dakota aquifer following steady-state and transient model calibrations. The vertical hydraulic conductivity was assigned a value that was 1/10th the horizontal.
- Visual MODFLOW uses the parameter specific storage (Ss), which is defined by the flowing equations:

  $S_s = S/B$

  Where:

  S = Storativity
  B = aquifer thickness.

  Using the average storativity value of 3.3×10^{-4} from Table 2, and dividing this by the average aquifer thickness of 100 feet, provides an average specific storage value of 3.3×10^{-6} ft^{-1}. This parameter was kept uniform across the entire Lower Dakota aquifer.
- The bottom boundary of the model (Layer 4) was an arbitrary horizontal plane that was 100 meters below the lowest elevation of the Lower Dakota aquifer.

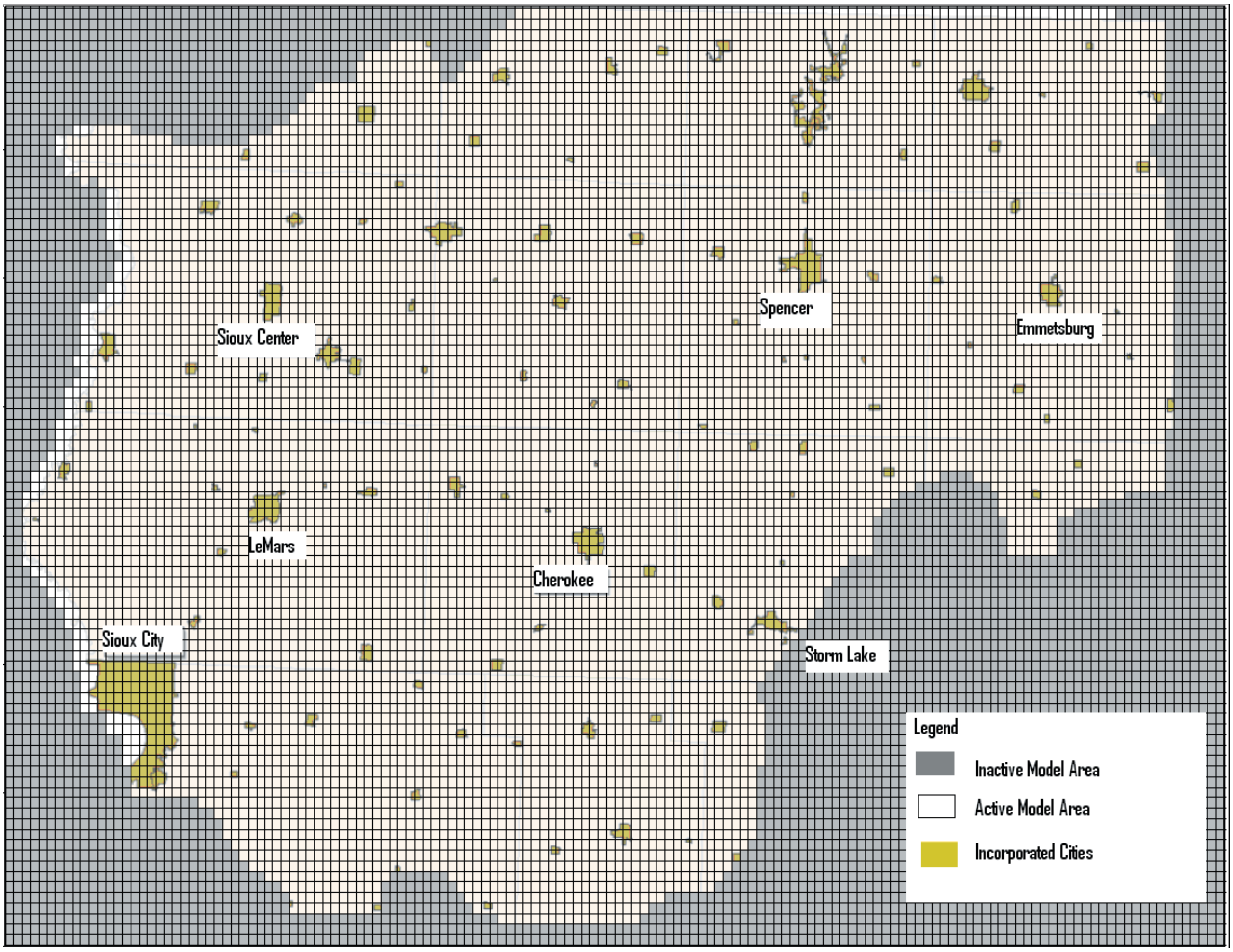


Figure 27. Model grid within active model area of the Lower Dakota aquifer. The white area shows the active model area (gray area is the inactive model area). Incorporated cities are shown in gold.

- Table 3 lists the hydraulic conductivity of Layer 4. Values were assigned based on the primary lithology and on known permeability values.

MODFLOW Grid

The model grid for the Lower Dakota aquifer was defined by 200 columns and 200 rows as shown in Figure 26. Rows were aligned east to west, and columns were aligned north to south. Each cell has dimensions of 1,300 meters east-west, and 1,600 meters north-south. The model grid size may be reduced by simply adding more columns or rows, which is highly recommended for local scale modeling.

Model Boundary Conditions

The model perimeter for the Lower Dakota aquifer was assigned using a combination of physical and hydraulic boundaries. Figure 29 shows the boundary conditions and includes the following:

- Flow-through boundaries were designated across the Iowa-Minnesota and Iowa-South

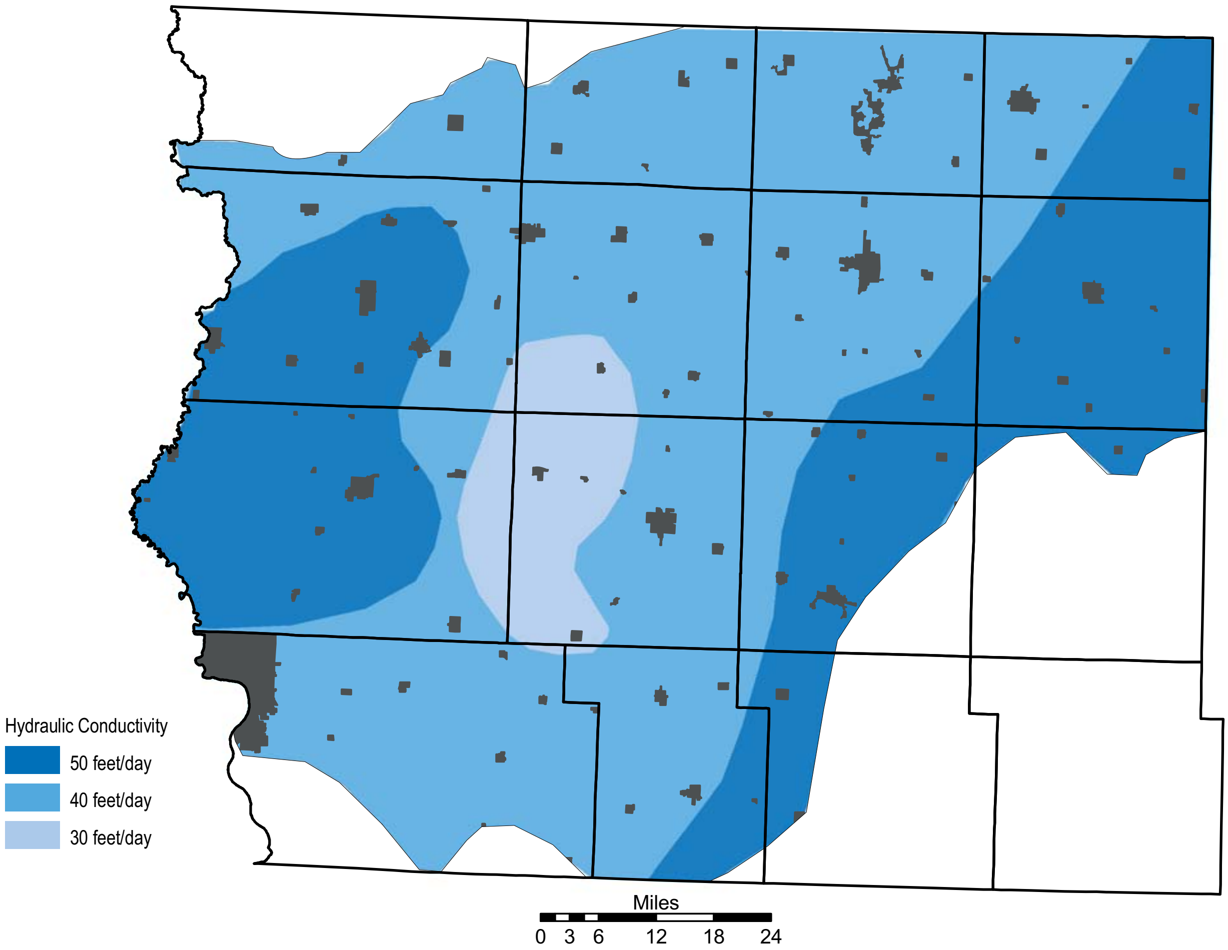


Figure 28. Hydraulic conductivity distribution within active model area of the Lower Dakota aquifer.

Dakota borders. These were represented by general head boundaries in the model. The general head values were based on the pre-development potentiometric map.

- Groundwater discharge to the Missouri River near Sioux City was represented by using a constant head boundary. The values used in the constant head were based on the average river stage elevations.

- A short flow-through boundary was designated in parts of Ida and Buena Vista counties (southeast corner of the model) using constant head values. This short flow-though boundary represents the probable hydraulic connection between the sandstones of the Lower Dakota aquifer and the buried sand and gravels found within the bedrock valley.

- No-flow boundaries were designated along the eastern and most of the southern perimeter of the model. This was represented by simply deactivating the grid cells in these regions. The minimal layer thickness was designated as 1 meter to not violate the principle of the continuity of flow. This was used for the bedrock valleys and other areas within the active model where the Lower Dakota aquifer is thin or absent.

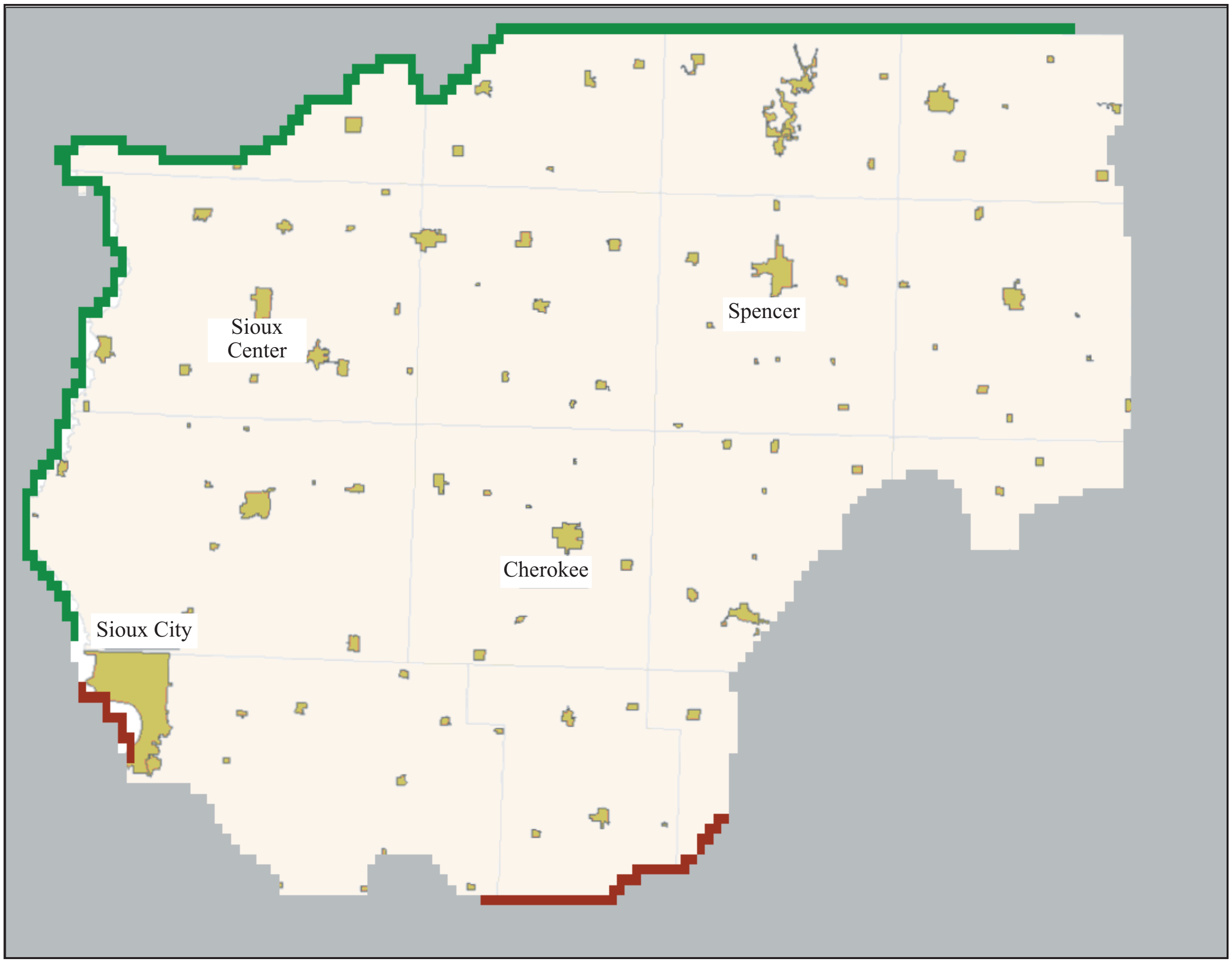


Figure 29. Boundary conditions in the Lower Dakota aquifer. Discharge boundaries represented by constant head cells shown in red. Flow-through boundaries are represented by general head cells shown in green.

- Boundary conditions in Layer 4 were assumed to be similar to Layer 3. Very little water level data is available from the sub-Cretaceous units. Boundaries were set approximately 1 to 2-meters lower than those in Layer 3 to simulate a downward hydraulic gradient.
- Boundary conditions in Layers 1 and 2 were assumed to be no-flow boundaries represented by the deactivation of grid cells.
- Net recharge values were used to simulate the recharge that passes through the base of the Quaternary layer. This method avoided the task of trying to include the alluvial and glacial drift hydrology, losing and gaining streams, evapotranspiration, and the large withdrawals in shallow alluvial wells. The calibrated recharge distribution is shown in Figure 30.

Steady-State Conditions

Fifteen historic water levels were assumed to represent predevelopment steady-state conditions (Table 5). To better define pre-development steady-state conditions several assumptions were made. These include the following:

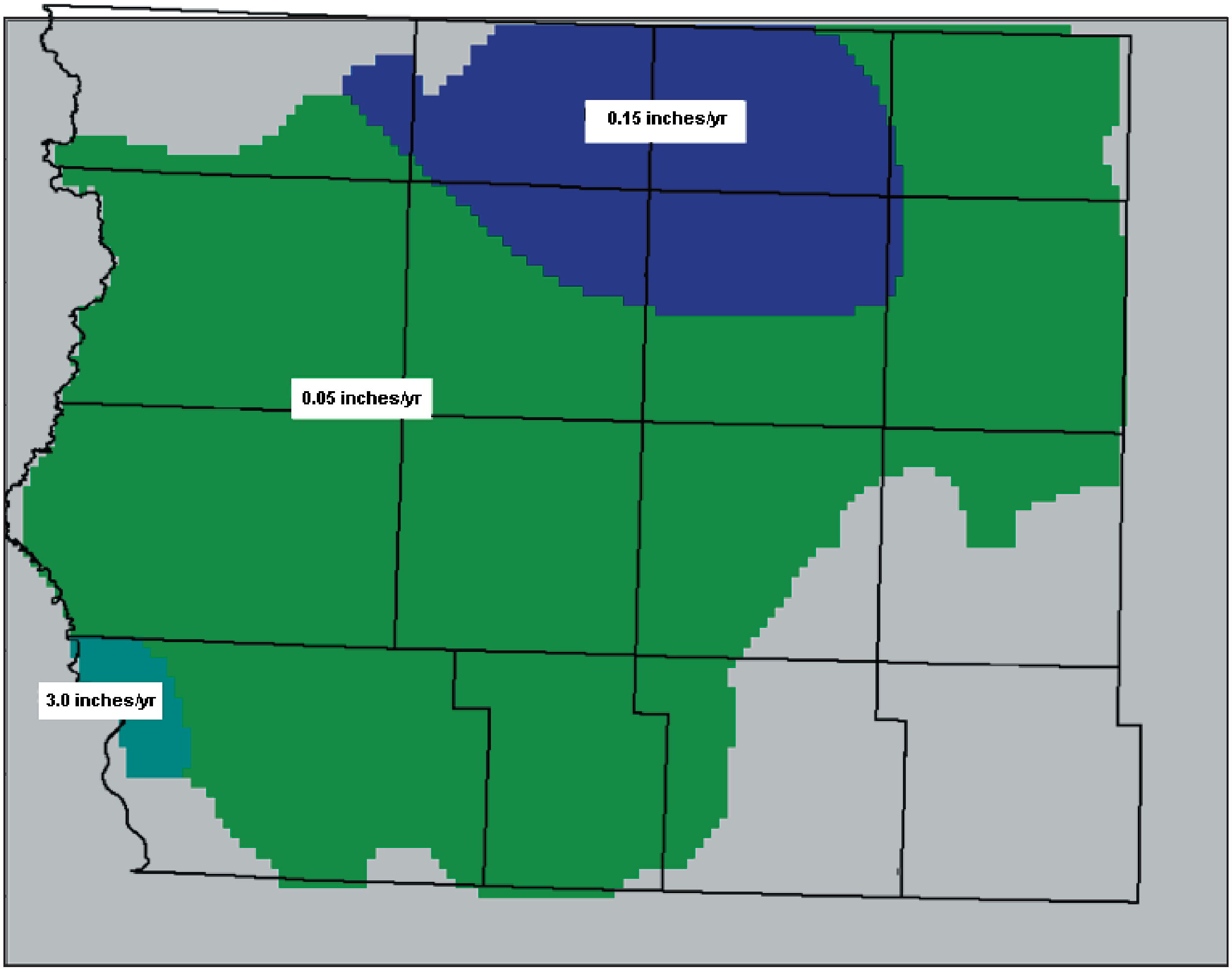


Figure 30. Recharge zones entering the top of the upper Cretaceous shale. The recharge in the Sioux City Area was entered in Layer 1.

- Static water levels collected from wells 10 miles outside major withdrawal centers also represented pre-development conditions (Table 6). If more than one water level was recorded, the oldest measured value was used. A major withdrawal center was defined as a daily pumping rate of 100,000 gallons per day or greater. This assumes that smaller withdrawals and private wells have little or no impact on hydraulic head conditions. The exception to this was in the Sioux City area where water level data was needed near the Missouri River.

- There were no seasonal fluctuations in hydraulic heads.

- Boundary conditions as outlined previously represented pre-development conditions.

- A total of 62 wells were found that had historic water level data and/or were 10-miles outside major pumping centers. These wells are shown on Figure 31. Each of these water levels was converted to elevation.

Table 5. Historic water levels used for pre-development calibration.

W-Number	Location	Date recorded	Water level (ft)	Water Elev. (feet)
289	Sibley	4/1/1935	283	1224
487	Boyden	2/1/1937	234	1179
424	Primghar	1937	330	1195
597	Estherville	7/1/1934	104	1183
696	Aurelia	1937	205	1184
957	Hull	7/11/1939	242	1183
2395	Cherokee	4/23/1946	26	1152
5120	Holstein	1951	325	1128
7264	Ida Grove	1955	95	1133
8630	Ruthven	7/1/1957	210	1200
19423	Le Mars	1966	225	1150
817	Hartley	11/12/1938	260	1201
30940	Ayrshire	1921	116	1196
30070	Rembrandt	1935	140	1186
679	Sioux City	1937	34	1074

Calibration

Steady-state calibration involved adjusting hydraulic properties and recharge rates to reduce model calibration error. There were no pumping wells activated during the calibration period in order to represent pre-development conditions.

A total of sixty-two observation wells (Figure 31) screened in the sandstones of the Lower Dakota aquifer were used in the calibration. In order to evaluate model results, the root mean square error (RMSE) of the residuals between observed and simulated water levels was used based on the following equation:

$$RMSE = \sqrt[N]{\sum (M - S)^2 / N}$$

Where

N = number of observations.
M = the measured head value in meters.
S = the simulated head value in meters.

The smaller the RMSE value, the closer the overall match is between the simulated and observed heads. The calibration method consisted of adjusting model input parameters within hydrologically justifiable limits to minimize the RMSE values. The primary parameters that were adjusted were net recharge and hydraulic conductivity.

The lowest value for the RMSE during the original steady-state calibration was 12.1 feet. During the transient calibration (using 2001 through 2006 pumping rates), the hydraulic conductivity values were adjusted slightly to reduce the RMSE. The hydraulic conductivity values used in the final calibration corresponded closely to the values obtained from aquifer pump tests (Table 2). The hydraulic conductivity values used to calibrate the original steady-state or non-pumping conditions may simply reflect the assumption used to represent predevelopment water level conditions. The water level values found in Tables 5 and 6 were most likely influenced by some historic pumping.

Figure 32 shows the observed pressure head levels versus simulated values for the final steady-state calibration. The RMSE increased slightly to 14.8 feet. This error was considered to be relatively small compared to the size of the entire Lower Dakota aquifer. For comparison, the RMSE for the Ogallala aquifer in North Texas was 36 feet for steady-state conditions (Anderson

Table 6. Additional water levels used for pre-development calibration.

W-Number	Location	Water Level (feet)	Groundwater Elev. (ft)
8104	Buena Vista	198	1172
8226	Buena Vista	260	1156
10884	Buena Vista	275	1139
10501	Cherokee	250	1163
10374	Cherokee	260	1185
25114	Cherokee	158	1150
25521	Cherokee	149	1150
12276	Cherokee	195	1176
10499	Cherokee	184	1144
8229	Cherokee	214	1159
4775	Clay	160	1187
10921	Clay	233	1181
2909	Dickinson	258	1184
6960	Dickinson	282	1184
9542	Ida	222	1127
24736	Ida	209	1137
25523	Lyon	103	1174
30870	Lyon	230	1183
8512	Obrien	230	1173
25964	Obrien	253	1187
8532	Obrien	180	1185
24557	Obrien	42	1187
25900	Osceola	241	1201
9044	Osceola	260	1188
25899	Osceola	193	1205
25108	Osceola	347	1216
4971	Palo Alto	95	1173
5111	Palo Alto	20	1187
24556	Plymouth	125	1155
10381	Plymouth	110	1145
30941	Pocahontas	37	1190
25737	Pocahontas	137	1195
9380	Sac	291	1144
25941	Sioux	200	1176
25965	Sioux	230	1179
343	Sioux	265	1134
2310	Sioux	264	1136
8957	Woodbury	40	1125
25594	Woodbury	200	1141
25593	Woodbury	26	1156
25591	Woodbury	128	1140
39538	Woodbury	48	968
39537	Woodbury	45	971
42502	Woodbury	19	939
5136	Woodbury	85	1018
1573	Woodbury	28	917
1574	Woodbury	19	927

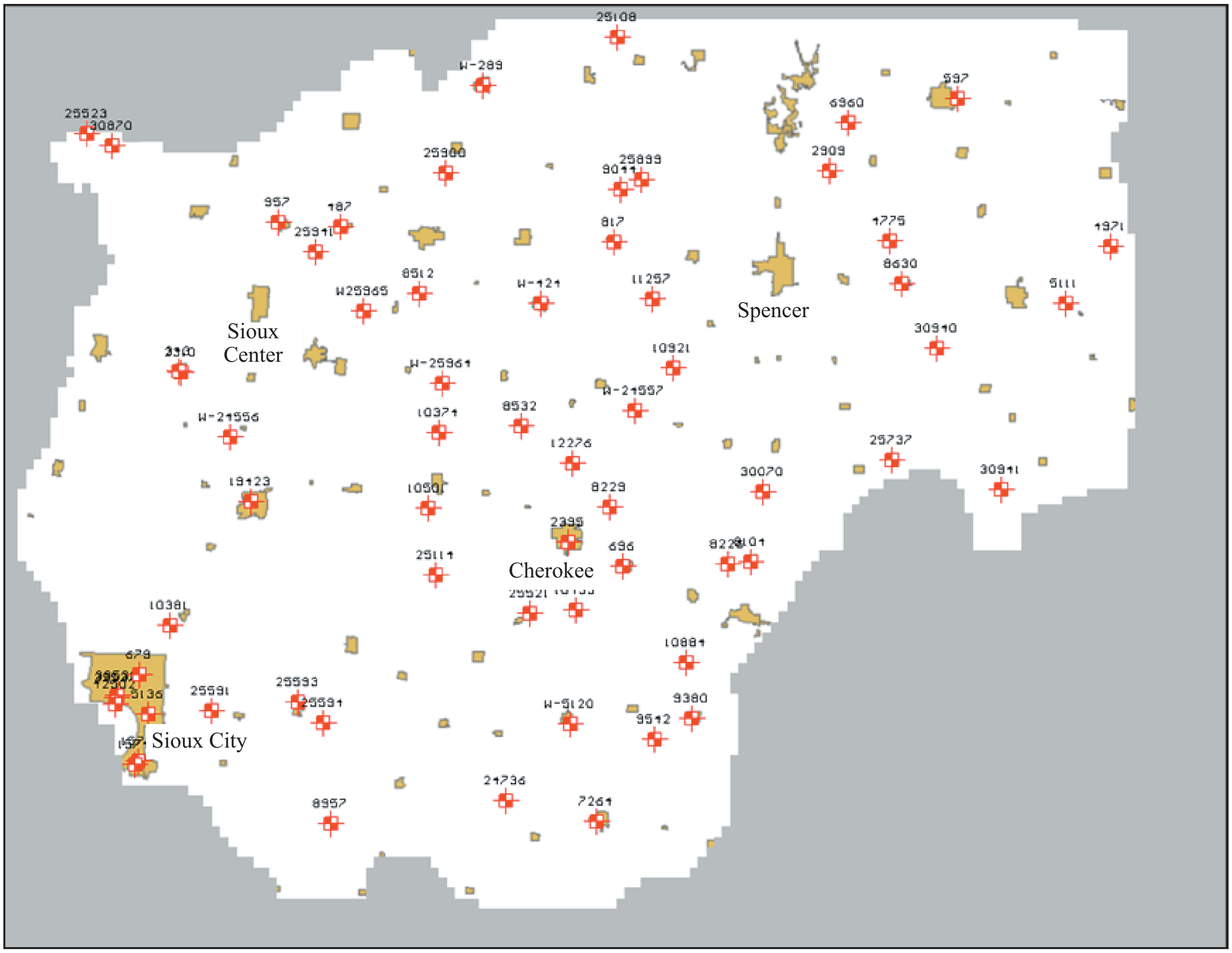


Figure 31. Observation wells used for pre-development steady-state calibration are shown in red. Well numbers correspond to W- numbers found in the GEOSAM database and Tables 5 and 6.

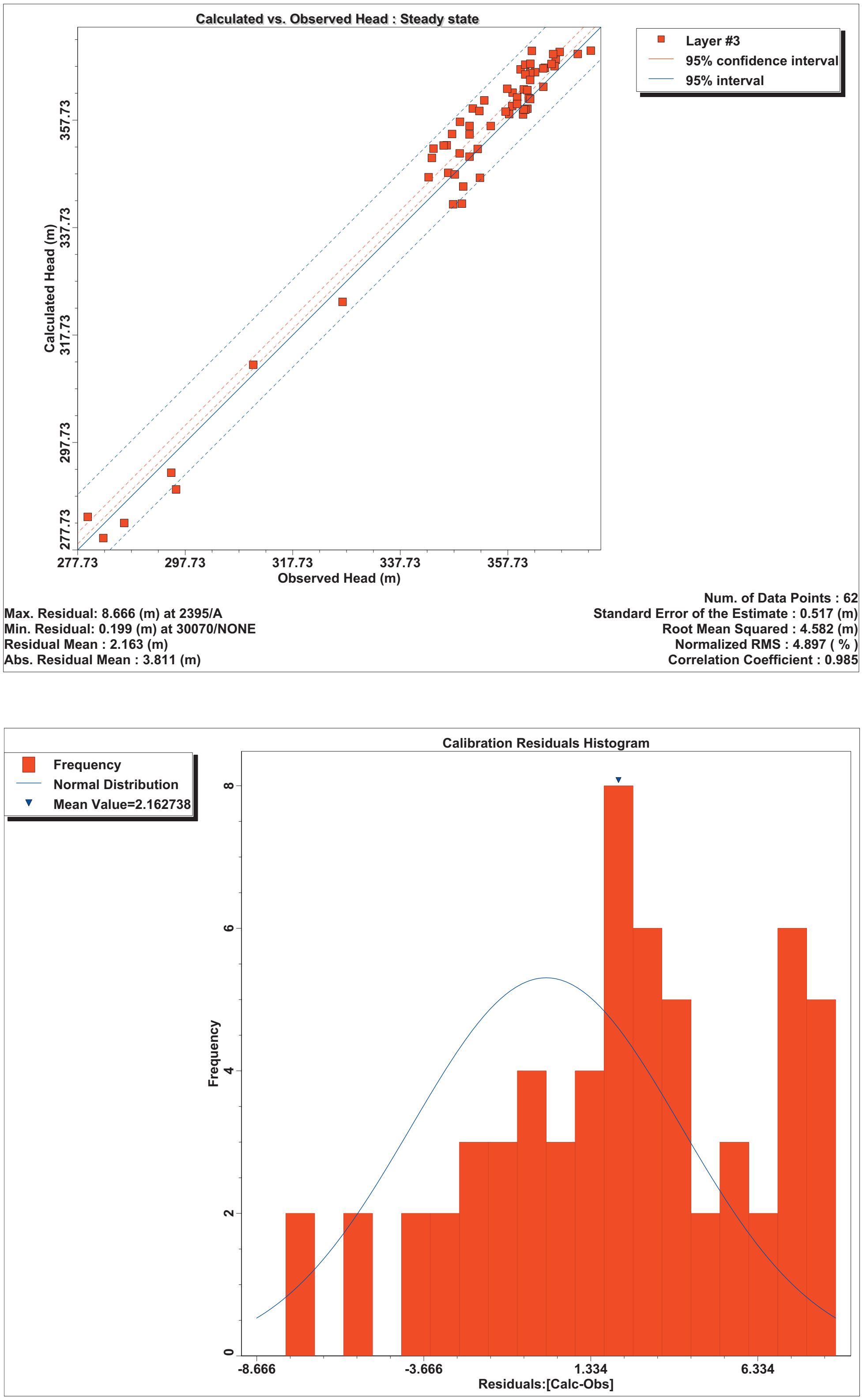
and Woessner, 1992), and 13.6 feet for the Silurian-Devonian aquifer in Johnson County, Iowa (Tucci and McKay, 2005).

The correlation coefficient between observed and simulated pressure head values was 0.986. The range of errors was 28.8 feet in well W-4971 to 0.65 feet in well W-30070, with an absolute error of 12.5 feet. Of the 62 measured water levels used for comparison to simulated water levels, 39 were lower than simulated values, and 23 were higher than simulated values.

Figures 33 and 34 represent the observed and simulated potentiometric surfaces for the Lower Dakota aquifer. The observed and simulated potentiometric contours were very similar in elevation.

Sensitivity Analysis

A sensitivity analysis was conducted to observe the relative impact on the RMSE by adjusting one parameter and holding the other parameters constant. The approach used in the Lower Dakota aquifer was to vary one parameter by a certain percentage from the calibrated values and evaluate the RMSE. Table 7 presents the changes in RMSE for recharge and hydraulic conductivity



Num. of Data Points : 62
Standard Error of the Estimate : 0.517 (m)
Root Mean Squared : 4.582 (m)
Normalized RMS : 4.897 (%)
Correlation Coefficient : 0.985

Max. Residual: 8.666 (m) at 2395/A
Min. Residual: 0.199 (m) at 30070/NONE
Residual Mean : 2.163 (m)
Abs. Residual Mean : 3.811 (m)

Figure 32. Model generated head versus observed head for steady-state calibration.

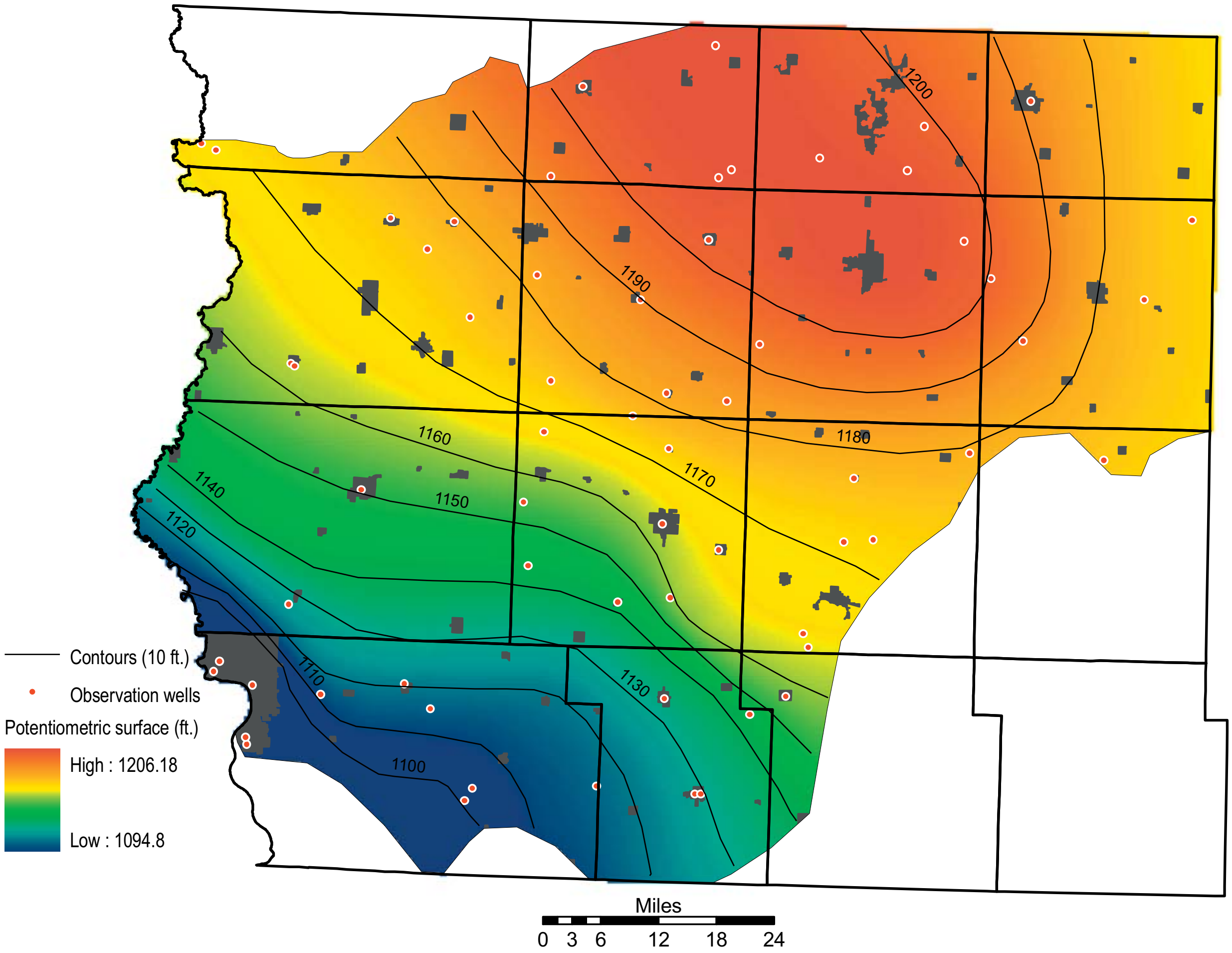


Figure 33. Observed potentiometric surface for estimated pre-development steady-state conditions.

based on this approach. The steady-state model appears to be much more sensitive to changes in recharge than hydraulic conductivity.

The final calibrated recharge values were held constant in both the steady-state and transient models. Hydraulic conductivity values were adjusted in the transient calibration to reduce the RMSE related to pumping stress. The final hydraulic conductivity distribution used in both the steady-state and transient models is shown on Figure 28.

A noticeable increase in RMSE occurred when the recharge rate was increased by 100% or higher. The most likely reason for the large increase in RMSE may be related to the recharge values exceeding the downward leakage of groundwater from the Lower Dakota aquifer into the underlying Paleozoic units. When this threshold value was exceeded, the resulting head values increased dramatically.

Transient Model

The transient model was identical to the steady-state model except for the addition of transient production well data. To compensate for the lack of accurate historical pumping data the transient model was run used the initial head values found on Figure 24. Time series water level data was also included for a small subset of observa-

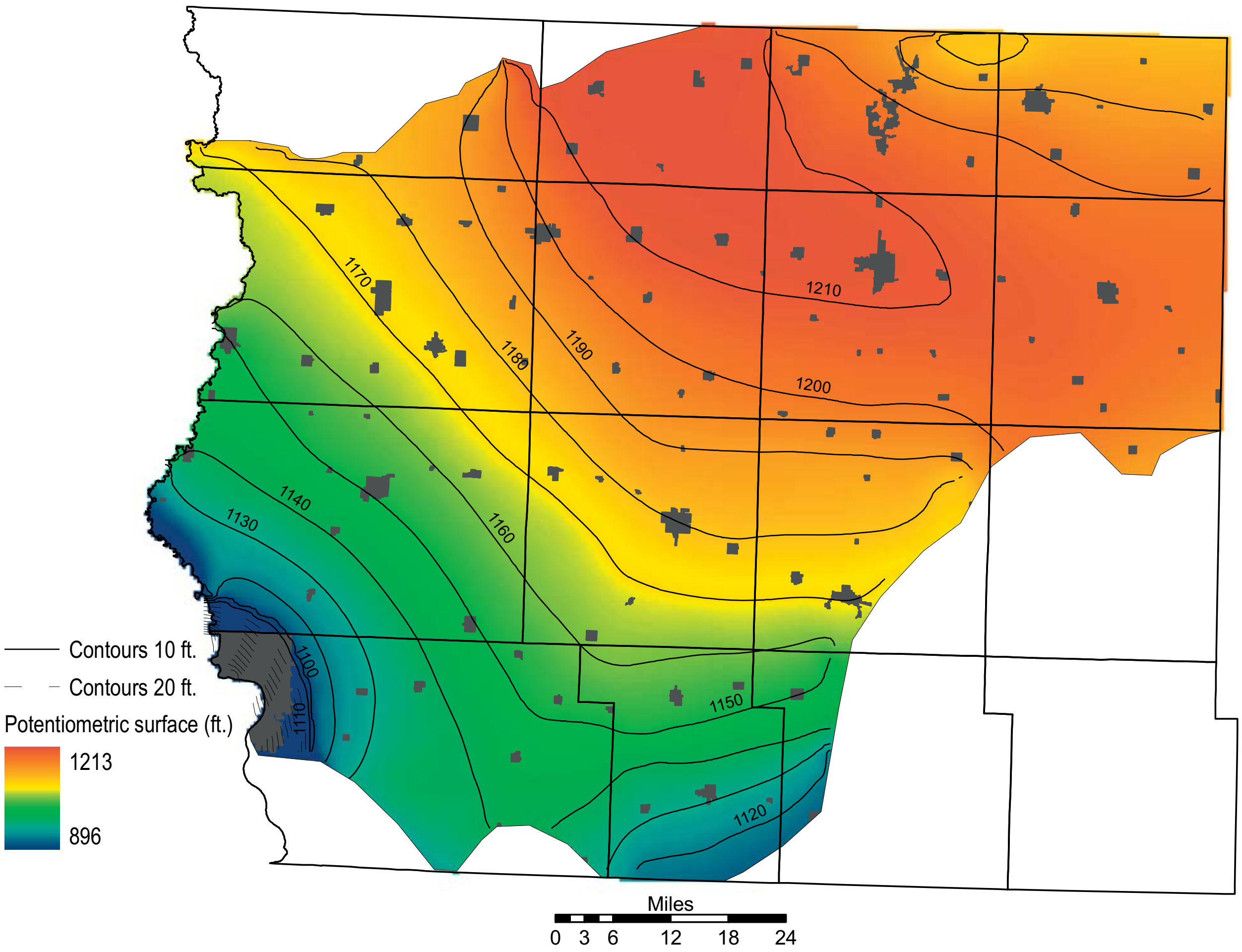


Figure 34. Simulated potentiometric surface steady-state.

tion wells. The time series data was provided by the Watershed Monitoring and Assessment Section of the IDNR, and collected by the United States Geological Survey under contract with the IDNR.

Production data

The transient model used pumping data from year 2001 through 2006, and included public wells, industrial wells, irrigation wells, and other permitted users with daily usage greater than 25,000 gallons. This data was downloaded from the IDNR Water Use Database, and included a total of 92 water-use permits. The spatial distribution of the water use wells are shown in Figure 35. The seasonal variations in water usage were factored into the input values. When possible, actual monthly usage was entered. If monthly data was not available it was assumed that summer usage was approximately 50% higher than winter usage. Production data for irrigation wells was approximated using total annual production divided by the number of days the wells were used. In most cases agricultural irrigation usage varied from 60 to 90 days, and golf course irrigation varied from 90 to 200 days. The production well data is included in Appendix B.

The model also included approximately 1,900 private wells with daily usage that varied from

Table 7. Sensitivity analyses.

Parameter	% Adjustment	RMSE (meters)	RMSE (feet)
Recharge	-50%	No Convergence	---
Datum Figure 30	100%	5.3	17.3
	300%	8.9	29.2
Hydraulic Conductivity (Steady-state)	0%	4.517	14.8
Datum Figure 28	50%	3.84	12.6
	-50%	7.54	24.7
	100%	3.69	12.1
	300%	3.79	12.4
Hydraulic Conductivity (Transient)	0%	2.879	9.44
Datum Figure 28	50%	2.902	9.51
	-50%	3.15	10.3

400 gallons per day for a rural home, to 1,000 gallons per day for livestock. The well locations were obtained from GEOSAM and the private well tracking system databases. The private well production values were based on an average family size of 4, and an additional 600 gallons per day for farm use. Obviously there are many livestock farms that use more than 1,000 gallons per day, but it is difficult to determine which farms have livestock and which ones do not. The larger livestock producers would need a water-use permit if their daily usage exceeds 25,000 gallons per day. The spatial distribution of the private wells is shown in Figure 36.

Time Series Data

The use of time series water level data is extremely valuable for evaluating the transient response of groundwater flow models to pumping stress. For the Lower Dakota aquifer model there were a total of eleven (11) observation wells that had time series water level data as shown in Figure 37. A winter water level measurement and a midsummer water level measurement were included for each year to observe the model response to a higher summer usage period versus a lower winter time usage period. Figures 38 through 48 compare the observed head elevations with the simulated head elevations for the eleven time series data sets. The simulated results indicate the transient model correlated relatively well with the observed results. The simulated results indicate that the model slightly under-predicts head values in observation wells W-24556, W-25965, and W-25114. The simulated heads in the remaining wells closely followed the observed values and varied primarily in datum elevation only.

Continuing the monitoring well network is crucial for the future evaluation of the Lower Dakota aquifer model as a predictive tool. It would also be helpful to add additional observation wells, especially near the major water-use zones as identified in the zone budgeting section of this report. Having observation well data near the major water-use zones would more accurately measure the effects of pumping stress on the aquifer.

The eleven wells used in the time series evaluation were also used together to compare summer usage to winter usage. Figures 49 and 50 show the observed versus the simulated head values for July 2006 and December 2006. The correlation coefficients are identical, and the RMSEs are 2.879 meters (9.44 feet) in July versus 2.889 meters (9.48 feet) in December.

Summer usage versus winter usage.

The approximate daily water use in millions of gallons per day (mgd) for summer and winter pumping seasons are shown in Figures 51 and 52, and the percentages of the total are also shown.

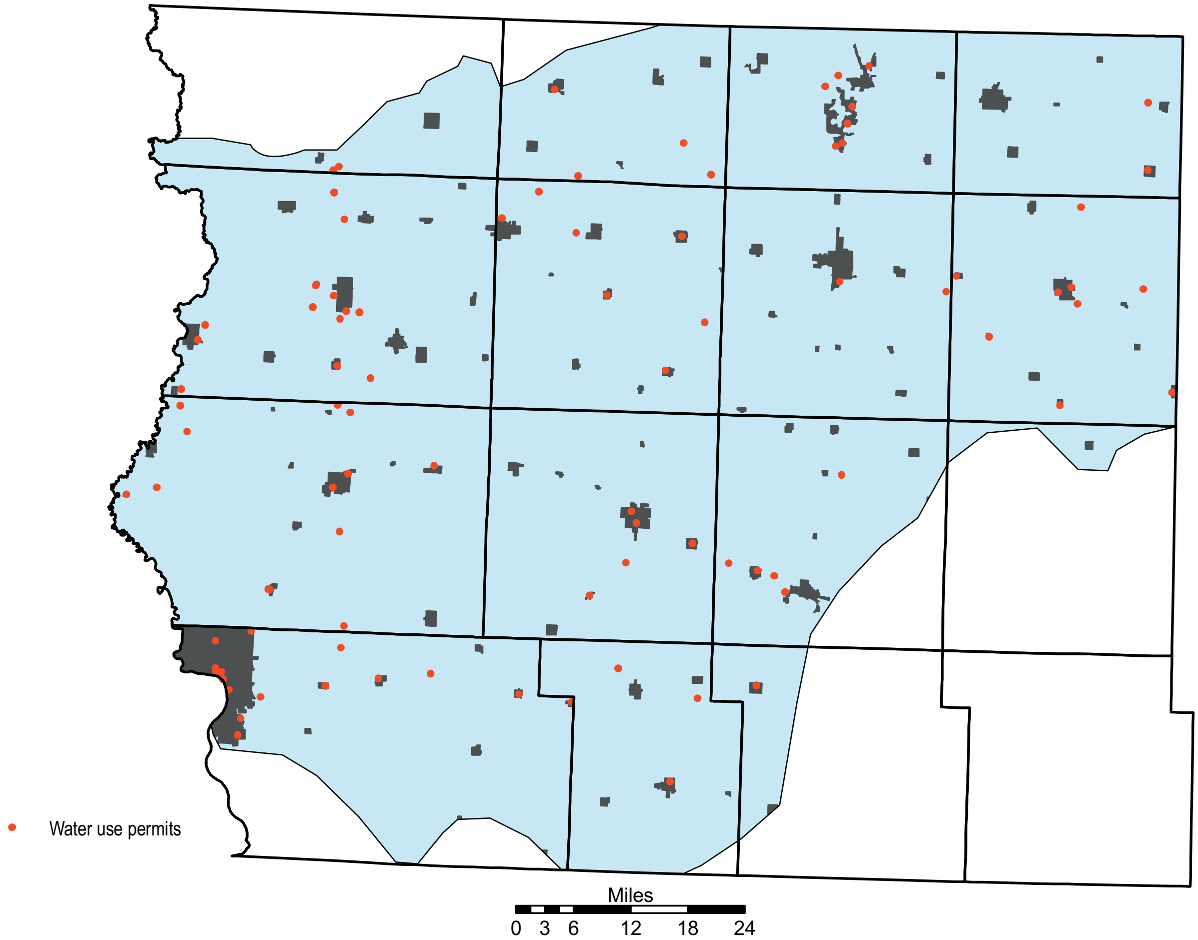


Figure 35. Water-use permits used for transient simulation.

The largest withdrawals in the Lower Dakota aquifer are for public water supplies, which vary from 12.8 mgd during the winter to 17.7 mgd during the summer. Agricultural usage varies from 1.5 mgd during the winter to 9 mgd during the summer. Most of this usage was related to irrigation. Industrial usage remained relatively constant at 1.8 mgd.

Total yearly withdrawals for various users from 2001 through 2006 are shown in Figure 53. Increased usage in irrigation from the Lower Dakota aquifer may occur if corn prices continue at record high levels. The number of new irrigation permits could also accelerate if a drought or dry summer occurs. An increase in industrial water use will occur when several new ethanol plants go on-line. Additional permits have been issued for the VeraSun plant in Hartley, Iowa, and Superior Ethanol near Superior, Iowa, which will add approximately 3.2 mgd to the industrial usage total.

Figures 54 and 55 show the simulated potentiometric surfaces for the summer of 2006 and the winter of 2006. The main difference in the two surfaces is the increase in drawdown in the Le Mars area, and the prominent drawdown in eastern Clay County caused by the Clasing, Inc. irrigation permit. It should be noted that the Clasing Inc. permit had the second highest peak daily discharge in 2004 (exceeded only by the City of Sioux City). By December of 2006 the cone of depression caused by the Clasing irrigation well(s) had almost completely recovered.

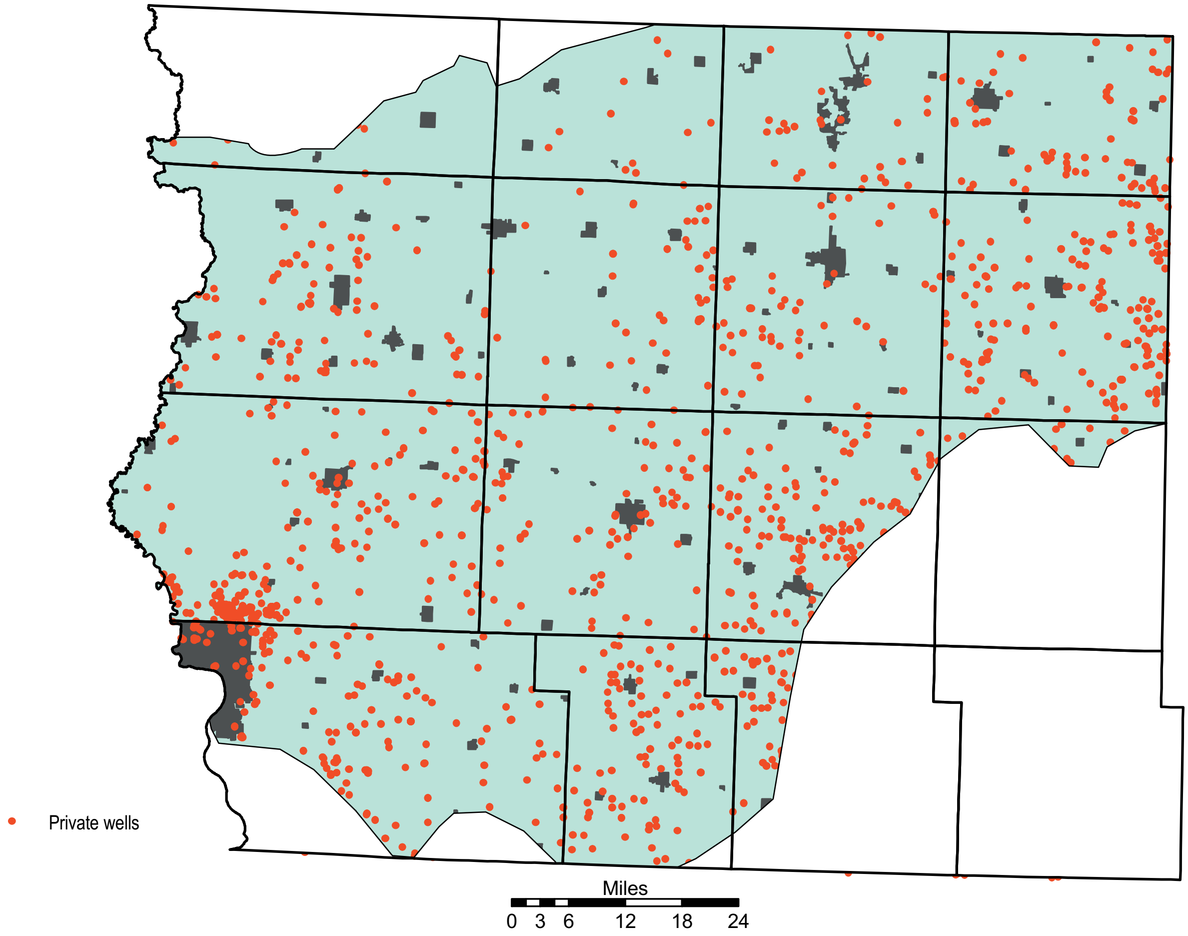


Figure 36. Private wells used as pumping centers in transient model.

ZONE BUDGETING

Zone budgeting is a powerful management tool in Visual MODFLOW Version 4.2 that allows the user to conduct water balance analyses within specified zones or areas. This is especially useful in major producing areas to evaluate permit allocation questions, and to assess the groundwater available for future development. The use of zone budgeting reduces the risk of over-allocation and the potential for severe well interference and/or groundwater mining.

Zone Locations

A total of eleven zones were delineated in the Lower Dakota aquifer as shown in Figure 56. The zones were chosen for their relatively high current pumping rate, or anticipated high future usage (a water-use permit that has been approved, but the wells have not yet gone on-line). The shape of each polygon was drawn to include the various water use permits in each zone. An attempt was made to try and make the area of each zone approximately equal. The results for each of the zones using water use data from the summer 2006 and winter 2006 can be found in Appendix C. For zones with high future usage the permitted withdrawal amount was used in the analyses. The summer of 2006 was chosen based on the highest peak water usage for the period 2001 to 2006. The winter of 2006 water usage was an average non-peak usage period.

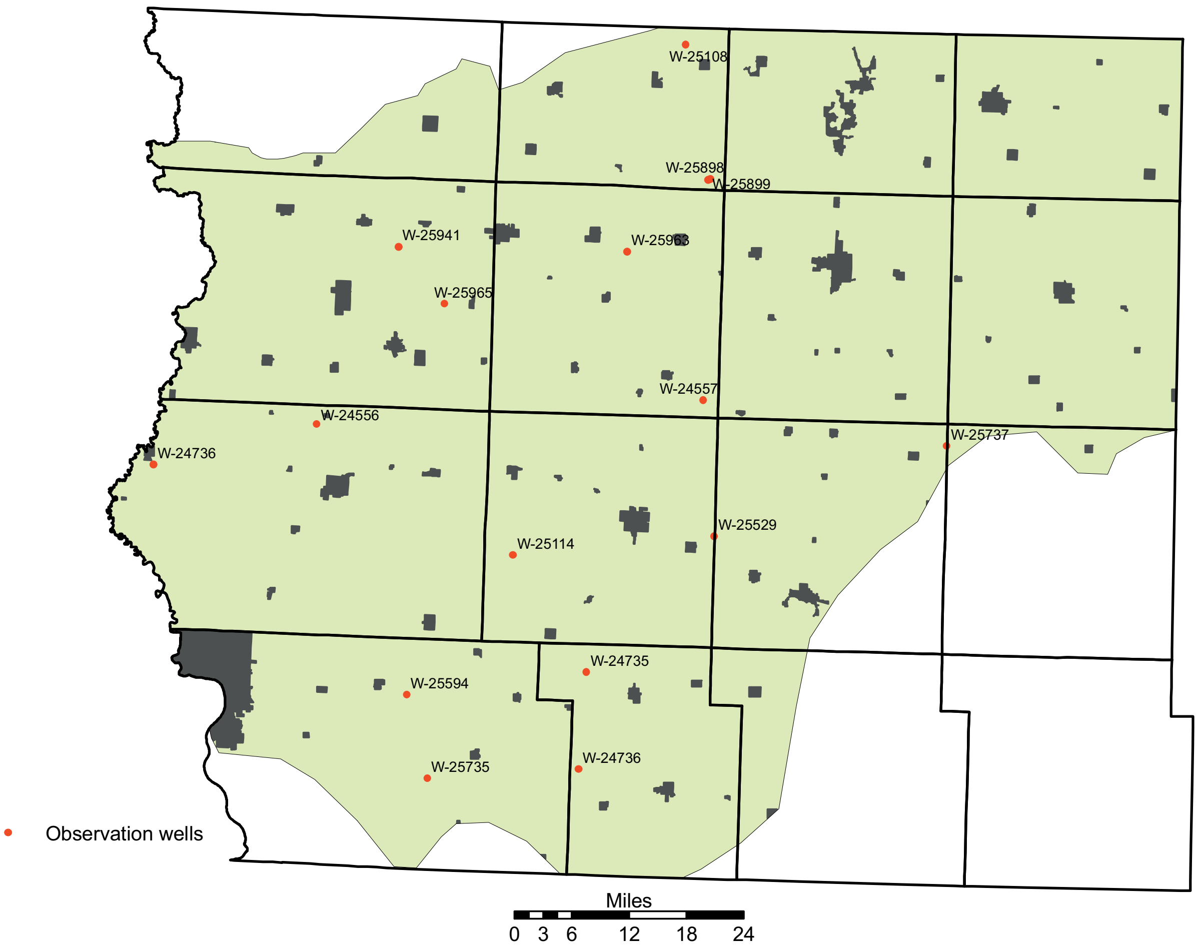


Figure 37. Observation well locations for time series data wells. Wells W24735, W25529, W25737, W25898, and W25963 either had too few measurements or were located near another observation well.

The use of water budgets or water balance equations to predict long-term groundwater availability is a powerful tool, but it does have limitations. Limiting total production to below the recharge rate does not ensure sustainability, because well locations do not conform to the capturable recharge (Harden, Griffin, and Nicot, 2007). In addition, recharge is only one factor in the water balance equation. Other factors that can be of equal or greater importance include groundwater inflow minus outflow, changes in aquifer storage, and river boundary contributions. The groundwater inflow minus outflow is especially important in thick confined aquifers with relatively high transmissivities, which is exhibited by a large portion of the Lower Dakota aquifer.

Groundwater Availability Regionally

The water budget for the Lower Dakota aquifer indicates a recharge rate of 38.4 mgd. Total pumping during the winter was estimated to be 20.3 mgd, increasing during the summer to 31.6 mgd. One method to evaluate groundwater availability is to divide the pumping rate by the recharge rate (Q/R). The Q/R value is primarily used to compare areas or zones within an aquifer that may be under stress or risk of groundwater mining. A relatively high Q/R does not necessarily mean that groundwater mining is occurring, because groundwater inflow, changes in storage, or river recharge may be supplying groundwater to the system. A high Q/R should alert water planners and hydrologists that a more detailed evalu-

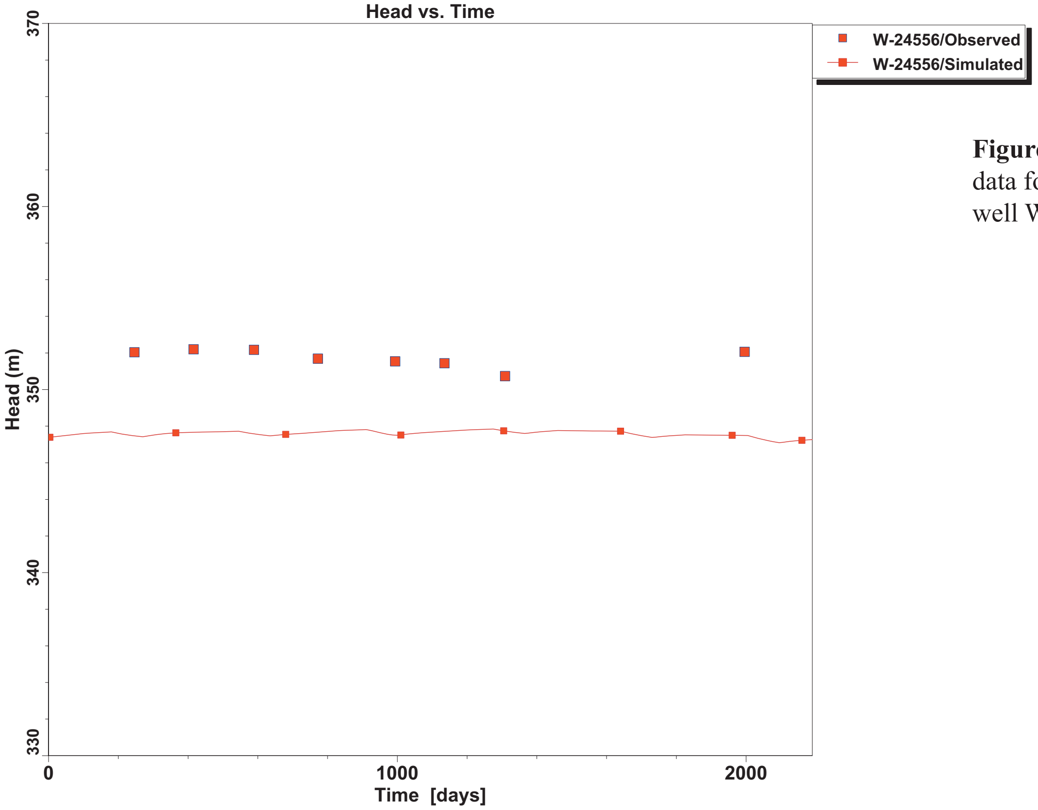


Figure 38. Time series data for observation well W-24556.

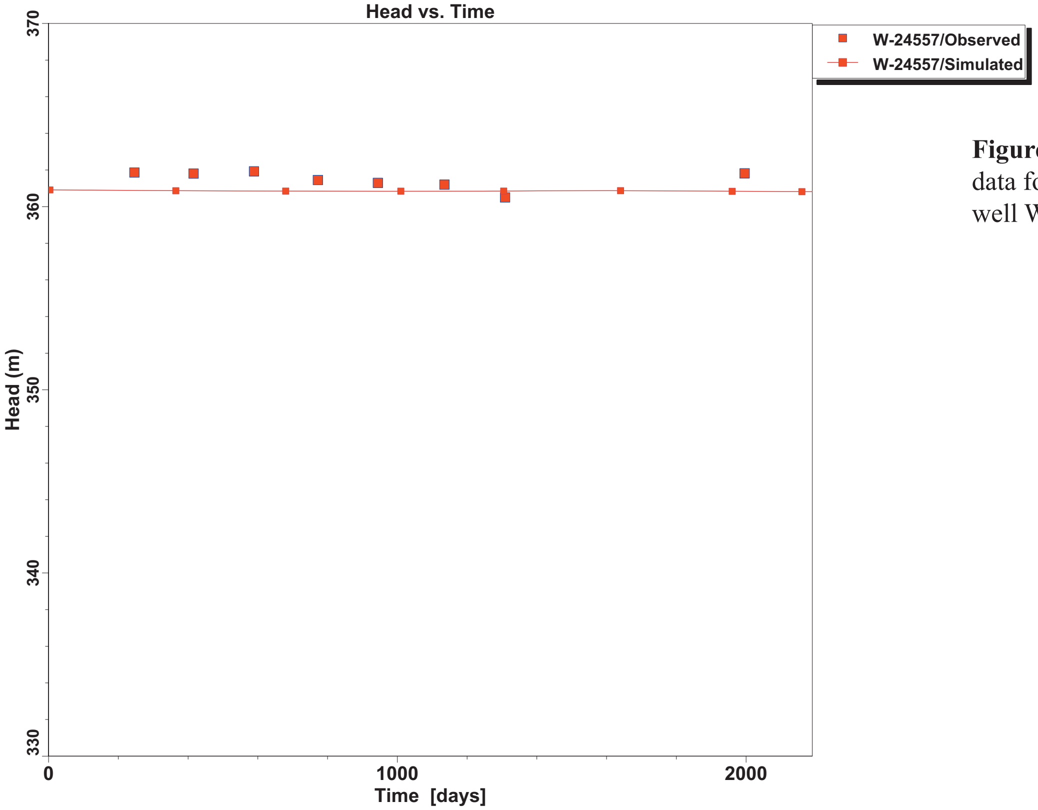


Figure 39. Time series data for observation well W-24557.

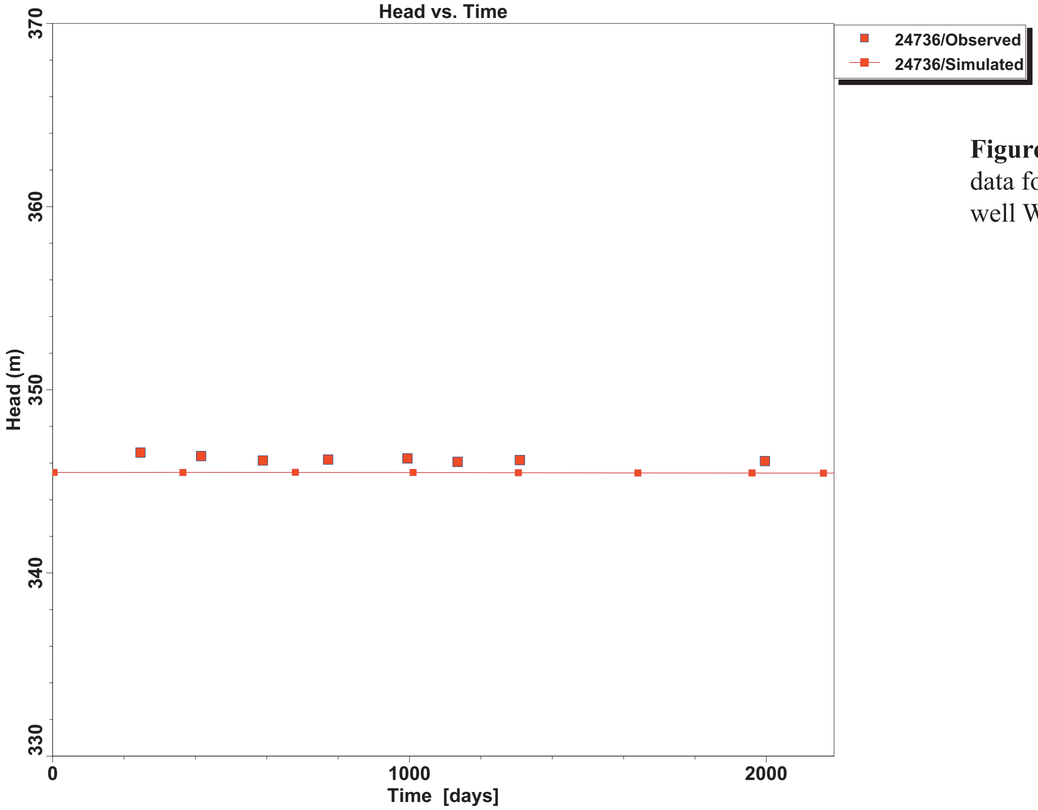


Figure 40. Time series data for observation well W-24736.

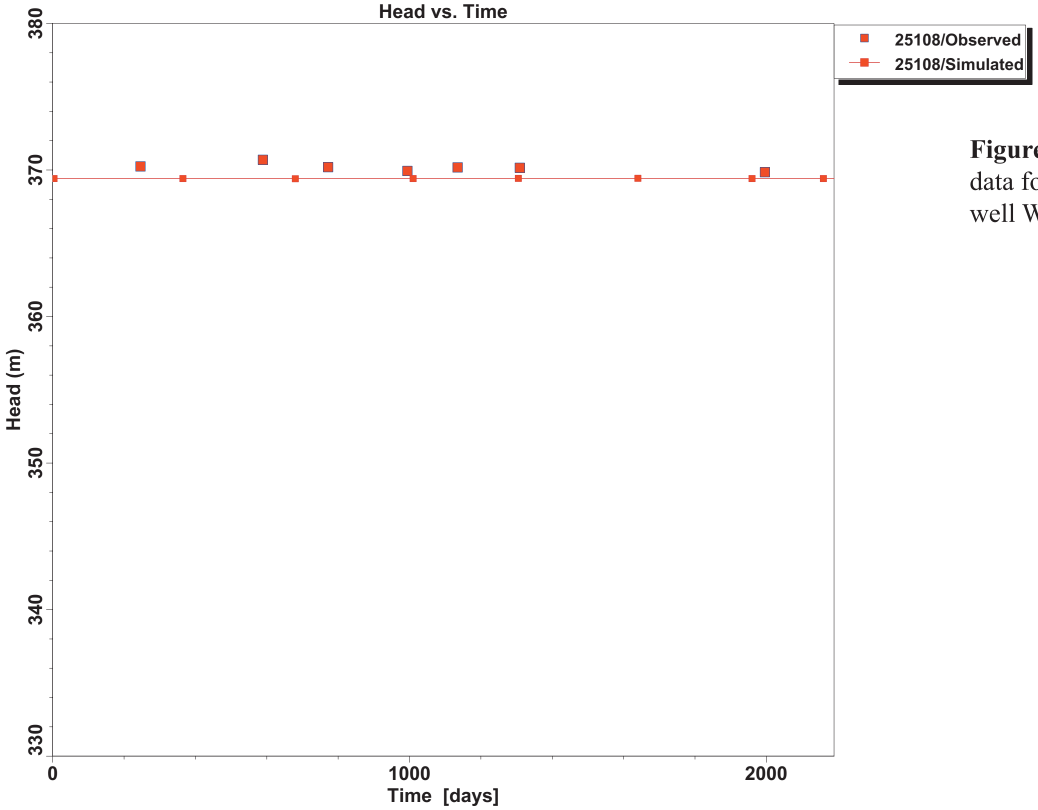


Figure 41. Time series data for observation well W-25108.

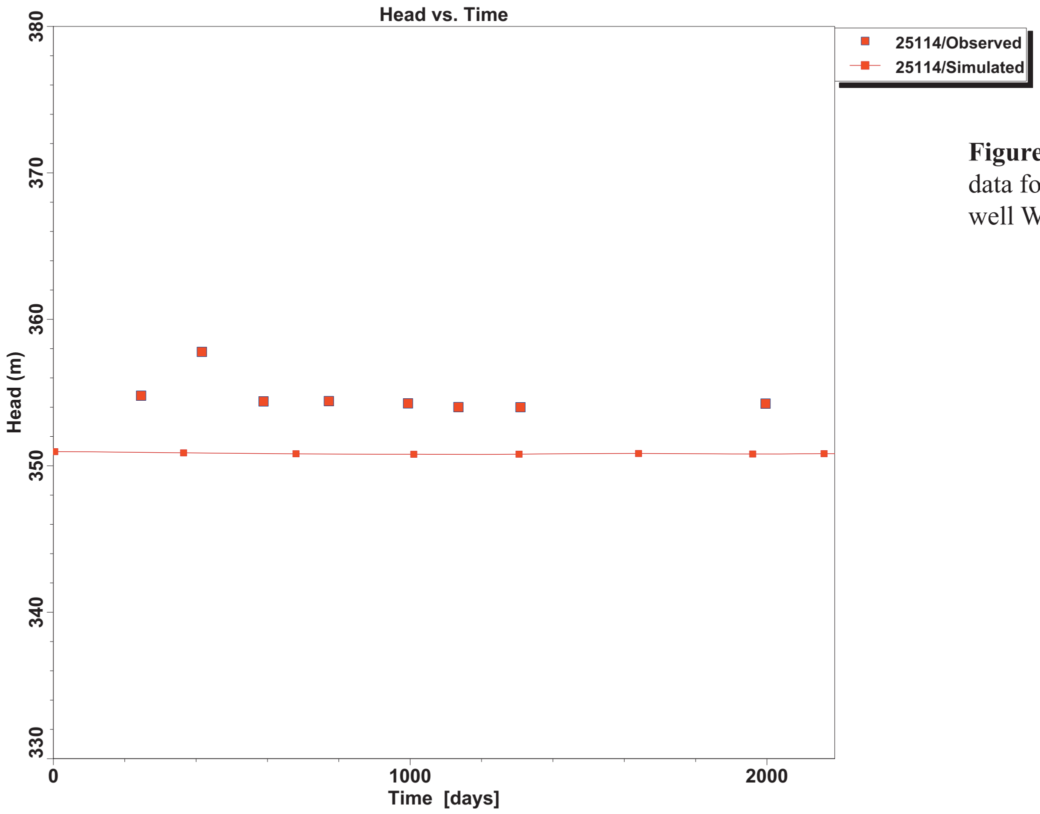


Figure 42. Time series data for observation well W-25114.

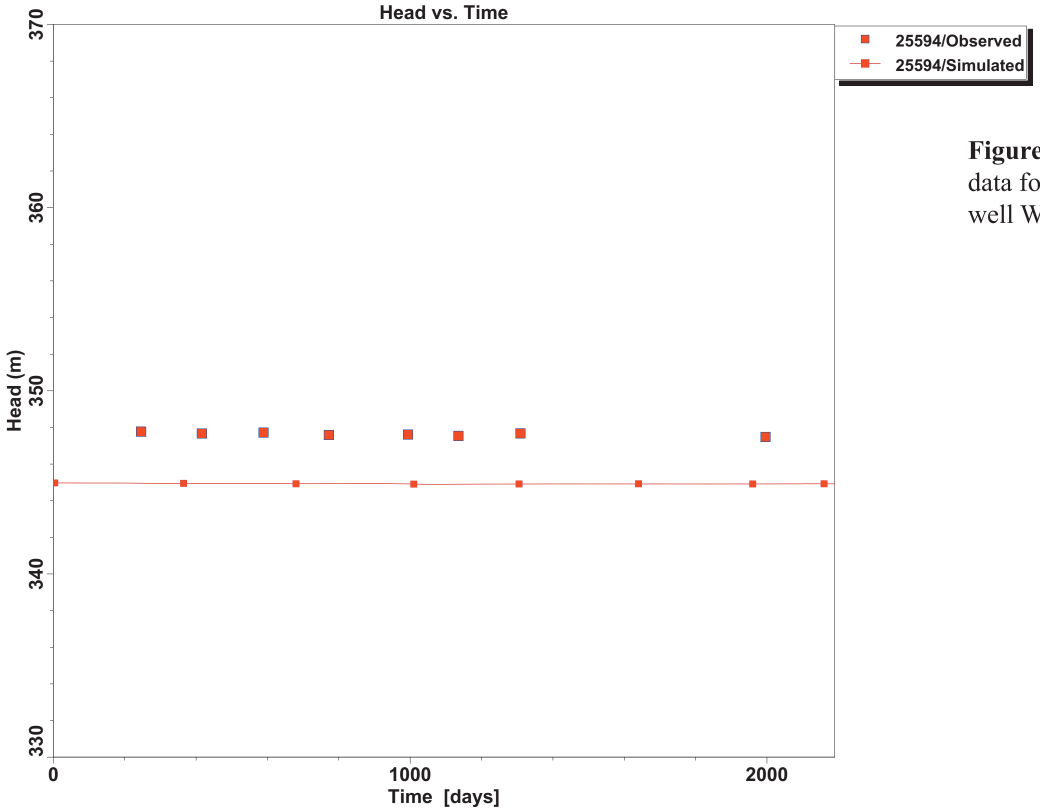


Figure 43. Time series data for observation well W-25594.

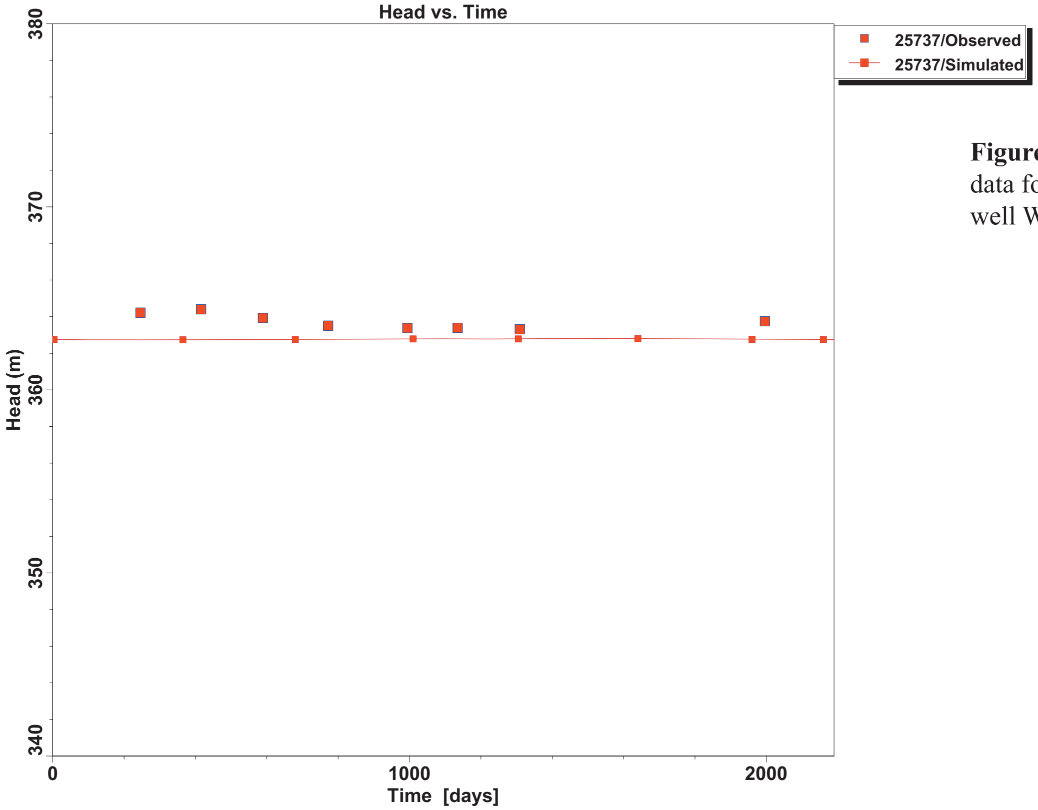


Figure 44. Time series data for observation well W-25737.

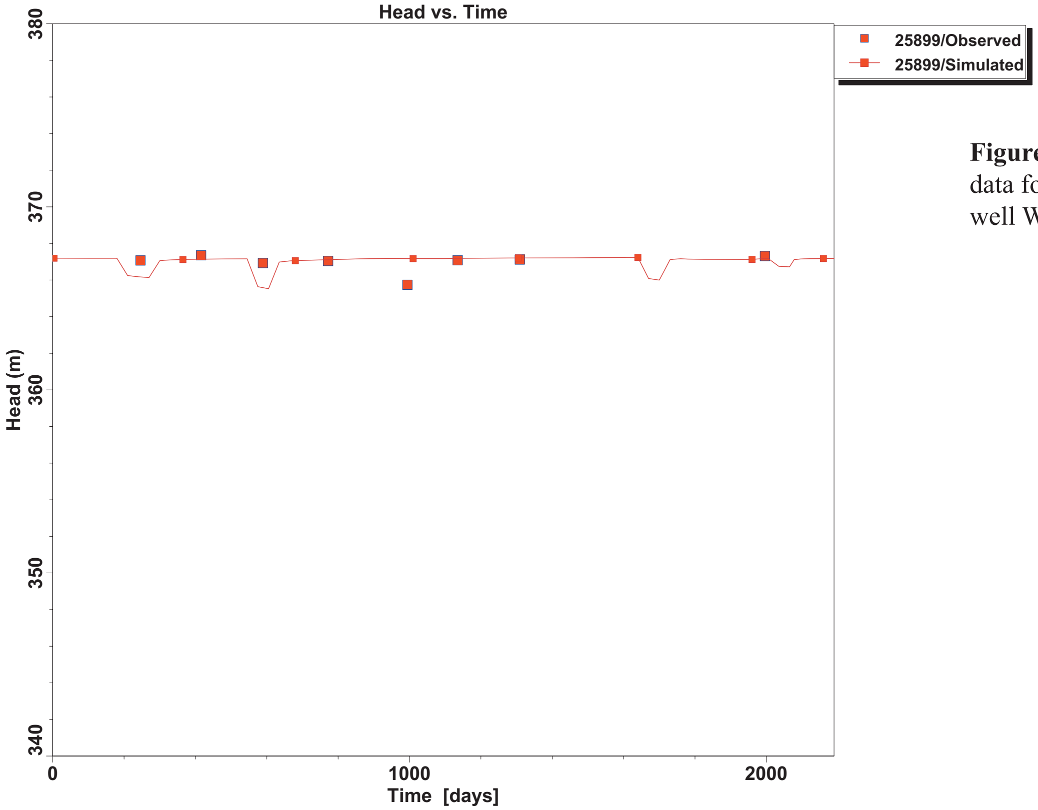


Figure 45. Time series data for observation well W-25899.

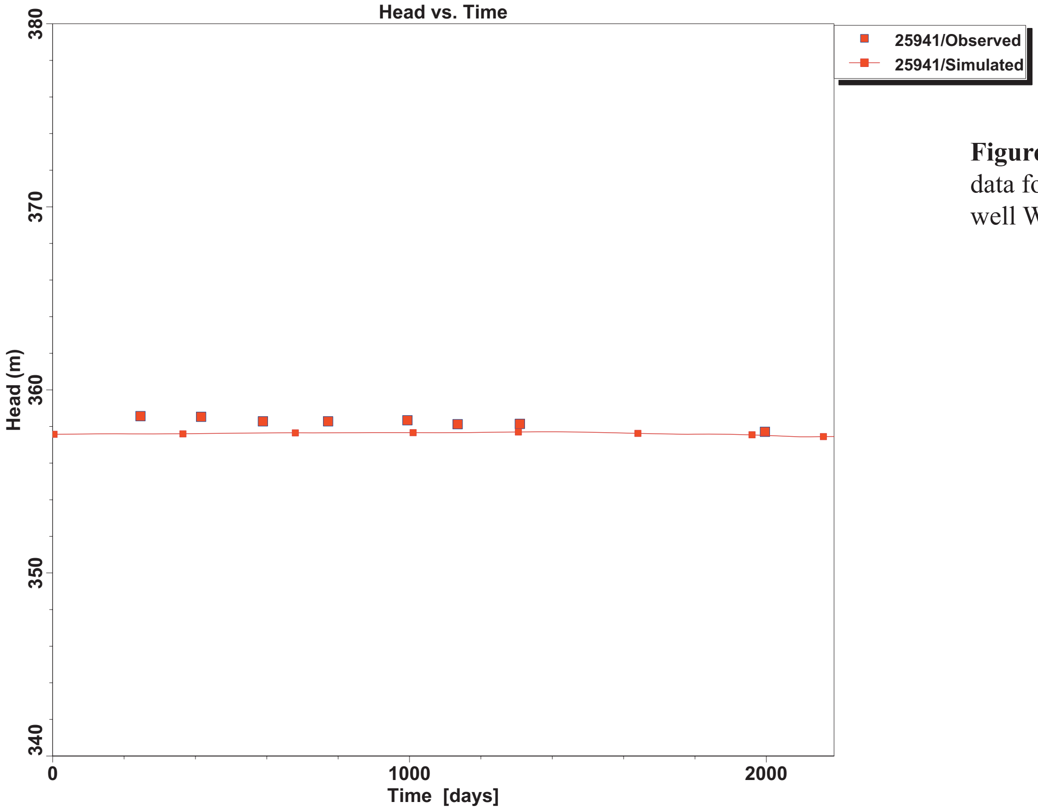


Figure 46. Time series data for observation well W-25941.

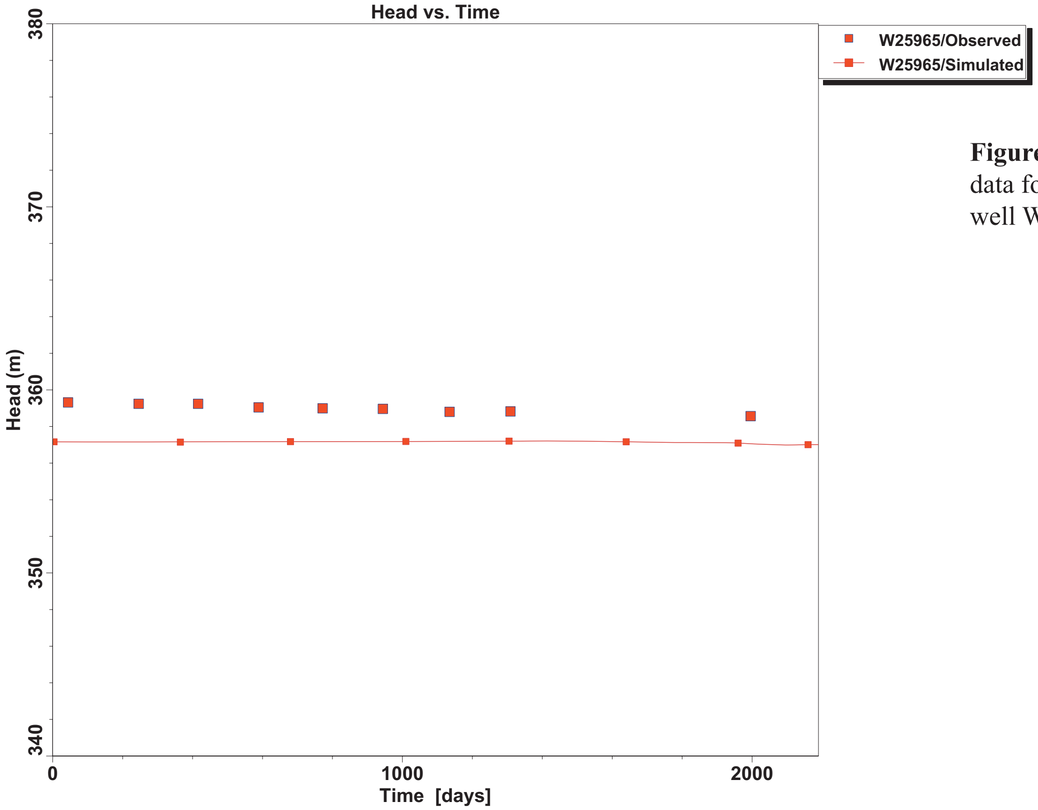


Figure 47. Time series data for observation well W-25965.

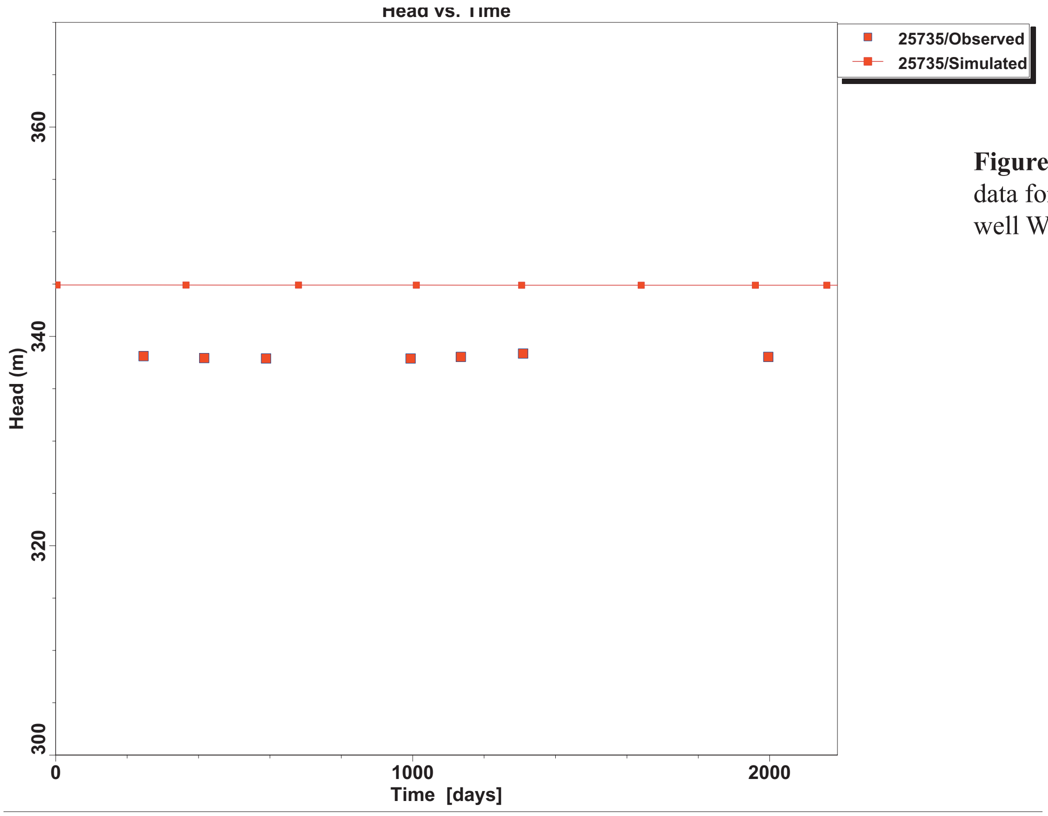


Figure 48. Time series data for observation well W-25735.

ation and/or local model simulation should be conducted.

The regional ratio of pumping rate to recharge rate (Q/R) in the Lower Dakota aquifer is 0.53 in the winter and increases to 0.82 in the summer. This compares to a Q/R of between 20 and 30 in the Ogallala aquifer in North Texas (Dutton, Reedy, & Mace, 2001), which has experienced substantial groundwater mining.

Based on the regional water budget, the Lower Dakota aquifer does not appear to be experiencing substantial drawdown or long term sustainability issues. This does not mean that there is no local stress or substantial drawdown concerns within major pumping centers. Based on the use of Zone Budgeting, local aquifer stress, long term availability, and water budgets can be simulated.

Zone Budgeting for Winter Usage

Table 8 summarizes the water budgets for each of the eleven zones during an average winter water usage period (December 2006 plus new permits). The top three water usage zones include:

1. Sioux City - 4.6 million gallons per day (mgd)
2. Storm Lake – 3.3 mgd
3. Le Mars – 3.1 mgd

The Q/R ratios for each of the zones is also summarized in Table 8. They vary from 0.05 in the rural areas to 14.8 in the Le Mars zone. The relatively high pumping rate at Le Mars is more than offset by the high transmissivity value and groundwater inflow minus outflow value of 3 mgd. If the recharge rate was the only water balance variable considered, the Lower Dakota aquifer in the Le Mars area would appear to be extremely stressed, and moderate groundwater mining would be taking place. The relatively high hydraulic conductivity of 50 feet/day, plus an average sandstone thickness of between 200 and 300-feet, allows for a large inflow of groundwater to the zone.

Obviously, the Lower Dakota aquifer in the Le Mars area could be stressed beyond its sustainable rate. The sustainable pumping rate for the Le Mars zone will be addressed in the Predictive section of this report.

The Storm Lake Q/R ratio is 11.4 during the winter or non-peak usage period. The difference in recharge rate versus pumping rate is made up by groundwater inflow into the zone and storage. Approximately 900,000 gallons per day is coming from storage, which indicates the aquifer is under stress. There is some uncertainty in how much higher future pumping rates can be increased in the Storm Lake zone. Unlike the Le Mars Zone, which has a sandstone thickness that averages between 200 and 300 feet, the Lower Dakota sandstone in the Storm Lake area is only 100 to 180 feet thick or less. This limits the groundwater inflow that can occur during pumping stress. The sustainable pumping rate for the Storm Lake zone will be addressed in the predictive section of this report.

The Sioux City Q/R ratio is only 0.32, which is largely a function of the high recharge rate in the Missouri River Valley of 3-inches per year, and the close hydraulic connection between the Missouri River alluvium and the underlying Dakota sandstone. The 3-inches per year of recharge corresponds to a recharge volume of 14.5 mgd, which exceeds the pumping rate of 4.6 mgd.

Zone Budgeting for Summer Usage

Table 9 summarizes the water budgets for each of the eleven zones during a high water usage period (July 2006 plus new permits). The top four water usage zones include:

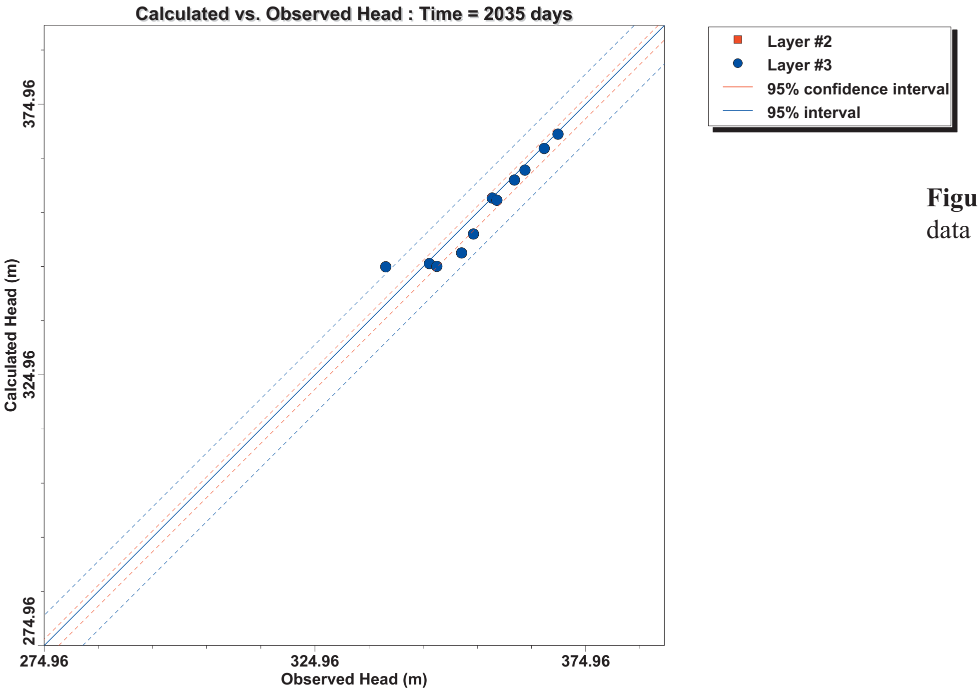
1. Sioux City - 9.1 mgd
2. Le Mars – 4.15 mgd
3. Storm Lake – 3.3 mgd
4. Clasing, Inc. (irrigation Permit)
   – 3 mgd (4.9 mgd in 2004)

The Q/R ratios for each of the zones is also summarized in Table 9. They vary from 0.21 in the rural areas to 19.8 in the Le Mars zone. The Q/R ratio for Le Mars represents the higher summer water usage, and the corresponding stress on the Lower Dakota aquifer. Approximately 730,000 gallons per day is coming from storage during the summer. The loss in storage appears to be off-set by a gain in storage during the winter or non-peak usage period. The Storm Lake Q/R ratio remains at 11.4 during the summer water usage period.

The Sioux City water budget does not show a net loss even though the pumping rate increases to 9.1 mgd. The increase in the summer pumping rate is off-set by 14.5 mgd of recharge. Based on the water balance in the Sioux City area, there does not appear to be concern related to groundwater mining due to the large amount of recharge from the Missouri River alluvium, groundwater inflow minus outflow, and the induced recharge from the Missouri River itself. The sustainable pumping rate for the Sioux City zone will be addressed in the Predictive section of this report.

The Clasing, Inc. (irrigation permit) water-use permit had a usage of 3 mgd during the summer of 2006. The Q/R was 7.8 and there was a temporary net loss of groundwater out of this zone. The water balance in this zone easily recovers during the 9-months of lower usage when the Q/R ratio is only 0.33.

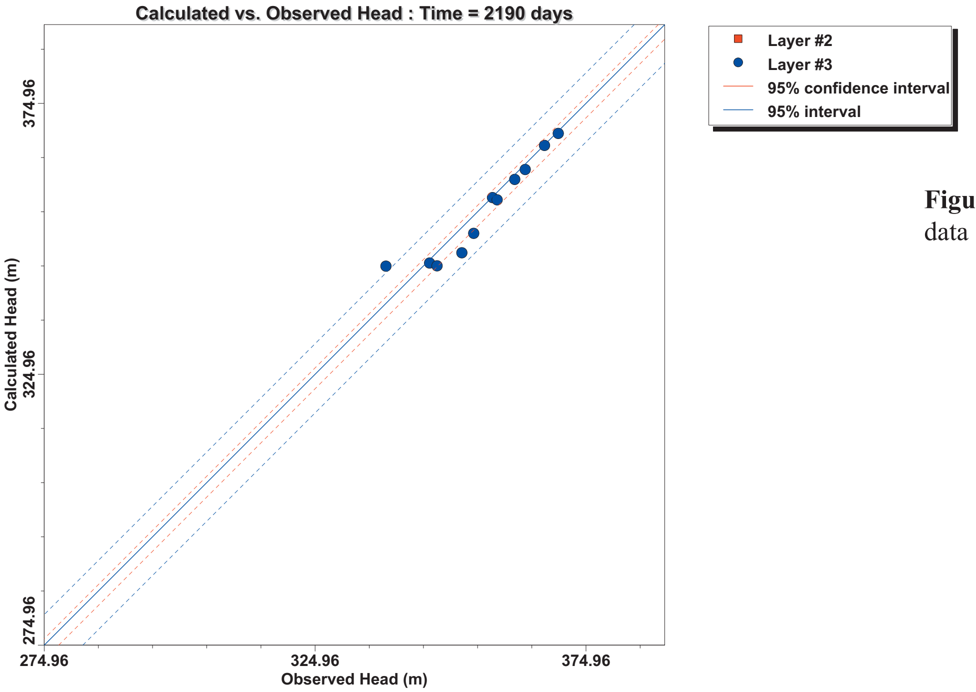
The highest recorded usage (2001 to 2006) for the Clasing Inc. permit was 4.9 mgd in the summer of 2004, and the Q/R ratio was 12.3. During the summer of 2004, the Clasing zone had the second highest pumping rate of the eleven major producing areas. The Clasing, Inc. permit illustrates the significance of irrigation within the Lower Dakota aquifer. If a moderate to severe drought impacts northwest Iowa the state may see addi-



Max. Residual: 6.867 (m) at 25735/NONE
Min. Residual: -0.099 (m) at 25941/NONE
Residual Mean : -0.766 (m)
Abs. Residual Mean : 2.015 (m)

Num. of Data Points : 11
Standard Error of the Estimate : 0.87 (m)
Root Mean Squared : 2.857 (m)
Normalized RMS : 8.983 (%)
Correlation Coefficient : 0.955

Figure 49. Calibration data for July 2006.



Max. Residual: 6.865 (m) at 25735/NONE
Min. Residual: -0.115 (m) at 25899/NONE
Residual Mean : -0.747 (m)
Abs. Residual Mean : 1.995 (m)

Num. of Data Points : 11
Standard Error of the Estimate : 0.876 (m)
Root Mean Squared : 2.868 (m)
Normalized RMS : 9.018 (%)
Correlation Coefficient : 0.954

Figure 50. Calibration data for December 2006.

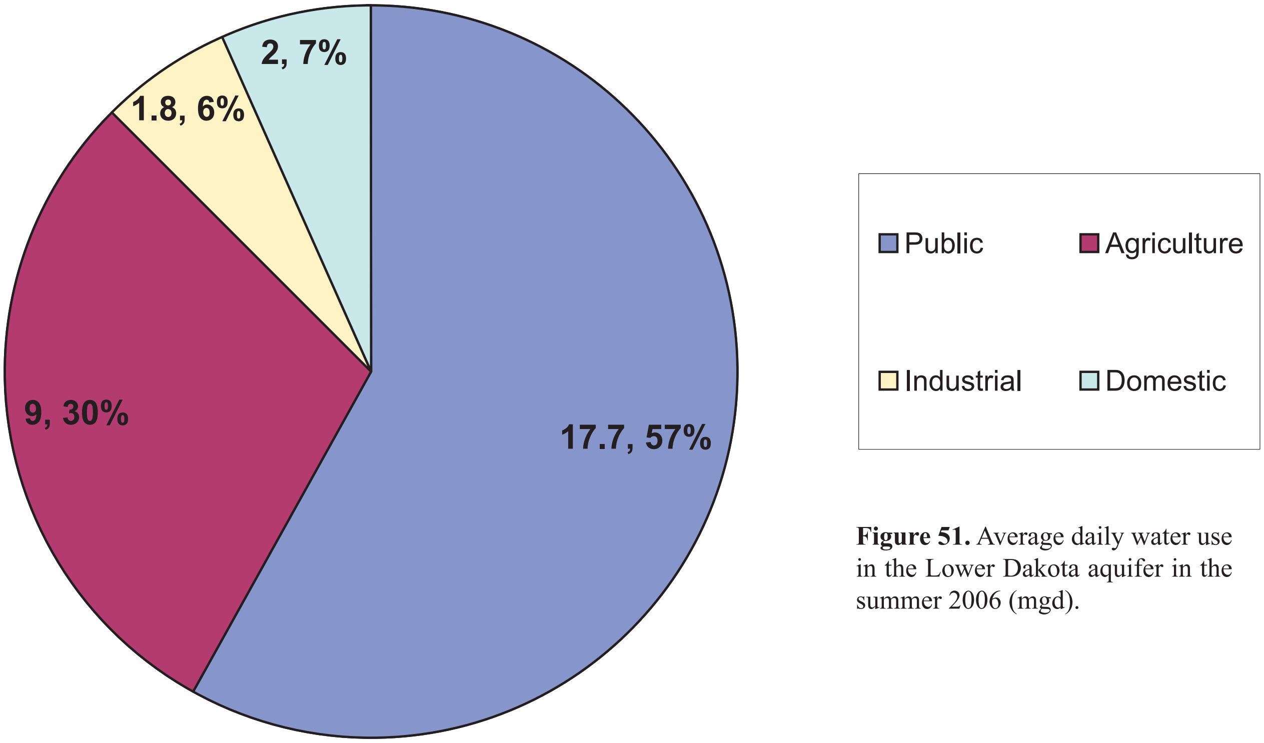


Figure 51. Average daily water use in the Lower Dakota aquifer in the summer 2006 (mgd).

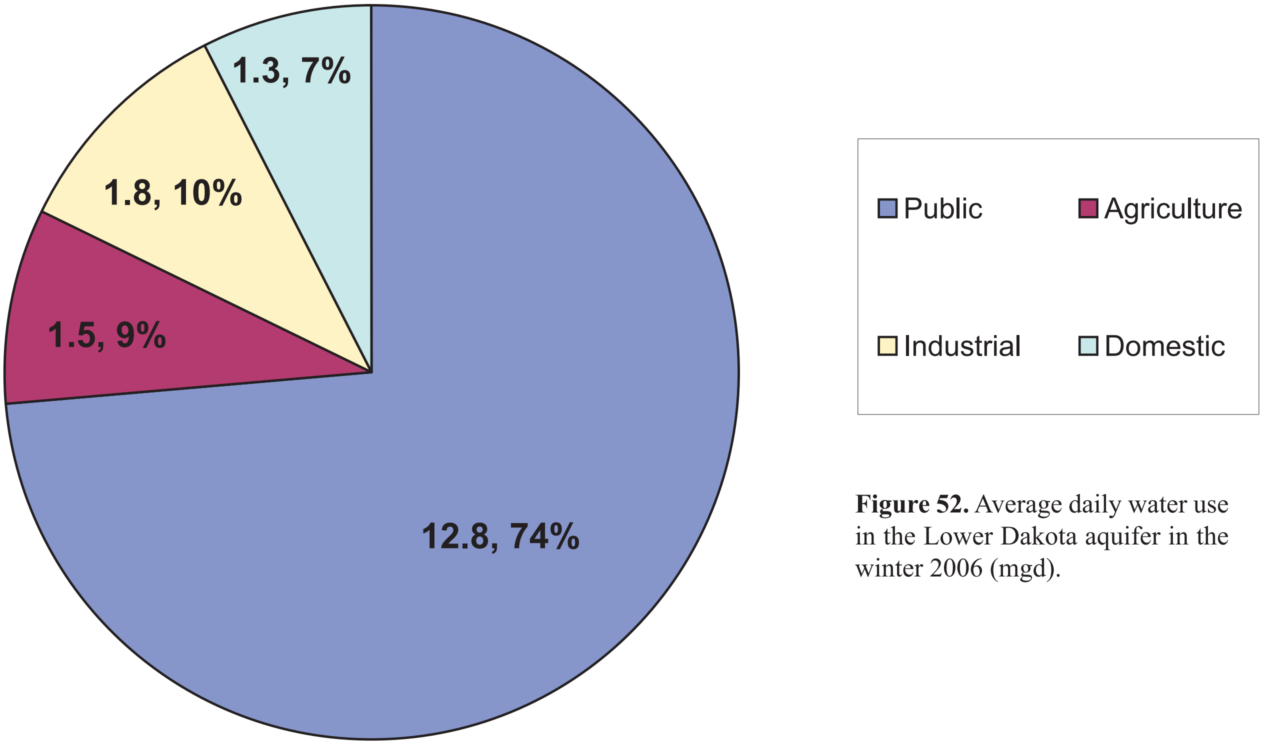


Figure 52. Average daily water use in the Lower Dakota aquifer in the winter 2006 (mgd).

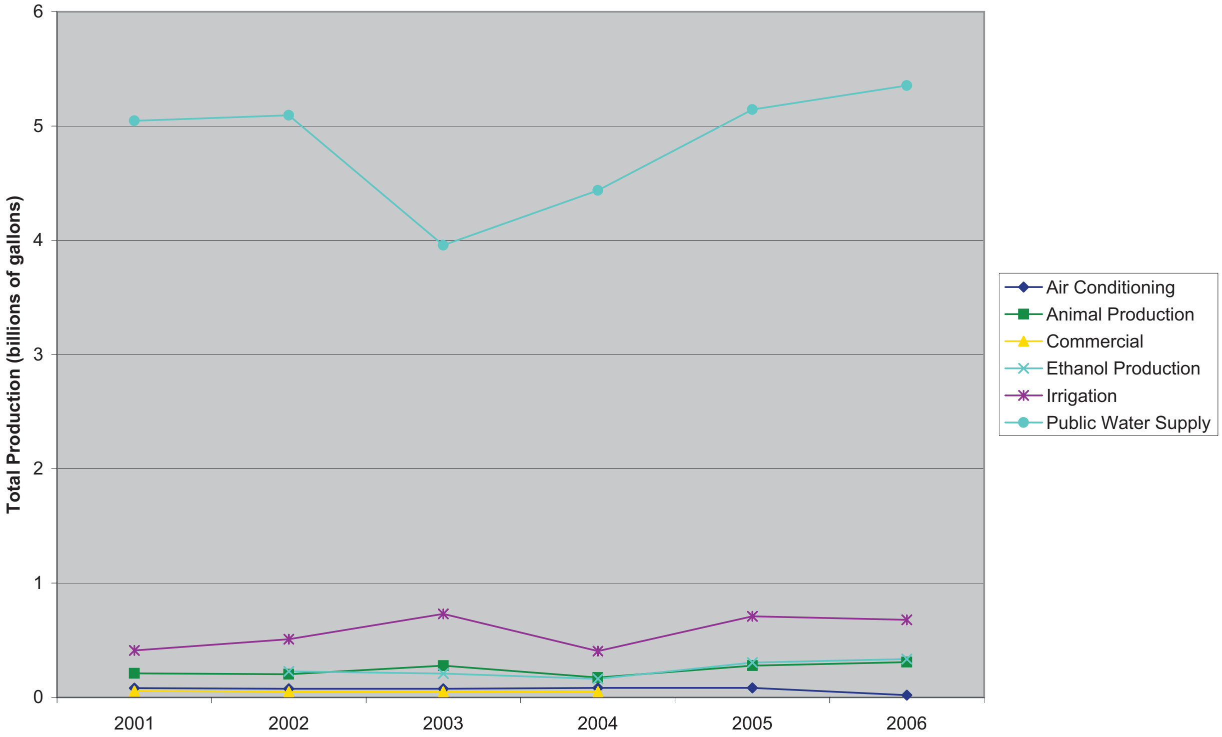


Figure 53. Total yearly water use for years 2001 through 2006 minus domestic use (billion gallons per year).

tional irrigation permit applications, especially if commodity prices continue to stay high.

Based on the water budgets, none of the eleven major groundwater pumping centers are currently experiencing long term groundwater mining. The Storm Lake area may be at or approaching its sustainable pumping rates. The Le Mars area could also be approaching its sustainable groundwater pumping rate. Some additional pumping capacity is likely available in the Le Mars area due to the high hydraulic conductivity and sandstone thickness.

PREDICTIONS FOR FUTURE USAGE

One of the most powerful uses of a calibrated regional groundwater flow model is using the model to predict future impacts to an aquifer based on various pumping scenarios. It should be pointed out that uncertainty in projected pumping rates may be the most important factor in determining the accuracy of the flow model (Konikow, 1986). Calibration error that is related to allocating pumping too many or too few wells is compounded if the projection of total future pumping does not prove accurate (Dutton, Reedy, Mace, 2001). As pointed out earlier, precipitation has little or no direct impact on the head values within most of the Lower Dakota aquifer. However, usage or pumping rates often double or triple during droughts, which can have a major impact on groundwater head values.

Even more important than actual pumping rates is predicting the approximate locations of future wells and permits. Locations for future wells are more likely within the current major producing zones, since industry and population growth generally occur in these areas. The exceptions to this would be the future expansion of the ethanol industry and additional irrigation permits.

Four different future water usages were simulated using the calibrated transient model. They

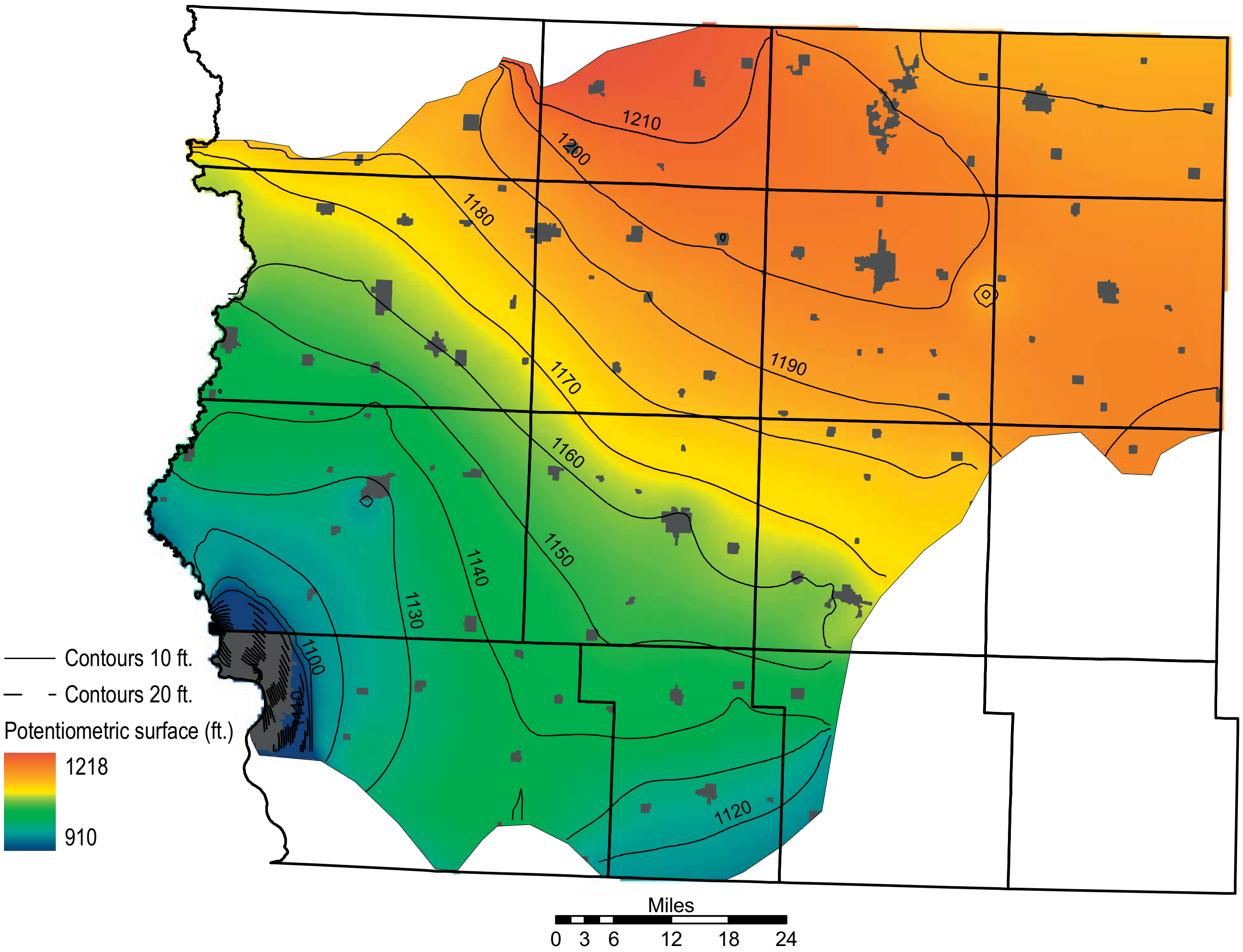


Figure 54. Simulated potentiometric surface (pressure head) for July 2006.

include a low, medium, high, and irrigation expansion prediction. Each of these simulations and the assumptions that were used are described in the following sections.

Low Future Usage

The low future usage prediction assumes a stagnant population growth, which limits the future usage to the 2001 to 2006 values plus the new water-use permits that have not gone online. For simplicity, the average daily water-use pumping rates was used throughout the year. Additional ethanol permits are predicted in Ida, Cherokee, and Sioux Counties, with an average daily usage at each of 1.6 mgd. Irrigation permits are assumed to remain unchanged. The simulated pumping period is 2008 to 2028.

Medium Future Usage

The medium usage prediction 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 again assumed to remain unchanged, and the simulated pumping period is 2008 to 2028.

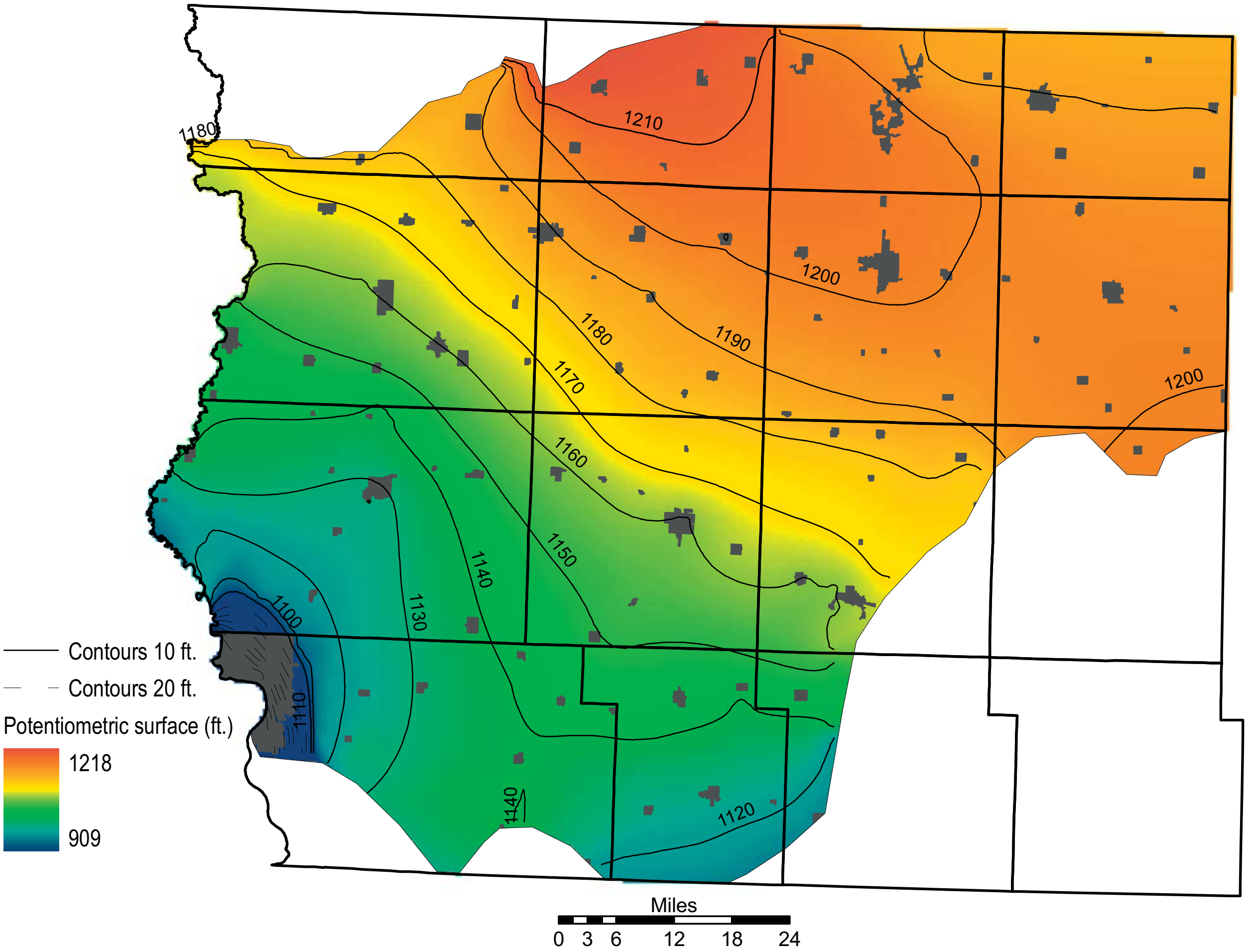


Figure 55. Simulated potentiometric surface (pressure head) for December 2006.

High Future Usage

The high usage prediction assumes a 50% increase in pumping rates 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 again assumed to remain unchanged, and the simulated pumping period is 2008 to 2028.

Irrigation Expansion

Since the expansion of irrigation permits is largely outside the major producing zones, a future-use scenario that addresses irrigation was simulated in a separate predictive model. The expansion of future irrigation permits is much more uncertain, because they are unrelated to population centers, and most of the 16-county area is 80 to 90 percent row crop acreage. It was assumed that a worse case scenario would create new irrigation permits on a five mile by five mile grid where the Lower Dakota aquifer is greater than 100-feet thick. It is also assumed that each irrigation permit has a pumping rate of 2 mgd for a 90-day pumping period (June through August). The irrigation scenario assumes a two-year back to back drought. The drought phase of the simula-

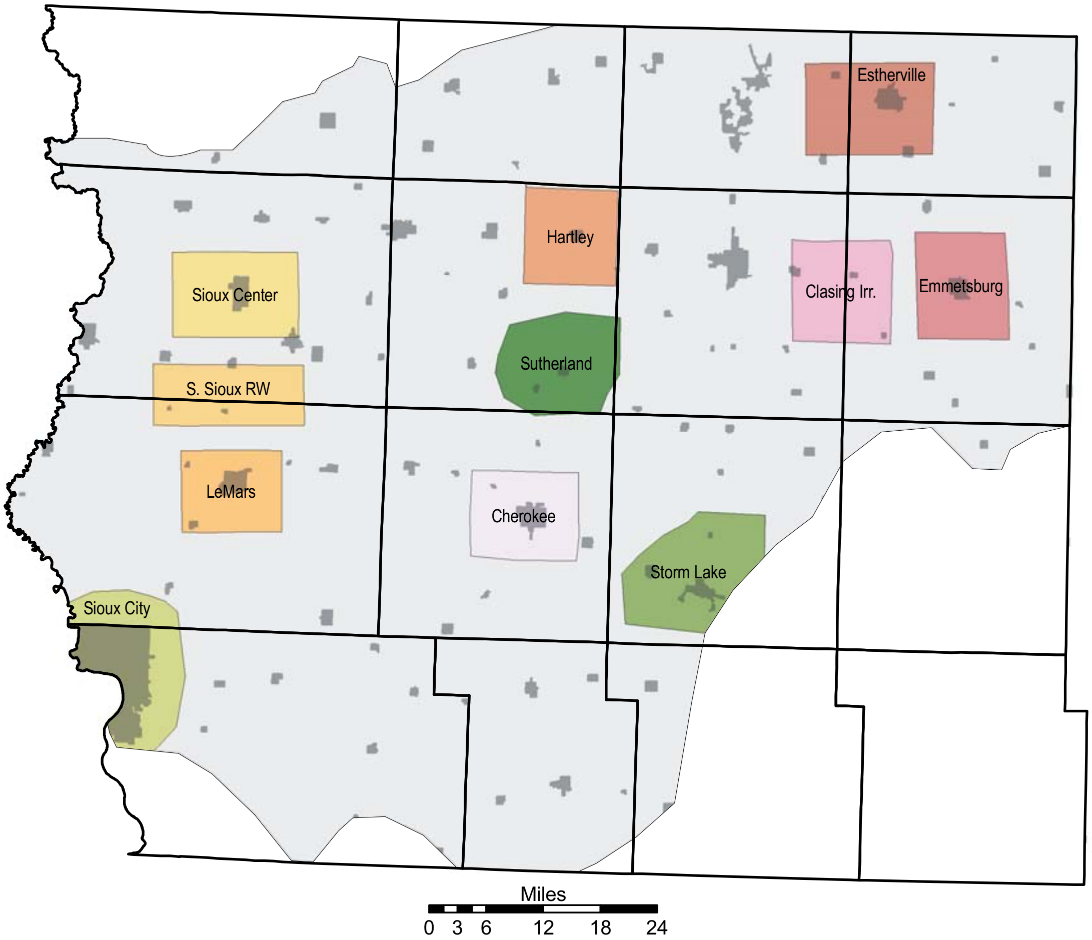


Figure 56. Zone budget locations used in localized water balance evaluation.

tion was run for 2008 to 2009. The remaining water-use permits use the medium usage pumping rate for the remaining 18-year simulation (2010 to 2028). A total of 161 additional irrigation permits were used for the irrigation expansion.

Prediction Results

For comparison purposes the additional drawdown maps were used for each of the four predictive scenarios. The initial head values used in each model simulation were the calculated head values from December 2006.

Low Future-use Results

Figure 57 shows the additional drawdown for the low future usage prediction in 2028 compared to 2006. The most significant areas of drawdown occur in the Cherokee budget zone, Storm Lake budget zone, Hartley budget zone (new ethanol plant), 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 Lower Dakota aquifer can handle the increase in water use caused by the new permits and the three proposed ethanol permits.

Medium Future-use Results

Figure 58 shows the additional drawdown for the medium future usage prediction in 2028 using a 20-year simulation period. Additional drawdown is observed near the proposed ethanol plants in Clay and Osceola counties. Additional drawdown is also observed near Storm Lake, Cherokee, and the Hartley ethanol plant. The Hartley, Storm Lake, and Cherokee areas show the largest amount of additional drawdown that ranges between 12 and 15 feet. Additional drawdowns of 6 to 12 feet are also noted in the Le Mars, Sioux Center, and South Sioux Rural Water District areas, but these appear to stabilize after 10 years of pumping.

Based on the 25% increase in pumping rates for the medium usage prediction, all the zones except the Cherokee and Storm Lake zones appear to have some additional water use expansion capacity. The Storm Lake and Cherokee budget zone areas show significant drawdown when pumping rates are increased by 25%. These additional drawdowns begin to stabilize after 18 to 20 years of pumping. This suggests that the Storm Lake and Cherokee areas may be approaching their sustainable groundwater withdrawal rate based on current water use permits. Future water use permits should be evaluated using a local scale model within the regional MODFLOW model. The grid size should be reduced to a few hundred feet to improve the accuracy of the results. Well interference with other wells should also be evaluated using local scale conditions.

High Future-use Results

Figure 59 shows the additional drawdown for the high future usage prediction in 2028 using a 20-year simulation period. 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 appear to 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 with the high future use simulation. Future water use permits should be evaluated using a local scale model within the regional MODFLOW model.

Irrigation Expansion Results

Figure 60 shows the additional drawdown for the irrigation expansion prediction for a back-to-back two year drought. Significant additional drawdown values of 60 feet are observed during the irrigation season. The most significant drawdown is observed in Sioux, Plymouth, and Obrien Counties. The use of this irrigation expansion simulation may be limited, since a uniform 5-mile grid is unrealistic. The simulation is helpful in knowing the limitations of the Lower Dakota aquifer in supplying irrigation and other large withdrawals. The per day usage during the irrigation simulation is approximately 360 mgd. This may be sustainable for short periods of time where the Lower Dakota aquifer is thick, but a significant number of nearby private and public wells would experience well interference problems, especially where the sandstone thins or no-flow boundaries occur.

Even with a 9-month lower water-use period the aquifer does not recover from the irrigation stress placed on the system. Figure 61 shows the additional drawdown after 9-months of recovery. Twenty-seven feet of additional drawdown occurs in Sioux and Plymouth Counties. Based on the additional drawdown coverage, it takes approximately 5 to 6 years for the regional Lower Dakota aquifer to recover from a back-to-back 2-year drought. The 5- to 6-year recovery period would assume normal or above precipitation during the growing season to reduce or limit the irrigation withdrawal.

Groundwater Availability Map

Using the combined results for Zone Budgeting and the various future water use predictive scenarios, an evaluation of future groundwater available was estimated for the eleven zone bud-

Table 8. Water balance during the winter.

Zone	Pumping (Q) (mgd)	Recharge (R) (mgd)	Inflow-Outflow (mgd)	From Storage (mgd)	Q/R
LeMars	3.10	0.21	3.00	-0.11	14.8
Emmetsburg	0.81	0.22	0.52	0.07	3.7
Cherokee	0.92	0.24	0.79	0.00	3.8
Hartley	1.90	0.69	1.14	0.08	2.7
Estherville	1.20	0.46	0.69	0.05	2.6
Sioux City	4.60	14.50	-9.90	0.00	0.32
Sioux Center	0.58	0.27	0.21	0.10	2.1
Storm Lake	3.30	0.29	2.10	0.90	11.4
S. Sioux Rural Water	1.10	0.26	0.93	-0.09	4.2
Sutherland	0.13	0.26	--	--	0.5
Clasing, Inc.	0.13	0.40	0.35	-0.62	0.33
Rural Areas	2.50	20.60	--	--	0.05
Total	20.27	38.40			

get areas. For the area outside the eleven zones the term safe yield was used. Safe yield is based on threshold drawdowns that do not exceed one-half the available drawdown. Available drawdown is defined as the difference in elevation of the potentiometric head and the top of the Lower Dakota aquifer. The available drawdown was multiplied by the specific capacity value to obtain a volume. The well loss was assumed to be 50%. Figures 62 and 63 represent the potential groundwater availability and safe yield maps. These maps should be used with caution. Actual availability for a specific water use permit should be modeled at the local scale to evaluate the potential long term interference with existing well owners. This is especially true within one of the eleven budget zones.

LIMITATIONS OF THE MODEL

As with all models, limitations exist regarding the potential future use. Models are tools to assist with water use planning and water allocations. Future improvements in aquifer parameters, water level data, assumptions, and water use information will require further refinement and adjustment of the model. The following are known limitations:

- Additional wells may need to be added during local scale model simulations. Many of the water use permits do not specify the total number of wells screened in the Lower Dakota aquifer, or the percentage of water pumped from each well. A centroid point was used to represent a water use permit with multiple wells and little or no information concerning the actual number, specific locations, or specific production by well. When an actual number of wells and locations were known, but the percentage of water use was unknown, pumping rates were equally divided among the active wells. Improvements in monthly water use reporting would be extremely useful for transient model simulation.
- Head values near flow-through boundaries may not accurately represent observed values. This error increases at higher pumping rates and the closer the wells are to the actual flow-through boundary. These transient head values would need to be observed during actual pumping conditions, and over a relatively large section of the boundary.
- An accurate compilation of historical pumping rates would be useful for future transient model calibration.

Table 9. Water balance during the summer.

Zone	Pumping (Q) (mgd)	Recharge (R) (mgd)	Inflow-Outflow (mgd)	From Storage (mgd)	Q/R
LeMars	4.15	0.21	3.200	0.73	19.8
Emmetsburg	0.81	0.22	0.521	0.07	3.7
Cherokee	1.32	0.24	0.890	0.20	5.5
Hartley	1.90	0.69	1.140	0.08	2.7
Estherville	1.20	0.46	0.690	0.05	2.6
Sioux City	9.10	14.50	--	--	0.6
Sioux Center	0.58	0.27	0.210	0.10	2.1
Storm Lake	3.30	0.29	2.100	0.90	11.4
S. Sioux Rural Water	1.66	0.26	1.000	0.40	6.4
Sutherland	0.13	0.26	-0.190	0.06	0.5
Clasing, Inc.	3.00	0.40	0.450	2.30	7.8
Rural Areas	4.40	20.60	--	--	0.2
Total	31.55	38.40			0.82

- Many water use permits exist outside our active model area. Due to the discontinuity of the lower Dakota sandstones, these wells could not be simulated with the regional model. The layers in these areas can be reactivated, and local scale models can be run. Aquifer parameter information, boundary conditions, well locations, pumping rates, and observation well data would need to be entered. The local scale model would also need to be calibrated based on observed water level data.

  Because the recharge was entered as net recharge, simulated water level values in the Quaternary layer were not simulated, and do not represent actual conditions.

CONCLUSIONS

While Iowa is not facing an immediate water shortage, increased demand for groundwater by agriculture, industries, and municipalities have raised concerns for the future of the resource. However, the information necessary for decision makers to answer basic questions regarding how much water can be withdrawn from Iowa's aquifers on a sustainable basis were not available. The 2007 Iowa General Assembly, recognizing this lack of information, approved funding for the first year of a multi-year evaluation and modeling of Iowa's major bedrock aquifers by the Iowa Geological and Water Survey (IGWS). The first aquifer studied was the Dakota aquifer in a sixteen-county area of northwest Iowa.

An intensive one-year investigation of the geology and hydrogeology of the study area was undertaken to provide a more quantitative assessment of the aquifer, and to construct a groundwater flow model that can be used as a planning tool for future water resource development. The geology of the northwest Iowa area was investigated in detail utilizing a variety of resources including the IGWS Geosam geologic database, microscopic study of well samples from the Survey's Oakdale Rock Library, study of surface exposures, and review of previous geologic investigations in the region. Special attention was given to the Cretaceous Dakota Formation, which includes the major bedrock aquifer in the northwest Iowa. The major water producing sandstone interval, the Lower Dakota aquifer, was identified and mapped. The Lower Dakota aquifer includes most of the basal member of the Dakota Formation, the Nishnabotna Member, and sandstones in the overlying Woodbury Member that directly overlie and are in hydrologic connection with

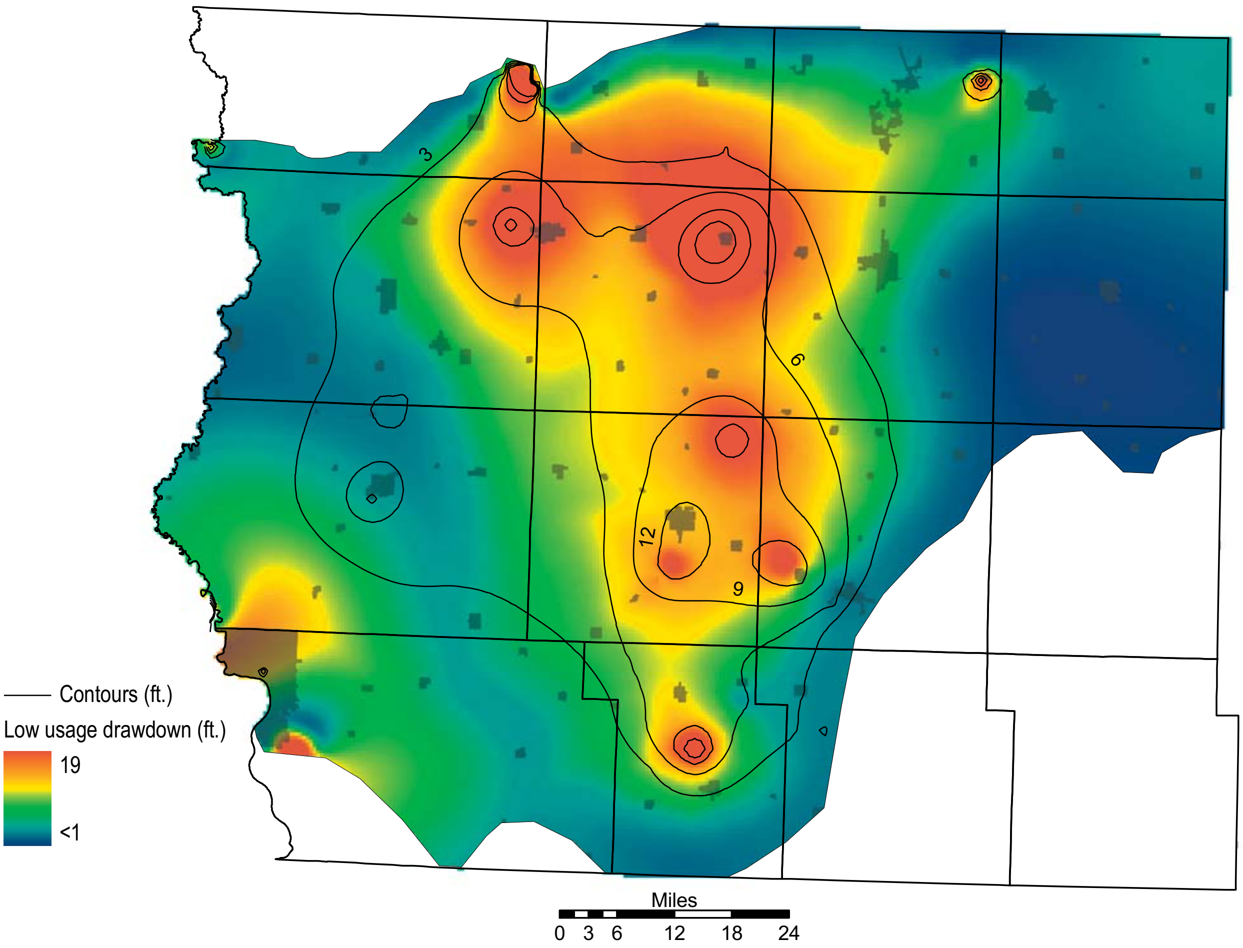


Figure 57. Low future usage additional drawdown after 20-years (initial head values December 2006).

the lower sandstones. A series of maps were produced, including the elevation of the top of the Lower Dakota aquifer and its thickness, as well as maps of the thickness of the shale-dominated Cretaceous rocks that lie above the aquifer, the thickness of the Quaternary materials that lie at the land surface, the bedrock geology of the region, the limits of the geologic units that lie below the aquifer, and others. These maps defined the geometry of the Lower Dakota aquifer and the other major geologic packages that defined the model.

The hydrologic characteristics of the geologic layers included in the modeling of the Lower Dakota aquifer were investigated. An important component of this study was a network of approximately 60 wells, used to evaluate water levels. Key to the investigation were eleven observation wells which had time series data. These data were used for the transient model development. Other important 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 within the study area.

With this information a numerical groundwater flow model of the Lower Dakota aquifer was developed using four hydrogeologic layers. The

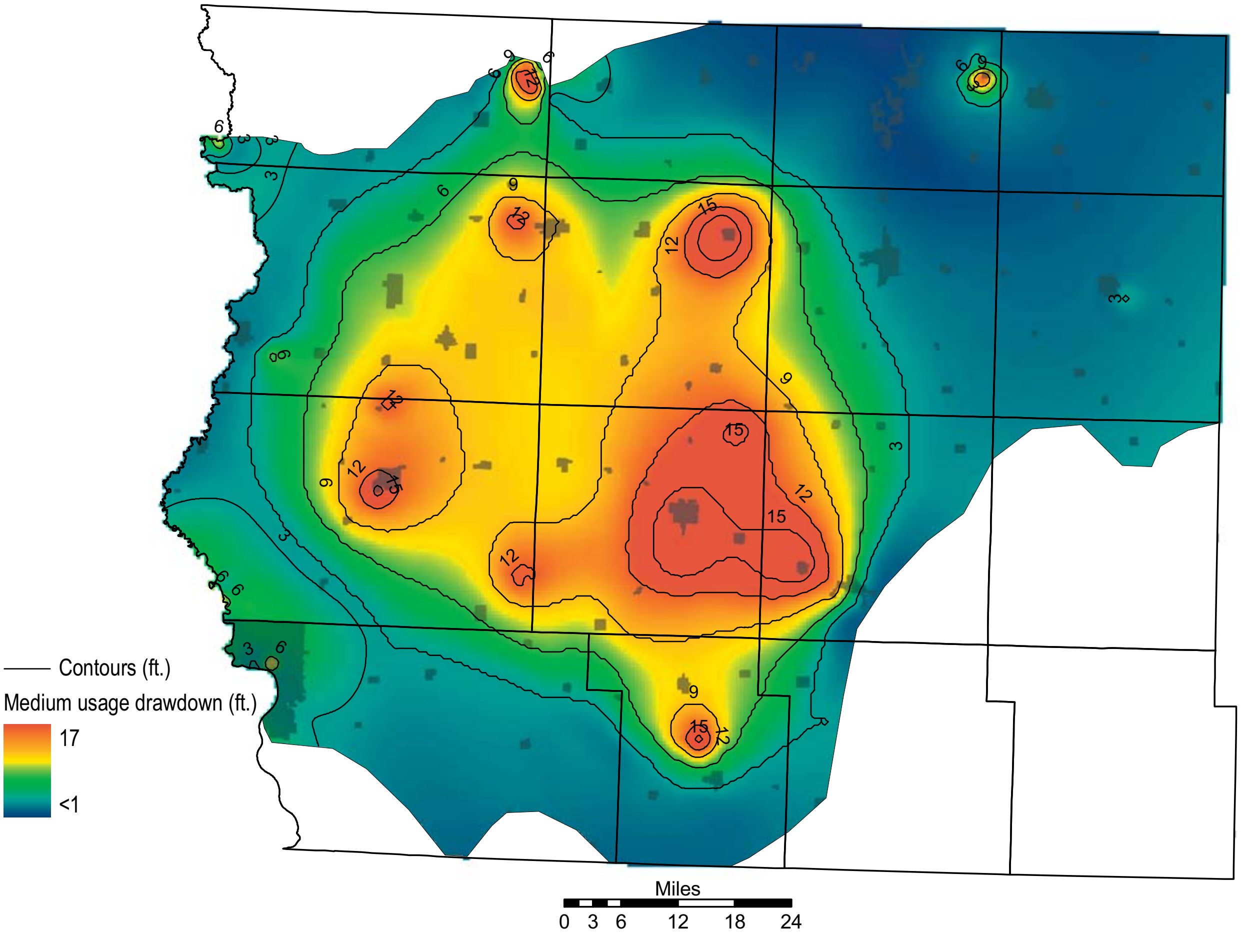


Figure 58. Medium future usage additional drawdown after 20-years (initial head values December 2006).

model was created 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 boundary, and groundwater upwelling.

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. An additional simulation was run to predict the additional drawdown for a 2-year drought using 161 new irrigation permits.

The hydraulic properties of the Lower Dakota 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

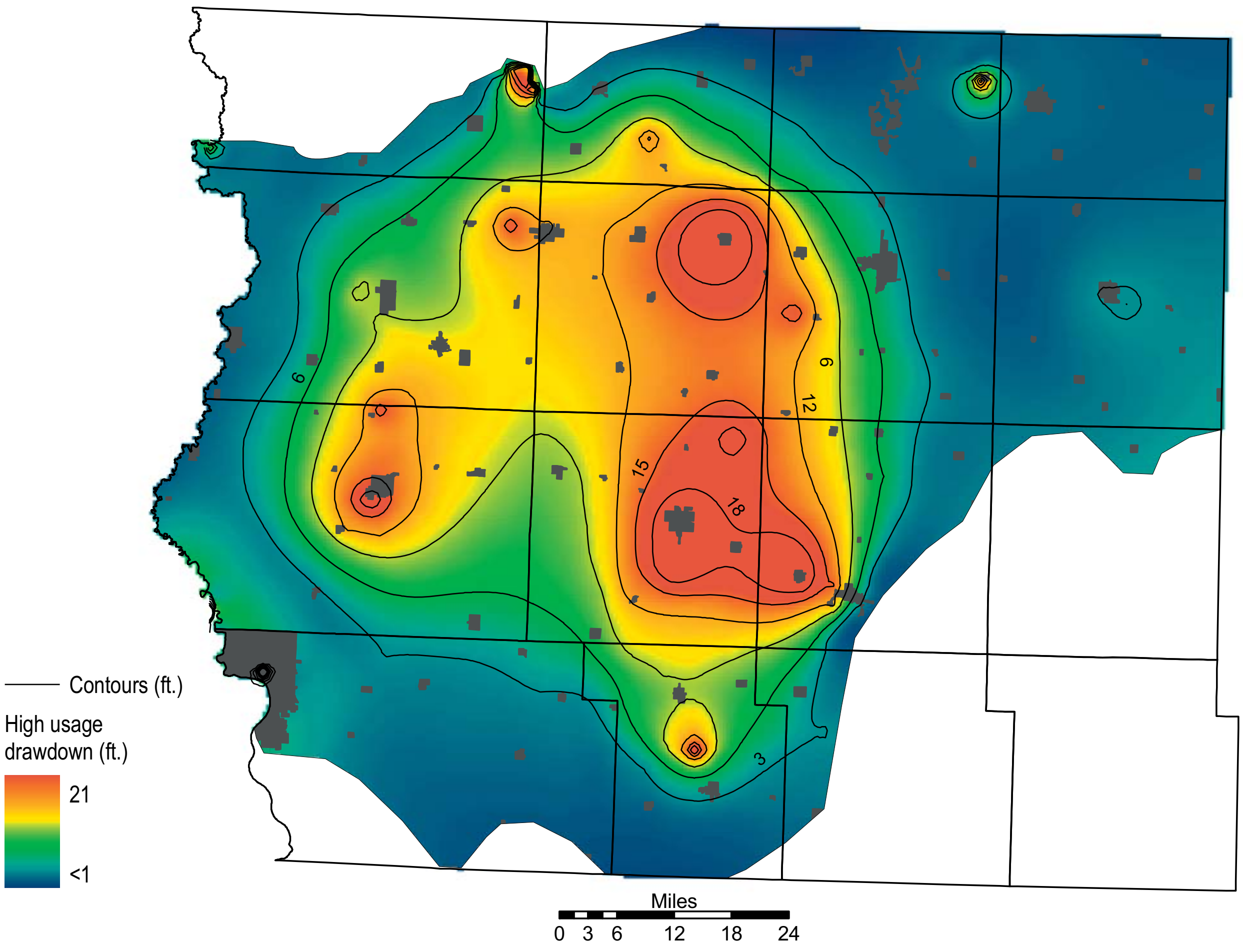


Figure 59. High future usage additional drawdown after 20-years (initial head values December 2006).

22 to 81 feet per day, with an arithmetic mean of 47 feet per day. Transmissivity values range from 2,700 to 12,000 feet squared per day, and are controlled primarily by the aquifer thickness. The storage coefficient of the Lower Dakota aquifer ranges from 1.8×10^{-5}, to 2×10^{-3}. The arithmetic mean storage coefficient is 3.3×10^{-4}.

Recharge to most of the Lower Dakota 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 to the lower Dakota is very small. Calibrated recharge rates varied from 0.15 inches per year to 0.05 inches per year over most of the study area. A calibrated recharge rate of 3 inches per year was used in the Sioux City area due to 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 feet were relatively small errors over an area of 8,100 square miles. Simulated water level changes are most sensitive to recharge in the steady-state model, and pumping rates in the transient model.

The Lower Dakota aquifer has tremendous development capacity. The current summer time usage was estimated to be approximately 31.6 mgd. This withdrawal is well below the development

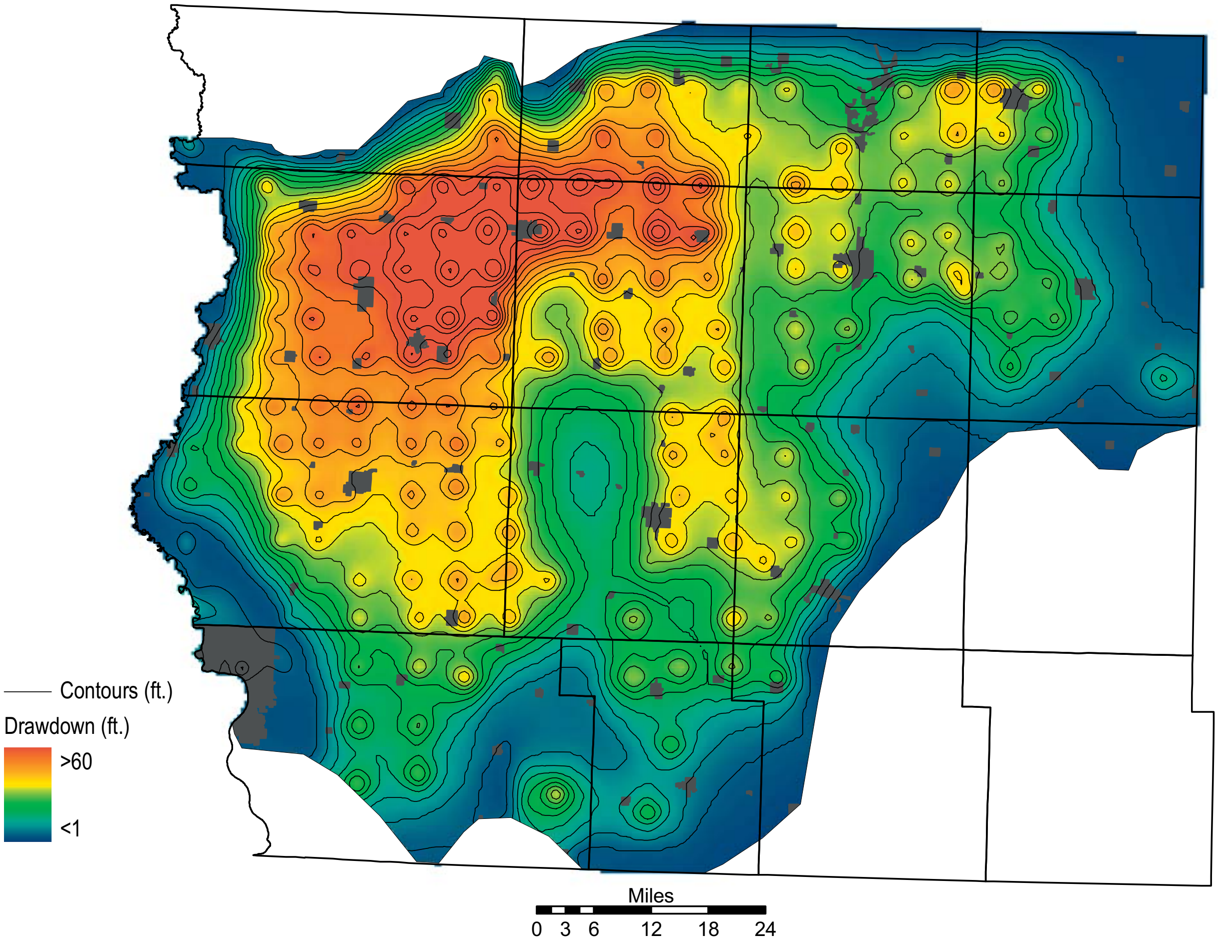


Figure 60. Additional drawdown after 2-year drought and expanded irrigation usage.

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.

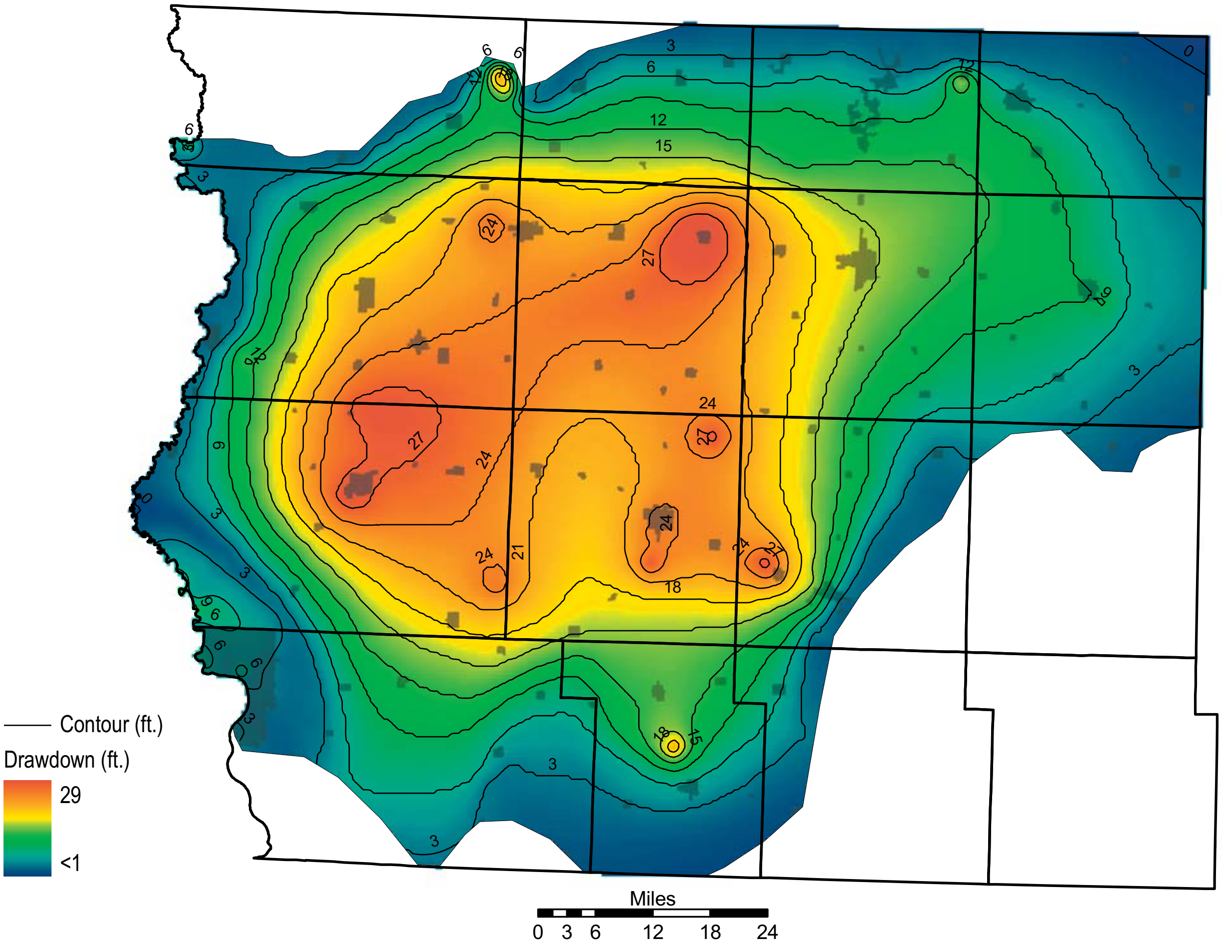


Figure 61. Additional drawdown 9-months following irrigation season (2-year drought).

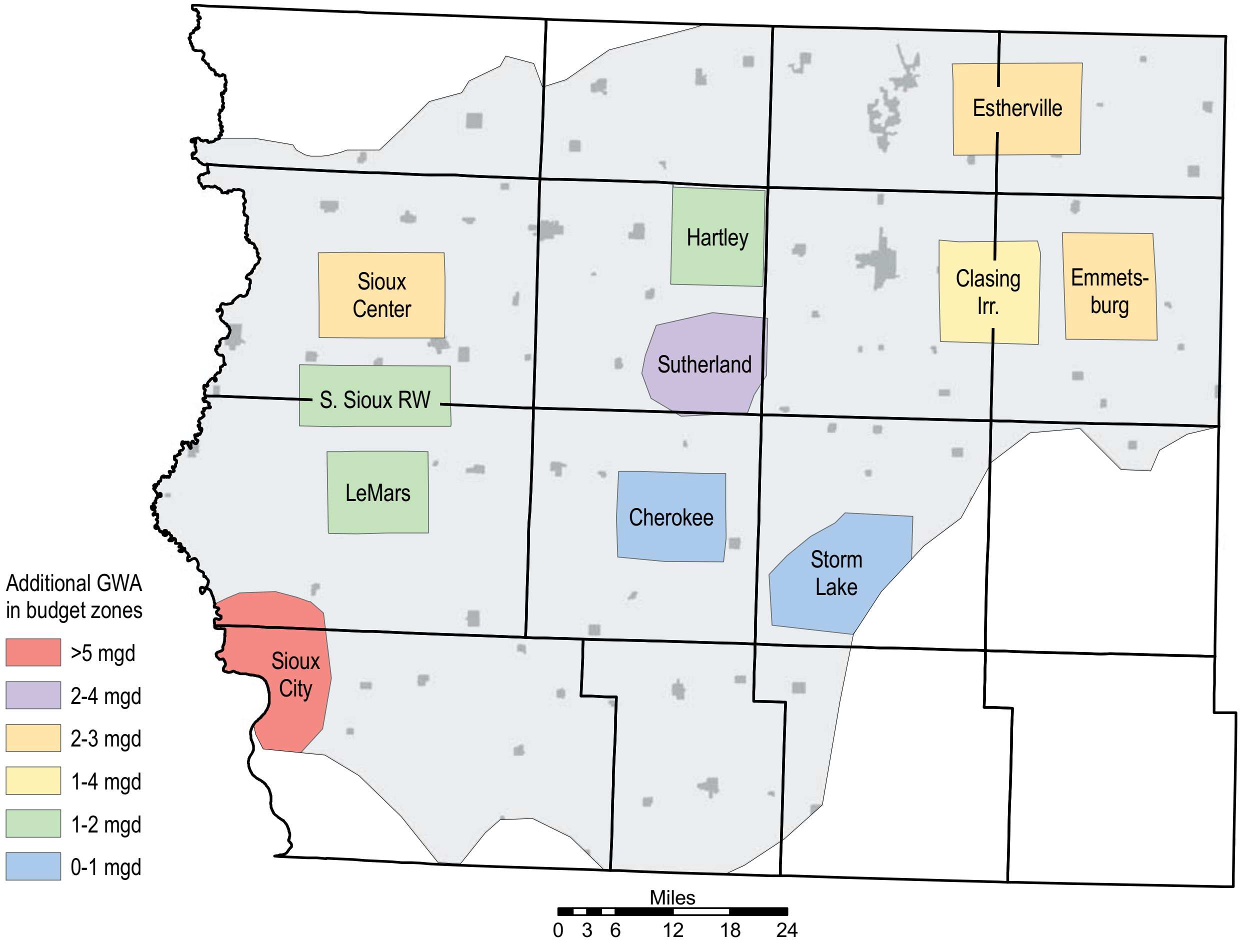


Figure 62. Groundwater availability (GWA) map based on zone budget analyses and predictive modeling.

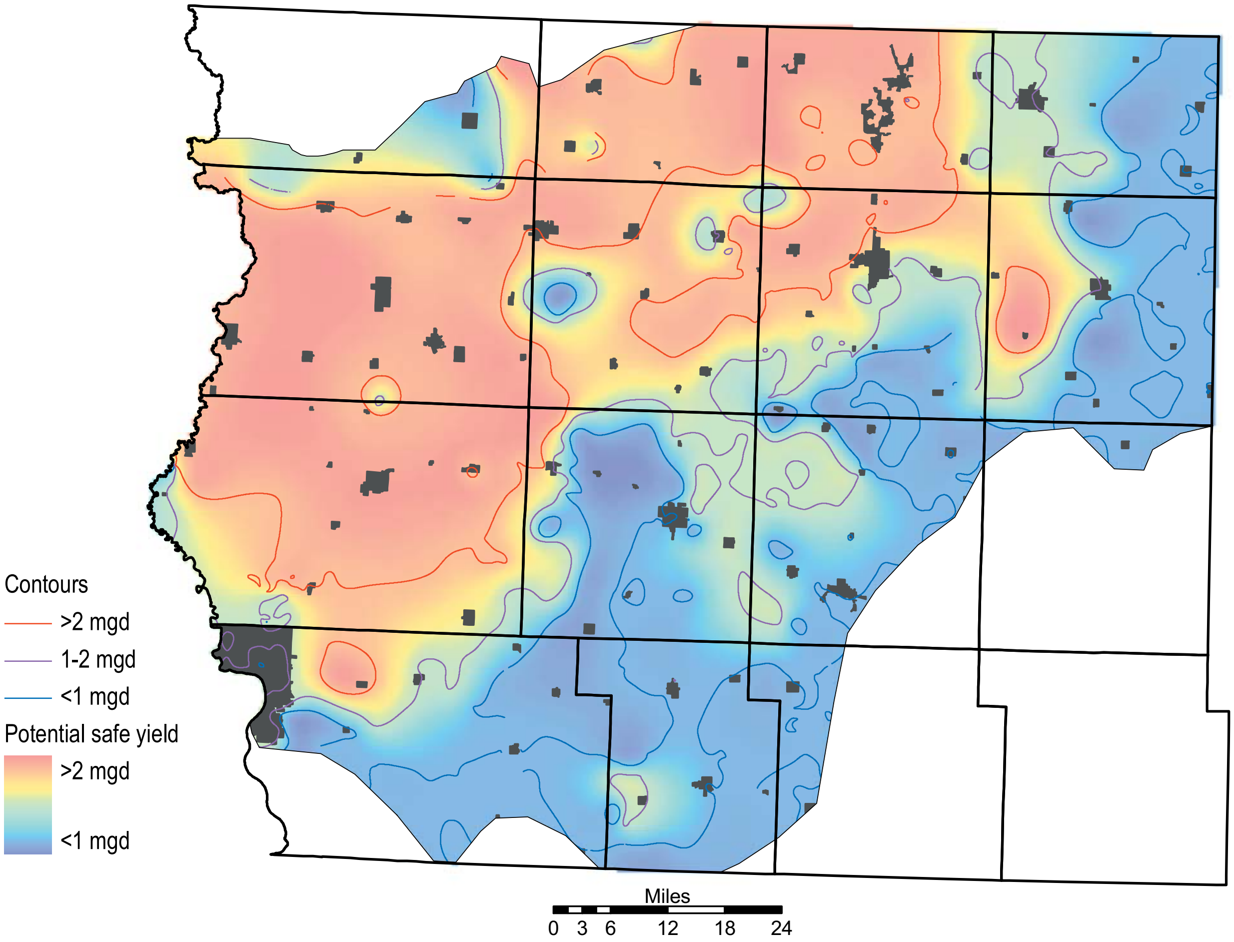


Figure 63. Potential safe yield map based on specific capacity, aquifer thickness, and 50% well loss.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the many individuals who assisted in the production of this report. First, much of our understanding of the Cretaceous Dakota Formation is built on the work of previous Iowa Geological Survey (IGS) geologists, especially studies by Jim Munter and Greg Ludvigson. We would also like to thank the many people who helped to collect, prepare, and analyze the data that was the basis of this report. Amy Sabin (IGS Geotechnician) and Christy Kloberdanz (student employee) prepared drill samples for microscopic study and scanned driller's logs and related materials. Tom Marshall and Michael Bounk (IGWS geologists) spent many hours at the microscope studying well chip samples and preparing lithologic strip logs for key wells in the study area. We would also like to thank Rick Langel (IGWS Watershed Monitoring and Assessment Section) for providing observation well data that was critical in developing the transient model.

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APPENDIX A.

AQUIFER TEST DATA

LISTING OF AQUIFER PUMP TEST RESULTS AND DATA IN APPENDIX A

City of LeMars Well 12

City of LeMars Well 11

Orange City Well 12

Orange City Old Well

Superior Ethanol

South Sioux Rural Water D-1

South Sioux Rural Water D-2

South Sioux Rural Water D-3

Emmetsburg Well 6

Osceola County RWS

Hartley VeraSun Ethanol

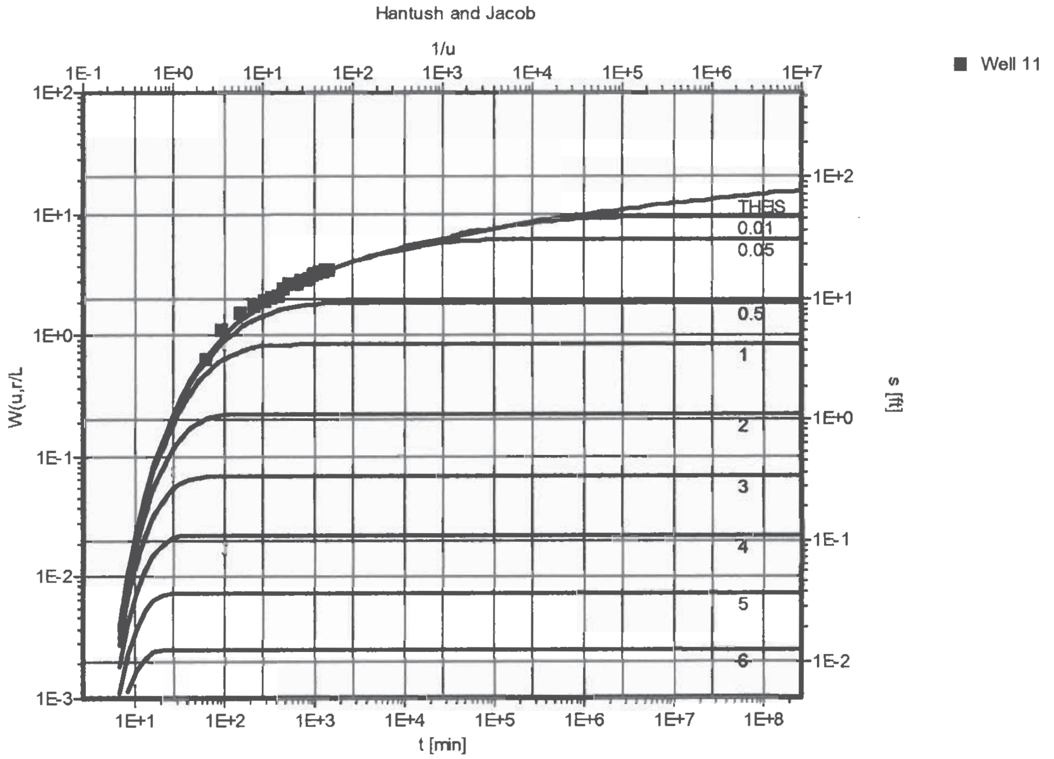
City of Remsen Well 9

Sioux Center Land Development Well 1

Waterloo Hydrogeologic, Inc. 180 Columbia St. Unit 1104 Waterloo, Ontario, Canada Phone: +1 519 746 1798	**Pumping test analysis** No: Project: LeMars Client:

Location: City Well 11	Pumping test: Well 12	Pumping well: Well 12

Test performed by: Mike Gannon Test date: 2/20/2008	Evaluated by: Evaluation date: 2/20/2008
Analysis method: Hantush and Jacob	Aquifer thickness: 128 Discharge rate: 2204 [U.S. gal/min]

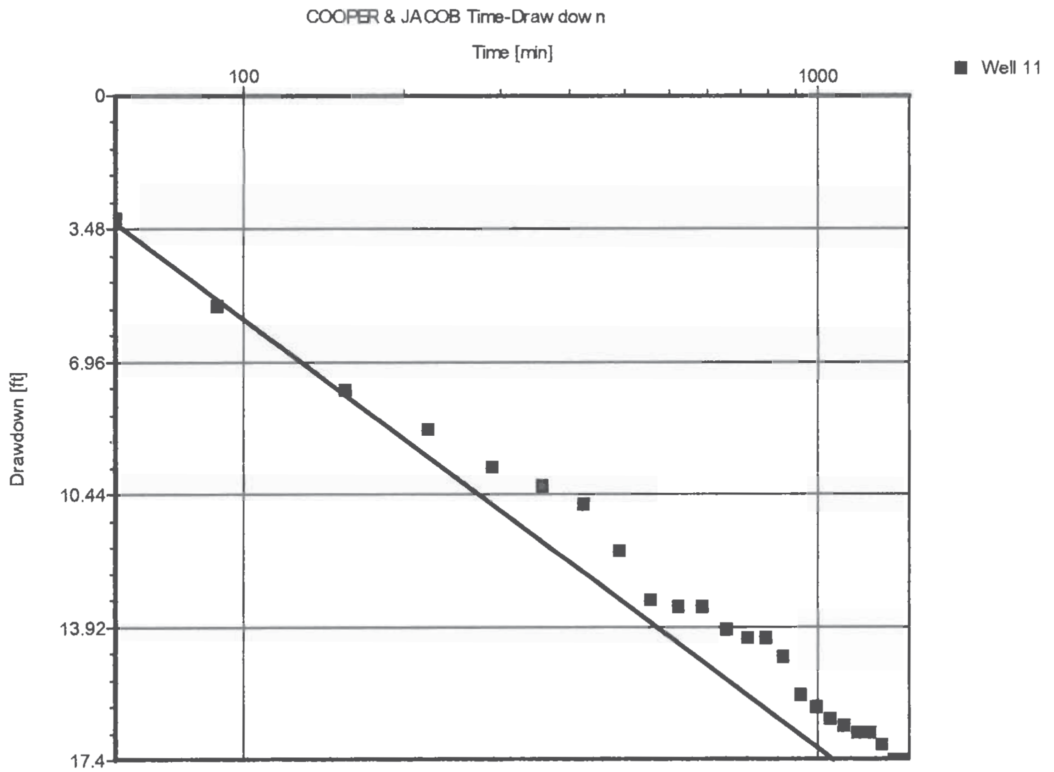


Transmissivity:	6.80×10^+3 [ft²/d]
Conductivity:	5.32×10^+1 [ft/d]
Storativity:	1.80×10^-5
c :	5.83×10^+10 [min]

Waterloo Hydrogeologic, Inc. 180 Columbia St. Unit 1104 Waterloo, Ontario, Canada Phone: +1 519 746 1798	**Pumping test analysis** No: Project: LeMars Client:

Location: City Well 11	Pumping test: Well 12	Pumping well: Well 12

Test performed by: Mike Gannon Test date: 2/20/2008	Evaluated by: Evaluation date: 2/20/2008
Analysis method: COOPER & JACOB Time-Drawdown	Aquifer thickness: 128 Discharge rate: 2204 [U.S. gal/min]



Transmissivity: 6.88×10^+3 [ft²/d]

Conductivity: 5.38×10^+1 [ft/d]

Storativity: 1.19×10^-5

Layne-Western
5600 Gateway Drive, Suite B
Grimes, IA 50111
(515) 986-3462 / 3474 Fax

WELL TEST DATA REPORT

PROJECT:	City of Le Mars	**DATE TESTED:**	9/30/04 - 10/1/04
LOCATION:	Le Mars, Iowa	**TESTED BY:**	Will Penney
WELL NO:	11 - Observations during Well 12 Test	**DRIVER:**	
WELL DIAMETER:	17 inches I.D.	**COLUMN AND SHAFT:**	
WELL DEPTH:	388.0 feet - from grade	**BOWL SIZE & MAKE:**	
TOP OF SCREEN:	260.0 feet - from grade	**MANUFACTURER:**	
STATIC LEVEL:	77.3 feet - from top of casing	**SERIAL NUMBER:**	
ORIFICE SIZE:			

TIME	PIEZ. READ. (IN)	FLOW RATE (GPM)	AIRLINE READING (FEET)	WATER LEVEL (FEET)	DRAW DOWN (FEET)	DISCHARGE PRESSURE (LBS.)	BARAMETRIC PRESSURE (Inches Hg)	SPEC. CAPACITY (GPM/FT)	REMARKS
60 min.	N/A	N/A	N/A	80.5	N/A	N/A	28.47	N/A	
90				82.8			28.47		
150				85.0			28.46		
210				86.0			28.44		
270				87.0			28.42		
330				87.5			28.40		
390				88.0			28.39		
450				89.2			28.38		
510				90.5			28.38		
570				90.7			28.39		
630				90.7			28.39		
690				91.3			28.38		
750				91.5			28.37		
810				91.5			28.37		
870				92.0			28.36		
930				93.0			28.33		
990				93.3			28.33		
1050				93.6			28.31		
1110				93.8			28.28		
1170				94.0			28.31		
1230				94.0			28.30		
1290				94.3			28.30		
1350				94.7			28.31		
1410				94.7			28.32		
1440				94.7			28.33		

PAGE 1 - Pumping Observ.

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Grimes, IA 50111
(515) 986-3462 / 3474 Fax

WELL TEST DATA REPORT

PROJECT: City of Le Mars
LOCATION: Le Mars, Iowa
WELL NO: 11 - Observations during Well 12 Test
WELL DIAMETER: 17 inches I.D.
WELL DEPTH: 388.0 feet - from grade
TOP OF SCREEN: 260.0 feet - from grade
STATIC LEVEL: 77.3 feet - from top of casing
ORIFICE SIZE:

DATE TESTED: 10/1/04 - 10/2/04
TESTED BY: Will Penney
DRIVER:
COLUMN AND SHAFT:
BOWL SIZE & MAKE:
MANUFACTURER:
SERIAL NUMBER:

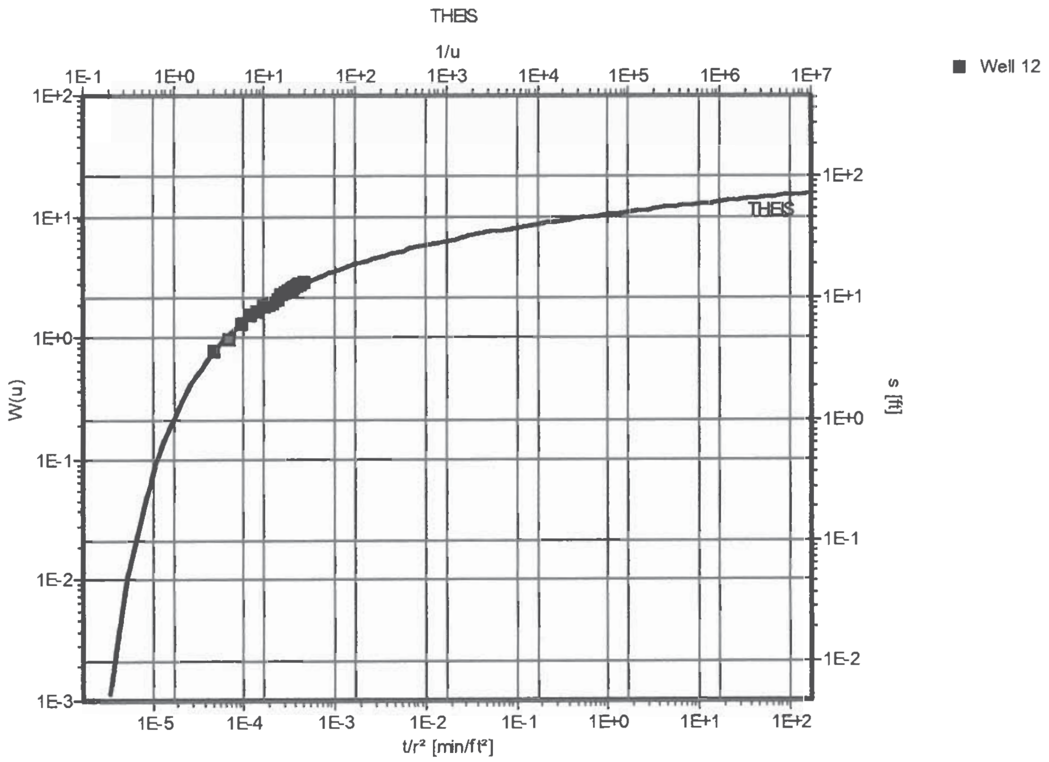
TIME	PIEZ. READ. (IN)	FLOW RATE (GPM)	AIRLINE READING (FEET)	WATER LEVEL (FEET)	DRAW DOWN (FEET)	DISCHARGE PRESSURE (LBS.)	BARAMETRIC PRESSURE (Inches Hg)	SPEC. CAPACITY (GPM/FT)	REMARKS
30 min.	N/A	N/A	N/A	93.2	N/A	N/A	28.35	N/A	
60				91.7			28.37		
90				90.3			28.41		
120				90.0			28.52		
150				88.9			28.50		
180				88.0			28.53		
210				87.5			28.55		
240				87.0			28.56		
270				86.5			28.59		
300				86.2			28.61		
330				86.0			28.63		
360				86.0			28.63		
390				85.8			28.65		

Waterloo Hydrogeologic, Inc.
180 Columbia St. Unit 1104
Waterloo, Ontario, Canada
Phone: +1 519 746 1798

Pumping test analysis
No:
Project: LeMars
Client:

Location: City Well 11	Pumping test: Well 11	Pumping well: Well 11

Test performed by:	Mike Gannon	Evaluated by:	Mike Gannon
Test date:	2/20/2008	Evaluation date:	2/20/2008
Analysis method:	THEIS	Aquifer thickness:	128
		Discharge rate:	2204 [U.S. gal/min]

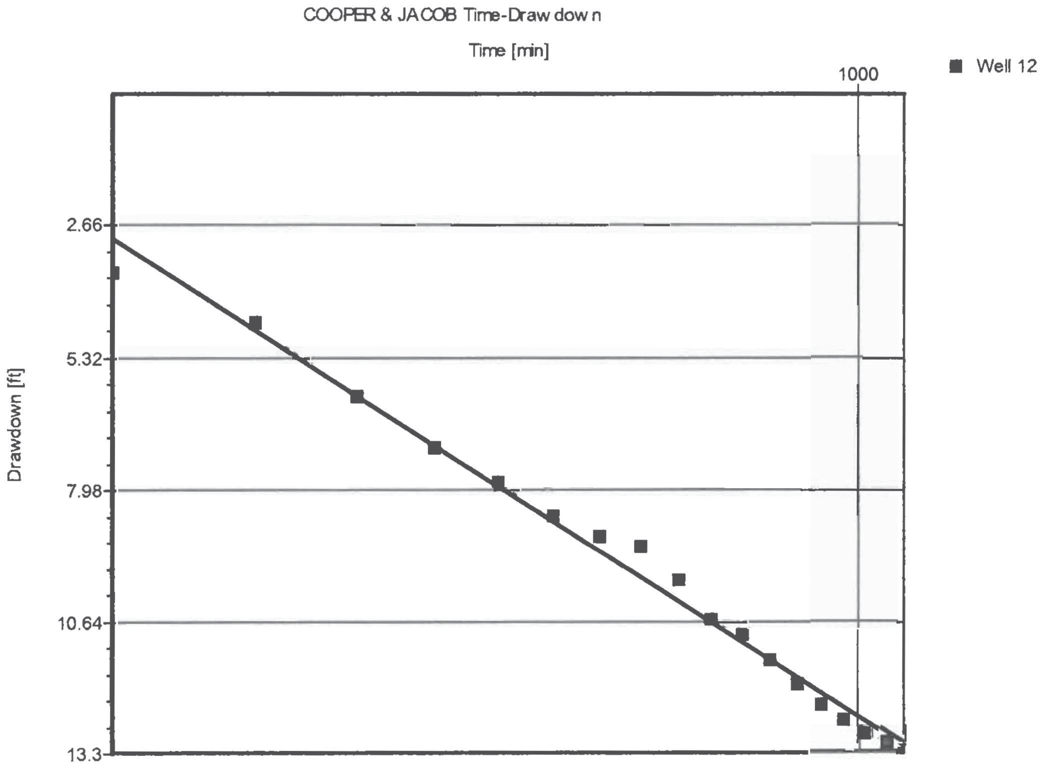


Transmissivity:	7.21×10^+3 [ft²/d]
Conductivity:	5.63×10^+1 [ft/d]
Storativity:	3.41×10^-4

Waterloo Hydrogeologic, Inc. 180 Columbia St. Unit 1104 Waterloo, Ontario, Canada Phone: +1 519 746 1798	**Pumping test analysis** No: Project: LeMars Client:

Location: City Well 11	Pumping test: Well 11	Pumping well: Well 11

Test performed by:	Mike Gannon	Evaluated by:	Mike Gannon
Test date:	2/20/2008	Evaluation date:	2/20/2008
Analysis method:	COOPER & JACOB Time-Drawdown	Aquifer thickness:	128
		Discharge rate:	2204 [U.S. gal/min]



Transmissivity: 7.42×10^+3 [ft²/d]

Conductivity: 5.80×10^+1 [ft/d]

Storativity: 2.86×10^-4

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5600 Gateway Drive, Suite B
Grimes, IA 50111
(515) 986-3462 / 3474 Fax

WELL TEST DATA REPORT

PROJECT: City of Le Mars
LOCATION: Le Mars, Iowa
WELL NO: 12 - Observations during Well 11 Test
WELL DIAMETER: 17 inches I.D.
WELL DEPTH: 374.0 feet - from grade
TOP OF SCREEN: 244.0 feet - from grade
STATIC LEVEL: 67.4 feet - from top of casing
ORIFICE SIZE:

DATE TESTED: 9/21/04 - 9/22/04
TESTED BY: Will Penney
DRIVER:
COLUMN AND SHAFT:
BOWL SIZE & MAKE:
MANUFACTURER:
SERIAL NUMBER:

TIME	PIEZ. READ. (IN)	FLOW RATE (GPM)	AIRLINE READING (FEET)	WATER LEVEL (FEET)	DRAW DOWN (FEET)	DISCHARGE PRESSURE (LBS.)	BARAMETRIC PRESSURE (Inches Hg)	SPEC. CAPACITY (GPM/FT)	REMARKS
60	N/A	N/A	N/A	67.4	N/A	N/A		N/A	
120				71.0					
180				72.0					
240				73.5					
300				74.5					
360				75.2					
420				75.9					
480				76.3					
540				76.5					
600				77.2					
660				78.0					
720				78.3					
780				78.8					
840				79.3					
900				79.7					
960				80.0					
1020				80.3					
1080				80.5					
1140				80.7					
1200				79.0					**Recovery - pumping test terminated at approximately 1200 minutes due to broken gear shaft.**
1260				76.3					
1320				75.4					
1380				74.0					
1440									

PAGE 1 - Observ./Recovery

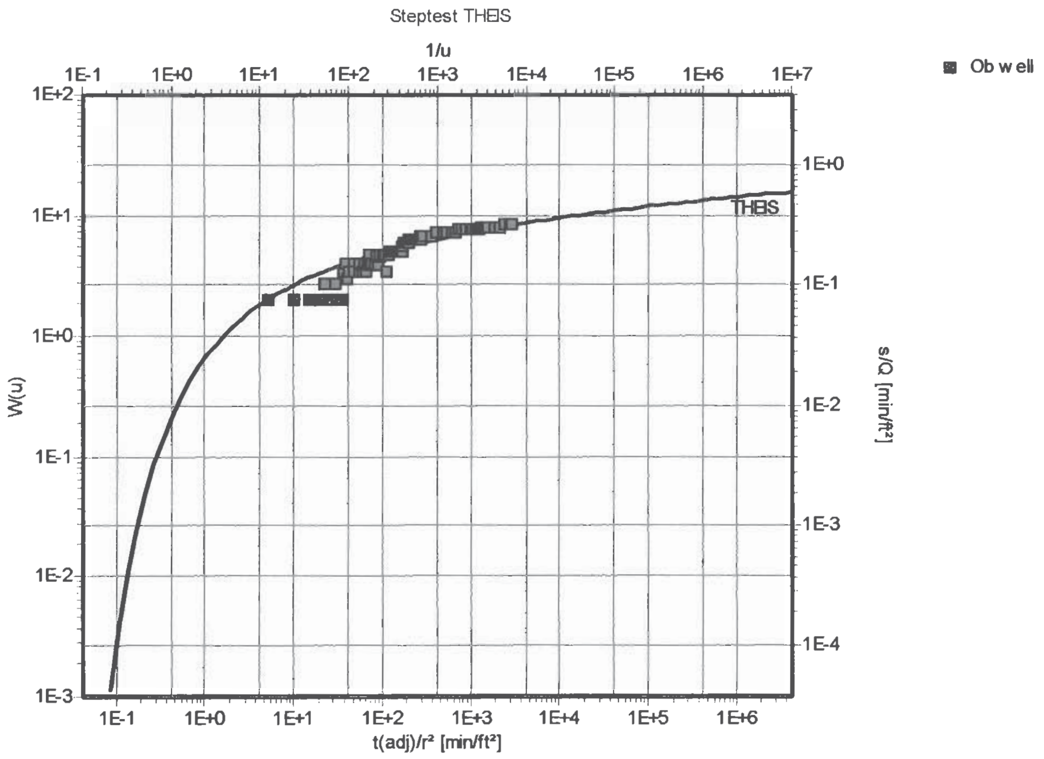
Waterloo Hydrogeologic, Inc.
180 Columbia St. Unit 1104
Waterloo, Ontario, Canada
Phone: +1 519 746 1798

Pumping test analysis
No: Dakota Aquifer
Project: Orange City
Client: IDNR

Location:
Pumping test: New pumping test
Pumping well:

Test performed by:
Test date: 9/24/2007
Evaluated by:
Evaluation date: 9/24/2007

Analysis method: Steptest THEIS
Aquifer thickness: 121
Discharge rate: 428.98841 [U.S. gal/min]



Transmissivity: 3.05×10^+3 [ft²/d]

Conductivity: 2.52×10^+1 [ft/d]

Storativity: 3.52×10^+0

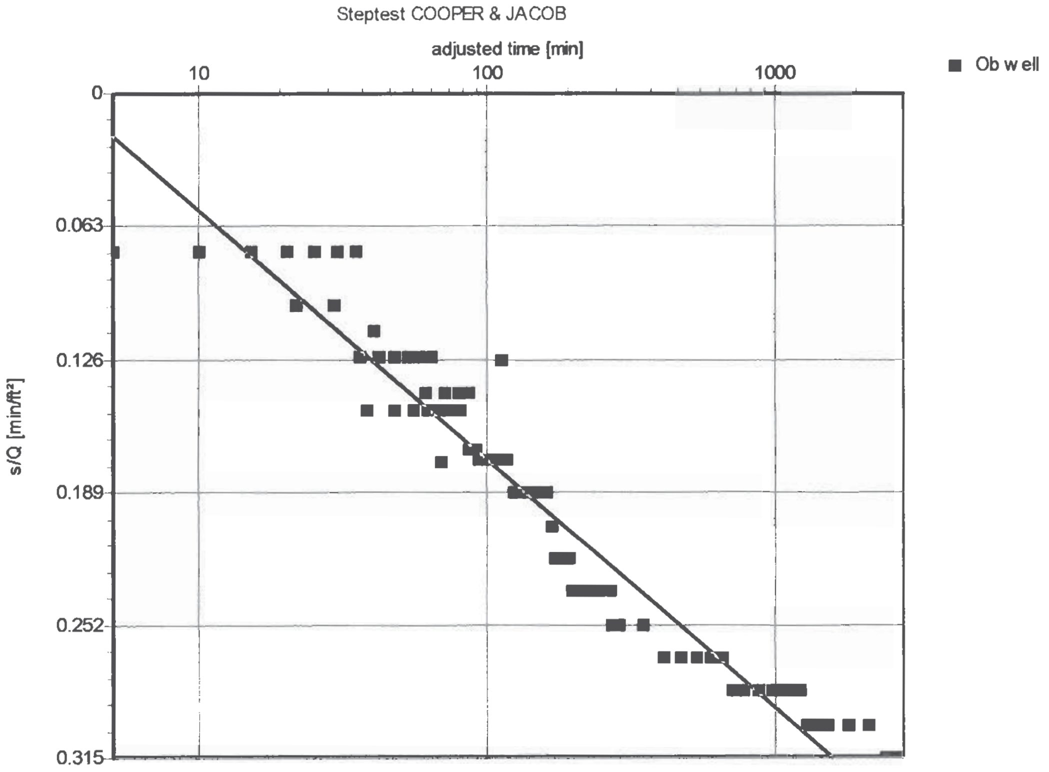
Waterloo Hydrogeologic, Inc.
180 Columbia St. Unit 1104
Waterloo, Ontario, Canada
Phone: +1 519 746 1798

Pumping test analysis
No: Dakota Aquifer
Project: Orange City
Client: IDNR

Location:
Pumping test: New pumping test
Pumping well: Production

Test performed by:
Test date: 9/24/2007
Evaluated by:
Evaluation date: 9/24/2007

Analysis method: Steptest COOPER & JACOB
Aquifer thickness:
Discharge rate: 433.36694 [U.S. gal/min]



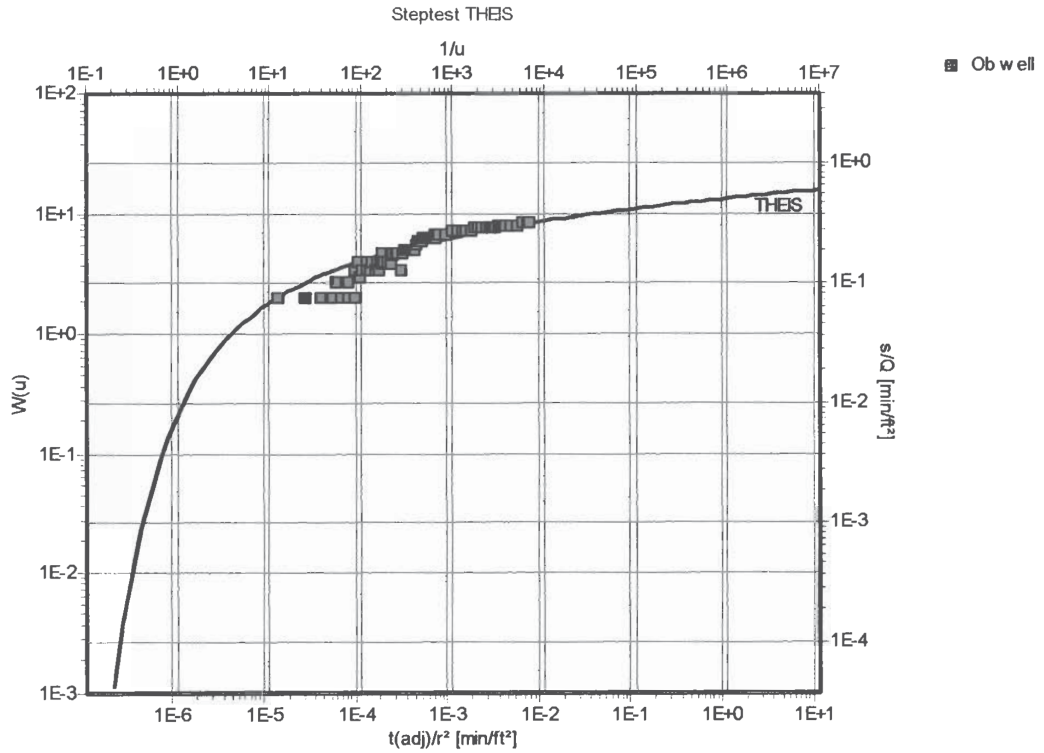
Transmissivity: 2.24×10^+3 [ft²/d]

Storativity: 3.24×10^-5

Waterloo Hydrogeologic, Inc. 180 Columbia St. Unit 1104 Waterloo, Ontario, Canada Phone: +1 519 746 1798	**Pumping test analysis** No: Dakota Aquifer Project: Orange City Client: IDNR

Location:	Pumping test: New pumping test	Pumping well: Production

Test performed by:	**Evaluated by:**
Test date: 9/24/2007	**Evaluation date:** 9/24/2007
Analysis method: Steptest THEIS	Aquifer thickness: Discharge rate: 433.36694 [U.S. gal/min]



Transmissivity: 3.05×10^+3 [ft²/d]

Storativity: 9.79×10^-6

Waterloo Hydrogeologic, Inc. 180 Columbia St. Unit 1104 Waterloo, Ontario, Phone: +1 519 746	**Data**	
	Project: Orange City	
	No: Dakota Aquifer	Page 1
	Client: IDNR	

Location:	Pumping test: New pumping test	Pumping well: Product

Test performed

at 9/24/2007

Data observed at: Depth to static WL: 137

Distance from pumping well: 600 [ft]

	Time [min]	Depth to WL [ft]	Drawdown [ft]	
1	0	137.00	0.00	
2	5	139.00	2.00	
3	10	139.00	2.00	
4	15	139.00	2.00	
5	20	139.00	2.00	
6	25	139.00	2.00	
7	30	139.00	2.00	
8	35	139.00	2.00	
9	40	140.00	3.00	
10	45	141.00	4.00	
11	50	141.00	4.00	
12	55	142.00	5.00	
13	60	142.00	5.00	
14	65	142.00	5.00	
15	70	142.00	5.00	
16	75	142.00	5.00	
17	80	142.00	5.00	
18	85	144.00	7.00	
19	90	145.00	8.00	
20	95	145.00	8.00	
21	100	145.00	8.00	
22	105	145.00	8.00	
23	110	145.00	8.00	
24	115	145.00	8.00	
25	120	145.00	8.00	
26	125	146.00	9.00	
27	130	146.00	9.00	
28	135	146.00	9.00	
29	140	146.00	9.00	
30	145	146.00	9.00	
31	150	146.00	9.00	
32	155	148.00	11.00	
33	160	148.00	11.00	
34	165	148.00	11.00	
35	170	145.00	8.00	

Waterloo Hydrogeologic, Inc.
180 Columbia St. Unit 1104
Waterloo, Ontario,
Phone: +1 519 746

Data			
Project:	Orange City		
No:	Dakota Aquifer	Page 2	
Client:	IDNR		

Location:	Pumping test: New pumping test	Pumping well: Product

Test performed
at 9/24/2007

Data observed at: Depth to static WL: 137
Distance from pumping well: 600 [ft]

	Time [min]	Depth to WL [ft]	Drawdown [ft]	
36	175	148.00	11.00	
37	180	149.00	12.00	
38	185	149.00	12.00	
39	190	149.00	12.00	
40	195	149.00	12.00	
41	200	149.00	12.00	
42	205	149.00	12.00	
43	210	149.00	12.00	
44	215	149.00	12.00	
45	220	150.00	13.00	
46	225	151.00	14.00	
47	230	151.00	14.00	
48	235	151.00	14.00	
49	240	151.00	14.00	
50	245	151.00	14.00	
51	250	152.00	15.00	
52	255	152.00	15.00	
53	260	152.00	15.00	
54	265	152.00	15.00	
55	270	152.00	15.00	
56	275	152.00	15.00	
57	280	152.00	15.00	
58	285	152.00	15.00	
59	290	152.00	15.00	
60	295	152.00	15.00	
61	300	152.00	15.00	
62	305	152.00	15.00	
63	310	152.00	15.00	
64	315	152.00	15.00	
65	320	153.00	16.00	
66	325	153.00	16.00	
67	330	153.00	16.00	
68	335	153.00	16.00	
69	395	153.00	16.00	
70	455	154.00	17.00	

Waterloo Hydrogeologic, Inc. 180 Columbia St. Unit 1104 Waterloo, Ontario, Phone: +1 519 746	**Data**		
	Project:	Orange City	
	No:	Dakota Aquifer	Page 3
	Client:	IDNR	

Location:

Pumping test: New pumping test

Pumping well: Product

Test performed at 9/24/2007

Data observed at:

Depth to static WL: 137

Distance from pumping well: 600 [ft]

	Time [min]	Depth to WL [ft]	Drawdown [ft]	
71	515	154.00	17.00	
72	575	154.00	17.00	
73	635	154.00	17.00	
74	695	154.00	17.00	
75	755	155.00	18.00	
76	815	155.00	18.00	
77	910	155.00	18.00	
78	1020	155.00	18.00	
79	1080	155.00	18.00	
80	1140	155.00	18.00	
81	1200	155.00	18.00	
82	1260	155.00	18.00	
83	1320	156.00	19.00	
84	1380	156.00	19.00	
85	1440	156.00	19.00	
86	1500	156.00	19.00	
87	1560	156.00	19.00	
88	1825	156.00	19.00	
89	2155	156.00	19.00	
90	2450	157.00	20.00	
91	2700	157.00	20.00	
92	2770	157.00	20.00	
93	2805	157.00	20.00	

5225

T. Al Austin, P.E.
Consulting Engineer

1954 390th Street
Stanhope, Iowa 50246
(515) 826-3301

Hydrology
Hydraulics
Ground Water

June 26, 1992

Mr. Chris Jens
Municipal Engineering Consultants, P.C.
Box 220
Sergeant Bluff, Iowa 51504

RE: Orange City Pumping Test Analysis

Dear Chris:

I have reviewed the pumping test data on the Orange City well conducted on May 11-13, 1992. This is a step drawdown test where the rate of pumping was increased from 100 to 475 gpm. I used the modified Theis solution method to determine the aquifer transmissivity and storativity from the production well data and the observation well data. I analyzed each different pumping rate (five in total) separately so I obtained five estimates of the aquifer properties. I used these estimated properties to evaluate the drawdown under various pumping rates. The results are presented herein.

Table 1 shows the range of transmissivities and storativities obtained in my analysis of the observation well data. These were the result of regression fits of the drawdown for each pumping segment versus log of the time since the pumping rate was changed. The way this was conducted was to fit the line to the 100 gpm drawdown data and extend the line through all the pumping test to "predict" the drawdowns if the well was pumped at 100 gpm continuously.

Table 1. Transmissivity and Storativity from Observation Well Data

Segment	Discharge (gpm)	Transmissivity (gpd/ft)	Storativity (Dim x 10^{-4})
1	100	24,000	1.06
2	200	17,300	3.23
3	300	24,400	1.30
4	400	25,000	1.02
5	475	26,400	1.28
Geometric Mean		23,400	1.42
Arithmetic Average		23,600	1.58

I then subtracted these predicted values from the second segment drawdown data to obtain the effect of the incremental flow (going from 100 to 200 gpm). These second segment data were fit with regression and extended through the entire pumping test. The third segment residuals were obtained by subtracting the first and second segment effects. This procedure was continued until all segments were analyzed.

As can be seen from Table 1 there is a good agreement the between the parameter estimates for all the segments, with possible exception of segment two. I used the geometric mean values to reconstruct the drawdowns and I have shown the reconstructed and observed values in Figure 1. The degree of fit is excellent up to about 1000 minutes into the test. There appears to be some leveling off of the drawdown at the end of the test which is evidence of some recharge into the system.

When I used the parameter estimates from the observation well data to predict the drawdown in the production well, I obtained Figure 2. The predicted drawdown was lower than observed throughout the test, resulting in a difference of about 10 feet of drawdown at the end of the test. The pumping well will have well losses due to the convergence of water to the well resulting in higher velocities. When I estimated the well losses and fit the data from the first segment of the production well data, I obtained a lower transmissivity. The estimated transmissivity for the production well data was 20,000 gpd/ft and the storativity was 1.3×10^{-4}. Figure 3 shows the fit of the production well data and the agreement between predicted and observed is excellent. Well losses were estimated using the following equation:

$$W_L = 1.08 \times 10^{-5} * Q_{gpm}^{\,2}$$

The conclusion from the pumping test analysis is the Transmissivity is probably between 20,000 gpd/ft and 25,000 gpd/ft. If the drawdown effects are evaluated using the lower T values then the answers will be "conservative".

You indicated over the phone that the city average daily demand is projected to be 0.794 MGD with a peak day rate of 2.379 MGD, based on a 20 hour pumping time. You also said the nearest well was about 1 mile away and the South Sioux County Rural Water System well field was about 2 miles away. The peak day would require 1982 gpm for a 20 hour pumping day. If we assume two wells, that requires each well to pump 990 gpm. I do not believe this formation can stand that high of pumping rate. The drawdown in the production wells pumping at 1000 gpm would be about 125 ft. Figure 4 shows the variation of drawdown with pumping rate in the production well. From the drillers log, the top of the sandstone unit is about 258 feet below surface. The primary water bearing formation seems to be between 334 and 460 feet below surface. The static water level was about 140 feet below surface. To keep the potentiometric level above the top of the sandstone unit, the maximum drawdown would be 118 feet (258-140). From Figure 4 with 118 feet drawdown the pumping rate would be about 900 gpm. My feeling is that the long term pumping rate should be around 700 gpm, it may be possible to get as much as 800 gpm, as you desired.

I analyzed the drawdown radially from two well producing 700 gpm each using transmissivities of 20,000 gpd/ft and 24,500 gpd/ft. These results are shown in Figures 5 and 6. The drawdown due to the Orange City wells pumping at 1 and 2 miles will be about 10 feet and 2 feet, respectively. These drawdowns should not limit the ability of these surrounding owners to withdraw their permitted amount from a properly constructed well.

I also analyzed drawdowns over a longer pumping time. I chose 3 years continuous pumping. Figure 7 shows the cone of depressions from one well pumping at various rates. The 600 gpm rate has a drawdown of about 90 feet while the 800 gpm had a drawdown of 125 feet.

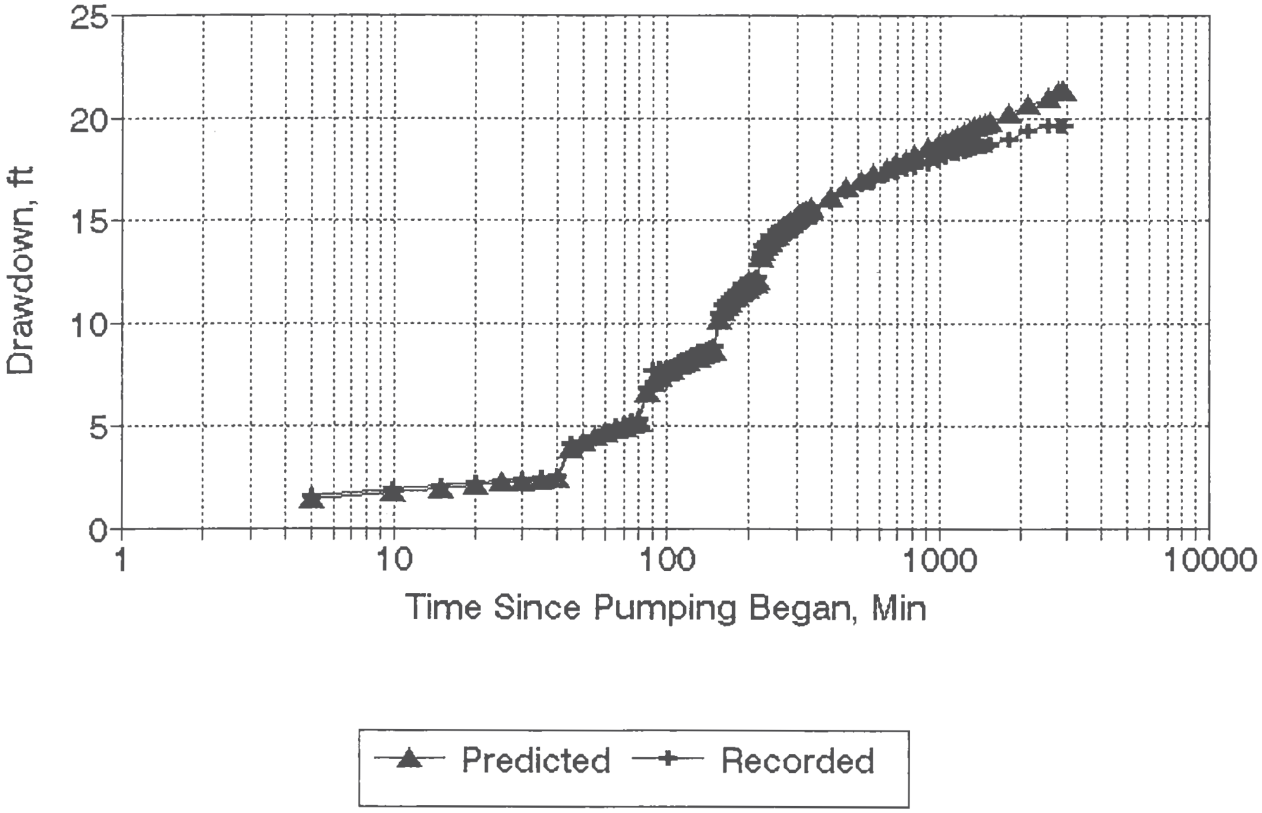
I believe that the best pumping rate would be around 600 to 700 gpm from this well. It could be that 800 gpm is achievable, but I think the lower rate is more reasonable. I would recommend a 14 inch minimum casing at pumping rate of 600-700 gpm. At 800 gpm you may want to increase the diameter to 16 inch. You will need a hole of about 20 inch diameter. Based on the sand grain size distribution curve, it would appear that a No. 20 Johnson wire wound screen with a gravel pack would be adequate. The gravel should have an effective size of about 0.02" to 0.04" with a uniformity coefficient equal about 2.5.

In conclusion, I believe the transmissivity of the aquifer is between 20,000 gpd/ft and 25,000 gpd/ft and the storativity is between 1.3×10^{-4} and 1.3×10^{-4}. I believe a well with a pumping rate of 600 to 700 gpm can be developed at this location. Drawdowns at surrounding existing wells should not be excessive. A minimum 14" diameter casing in a 20" bore hole will be necessary.

I hope this letter report will be helpful in your project. If you need any further analysis, please contact me. I will be back in town after July 6.

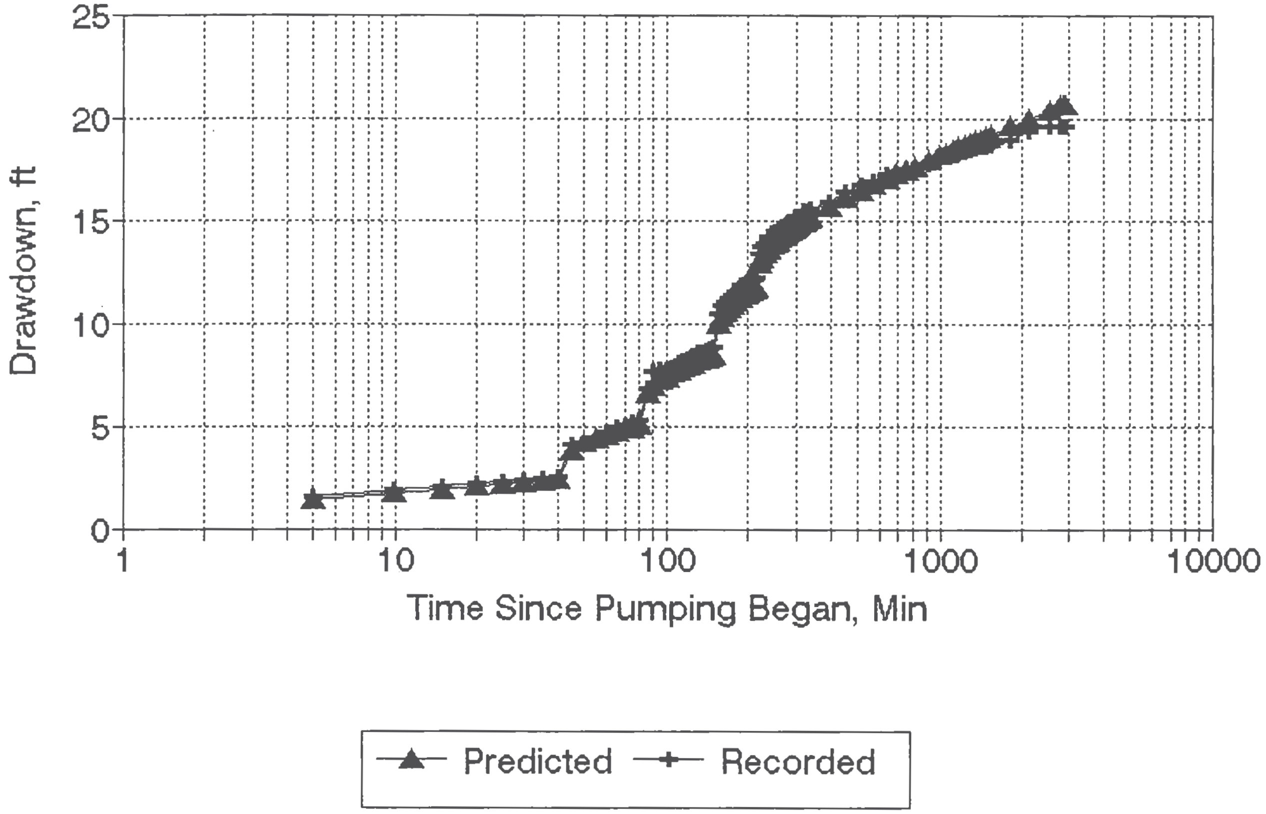
Sincerely,

T. Al Austin, Ph.D., P.E.
Iowa Registration No. 7042



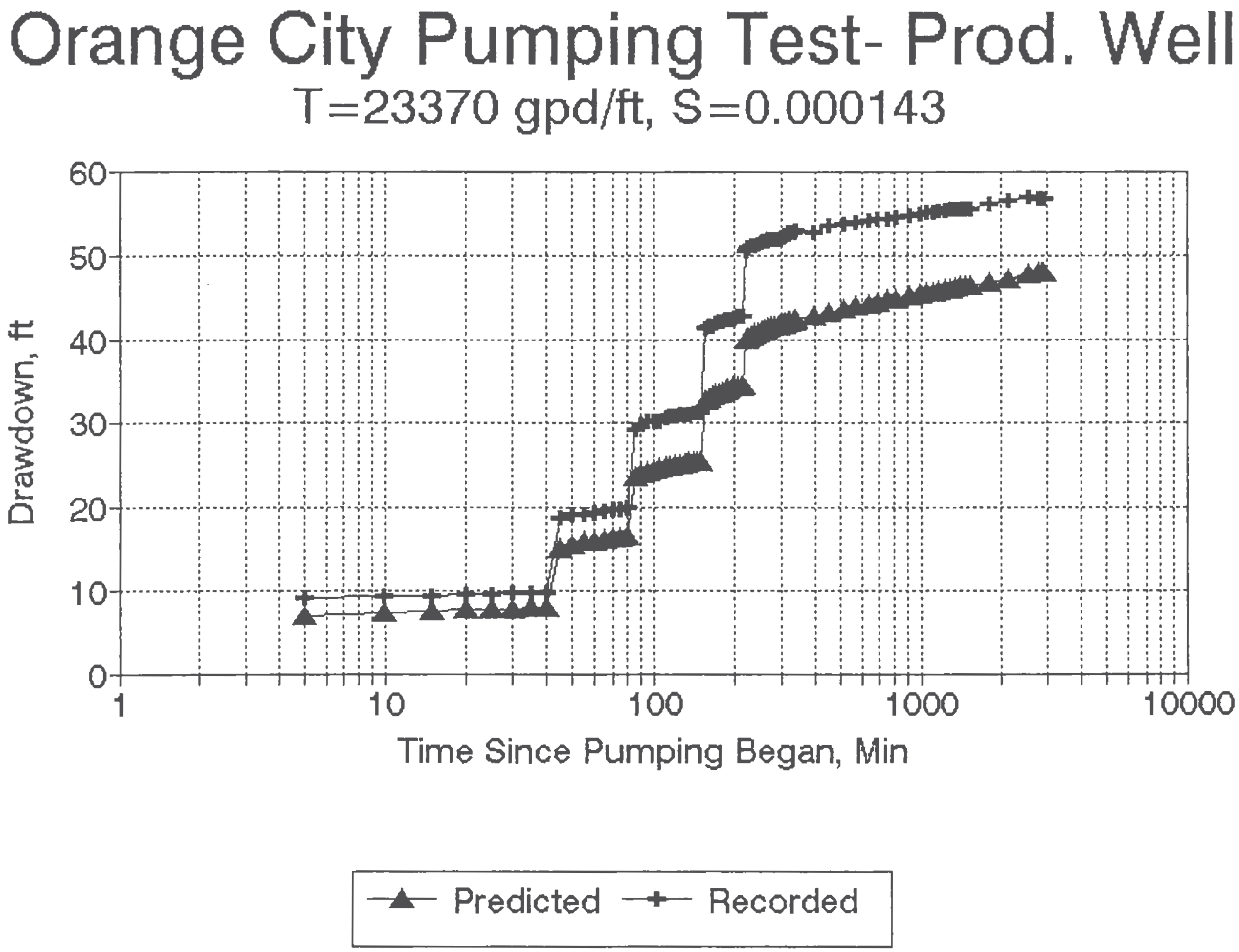
Orange City Pumping Test- Ob. Well

T=23370 gpd/ft, S=0.000142



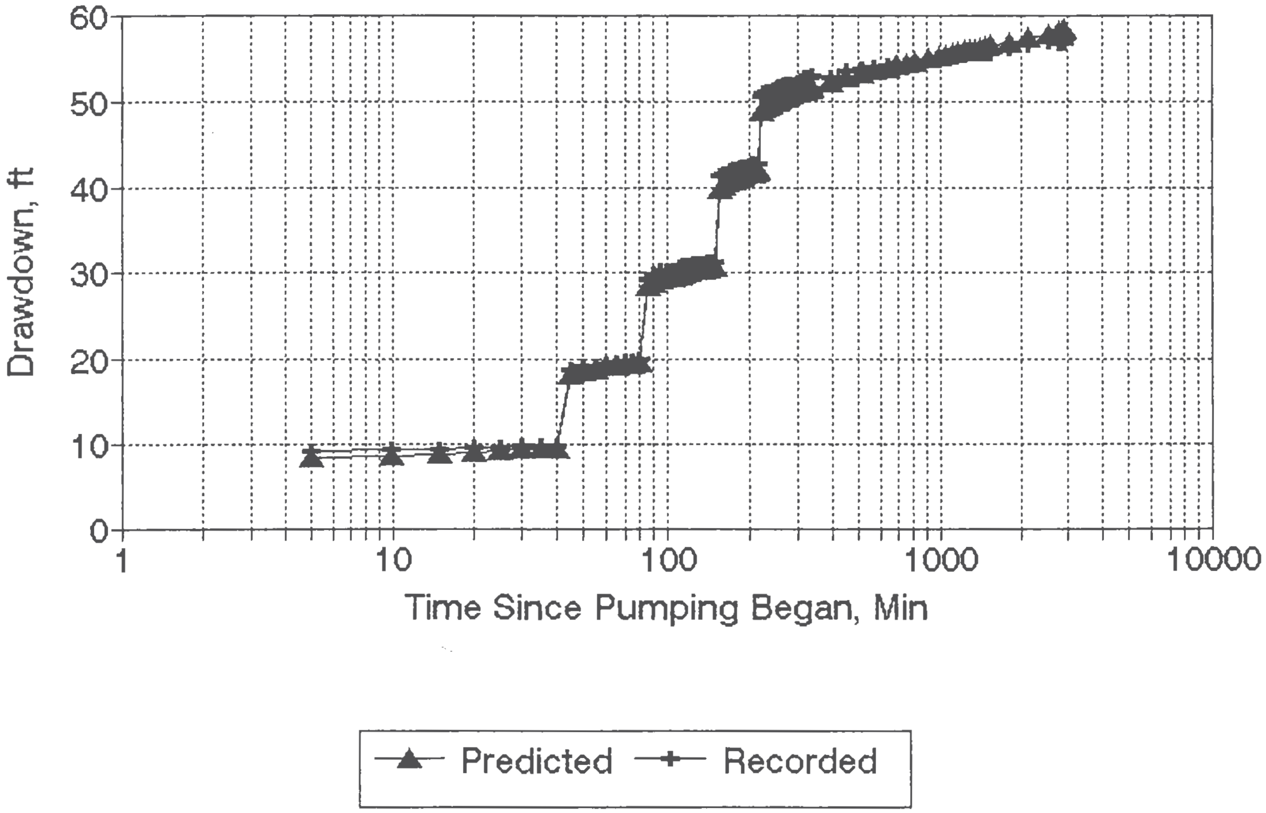
Orange City Pumping Test- Ob. Well

T=24500 gpd/ft, S=0.00011



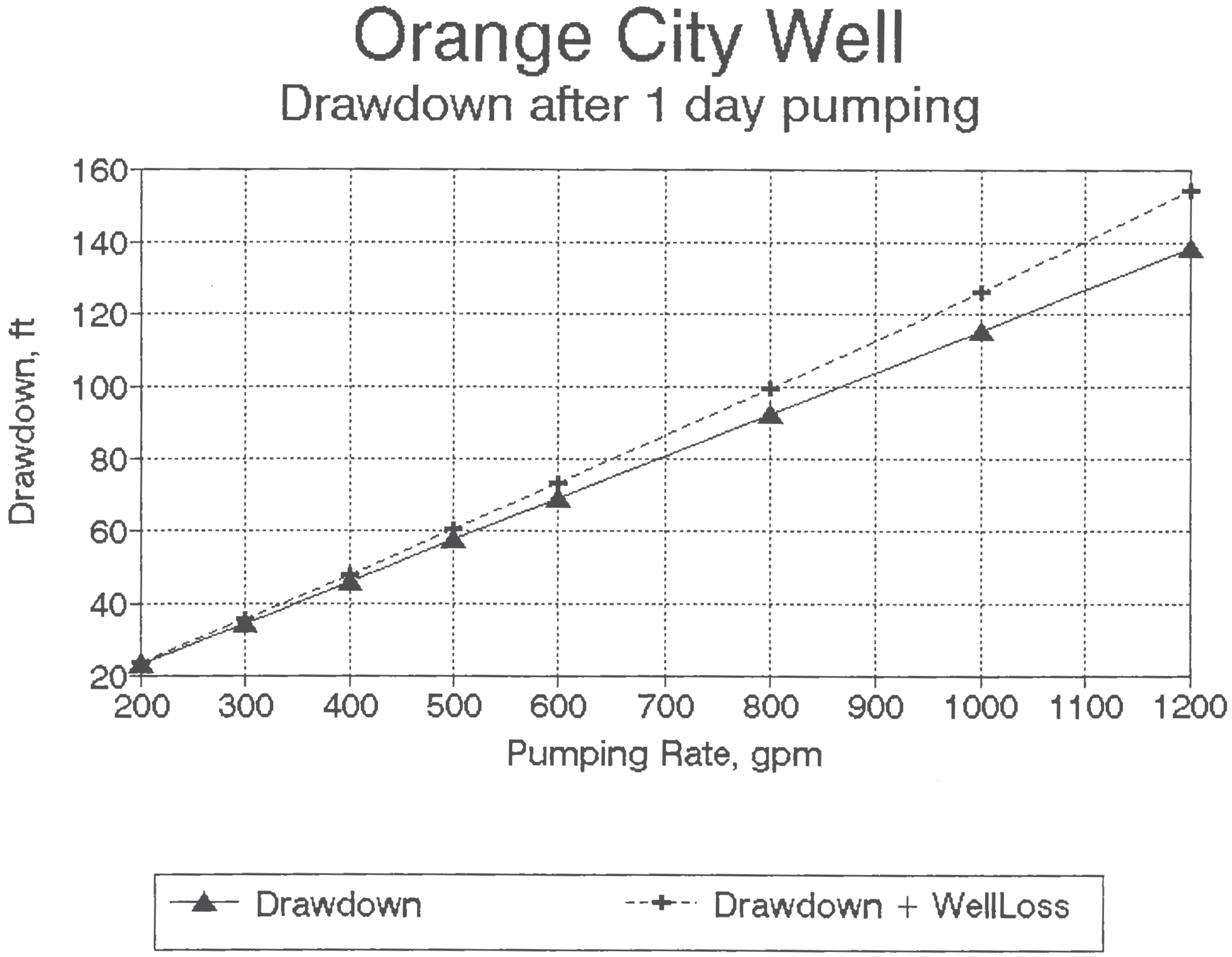
Orange City Pumping Test- Prod. Well

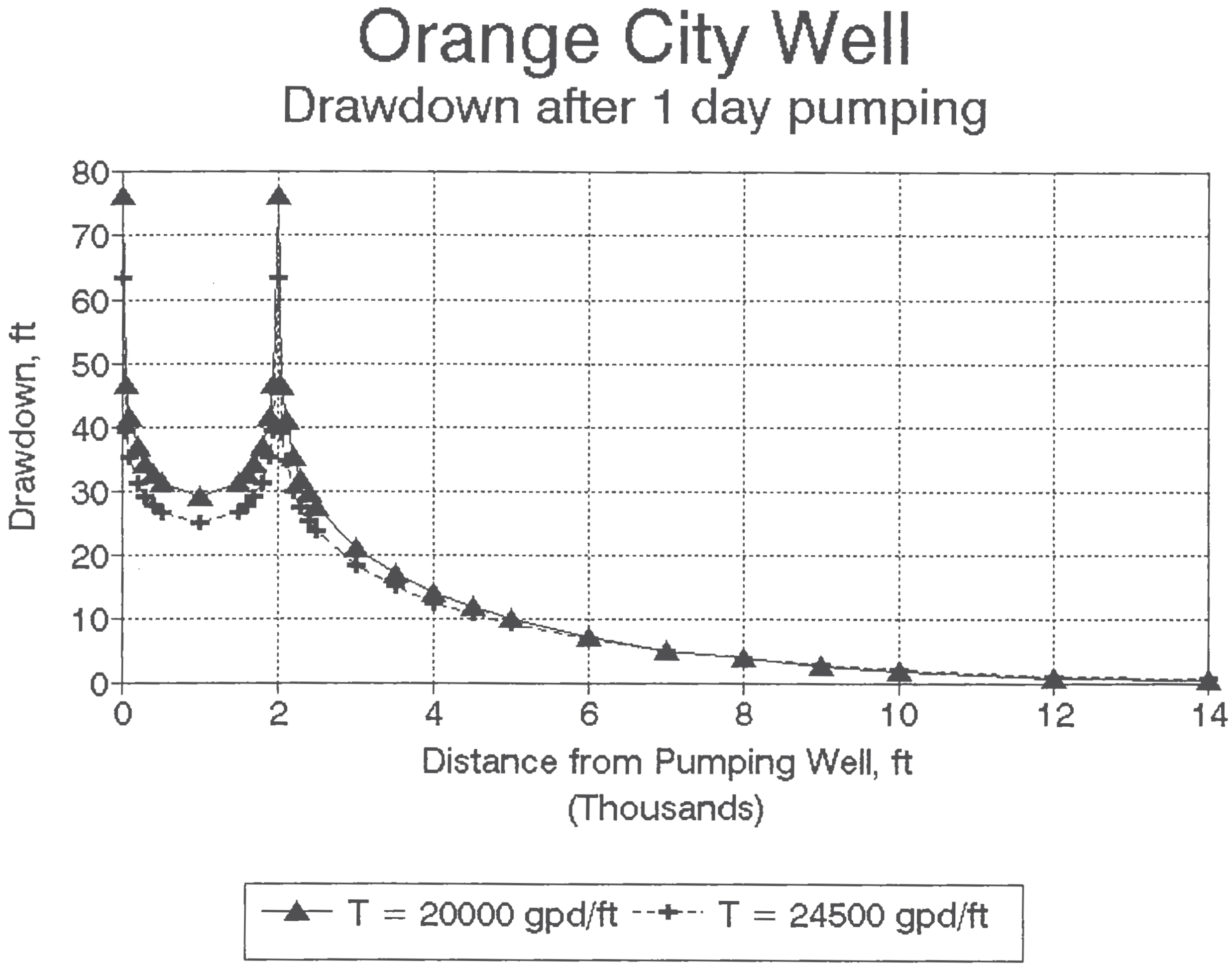
T=23370 gpd/ft, S=0.000143

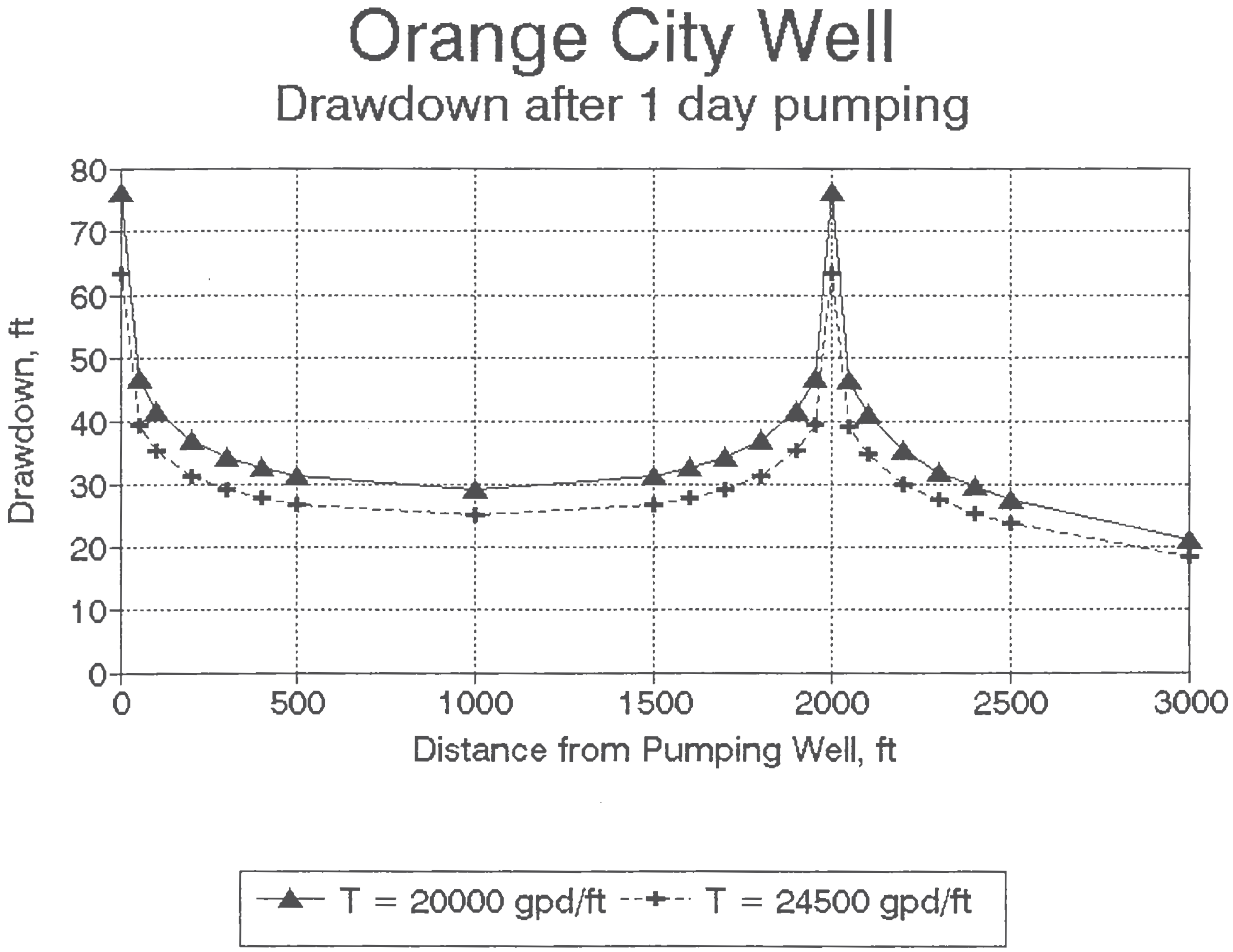


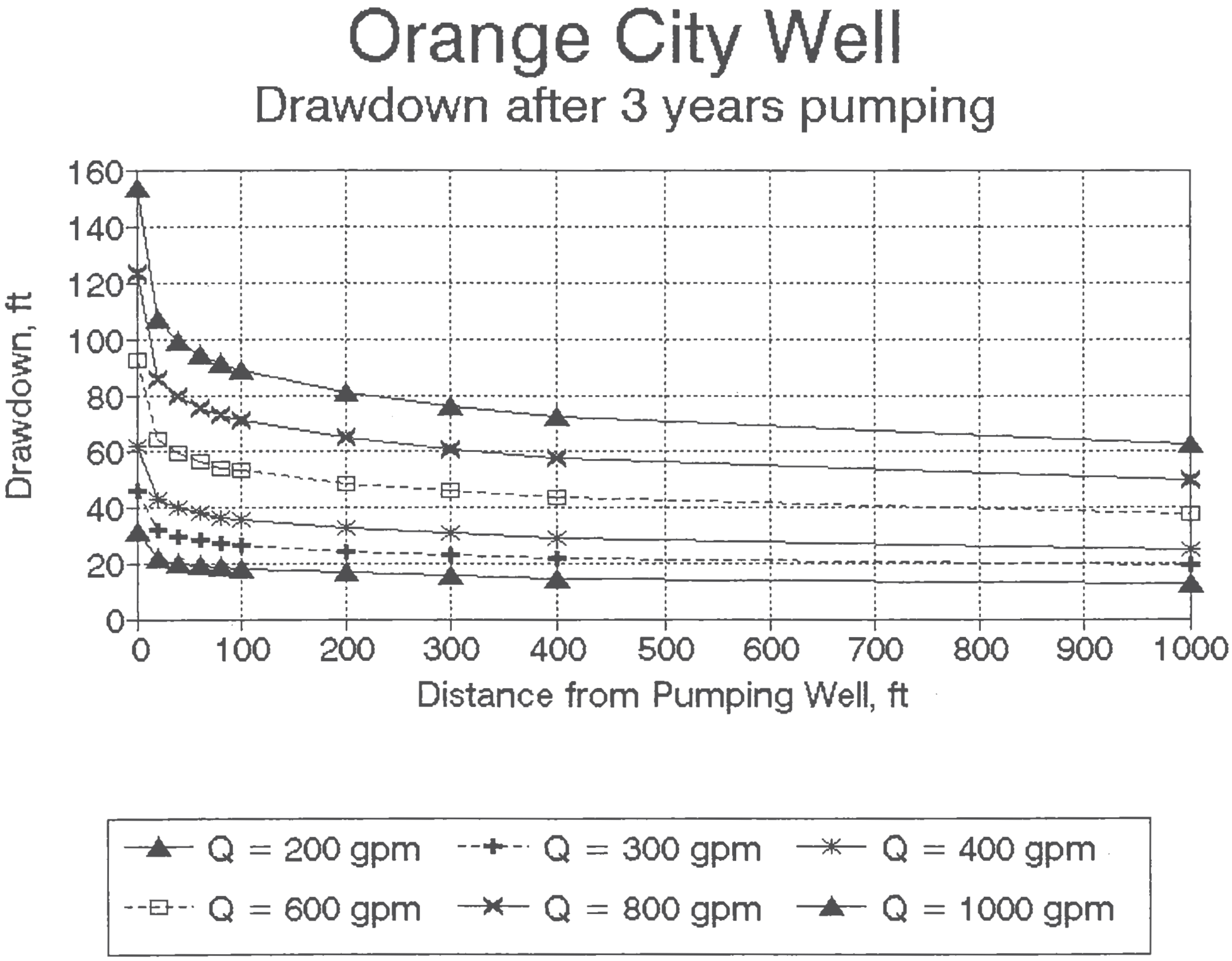
Orange City Pumping Test- Prod. Well

T=20000 gpd/ft, S=0.00013


Orange City Well
Drawdown after 1 day pumping
Drawdown, ft
160
140
120
100
80
60
40
20
200
300
400
500
600
700
800
900
1000
1100
1200
Pumping Rate, gpm
Drawdown
Drawdown + WellLoss


Orange City Well
Drawdown after 1 day pumping
Drawdown, ft
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Distance from Pumping Well, ft
(Thousands)
T = 20000 gpd/ft
T = 24500 gpd/ft


Orange City Well
Drawdown after 1 day pumping
Drawdown, ft
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
Distance from Pumping Well, ft
T = 20000 gpd/ft
T = 24500 gpd/ft


Orange City Well
Drawdown after 3 years pumping
Drawdown, ft
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000
Distance from Pumping Well, ft
Q = 200 gpm
Q = 300 gpm
Q = 400 gpm
Q = 600 gpm
Q = 800 gpm
Q = 1000 gpm

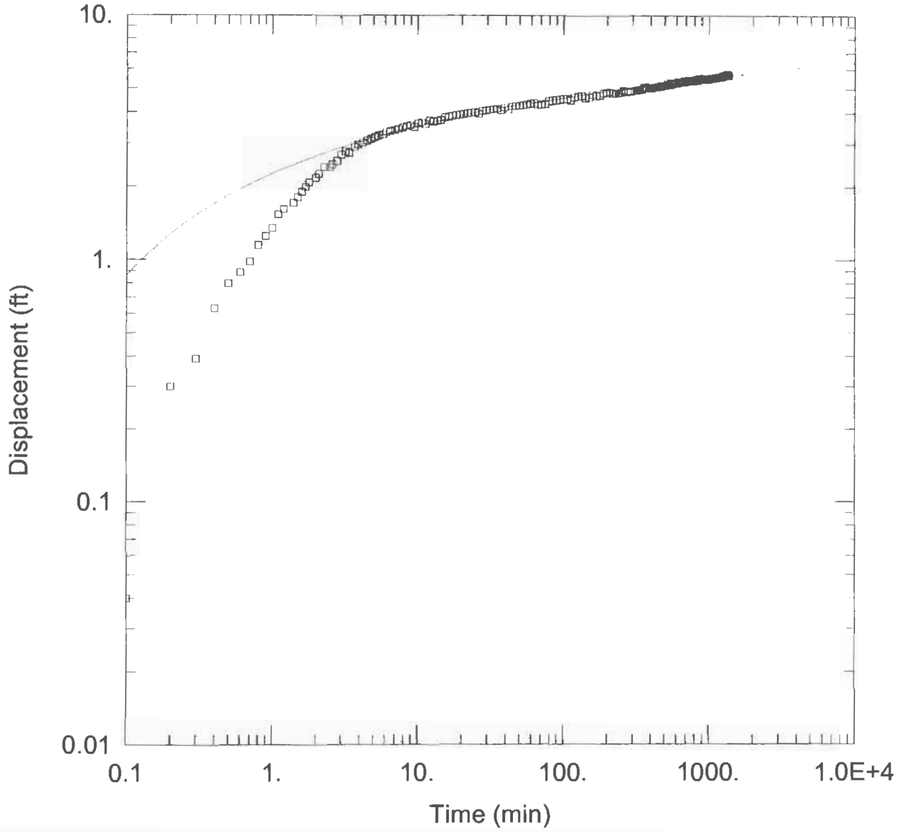


FIGURE 1

PROJECT INFORMATION

Company: Layne
Client: GPRE
Location: Superior,IA
Test Well: PW-1
Test Date: 12/7/2007

AQUIFER DATA

Saturated Thickness: 200. ft
Aquitard Thickness (b'): 1. ft
Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ TW-1	45	0

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush

T = 6380.9 ft^2/day
r/B' = 0.03
r/B" = 0.
S = 0.0001875
ß' = 0.1
ß" = 0.

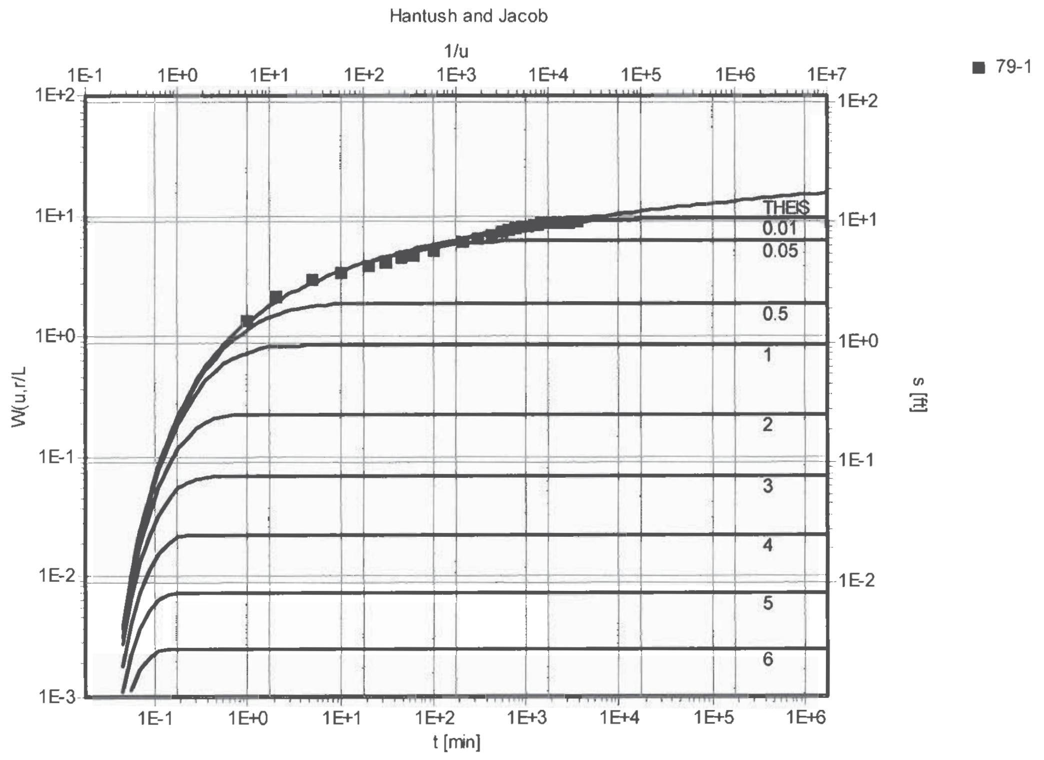
Waterloo Hydrogeologic, Inc.
180 Columbia St. Unit 1104
Waterloo, Ontario, Canada
Phone: +1 519 746 1798

Pumping test analysis
No:
Project: S. Sioux RW Maurice
Client:

Location:
Pumping test: Maurice
Pumping well: d-1

Test performed by: DGR
Test date: 10/29/1979
Evaluated by: IDNR-IGS
Evaluation date: 6/5/2008

Analysis method: Hantush and Jacob
Aquifer thickness:
Discharge rate: 610 [U.S. gal/min]



Transmissivity: 8.29×10^+3 [ft²/d]

Storativity: 3.19×10^-4

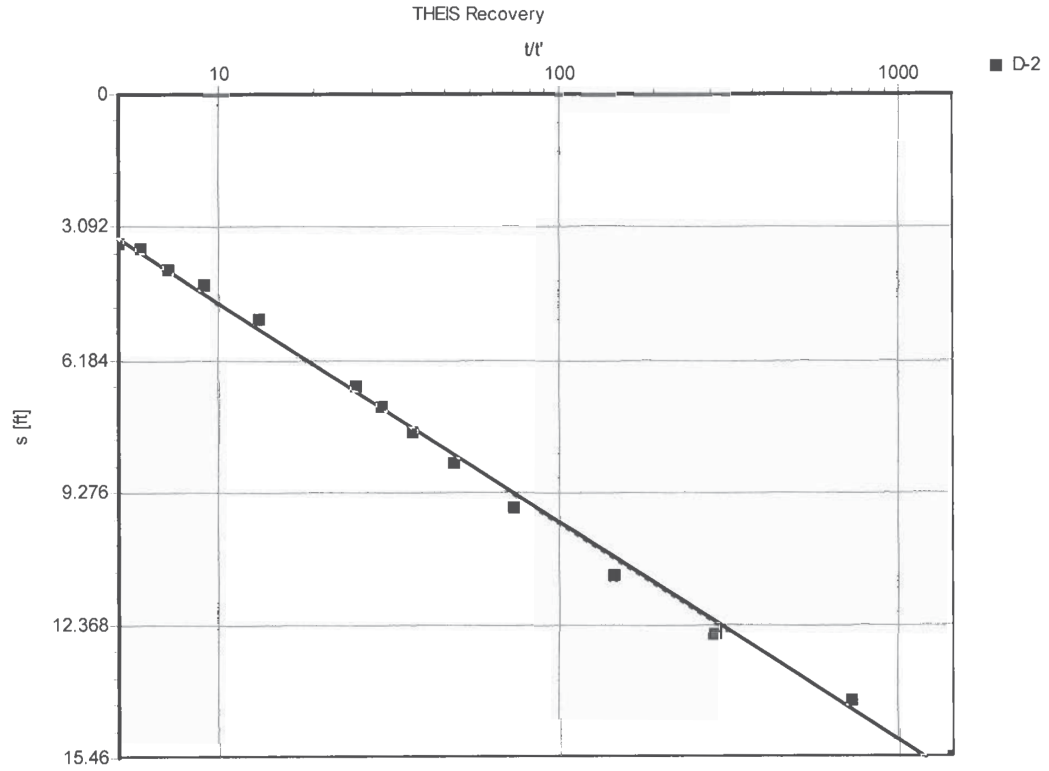
c : 2.18×10^+7 [min]

Waterloo Hydrogeologic, Inc.
180 Columbia St. Unit 1104
Waterloo, Ontario, Canada
Phone: +1 519 746 1798

Pumping test analysis
No:
Project: S. Sioux RW Maurice
Client:

Location:	Pumping test: S. Sioux RW	Pumping well: D-2

Test performed by:	Layne Western	Evaluated by:	
Test date:	3/30/1990	Evaluation date:	6/5/2008
Analysis method:	THEIS Recovery	Aquifer thickness:	157
		Discharge rate:	1004 [U.S. gal/min]



Transmissivity: 6.95×10^+3 [ft²/d]

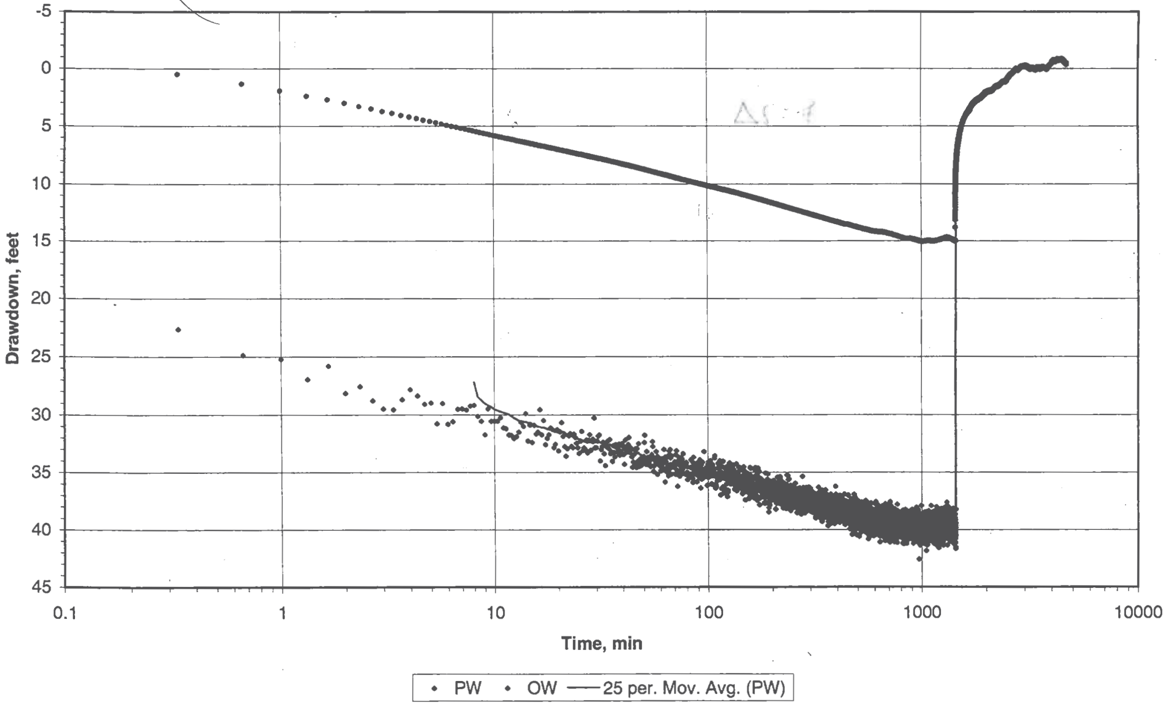
Conductivity: 4.42×10^+1 [ft/d]

1,000 gpm

[illegible]

66,000 gpd/ft

SSCRWS Well D-3 24-hr Test
June 8-9, 2001



p:\08\018\05\welld3\pumptest\d3_test.xls

Waterloo Hydrogeologic, Inc.
180 Columbia St. Unit 1104
Waterloo, Ontario, Canada
Phone: +1 519 746 1798

Pumping test analysis

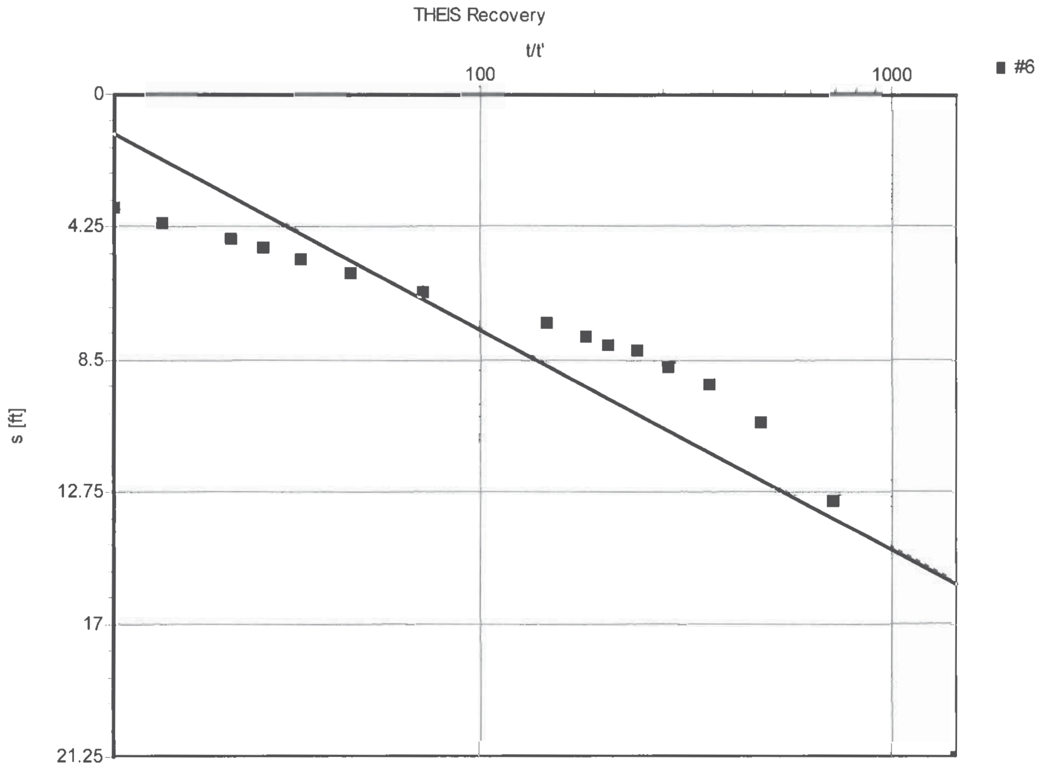
No:

Project: Emmetsburg

Client:

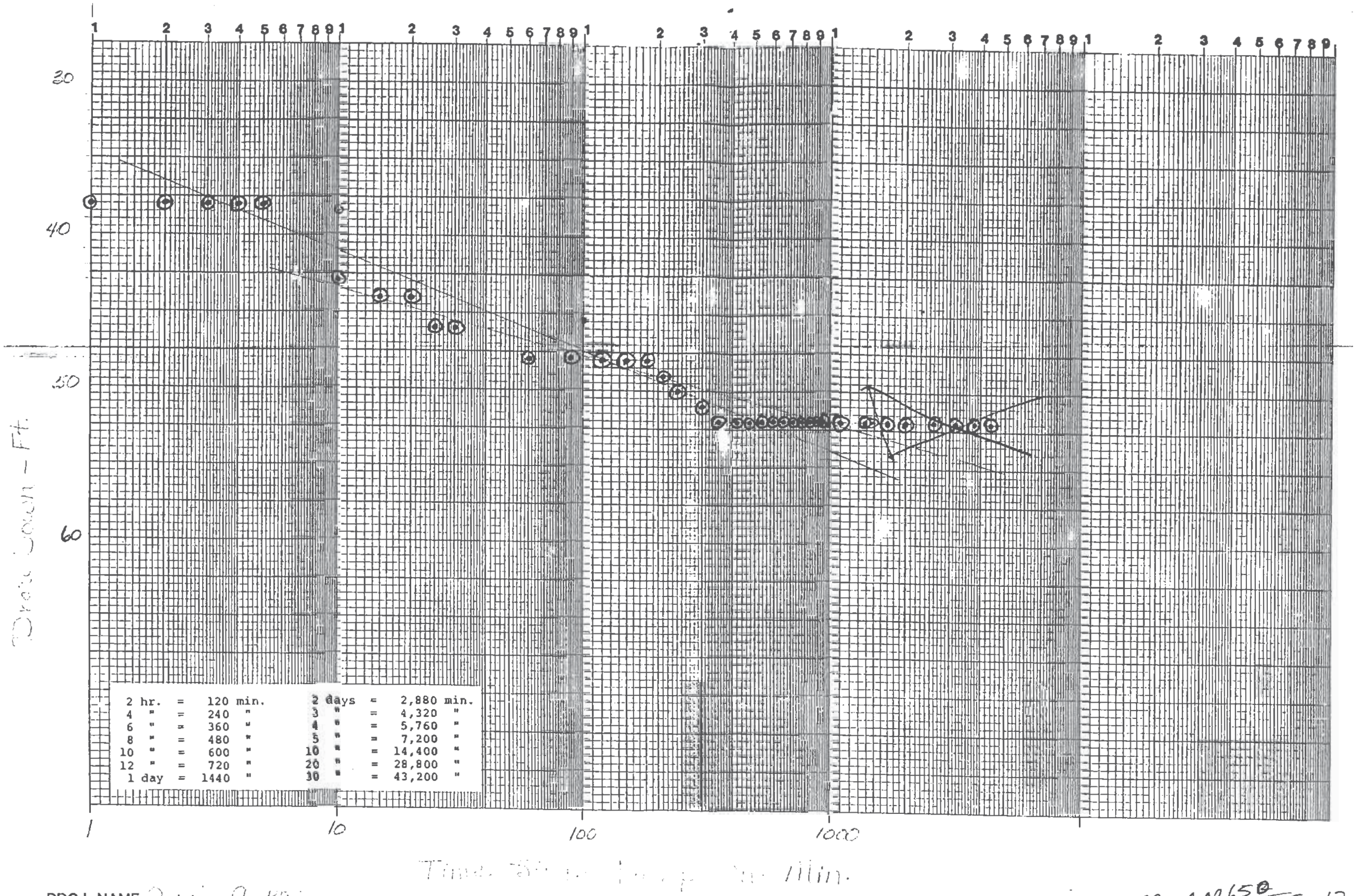
Location:	Pumping test: Emmetsburg #6	Pumping well: #6

Test performed by:	Layne Western	Evaluated by:	IDNR-IGS
Test date:	3/11/1993	Evaluation date:	6/5/2008
Analysis method:	THEIS Recovery	Aquifer thickness:	75 [ft]
		Discharge rate:	1007 [U.S. gal/min]



Transmissivity: 5.02×10^+3 [ft²/d]

Conductivity: 6.70×10^+1 [ft/d]



2 hr.	=	120 min.	2 days	=	2,880 min.
4 "	=	240 "	3 "	=	4,320 "
6 "	=	360 "	4 "	=	5,760 "
8 "	=	480 "	5 "	=	7,200 "
10 "	=	600 "	10 "	=	14,400 "
12 "	=	720 "	20 "	=	28,800 "
1 day	=	1440 "	30 "	=	43,200 "

PROJ. NAME Q[illegible] Co PRC
WELL NO. DS 1
DATE TESTED 8-19-81 & 8-20-
PUMPING RATE (Q) ~~650~~ GPM ± 700
DIST. FROM PUMPED WELL (r)______FT.
Δs_1 6.5 Δs_2 4.4
6.95

$T = \frac{264(Q)}{\Delta s}$

T = 26,400 G/day/ft

T = 42,000 "

$S = \frac{0.3Tt_0}{r^2}$

$= \frac{0.3 \times \quad \times}{(\quad)^2}$

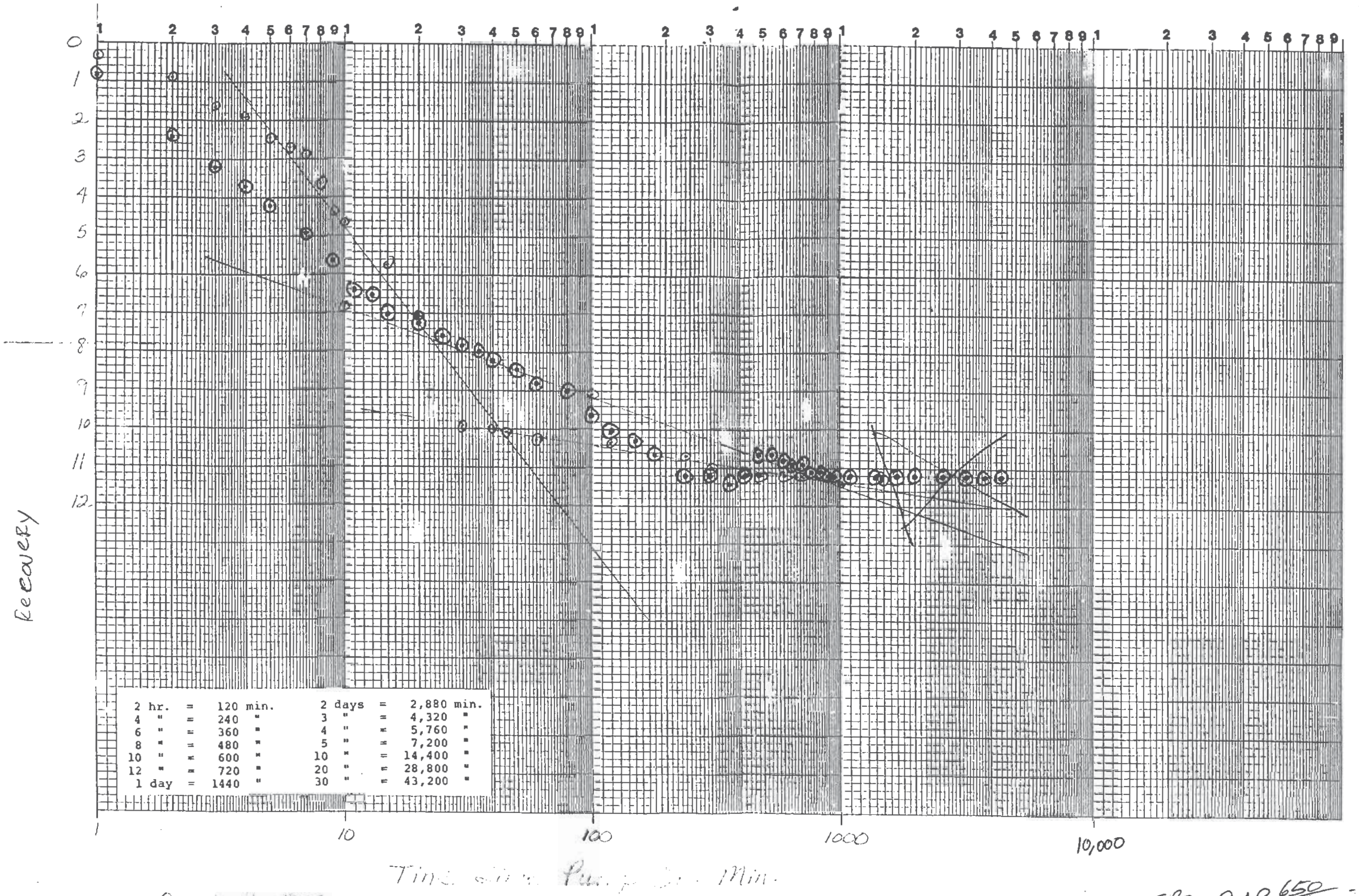
=

Spec. CAP $\frac{650}{52}$ = 12.5 GAL/FT DD

$\frac{700}{52}$ = 13.5

DeWild Grant Reckert & Associates Co.
Architecture Engineering Planning
Rock Rapids, Iowa
Sioux City, Iowa
Sioux Falls, South Dakota

Date
Drawn by
Approved
Revised



2 hr.	=	120 min.	2 days	=	2,880 min.
4 "	=	240 "	3 "	=	4,320 "
6 "	=	360 "	4 "	=	5,760 "
8 "	=	480 "	5 "	=	7,200 "
10 "	=	600 "	10 "	=	14,400 "
12 "	=	720 "	20 "	=	28,800 "
1 day	=	1440 "	30 "	=	43,200 "

PROJ. NAME Osceola Co. RWS
WELL NO. Observation 1-81
DATE TESTED 8-11-81
PUMPING RATE (Q) ~~650~~ GPM ± 700
DIST. FROM PUMPED WELL (r) 100 FT. ±
Δs. 2.35 Δ

$$T = \frac{264(Q)}{\Delta s}$$

T = ~~73,000~~ G/day/ft

T = 78,638 "

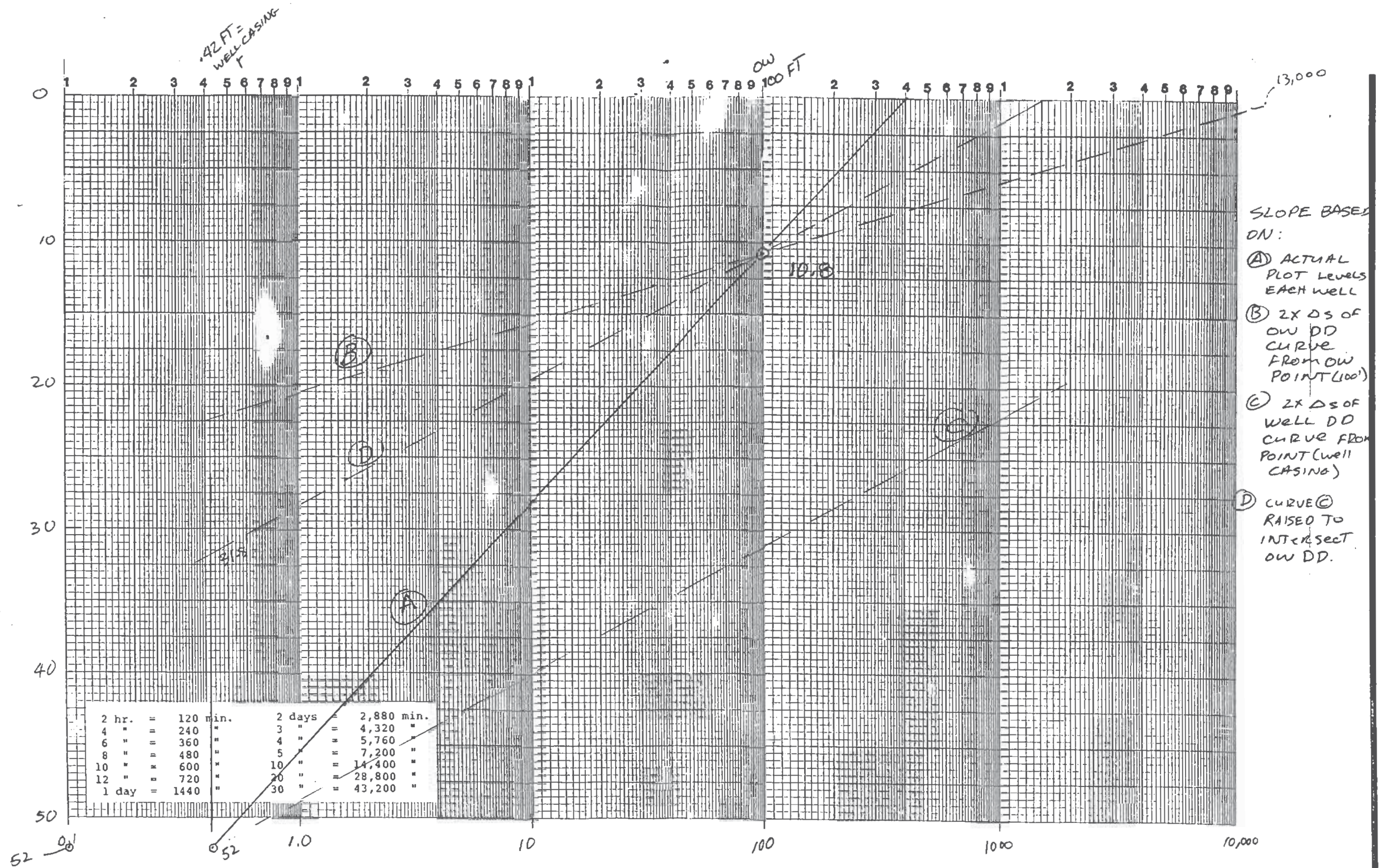
$$S = \frac{0.3Tt_o}{r^2}$$

$$= \frac{0.3 \times \quad \times}{(\quad)^2}$$

~~Spec. CAP. 650/11.21 = 586/FT DD~~

DeWild Grant Reckert & Associates Co.
Architecture Engineering Planning
Rock Rapids, Iowa
Sioux City, Iowa
Sioux Falls, South Dakota

Date
Drawn By
Approved
Revised



2 hr.	=	120 min.	2 days	=	2,880 min.
4 "	=	240 "	3 "	=	4,320 "
6 "	=	360 "	4 "	=	5,760 "
8 "	=	480 "	5 "	=	7,200 "
10 "	=	600 "	10 "	=	14,400 "
12 "	=	720 "	20 "	=	28,800 "
1 day	=	1440 "	30 "	=	43,200 "

SLOPE BASED ON:

Ⓐ ACTUAL PLOT LEVELS EACH WELL

Ⓑ 2X ΔS OF OW DD CURVE FROM OW POINT (100')

Ⓒ 2X ΔS OF WELL DD CURVE FROM POINT (WELL CASING)

Ⓓ CURVE Ⓒ RAISED TO INTERSECT OW DD.

PROJ. NAME OSCEOLA
WELL NO. DS-1
DATE TESTED
PUMPING RATE (Q) 700 GPM
DIST. FROM PUMPED WELL (r)______FT.

$T = \frac{264(Q)\,2}{\Delta s}$

T = $\boxed{21{,}120}$ G/day/ft

DDD

$S = \frac{0.3Tt}{r_0^2}$

$= 0.0273$

$S = \frac{0.3Tt_o}{r^2}$

$= \frac{0.3 \times \quad \times}{(\quad)^2}$

DIST VS DD
t = 1000 MIN. = .69 DAY

DeWild Grant Reckert & Associates Co.
Architecture Engineering Planning

Rock Rapids, Iowa
Sioux City, Iowa
Sioux Falls, South Dakota

Date
Drawn by
Approved
Revised

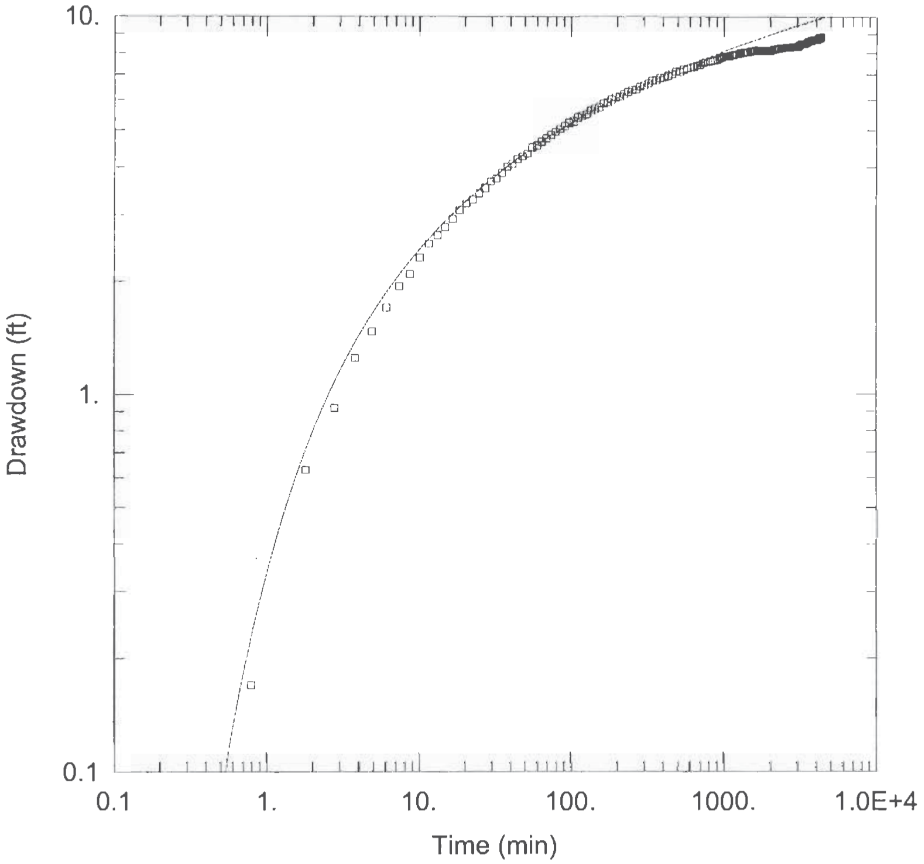


FIGURE 1B

PROJECT INFORMATION

Company: Layne
Client: VeraSun Energy
Location: Hartley,IA
Test Well: Test Well
Test Date: 9/19/07

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Test Well	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ OW-300	300	0

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 7831.1 ft^2/day
Kz/Kr = 1.
S = 0.0002147
b = 175. ft

44 ft/day

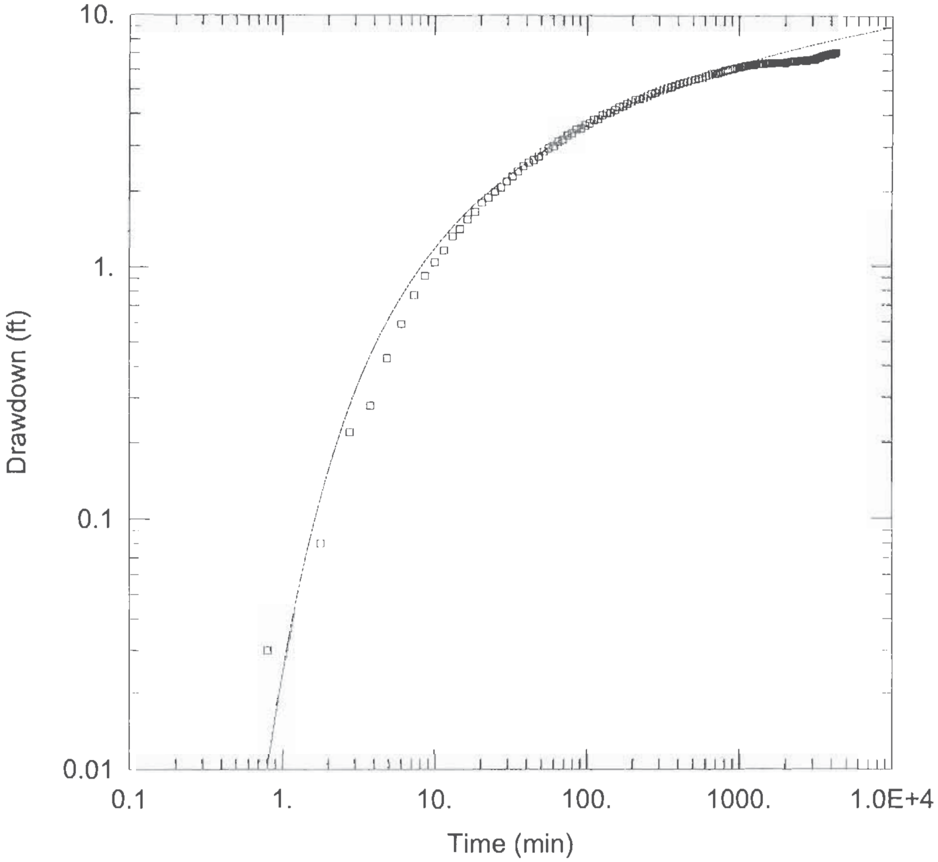


FIGURE 1C

PROJECT INFORMATION

Company: Layne
Client: VeraSun Energy
Location: Hartley,IA
Test Well: Test Well
Test Date: 9/19/07

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Test Well	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ OW-600	600	0

SOLUTION

Aquifer Model: Confined

Solution Method: Theis

T = 8321.7 ft²/day
Kz/Kr = 1.

S = 0.0001711
b = 175. ft

47 ft/day

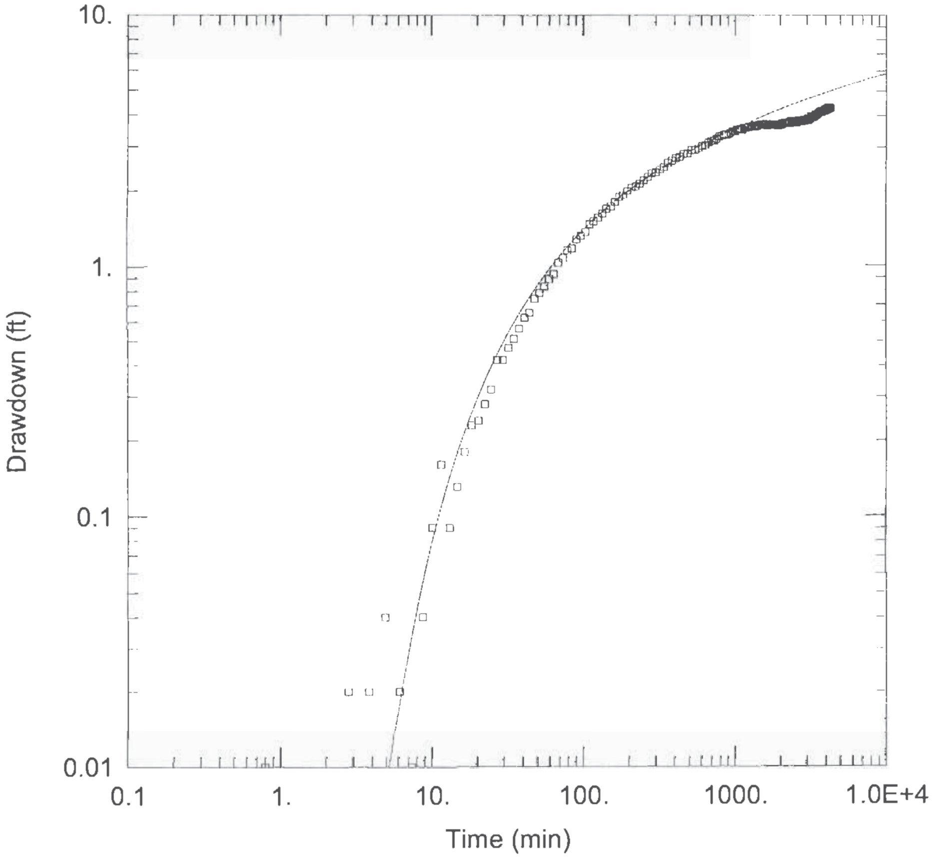


FIGURE 1D

PROJECT INFORMATION

Company: Layne
Client: VeraSun Energy
Location: Hartley,IA
Test Well: Test Well
Test Date: 9/19/07

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Test Well	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ **OW-1500**	1500	0

SOLUTION

Aquifer Model: Confined

Solution Method: Theis

T = 9740.7 ft²/day
Kz/Kr = 1.

S = 0.0002018
b = 175. ft

55.6 ft/day

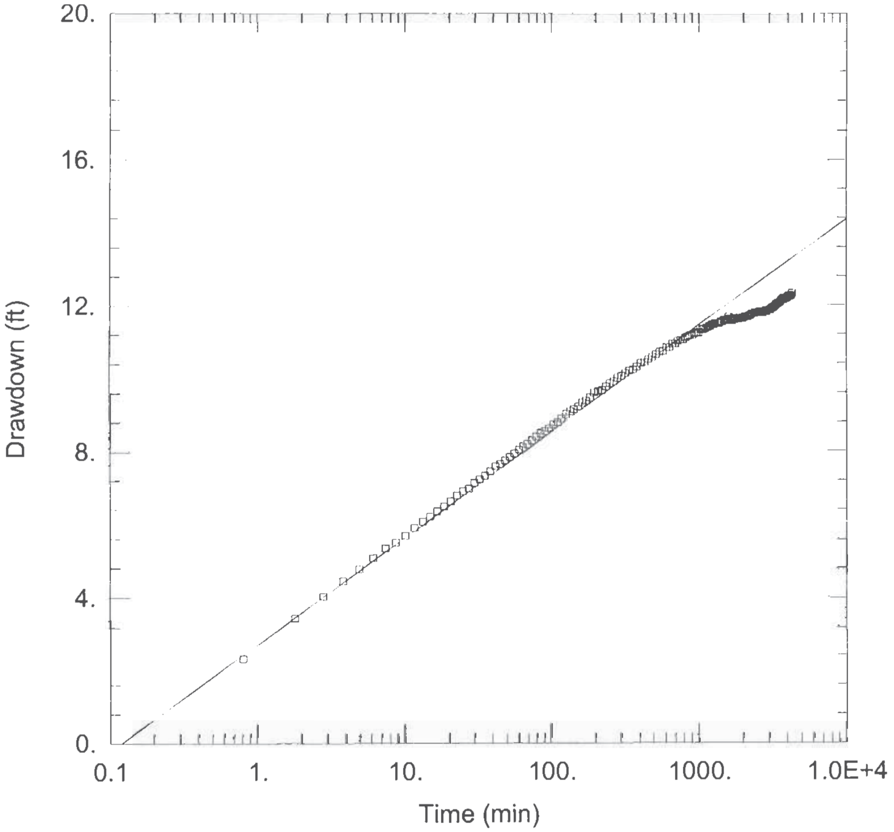


FIGURE 2A

PROJECT INFORMATION

Company: Layne
Client: VeraSun Energy
Location: Hartley,IA
Test Well: Test Well
Test Date: 9/19/07

AQUIFER DATA

Saturated Thickness: 175. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Test Well	0	0

Observation Wells

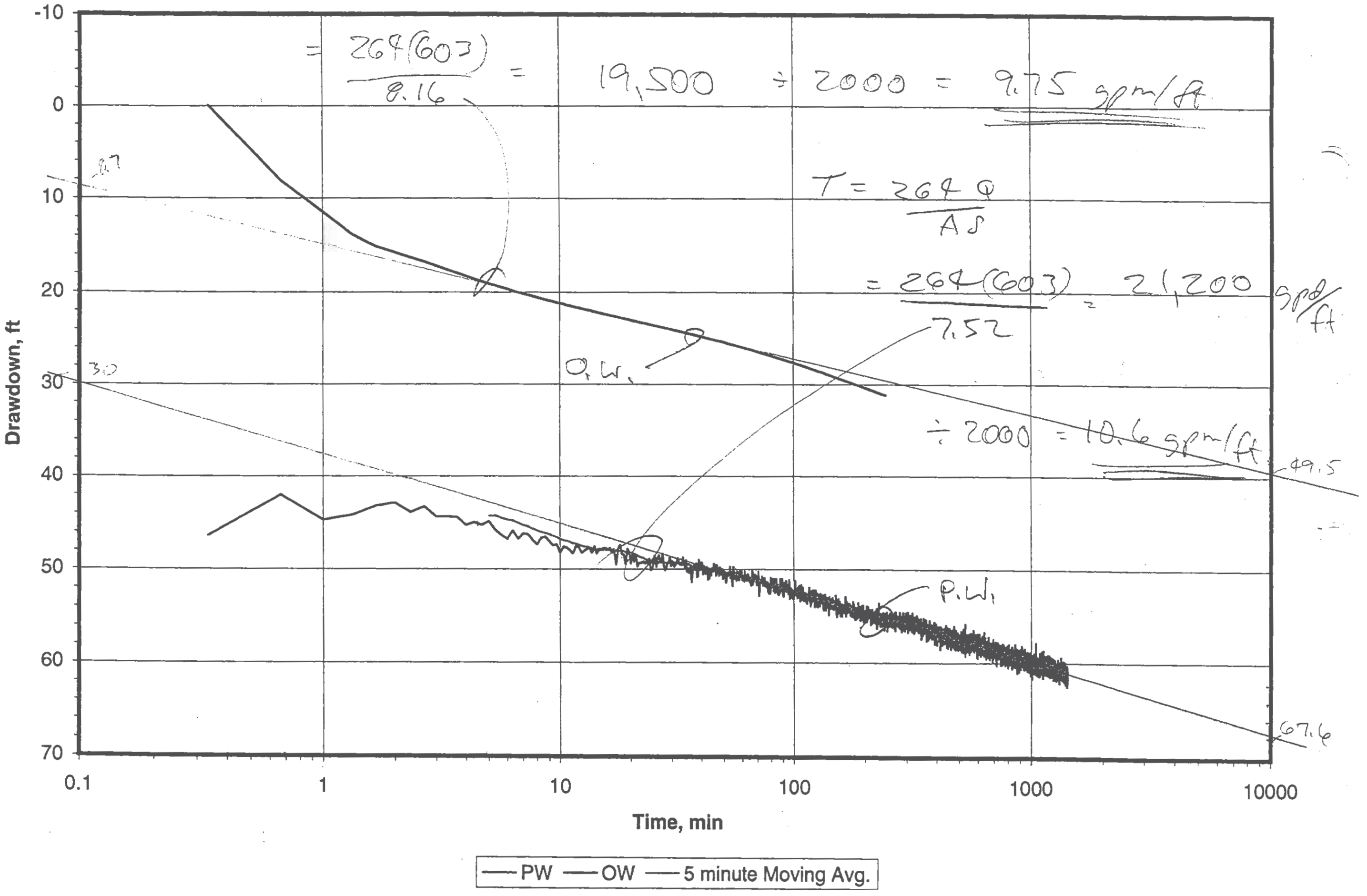
Well Name	X (ft)	Y (ft)
□ OW-100	100	0

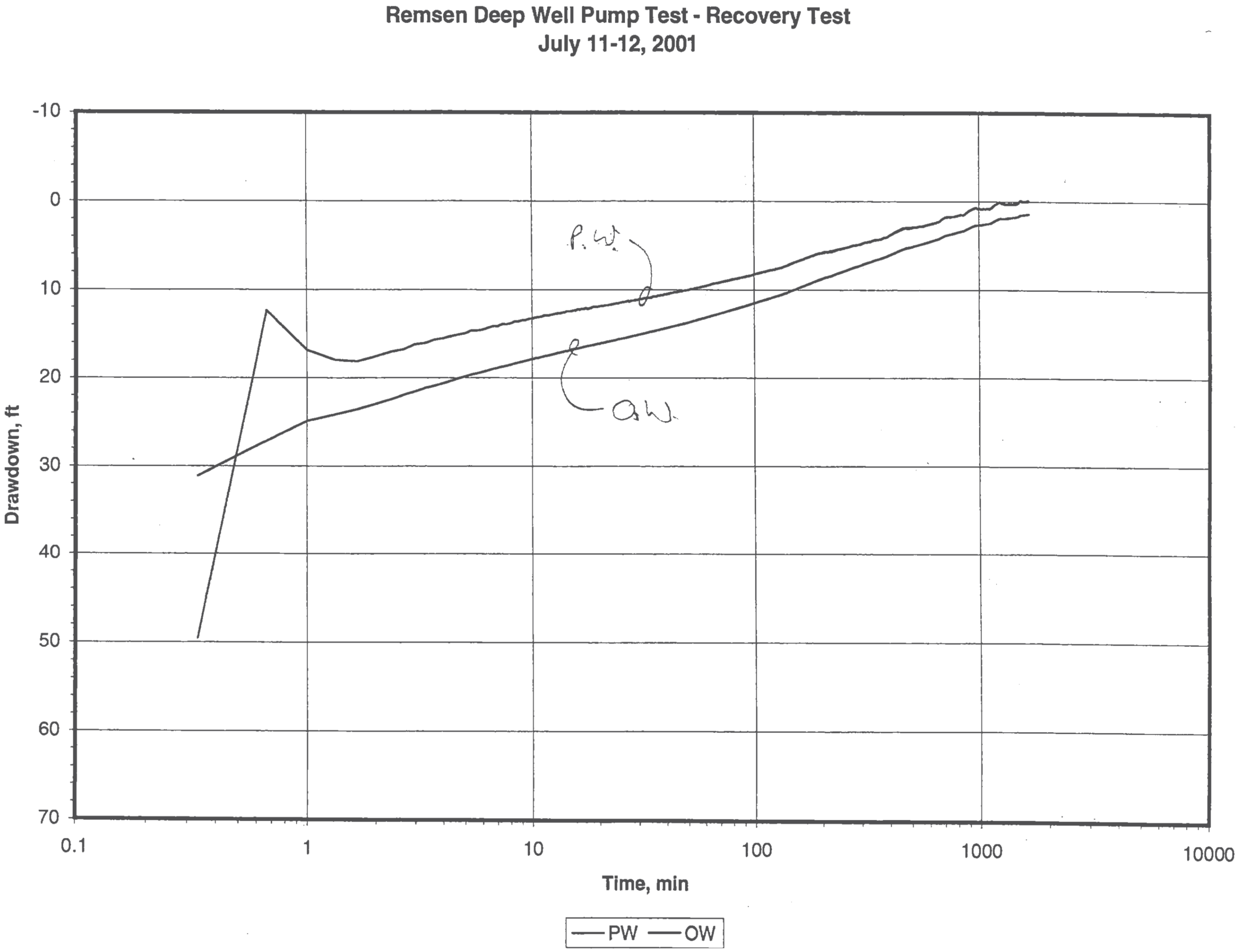
SOLUTION

Aquifer Model: Confined
Solution Method: Cooper-Jacob
T = 7755.5 ft^2/day
S = 0.0001433

44 ft/dy

Remsen Deep Well Pump Test - 24 hr Test
July 10-11, 2001





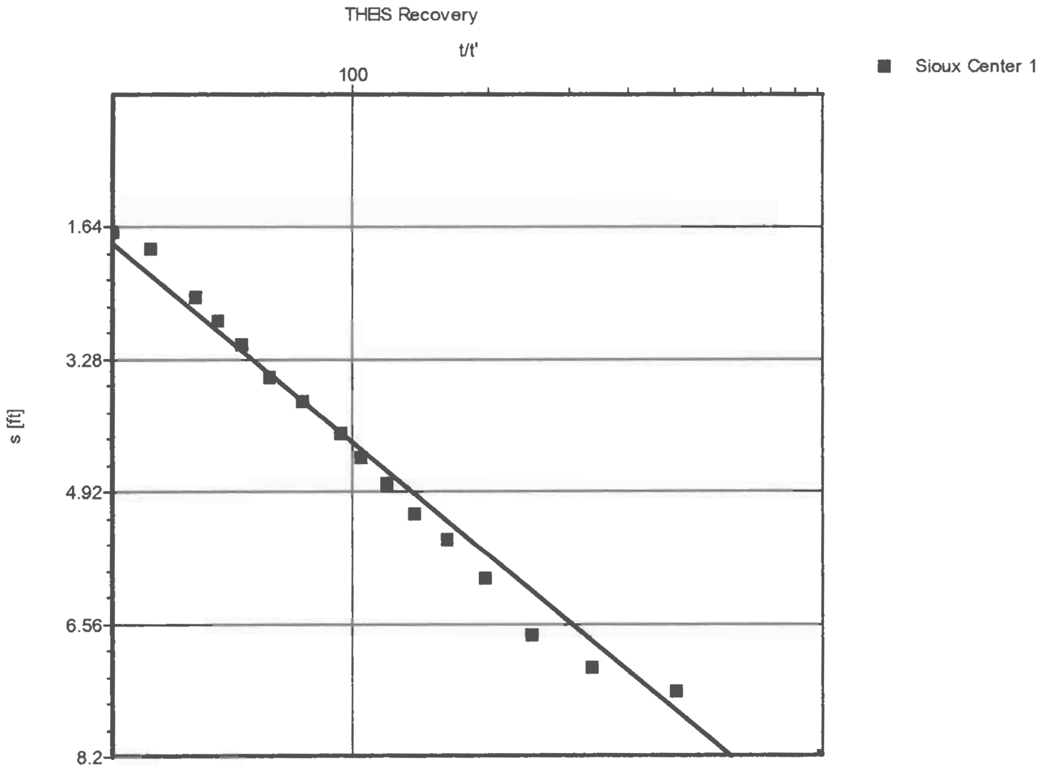
Remsen Deep Well Pump Test - Recovery Test
July 11-12, 2001

Waterloo Hydrogeologic, Inc.
180 Columbia St. Unit 1104
Waterloo, Ontario, Canada
Phone: +1 519 746 1798

Pumping test analysis
No:
Project: Sioux Center
Client:

Location: Sioux County, Iowa	Pumping test: Sioux Center	Pumping well: Sioux

Test performed by: Mike Gannon Test date: 2/20/2008	Evaluated by: Evaluation date: 2/20/2008
Analysis method: THEIS Recovery	Aquifer thickness: 87 [ft] Discharge rate: 550 [U.S. gal/min]



Transmissivity: 3.90×10^+3 [ft²/d]

Conductivity: 4.48×10^+1 [ft/d]

Layne-Western
5600 Gateway Drive, Suite B
Grimes, IA 50111
(515) 986-3462 / 3474 Fax

WELL TEST DATA REPORT

(CONSTANT-RATE TEST)

PROJECT:	Sioux Center Land Development	**DATE TESTED:**	4/19/07 - 4/20/07
LOCATION:	Sioux Center, Iowa	**TESTED BY:**	Mark Leslie
WELL NO:	1	**DRIVER:**	75-HP Submersible Motor
WELL DIAMETER:	12.00 inches I.D.	**COLUMN AND SHAFT:**	6" Drop Pipe
WELL DEPTH:	520.0 feet - from grade	**BOWL SIZE & MAKE:**	9RCLC, 3-Stage
TOP OF SCREEN:	440.0 feet - from grade	**MANUFACTURER:**	Goulds
STATIC LEVEL:	230.5 feet - from top of casing	**SERIAL NUMBER:**	
ORIFICE SIZE:	6" x 5"		

TIME	PIEZ. READ. (IN)	FLOW RATE (GPM)	AIRLINE READING (FEET)	WATER LEVEL (FEET)	DRAW DOWN (FEET)	DISCHARGE PRESSURE (LBS.)	DISCHARGE PRESSURE (FEET)	SPEC. CAPACITY (GPM/FT)	REMARKS
1 min.	19.5	550		298.0	67.5			8.1	Started 2:36 p.m.
2	19.5	550		299.4	68.9			8.0	
3	19.5	550		302.2	71.7			7.7	
4	19.5	550		303.6	73.1			7.5	
5	19.5	550		304.0	73.5			7.5	
6	19.5	550		304.2	73.7			7.5	
7	19.5	550		304.5	74.0			7.4	
8	19.5	550		304.6	74.1			7.4	
9	19.5	550		304.8	74.3			7.4	
10	19.5	550		304.9	74.4			7.4	
12	19.5	550		305.0	74.5			7.4	
14	19.5	550		305.3	74.8			7.4	
16	19.5	550		305.6	75.1			7.3	
18	19.5	550		306.1	75.6			7.3	
20	19.5	550		306.7	76.2			7.2	
25	19.5	550		307.2	76.7			7.2	
30	19.5	550		307.5	77.0			7.1	
35	19.5	550		307.9	77.4			7.1	
40	19.5	550		308.2	77.7			7.1	
45	19.5	550		308.4	77.9			7.1	
50	19.5	550		308.5	78.0			7.1	
55	19.5	550		308.7	78.2			7.0	
60	19.5	550		308.8	78.3			7.0	
90	19.5	550		309.5	79.0			7.0	
120	19.5	550		309.8	79.3			6.9	
150	19.5	550		310.1	79.6			6.9	
180	19.5	550		310.3	79.8			6.9	
210	19.5	550		310.5	80.0			6.9	
930	19.5	550		312.2	81.7			6.7	Ended 6:06 a.m.

PAGE 1 - PUMPING TEST

191 11 212

Layne-Western
5600 Gateway Drive, Suite B
Grimes, IA 50111
(515) 986-3462 / 3474 Fax

WELL TEST DATA REPORT

(RECOVERY READINGS)

PROJECT: Sioux Center Land Development
LOCATION: Sioux Center, Iowa
WELL NO: 1
WELL DIAMETER: 12.00 inches I.D.
WELL DEPTH: 520.0 feet - from grade
TOP OF SCREEN: 440.0 feet - from grade
STATIC LEVEL: 230.5 feet - from top of casing
ORIFICE SIZE: 6" x 5"

DATE TESTED: 4/20/07
TESTED BY: Mark Leslie
DRIVER: 75-HP Submersible Motor
COLUMN AND SHAFT: 6" Drop Pipe
BOWL SIZE & MAKE: 9CLC, 3-Stage
MANUFACTURER: Goulds
SERIAL NUMBER:

TIME	PIEZ. READ. (IN)	FLOW RATE (GPM)	AIRLINE READING (FEET)	WATER LEVEL (FEET)	DRAW DOWN (FEET)	DISCHARGE PRESSURE (LBS.)	DISCHARGE PRESSURE (FEET)	SPEC. CAPACITY (GPM/FT)	REMARKS
1 min.				238.7					Recovery started at
2				237.9					6:07 a.m.
3				237.6					
4				237.2					
5				236.5					
6				236.0					
7				235.7					
8				235.3					
9				235.0					
10				234.7					
12				234.3					
14				234.0					
16				233.6					
18				233.3					
20				233.0					
25				232.4					
30				232.2					Ended 6:37 a.m.

PAGE 2 - RECOVERY READINGS

APPENDIX B.

WATER USE DATA
2001-2006

Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
Alta #4	311685	4727181	330	288	1	365	-100,500
Alta #4	311685	4727181	330	288	1	730	-120,500
Alta #4	311685	4727181	330	288	1	1095	-107,500
Alta #4	311685	4727181	330	288	1	1460	-112,500
Alta #4	311685	4727181	330	288	1	1825	-118,000
Alta #4	311685	4727181	330	288	1	2190	-126,000
Alta #5	312633	4727183	305	276	1	365	-100,500
Alta #5	312633	4727183	305	276	1	730	-120,500
Alta #5	312633	4727183	305	276	1	1095	-107,500
Alta #5	312633	4727183	305	276	1	1460	-112,500
Alta #5	312633	4727183	305	276	1	1825	-118,000
Alta #5	312633	4727183	305	276	1	2190	-126,000
Angler Bay	333626	4817914	292	278	1	2190	-205
Aurelia #1	300486	4731854	345	319	1	365	-31000
Aurelia #1	300486	4731854	345	319	1	730	-29000
Aurelia #1	300486	4731854	345	319	1	2190	-25300
Aurelia #3	301222	4731972	313	270	1	365	-31000
Aurelia #3	301222	4731972	313	270	1	730	-29000
Aurelia #3	301222	4731972	313	270	1	2190	-25300
Aurelia #4	301205	4731976	331	311	1	365	-31000
Aurelia #4	301205	4731976	331	311	1	730	-29000
Aurelia #4	301205	4731976	331	311	1	2190	-25300
Aurthur #4	306379	4489743	315	281	1	2190	-11500
Ayrshire	350716	4766680	305	274	1	2190	-25000
Brooks LTD	327641	4805520	301	266	1	120	0
Brooks LTD	327641	4805520	301	266	1	320	-106000
Brooks LTD	327641	4805520	301	266	1	485	0
Brooks LTD	327641	4805520	301	266	1	685	-91000
Brooks LTD	327641	4805520	301	266	1	850	0
Brooks LTD	327641	4805520	301	266	1	1050	-89000
Brooks LTD	327641	4805520	301	266	1	1215	0
Brooks LTD	327641	4805520	301	266	1	1415	-91000
Brooks LTD	327641	4805520	301	266	1	1580	0
Brooks LTD	327641	4805520	301	266	1	1780	-88000
Brooks LTD	327641	4805520	301	266	1	1945	0
Brooks LTD	327641	4805520	301	266	1	2145	-86000
Brooks LTD	327641	4805520	301	266	1	2190	0
Cherokee #1	291397	4736537	317	307	1	180	-134000
Cherokee #1	291397	4736537	317	307	1	270	-194000
Cherokee #1	291397	4736537	317	307	1	365	-134000
Cherokee #1	291397	4736537	317	307	1	545	-129000
Cherokee #1	291397	4736537	317	307	1	635	-187000
Cherokee #1	291397	4736537	317	307	1	730	-129000
Cherokee #1	291397	4736537	317	307	1	910	-128000
Cherokee #1	291397	4736537	317	307	1	1000	-186000
Cherokee #1	291397	4736537	317	307	1	1095	-128000
Cherokee #1	291397	4736537	317	307	1	1275	-141000
Cherokee #1	291397	4736537	317	307	1	1365	-204000
Cherokee #1	291397	4736537	317	307	1	1460	-141000
Cherokee #1	291397	4736537	317	307	1	1640	-135000
Cherokee #1	291397	4736537	317	307	1	1730	-195000
Cherokee #1	291397	4736537	317	307	1	1825	-135000
Cherokee #1	291397	4736537	317	307	1	2005	-112800
Cherokee #1	291397	4736537	317	307	1	2095	-163000
Cherokee #1	291397	4736537	317	307	1	2190	-112800
Cherokee #10	290927	4733827	319	289	1	180	-134000
Cherokee #10	290927	4733827	319	289	1	270	-194000
Cherokee #10	290927	4733827	319	289	1	365	-134000
Cherokee #10	290927	4733827	319	289	1	545	-129000
Cherokee #10	290927	4733827	319	289	1	635	-187000
Cherokee #10	290927	4733827	319	289	1	730	-129000
Cherokee #10	290927	4733827	319	289	1	910	-128000

Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
Cherokee #10	290927	4733827	319	289	1	1000	-186000
Cherokee #10	290927	4733827	319	289	1	1095	-128000
Cherokee #10	290927	4733827	319	289	1	1275	-141000
Cherokee #10	290927	4733827	319	289	1	1365	-204000
Cherokee #10	290927	4733827	319	289	1	1460	-141000
Cherokee #10	290927	4733827	319	289	1	1640	-135000
Cherokee #10	290927	4733827	319	289	1	1730	-195000
Cherokee #10	290927	4733827	319	289	1	1825	-135000
Cherokee #10	290927	4733827	319	289	1	2005	-112800
Cherokee #10	290927	4733827	319	289	1	2095	-163000
Cherokee #10	290927	4733827	319	289	1	2190	-112800
Cherokee #11	292109	4736194	318	282	1	180	-134000
Cherokee #11	292109	4736194	318	282	1	270	-194000
Cherokee #11	292109	4736194	318	282	1	365	-134000
Cherokee #11	292109	4736194	318	282	1	545	-129000
Cherokee #11	292109	4736194	318	282	1	635	-187000
Cherokee #11	292109	4736194	318	282	1	730	-129000
Cherokee #11	292109	4736194	318	282	1	910	-128000
Cherokee #11	292109	4736194	318	282	1	1000	-186000
Cherokee #11	292109	4736194	318	282	1	1095	-128000
Cherokee #11	292109	4736194	318	282	1	1275	-141000
Cherokee #11	292109	4736194	318	282	1	1365	-204000
Cherokee #11	292109	4736194	318	282	1	1460	-141000
Cherokee #11	292109	4736194	318	282	1	1640	-135000
Cherokee #11	292109	4736194	318	282	1	1730	-195000
Cherokee #11	292109	4736194	318	282	1	1825	-135000
Cherokee #11	292109	4736194	318	282	1	2005	-112800
Cherokee #11	292109	4736194	318	282	1	2095	-163000
Cherokee #11	292109	4736194	318	282	1	2190	-112800
Cherokee #12	292094	4736292	320	301	1	180	-134000
Cherokee #12	292094	4736292	320	301	1	270	-194000
Cherokee #12	292094	4736292	320	301	1	365	-134000
Cherokee #12	292094	4736292	320	301	1	545	-129000
Cherokee #12	292094	4736292	320	301	1	635	-187000
Cherokee #12	292094	4736292	320	301	1	730	-129000
Cherokee #12	292094	4736292	320	301	1	910	-128000
Cherokee #12	292094	4736292	320	301	1	1000	-186000
Cherokee #12	292094	4736292	320	301	1	1095	-128000
Cherokee #12	292094	4736292	320	301	1	1275	-141000
Cherokee #12	292094	4736292	320	301	1	1365	-204000
Cherokee #12	292094	4736292	320	301	1	1460	-141000
Cherokee #12	292094	4736292	320	301	1	1640	-135000
Cherokee #12	292094	4736292	320	301	1	1730	-195000
Cherokee #12	292094	4736292	320	301	1	1825	-135000
Cherokee #12	292094	4736292	320	301	1	2005	-112800
Cherokee #12	292094	4736292	320	301	1	2095	-163000
Cherokee #12	292094	4736292	320	301	1	2190	-112800
Cherokee #4	291817	4736067	321	305	1	180	-134000
Cherokee #4	291817	4736067	321	305	1	270	-194000
Cherokee #4	291817	4736067	321	305	1	365	-134000
Cherokee #4	291817	4736067	321	305	1	545	-129000
Cherokee #4	291817	4736067	321	305	1	635	-187000
Cherokee #4	291817	4736067	321	305	1	730	-129000
Cherokee #4	291817	4736067	321	305	1	910	-128000
Cherokee #4	291817	4736067	321	305	1	1000	-186000
Cherokee #4	291817	4736067	321	305	1	1095	-128000
Cherokee #4	291817	4736067	321	305	1	1275	-141000
Cherokee #4	291817	4736067	321	305	1	1365	-204000
Cherokee #4	291817	4736067	321	305	1	1460	-141000
Cherokee #4	291817	4736067	321	305	1	1640	-135000
Cherokee #4	291817	4736067	321	305	1	1730	-195000
Cherokee #4	291817	4736067	321	305	1	1825	-135000

Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
Cherokee #4	291817	4736067	321	305	1	2005	-112800
Cherokee #4	291817	4736067	321	305	1	2095	-163000
Cherokee #4	291817	4736067	321	305	1	2190	-112800
Cherokee #5	290558	4734246	316	300	1	180	-134000
Cherokee #5	290558	4734246	316	300	1	270	-194000
Cherokee #5	290558	4734246	316	300	1	365	-134000
Cherokee #5	290558	4734246	316	300	1	545	-129000
Cherokee #5	290558	4734246	316	300	1	635	-187000
Cherokee #5	290558	4734246	316	300	1	730	-129000
Cherokee #5	290558	4734246	316	300	1	910	-128000
Cherokee #5	290558	4734246	316	300	1	1000	-186000
Cherokee #5	290558	4734246	316	300	1	1095	-128000
Cherokee #5	290558	4734246	316	300	1	1275	-141000
Cherokee #5	290558	4734246	316	300	1	1365	-204000
Cherokee #5	290558	4734246	316	300	1	1460	-141000
Cherokee #5	290558	4734246	316	300	1	1640	-135000
Cherokee #5	290558	4734246	316	300	1	1730	-195000
Cherokee #5	290558	4734246	316	300	1	1825	-135000
Cherokee #5	290558	4734246	316	300	1	2005	-112800
Cherokee #5	290558	4734246	316	300	1	2095	-163000
Cherokee #5	290558	4734246	316	300	1	2190	-112800
Cherokee #6	290585	4733944	317	282	1	180	-134000
Cherokee #6	290585	4733944	317	282	1	270	-194000
Cherokee #6	290585	4733944	317	282	1	365	-134000
Cherokee #6	290585	4733944	317	282	1	545	-129000
Cherokee #6	290585	4733944	317	282	1	635	-187000
Cherokee #6	290585	4733944	317	282	1	730	-129000
Cherokee #6	290585	4733944	317	282	1	910	-128000
Cherokee #6	290585	4733944	317	282	1	1000	-186000
Cherokee #6	290585	4733944	317	282	1	1095	-128000
Cherokee #6	290585	4733944	317	282	1	1275	-141000
Cherokee #6	290585	4733944	317	282	1	1365	-204000
Cherokee #6	290585	4733944	317	282	1	1460	-141000
Cherokee #6	290585	4733944	317	282	1	1640	-135000
Cherokee #6	290585	4733944	317	282	1	1730	-195000
Cherokee #6	290585	4733944	317	282	1	1825	-135000
Cherokee #6	290585	4733944	317	282	1	2005	-112800
Cherokee #6	290585	4733944	317	282	1	2095	-163000
Cherokee #6	290585	4733944	317	282	1	2190	-112800
Cherokee #8	290720	4734797	307	281	1	180	-134000
Cherokee #8	290720	4734797	307	281	1	270	-194000
Cherokee #8	290720	4734797	307	281	1	365	-134000
Cherokee #8	290720	4734797	307	281	1	545	-129000
Cherokee #8	290720	4734797	307	281	1	635	-187000
Cherokee #8	290720	4734797	307	281	1	730	-129000
Cherokee #8	290720	4734797	307	281	1	910	-128000
Cherokee #8	290720	4734797	307	281	1	1000	-186000
Cherokee #8	290720	4734797	307	281	1	1095	-128000
Cherokee #8	290720	4734797	307	281	1	1275	-141000
Cherokee #8	290720	4734797	307	281	1	1365	-204000
Cherokee #8	290720	4734797	307	281	1	1460	-141000
Cherokee #8	290720	4734797	307	281	1	1640	-135000
Cherokee #8	290720	4734797	307	281	1	1730	-195000
Cherokee #8	290720	4734797	307	281	1	1825	-135000
Cherokee #8	290720	4734797	307	281	1	2005	-112800
Cherokee #8	290720	4734797	307	281	1	2095	-163000
Cherokee #8	290720	4734797	307	281	1	2190	-112800
Cherokee CC	290333	4737190	306	281	1	100	0
Cherokee CC	290333	4737190	306	281	1	314	-114000
Cherokee CC	290333	4737190	306	281	1	2190	0
Cherokee RW	289593	4728391	316	303	1	365	-671000
Cherokee RW	289593	4728391	316	303	1	730	-706000

Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
Cherokee RW	289593	4728391	316	303	1	1095	-688000
Cherokee RW	289593	4728391	316	303	1	1460	0
Cherokee RW	289593	4728391	316	303	1	1825	-671000
Cherokee RW	289593	4728391	316	303	1	2190	0
City View Farm	302783	4769110	301	265	1	730	0
City View Farm	302783	4769110	301	265	1	1095	-25000
City View Farm	302783	4769110	301	265	1	1460	0
City View Farm	302783	4769110	301	265	1	1825	-25000
City View Farm	302783	4769110	301	265	1	2190	-22000
Clasing	343468	4774250	295	268	1	180	0
Clasing	343468	4774250	295	268	1	270	-1635151
Clasing	343468	4774250	295	268	1	545	0
Clasing	343468	4774250	295	268	1	635	-1686778
Clasing	343468	4774250	295	268	1	910	0
Clasing	343468	4774250	295	268	1	1030	-1662142
Clasing	343468	4774250	295	268	1	1275	0
Clasing	343468	4774250	295	268	1	1365	-1569246
Clasing	343468	4774250	295	268	1	1640	0
Clasing	343468	4774250	295	268	1	1700	-4923871
Clasing	343468	4774250	295	268	1	2005	0
Clasing	343468	4774250	295	268	1	2095	-2942609
Clasing	343468	4774250	295	268	1	2190	0
Correctionville	271369	4706277	293	281	1	2190	-22700
Craig Hemmingsen	214221	4755060	278	234	1	545	0
Craig Hemmingsen	214221	4755060	278	234	1	605	-172452
Craig Hemmingsen	214221	4755060	278	234	1	910	0
Craig Hemmingsen	214221	4755060	278	234	1	970	-282097
Craig Hemmingsen	214221	4755060	278	234	1	1275	0
Craig Hemmingsen	214221	4755060	278	234	1	1335	-229935
Craig Hemmingsen	214221	4755060	278	234	1	2190	0
Crawford Ck#2	285384	4683843	317	292	1	2190	-500
CTR Fresh Eggs	236559	4771730	297	266	1	365	-6000
CTR Fresh Eggs	236559	4771730	297	266	1	730	-32000
CTR Fresh Eggs	236559	4771730	297	266	1	1095	-43219
CTR Fresh Eggs	236559	4771730	297	266	1	1460	-41463
CTR Fresh Eggs	236559	4771730	297	266	1	1825	-71993
CTR Fresh Eggs	236559	4771730	297	266	1	2190	-123419
Day Break Foods #3	366180	4788515	285	275	1	2190	-30000
Day Break Foods #4	366248	4788522	282	273	1	2190	-30000
Dykstra Dairy	242899	4753930	283	253	1	2190	-160000
Easton James	214364	4757900	286	240	1	180	-416000
Easton James	214364	4757900	286	240	1	545	0
Easton James	214364	4757900	286	240	1	665	-366000
Easton James	214364	4757900	286	240	1	910	0
Easton James	214364	4757900	286	240	1	1030	-335000
Easton James	214364	4757900	286	240	1	1640	0
Easton James	214364	4757900	286	240	1	1760	-248000
Easton James	214364	4757900	286	240	1	2005	0
Easton James	214364	4757900	286	240	1	2095	-326000
Easton James	214364	4757900	286	240	1	2190	0
Emerald Hills	326815	4802640	300	258	1	485	0
Emerald Hills	326815	4802640	300	258	1	685	-153000
Emerald Hills	326815	4802640	300	258	1	850	0
Emerald Hills	326815	4802640	300	258	1	1050	-300000
Emerald Hills	326815	4802640	300	258	1	1215	0
Emerald Hills	326815	4802640	300	258	1	1415	-154000
Emerald Hills	326815	4802640	300	258	1	1580	0
Emerald Hills	326815	4802640	300	258	1	1780	-139000
Emerald Hills	326815	4802640	300	258	1	1945	0
Emerald Hills	326815	4802640	300	258	1	2145	-150000
Emerald Hills	326815	4802640	300	258	1	2190	0
Emmetsburg #6	362624	4774076	303	284	1	2190	-300000

Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
Farmer Coop	237048	4775270	281	238	1	365	-314949
Farmer Coop	237048	4775270	281	238	1	730	-149157
Farmer Coop	237048	4775270	281	238	1	1095	-117070
Farmer Coop	237048	4775270	281	238	1	2190	0
Feuerhelm	241105	4733840	292	252	1	365	-123000
Feuerhelm	241105	4733840	292	252	1	730	-170000
Feuerhelm	241105	4733840	292	252	1	1095	-168000
Feuerhelm	241105	4733840	292	252	1	2190	-180000
Hartley #1	298816	4783618	272	258	1	730	-100000
Hartley #1	298816	4783618	272	258	1	2190	-62000
Hartley #3	298851	4783595	281	262	1	730	-100000
Hartley #3	298851	4783595	281	262	1	2190	-62000
Hartley #4	298888	4783587	291	267	1	730	-100000
Hartley #4	298888	4783587	291	267	1	2190	-62000
Havelock #2	361008	4744113	329	307	1	2190	-9100
Havelock #3	360651	4743756	328	315	1	2190	-9100
Hawarden	217160	4766220	282	248	1	830	0
Hawarden	217160	4766220	282	248	1	1010	-77000
Hawarden	217160	4766220	282	248	1	1195	0
Hawarden	217160	4766220	282	248	1	1375	-77000
Hawarden	217160	4766220	282	248	1	1560	0
Hawarden	217160	4766220	282	248	1	1760	-85000
Hawarden	217160	4766220	282	248	1	1925	0
Hawarden	217160	4766220	282	248	1	2105	-89000
Hawarden	217160	4766220	282	248	1	2190	0
Hibbing Farms	303808	4794030	279	254	1	180	0
Hibbing Farms	303808	4794030	279	254	1	270	-332000
Hibbing Farms	303808	4794030	279	254	1	545	0
Hibbing Farms	303808	4794030	279	254	1	605	-534000
Hibbing Farms	303808	4794030	279	254	1	1640	0
Hibbing Farms	303808	4794030	279	254	1	1700	-407000
Hibbing Farms	303808	4794030	279	254	1	2005	0
Hibbing Farms	303808	4794030	279	254	1	2065	-155000
Hibbing Farms	303808	4794030	279	254	1	2190	0
Hilltop #1	293741	4736217	314	295	1	2190	-3800
Hilltop #2	293705	4736181	314	300	1	2190	-3800
Hillview Park #1	228061	4725558	303	282	1	2190	-500
Hinton #4	229320	4723356	326	309	1	2190	-67000
Hinton #5	229264	4724687	308	288	1	2190	-67000
Holstein Dairy	288115	4710730	315	268	1	2190	-80000
IDNR Spirit Lake	330499	4812350	301	257	1	2190	-50
Indian Hills golf	325234	4810740	297	249	1	120	0
Indian Hills golf	325234	4810740	297	249	1	320	-45000
Indian Hills golf	325234	4810740	297	249	1	480	0
Indian Hills golf	325234	4810740	297	249	1	680	-36000
Indian Hills golf	325234	4810740	297	249	1	1215	0
Indian Hills golf	325234	4810740	297	249	1	1415	-32000
Indian Hills golf	325234	4810740	297	249	1	1580	0
Indian Hills golf	325234	4810740	297	249	1	1780	-27000
Indian Hills golf	325234	4810740	297	249	1	2190	0
Ingham Lake Bible	362069	4797190	299	286	1	2190	-1000
Ireton #3	229725	4762989	286	270	1	2190	-26000
Ireton #4	229723	4762934	272	254	1	2190	-26000
J Borchers	215377	4750640	284	233	1	180	0
J Borchers	215377	4750640	284	233	1	210	-12000
J Borchers	215377	4750640	284	233	1	545	0
J Borchers	215377	4750640	284	233	1	605	-10000
J Borchers	215377	4750640	284	233	1	900	0
J Borchers	215377	4750640	284	233	1	1020	-381000
J Borchers	215377	4750640	284	233	1	1275	0
J Borchers	215377	4750640	284	233	1	1335	-9000
J Borchers	215377	4750640	284	233	1	1640	0

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J Borchers	215377	4750640	284	233	1	1700	-6000
J Borchers	215377	4750640	284	233	1	1825	0
J Borchers	215377	4750640	284	233	1	2005	-437000
J Borchers	215377	4750640	284	233	1	2190	0
Jack Borchers	218417	4768680	280	247	1	180	0
Jack Borchers	218417	4768680	280	247	1	240	-9755
Jack Borchers	218417	4768680	280	247	1	545	0
Jack Borchers	218417	4768680	280	247	1	605	-9262
Jack Borchers	218417	4768680	280	247	1	910	0
Jack Borchers	218417	4768680	280	247	1	1000	-266304
Jack Borchers	218417	4768680	280	247	1	1275	0
Jack Borchers	218417	4768680	280	247	1	1335	-6639
Jack Borchers	218417	4768680	280	247	1	1640	0
Jack Borchers	218417	4768680	280	247	1	1730	-4300
Jack Borchers	218417	4768680	280	247	1	2005	0
Jack Borchers	218417	4768680	280	247	1	2065	-376000
Jack Borchers	218417	4768680	280	247	1	2190	0
Karrer	241858	4717840	297	271	1	545	0
Karrer	241858	4717840	297	271	1	605	-64000
Karrer	241858	4717840	297	271	1	910	0
Karrer	241858	4717840	297	271	1	970	-322000
Karrer	241858	4717840	297	271	1	1640	0
Karrer	241858	4717840	297	271	1	1700	-272000
Karrer	241858	4717840	297	271	1	2190	0
Lawton #1	238742	4707635	295	268	1	2190	-29000
Lawton #2	238677	4707645	296	270	1	2190	-29000
Lawton #3	238687	4707988	294	272	1	2190	-29000
LeMars #10	239329	4739985	285	217	1	180	-345000
LeMars #10	239329	4739985	285	217	1	270	-498000
LeMars #10	239329	4739985	285	217	1	365	-345000
LeMars #10	239329	4739985	285	217	1	545	-345000
LeMars #10	239329	4739985	285	217	1	635	-498000
LeMars #10	239329	4739985	285	217	1	730	-345000
LeMars #10	239329	4739985	285	217	1	910	-345000
LeMars #10	239329	4739985	285	217	1	1000	-498000
LeMars #10	239329	4739985	285	217	1	1275	-345000
LeMars #10	239329	4739985	285	217	1	1365	-498000
LeMars #10	239329	4739985	285	217	1	1460	-345000
LeMars #10	239329	4739985	285	217	1	1640	-375000
LeMars #10	239329	4739985	285	217	1	1730	-542000
LeMars #10	239329	4739985	285	217	1	1825	-375000
LeMars #10	239329	4739985	285	217	1	2005	-405000
LeMars #10	239329	4739985	285	217	1	2095	-585000
LeMars #10	239329	4739985	285	217	1	2190	-405000
LeMars #11	238547	4739963	286	217	1	180	-345000
LeMars #11	238547	4739963	286	217	1	270	-498000
LeMars #11	238547	4739963	286	217	1	365	-345000
LeMars #11	238547	4739963	286	217	1	545	-345000
LeMars #11	238547	4739963	286	217	1	635	-498000
LeMars #11	238547	4739963	286	217	1	730	-345000
LeMars #11	238547	4739963	286	217	1	910	-345000
LeMars #11	238547	4739963	286	217	1	1000	-498000
LeMars #11	238547	4739963	286	217	1	1275	-345000
LeMars #11	238547	4739963	286	217	1	1365	-498000
LeMars #11	238547	4739963	286	217	1	1460	-345000
LeMars #11	238547	4739963	286	217	1	1640	-375000
LeMars #11	238547	4739963	286	217	1	1730	-542000
LeMars #11	238547	4739963	286	217	1	1825	-375000
LeMars #11	238547	4739963	286	217	1	2005	-405000
LeMars #11	238547	4739963	286	217	1	2095	-585000
LeMars #11	238547	4739963	286	217	1	2190	-405000
LeMars #12	238290	4739612	283	214	1	180	-345000

Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
LeMars #12	238290	4739612	283	214	1	270	-498000
LeMars #12	238290	4739612	283	214	1	365	-345000
LeMars #12	238290	4739612	283	214	1	545	-345000
LeMars #12	238290	4739612	283	214	1	635	-498000
LeMars #12	238290	4739612	283	214	1	730	-345000
LeMars #12	238290	4739612	283	214	1	910	-345000
LeMars #12	238290	4739612	283	214	1	1000	-498000
LeMars #12	238290	4739612	283	214	1	1275	-345000
LeMars #12	238290	4739612	283	214	1	1365	-498000
LeMars #12	238290	4739612	283	214	1	1460	-345000
LeMars #12	238290	4739612	283	214	1	1640	-375000
LeMars #12	238290	4739612	283	214	1	1730	-542000
LeMars #12	238290	4739612	283	214	1	1825	-375000
LeMars #12	238290	4739612	283	214	1	2005	-405000
LeMars #12	238290	4739612	283	214	1	2095	-585000
LeMars #12	238290	4739612	283	214	1	2190	-405000
LeMars #6	239314	4740388	290	268	1	180	-345000
LeMars #6	239314	4740388	290	268	1	270	-498000
LeMars #6	239314	4740388	290	268	1	365	-345000
LeMars #6	239314	4740388	290	268	1	545	-345000
LeMars #6	239314	4740388	290	268	1	635	-498000
LeMars #6	239314	4740388	290	268	1	730	-345000
LeMars #6	239314	4740388	290	268	1	910	-345000
LeMars #6	239314	4740388	290	268	1	1000	-498000
LeMars #6	239314	4740388	290	268	1	1275	-345000
LeMars #6	239314	4740388	290	268	1	1365	-498000
LeMars #6	239314	4740388	290	268	1	1460	-345000
LeMars #6	239314	4740388	290	268	1	1640	-375000
LeMars #6	239314	4740388	290	268	1	1730	-542000
LeMars #6	239314	4740388	290	268	1	1825	-375000
LeMars #6	239314	4740388	290	268	1	2005	-405000
LeMars #6	239314	4740388	290	268	1	2095	-585000
LeMars #6	239314	4740388	290	268	1	2190	-405000
LeMars #7	239403	4740369	290	223	1	180	-345000
LeMars #7	239403	4740369	290	223	1	270	-498000
LeMars #7	239403	4740369	290	223	1	365	-345000
LeMars #7	239403	4740369	290	223	1	545	-345000
LeMars #7	239403	4740369	290	223	1	635	-498000
LeMars #7	239403	4740369	290	223	1	730	-345000
LeMars #7	239403	4740369	290	223	1	910	-345000
LeMars #7	239403	4740369	290	223	1	1000	-498000
LeMars #7	239403	4740369	290	223	1	1275	-345000
LeMars #7	239403	4740369	290	223	1	1365	-498000
LeMars #7	239403	4740369	290	223	1	1460	-345000
LeMars #7	239403	4740369	290	223	1	1640	-375000
LeMars #7	239403	4740369	290	223	1	1730	-542000
LeMars #7	239403	4740369	290	223	1	1825	-375000
LeMars #7	239403	4740369	290	223	1	2005	-405000
LeMars #7	239403	4740369	290	223	1	2095	-585000
LeMars #7	239403	4740369	290	223	1	2190	-405000
LeMars #9	239339	4740216	290	275	1	180	-345000
LeMars #9	239339	4740216	290	275	1	270	-498000
LeMars #9	239339	4740216	290	275	1	365	-345000
LeMars #9	239339	4740216	290	275	1	545	-345000
LeMars #9	239339	4740216	290	275	1	635	-498000
LeMars #9	239339	4740216	290	275	1	730	-345000
LeMars #9	239339	4740216	290	275	1	910	-345000
LeMars #9	239339	4740216	290	275	1	1000	-498000
LeMars #9	239339	4740216	290	275	1	1275	-345000
LeMars #9	239339	4740216	290	275	1	1365	-498000
LeMars #9	239339	4740216	290	275	1	1460	-345000
LeMars #9	239339	4740216	290	275	1	1640	-375000

Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
LeMars #9	239339	4740216	290	275	1	1730	-542000
LeMars #9	239339	4740216	290	275	1	1825	-375000
LeMars #9	239339	4740216	290	275	1	2005	-405000
LeMars #9	239339	4740216	290	275	1	2095	-585000
LeMars #9	239339	4740216	290	275	1	2190	-405000
Leon Jalas	299516	4757794	311	294	1	2190	-37800
Loess Ridge #1	214975	4715908	261	225	1	2190	-141
Loess Ridge #2	214977	4715914	261	225	1	2190	-141
Mallard #5	362653	4755150	296	283	1	2190	-24000
Maurice #4	240711	4761890	292	253	1	1460	-15000
Maurice #4	240711	4761890	292	253	1	1640	0
Maurice #4	240711	4761890	292	253	1	1730	-114000
Maurice #4	240711	4761890	292	253	1	1825	0
Maurice #4	240711	4761890	292	253	1	2005	0
Maurice #4	240711	4761890	292	253	1	2065	-82000
Maurice #4	240711	4761890	292	253	1	2190	0
McCarthy Farm	226176	4716960	301	256	1	180	0
McCarthy Farm	226176	4716960	301	256	1	240	-926000
McCarthy Farm	226176	4716960	301	256	1	545	0
McCarthy Farm	226176	4716960	301	256	1	635	-316000
McCarthy Farm	226176	4716960	301	256	1	910	0
McCarthy Farm	226176	4716960	301	256	1	970	-174000
McCarthy Farm	226176	4716960	301	256	1	1640	0
McCarthy Farm	226176	4716960	301	256	1	1730	-668000
McCarthy Farm	226176	4716960	301	256	1	2005	0
McCarthy Farm	226176	4716960	301	256	1	2095	-718000
McCarthy Farm	226176	4716960	301	256	1	2190	0
Merrill #4	233327	4735074	292	280	1	2190	-60300
Milford #1	326016	4799375	304	281	1	180	0
Milford #1	326016	4799375	304	281	1	270	-20000
Milford #1	326016	4799375	304	281	1	545	0
Milford #1	326016	4799375	304	281	1	635	-20000
Milford #1	326016	4799375	304	281	1	910	0
Milford #1	326016	4799375	304	281	1	1000	-20000
Milford #1	326016	4799375	304	281	1	1275	0
Milford #1	326016	4799375	304	281	1	1365	-20000
Milford #1	326016	4799375	304	281	1	1640	0
Milford #1	326016	4799375	304	281	1	1730	-20000
Milford #1	326016	4799375	304	281	1	2005	0
Milford #1	326016	4799375	304	281	1	2095	-20000
Milford #1	326016	4799375	304	281	1	2190	0
Okoboji School	324808	4798870	300	266	1	1460	0
Okoboji School	324808	4798870	300	266	1	1610	-26000
Okoboji School	324808	4798870	300	266	1	1700	0
Okoboji School	324808	4798870	300	266	1	1825	-26000
Okoboji School	324808	4798870	300	266	1	1975	-28000
Okoboji School	324808	4798870	300	266	1	2065	0
Okoboji School	324808	4798870	300	266	1	2190	-28000
Okoboji View Golf	323215	4808239	301	291	1	485	0
Okoboji View Golf	323215	4808239	301	291	1	685	-110000
Okoboji View Golf	323215	4808239	301	291	1	850	0
Okoboji View Golf	323215	4808239	301	291	1	1050	-109000
Okoboji View Golf	323215	4808239	301	291	1	2190	0
Orange City #10	244462	4757130	280	263	1	2190	-100000
Orange City #11	244151	4757132	281	265	1	2190	-100000
Oregon Trail Ethanol	308649	4728573	331	289	1	2190	0
Orpheum Theatre	220214	4710480	273	254	1	2190	-10000
Osceola RW	299156	4799390	300	249	1	1760	0
Osceola RW	299156	4799390	300	249	1	1960	-140000
Osceola RW	299156	4799390	300	249	1	2190	0
Owens #1	249982	4745305	270	248	1	2190	-12000
Plymouth Ethanol	234650	4736028	275	223	1	2190	-390000

Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
Primghar #7	286201	4773666	293	258	1	2190	-67500
Primghar #8	286153	4773663	292	261	1	2190	-67500
Quad County	301504	4705660	315	293	1	365	0
Quad County	301504	4705660	315	293	1	730	-310000
Quad County	301504	4705660	315	293	1	1095	-390000
Quad County	301504	4705660	315	293	1	1460	-443000
Quad County	301504	4705660	315	293	1	1825	-424000
Quad County	301504	4705660	315	293	1	2190	-430000
Quimby #1	283282	4722990	310	298	1	2190	-18000
Reinholdt	241339	4714180	298	255	1	180	0
Reinholdt	241339	4714180	298	255	1	210	-450000
Reinholdt	241339	4714180	298	255	1	545	0
Reinholdt	241339	4714180	298	255	1	575	-667000
Reinholdt	241339	4714180	298	255	1	910	0
Reinholdt	241339	4714180	298	255	1	1000	-321000
Reinholdt	241339	4714180	298	255	1	1275	0
Reinholdt	241339	4714180	298	255	1	1305	-485000
Reinholdt	241339	4714180	298	255	1	1640	0
Reinholdt	241339	4714180	298	255	1	1670	-329000
Reinholdt	241339	4714180	298	255	1	2190	0
Rembrandt #2	322821	4743903	303	273	1	2190	-12700
Rembrandt Ent	325932	4743476	300	272	1	2190	-230000
Remsen #7	257096	4744783	302	285	1	2190	-33150
Remsen #9	257109	4745107	267	247	1	2190	-33150
Ridge Road #1	349407	4806953	306	293	1	2190	-2770
Rodman #1	375628	4764942	324	247	1	2190	-4300
Ruthven #3	345161	4776890	309	282	1	365	-91000
Ruthven #3	345161	4776890	309	282	1	730	-176000
Ruthven #3	345161	4776890	309	282	1	2190	-80000
S. Sioux RW	240036	4754917	292	266	1	180	-184000
S. Sioux RW	240036	4754917	292	266	1	270	-330000
S. Sioux RW	240036	4754917	292	266	1	365	-184000
S. Sioux RW	240036	4754917	292	266	1	545	-218000
S. Sioux RW	240036	4754917	292	266	1	635	-330000
S. Sioux RW	240036	4754917	292	266	1	730	-218000
S. Sioux RW	240036	4754917	292	266	1	910	-180000
S. Sioux RW	240036	4754917	292	266	1	1000	-330000
S. Sioux RW	240036	4754917	292	266	1	1095	-180000
S. Sioux RW	240036	4754917	292	266	1	1275	-170000
S. Sioux RW	240036	4754917	292	266	1	1365	-287000
S. Sioux RW	240036	4754917	292	266	1	1460	-170000
S. Sioux RW	240036	4754917	292	266	1	1640	-220000
S. Sioux RW	240036	4754917	292	266	1	1730	-350000
S. Sioux RW	240036	4754917	292	266	1	1825	-220000
S. Sioux RW	240036	4754917	292	266	1	2005	-250000
S. Sioux RW	240036	4754917	292	266	1	2095	-400000
S. Sioux RW	240036	4754917	292	266	1	2190	-250000
S. Sioux RW D-1	240815	4754875	293	265	1	180	-184000
S. Sioux RW D-1	240815	4754875	293	265	1	270	-330000
S. Sioux RW D-1	240815	4754875	293	265	1	365	-184000
S. Sioux RW D-1	240815	4754875	293	265	1	545	-218000
S. Sioux RW D-1	240815	4754875	293	265	1	635	-330000
S. Sioux RW D-1	240815	4754875	293	265	1	730	-218000
S. Sioux RW D-1	240815	4754875	293	265	1	910	-180000
S. Sioux RW D-1	240815	4754875	293	265	1	1000	-330000
S. Sioux RW D-1	240815	4754875	293	265	1	1095	-180000
S. Sioux RW D-1	240815	4754875	293	265	1	1275	-170000
S. Sioux RW D-1	240815	4754875	293	265	1	1365	-287000
S. Sioux RW D-1	240815	4754875	293	265	1	1460	-170000
S. Sioux RW D-1	240815	4754875	293	265	1	1640	-220000
S. Sioux RW D-1	240815	4754875	293	265	1	1730	-350000
S. Sioux RW D-1	240815	4754875	293	265	1	1825	-220000

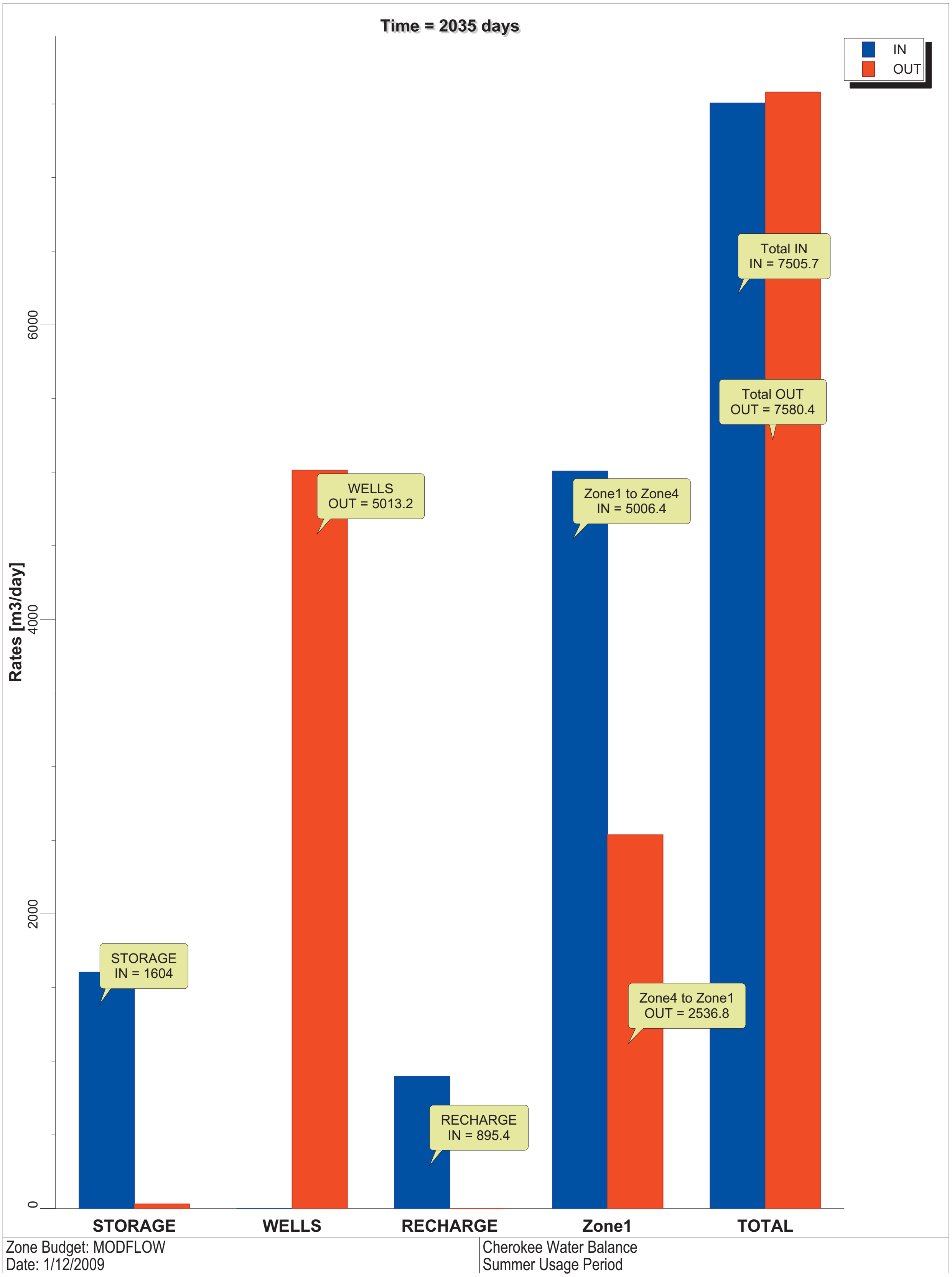
Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
S. Sioux RW D-1	240815	4754875	293	265	1	2005	-250000
S. Sioux RW D-1	240815	4754875	293	265	1	2095	-400000
S. Sioux RW D-1	240815	4754875	293	265	1	2190	-250000
S. Sioux RW D-2	240725	4755590	292	264	1	180	-184000
S. Sioux RW D-2	240725	4755590	292	264	1	270	-330000
S. Sioux RW D-2	240725	4755590	292	264	1	365	-184000
S. Sioux RW D-2	240725	4755590	292	264	1	545	-218000
S. Sioux RW D-2	240725	4755590	292	264	1	635	-330000
S. Sioux RW D-2	240725	4755590	292	264	1	730	-218000
S. Sioux RW D-2	240725	4755590	292	264	1	910	-180000
S. Sioux RW D-2	240725	4755590	292	264	1	1000	-330000
S. Sioux RW D-2	240725	4755590	292	264	1	1095	-180000
S. Sioux RW D-2	240725	4755590	292	264	1	1275	-170000
S. Sioux RW D-2	240725	4755590	292	264	1	1365	-287000
S. Sioux RW D-2	240725	4755590	292	264	1	1460	-170000
S. Sioux RW D-2	240725	4755590	292	264	1	1640	-220000
S. Sioux RW D-2	240725	4755590	292	264	1	1730	-350000
S. Sioux RW D-2	240725	4755590	292	264	1	1825	-220000
S. Sioux RW D-2	240725	4755590	292	264	1	2005	-250000
S. Sioux RW D-2	240725	4755590	292	264	1	2095	-400000
S. Sioux RW D-2	240725	4755590	292	264	1	2190	-250000
Sanborn	281059	4784240	289	251	1	2190	-300000
Schaller #1	311504	4708223	334	320	1	2190	-46000
Schaller #2	311350	4707545	325	296	1	2190	-46000
Sergeant Bluff #3	223582	4700198	230	209	1	2190	-398000
Sheldon #9	268568	4786715	282	246	1	365	-80000
Sheldon #9	268568	4786715	282	246	1	730	-10000
Sheldon #9	268568	4786715	282	246	1	830	0
Sheldon #9	268568	4786715	282	246	1	1073	-7200
Sheldon #9	268568	4786715	282	246	1	1095	0
Sheldon #9	268568	4786715	282	246	1	1249	-4325
Sheldon #9	268568	4786715	282	246	1	1560	0
Sheldon #9	268568	4786715	282	246	1	1740	-103000
Sheldon #9	268568	4786715	282	246	1	1925	0
Sheldon #9	268568	4786715	282	246	1	2078	-554752
Sheldon #9	268568	4786715	282	246	1	2190	0
Sibley	277391	4808430	281	259	1	485	0
Sibley	277391	4808430	281	259	1	605	-260000
Sibley	277391	4808430	281	259	1	850	0
Sibley	277391	4808430	281	259	1	1000	-191000
Sibley	277391	4808430	281	259	1	1215	0
Sibley	277391	4808430	281	259	1	1335	-109000
Sibley	277391	4808430	281	259	1	1945	0
Sibley	277391	4808430	281	259	1	2095	-97000
Sibley	277391	4808430	281	259	1	2190	0
Sioux Preme	241191	4769720	295	245	1	365	0
Sioux Preme	241191	4769720	295	245	1	730	0
Sioux Preme	241191	4769720	295	245	1	2190	0
Sioux City 1	221075	4710130	270	244	1	180	-4722200
Sioux City 1	221075	4710130	270	244	1	270	-6821000
Sioux City 1	221075	4710130	270	244	1	365	-4722200
Sioux City 1	221075	4710130	270	244	1	545	-3771600
Sioux City 1	221075	4710130	270	244	1	635	-5447800
Sioux City 1	221075	4710130	270	244	1	730	-3771600
Sioux City 1	221075	4710130	270	244	1	910	-3659000
Sioux City 1	221075	4710130	270	244	1	1000	-5285200
Sioux City 1	221075	4710130	270	244	1	1095	-3659000
Sioux City 1	221075	4710130	270	244	1	1275	-4117300
Sioux City 1	221075	4710130	270	244	1	1365	-5947300
Sioux City 1	221075	4710130	270	244	1	1460	-4117300
Sioux City 1	221075	4710130	270	244	1	1640	-2600200
Sioux City 1	221075	4710130	270	244	1	1730	-3755800

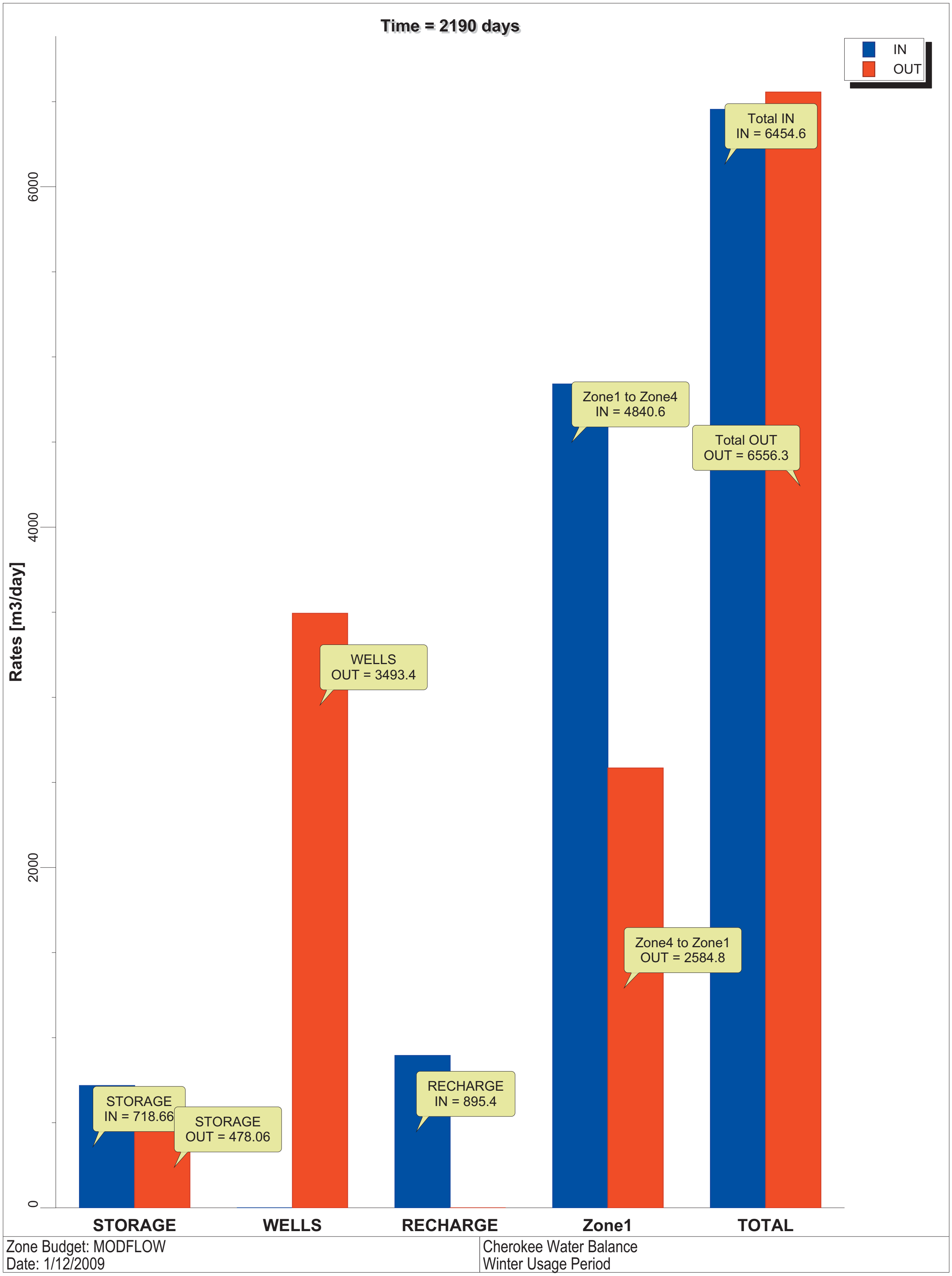
Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
Sioux City 1	221075	4710130	270	244	1	1825	-2600200
Sioux City 1	221075	4710130	270	244	1	2005	-4088000
Sioux City 1	221075	4710130	270	244	1	2095	-5904900
Sioux City 1	221075	4710130	270	244	1	2190	-4088000
Sioux City 2	224400	4702230	272	239	1	100	0
Sioux City 2	224400	4702230	272	239	1	314	-140000
Sioux City 2	224400	4702230	272	239	1	465	0
Sioux City 2	224400	4702230	272	239	1	679	-126000
Sioux City 2	224400	4702230	272	239	1	910	0
Sioux City 2	224400	4702230	272	239	1	940	-2064000
Sioux City 2	224400	4702230	272	239	1	1275	0
Sioux City 2	224400	4702230	272	239	1	1305	-1795000
Sioux City 2	224400	4702230	272	239	1	1640	0
Sioux City 2	224400	4702230	272	239	1	1670	-1129000
Sioux City 2	224400	4702230	272	239	1	2005	0
Sioux City 2	224400	4702230	272	239	1	2035	-1548000
Sioux City 2	224400	4702230	272	239	1	2190	0
Sioux City 3	222443	4707140	276	237	1	850	0
Sioux City 3	222443	4707140	276	237	1	1050	-98000
Sioux City 3	222443	4707140	276	237	1	1580	0
Sioux City 3	222443	4707140	276	237	1	1780	-154000
Sioux City 3	222443	4707140	276	237	1	1945	0
Sioux City 3	222443	4707140	276	237	1	2145	-5000
Sioux City 3	222443	4707140	276	237	1	2190	0
Sioux City CC	220167	4715380	295	246	1	465	0
Sioux City CC	220167	4715380	295	246	1	665	-115000
Sioux City CC	220167	4715380	295	246	1	830	0
Sioux City CC	220167	4715380	295	246	1	1030	-97000
Sioux City CC	220167	4715380	295	246	1	1195	0
Sioux City CC	220167	4715380	295	246	1	1395	-307350
Sioux City CC	220167	4715380	295	246	1	1560	0
Sioux City CC	220167	4715380	295	246	1	1760	-195182
Sioux City CC	220167	4715380	295	246	1	1925	0
Sioux City CC	220167	4715380	295	246	1	2125	-97000
Sioux City CC	220167	4715380	295	246	1	2190	0
Siouxland Energy	237239	4775530	278	210	1	1460	0
Siouxland Energy	237239	4775530	278	210	1	2190	-300000
Siouxland Res. #1	229266	4702775	268	249	1	2190	-1333
Siouxland Res#2	229251	4702761	268	251	1	2190	-1333
Spencer golf	325533	4775950	304	270	1	120	0
Spencer golf	325533	4775950	304	270	1	270	-142000
Spencer golf	325533	4775950	304	270	1	485	0
Spencer golf	325533	4775950	304	270	1	605	-167000
Spencer golf	325533	4775950	304	270	1	850	0
Spencer golf	325533	4775950	304	270	1	1000	-167000
Spencer golf	325533	4775950	304	270	1	1215	0
Spencer golf	325533	4775950	304	270	1	1305	-75000
Spencer golf	325533	4775950	304	270	1	1610	0
Spencer golf	325533	4775950	304	270	1	1700	-107000
Spencer golf	325533	4775950	304	270	1	1945	0
Spencer golf	325533	4775950	304	270	1	2065	-97000
Spencer golf	325533	4775950	304	270	1	2190	0
Stone St Pk #1	215315	4717483	311	301	1	2190	-10000
Stone St Pk #2	215273	4716798	316	298	1	2190	-10000
Storm Lake #14	317193	4724642	320	285	1	1460	0
Storm Lake #14	317193	4724642	320	285	1	1825	-508000
Storm Lake #14	317193	4724642	320	285	1	2190	-482660
Storm Lake #15	311151	4725095	322	276	1	1460	0
Storm Lake #15	311151	4725095	322	276	1	1825	-508000
Storm Lake #15	311151	4725095	322	276	1	2190	-482660
Storm Lake #16	316518	4722009	319	284	1	1460	0
Storm Lake #16	316518	4722009	319	284	1	1825	-508000

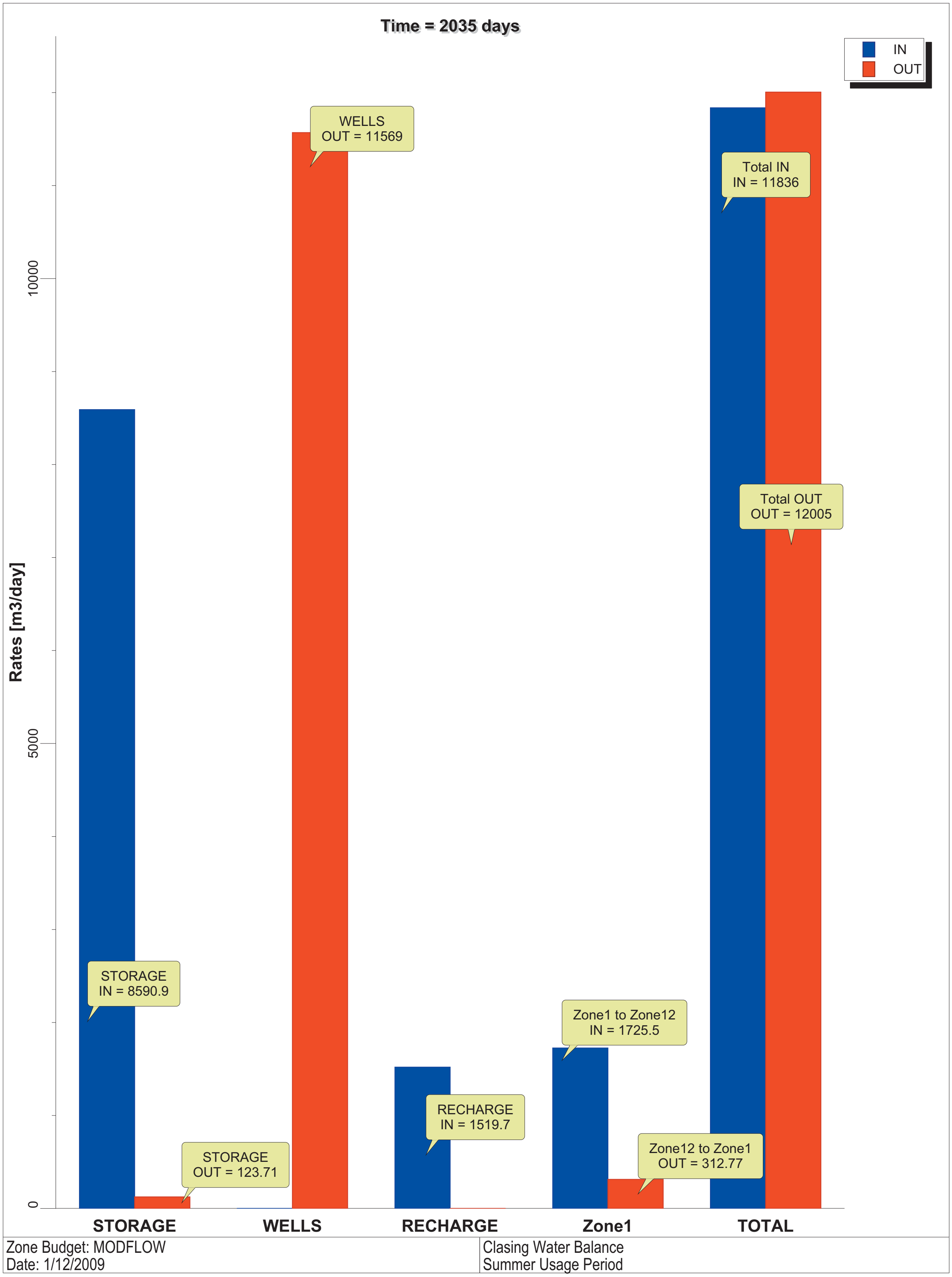
Well name	X UTM m	Y UTM m	top screen m	bottom screen m	Screen ID	stop time day	pumping rate gpd
Storm Lake #16	316518	4722009	319	284	1	2190	-482660
Sunrise Feeds	240176	4791041	276	259	1	2190	-46000
Superior Ethanol #1	341256	4810547	291	261	1	2190	0
Superior Ethanol #2	341403	4810568	292	261	1	2190	0
Sutherland #2	296124	4760970	260	254	1	2190	-32500
Sutherland #4	296133	4760977	326	301	1	2190	-26000
Truesdale #2	321168	4733074	320	272	1	2190	-5000
US West	220144	4710810	275	242	1	100	0
US West	220144	4710810	275	242	1	300	-360000
US West	220144	4710810	275	242	1	465	0
US West	220144	4710810	275	242	1	665	-405000
US West	220144	4710810	275	242	1	830	0
US West	220144	4710810	275	242	1	1030	-408000
US West	220144	4710810	275	242	1	1195	0
US West	220144	4710810	275	242	1	1395	-338000
US West	220144	4710810	275	242	1	1560	0
US West	220144	4710810	275	242	1	1760	-386000
US West	220144	4710810	275	242	1	1960	0
US West	220144	4710810	275	242	1	2160	-106000
US West	220144	4710810	275	242	1	2190	0
VeraSun Ethanol 1	296392	4783195	284	254	1	2190	0
VeraSun Ethanol 2	297238	4782874	287	254	1	2190	0
VeraSun Ethanol 3	297801	4782841	287	259	1	2190	0
VeraSun Ethanol 4	296982	4783635	291	258	1	2190	0
Voyager Ethanol	365649	4772240	301	286	1	1460	0
Voyager Ethanol	365649	4772240	301	286	1	2190	-500000
Wallingford #3	354140	4797996	267	238	1	2190	-10500
Westfield #3	205114	4740093	243	223	1	2190	-18000
Whispering Ck Golf	227729	4705850	267	240	1	485	0
Whispering Ck Golf	227729	4705850	267	240	1	685	-157000
Whispering Ck Golf	227729	4705850	267	240	1	850	0
Whispering Ck Golf	227729	4705850	267	240	1	1050	-195000
Whispering Ck Golf	227729	4705850	267	240	1	1580	0
Whispering Ck Golf	227729	4705850	267	240	1	1780	-110000
Whispering Ck Golf	227729	4705850	267	240	1	1945	0
Whispering Ck Golf	227729	4705850	267	240	1	2145	-195000
Whispering Ck Golf	227729	4705850	267	240	1	2190	0

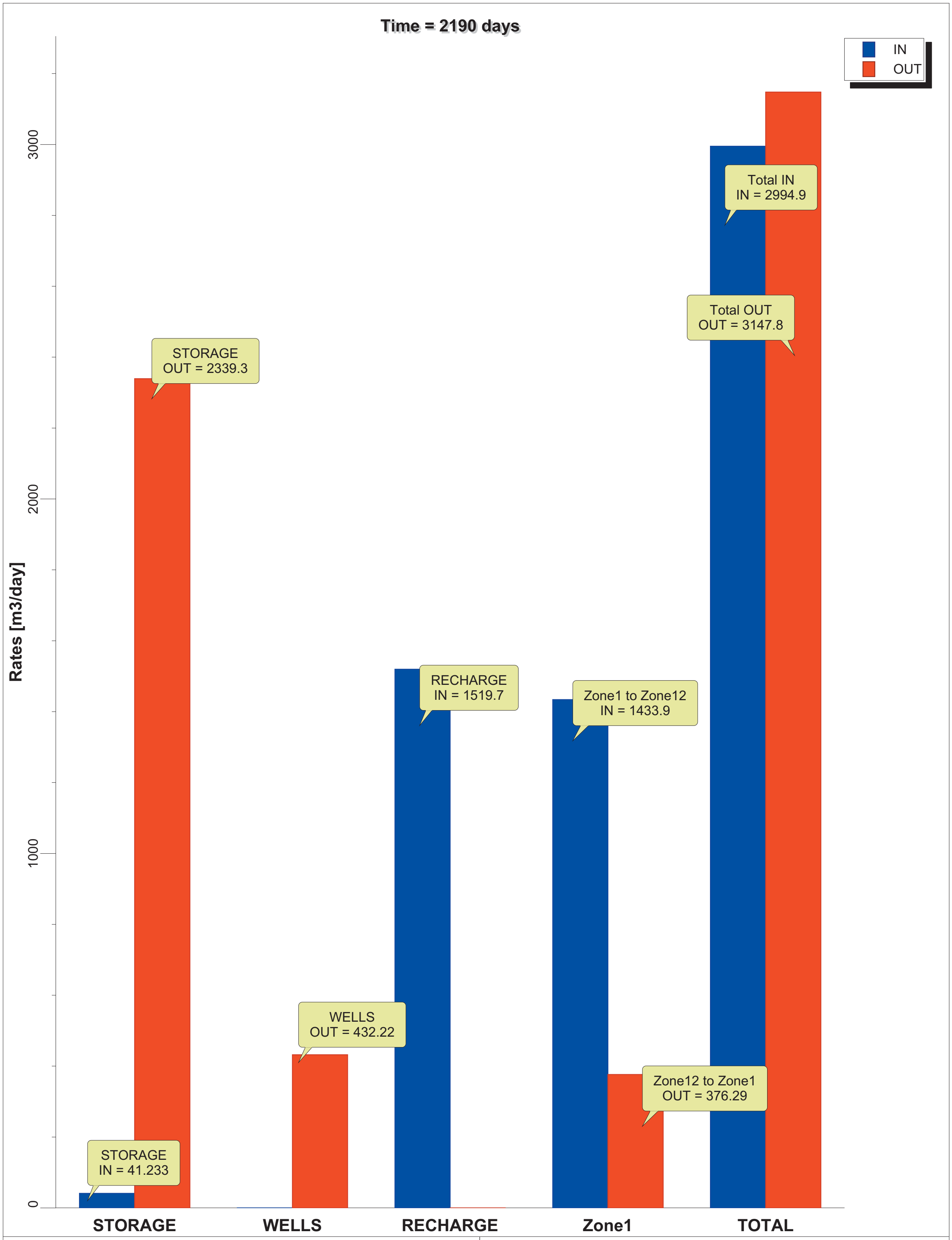
APPENDIX C.

ZONE BUDGET SIMULATION RESULTS

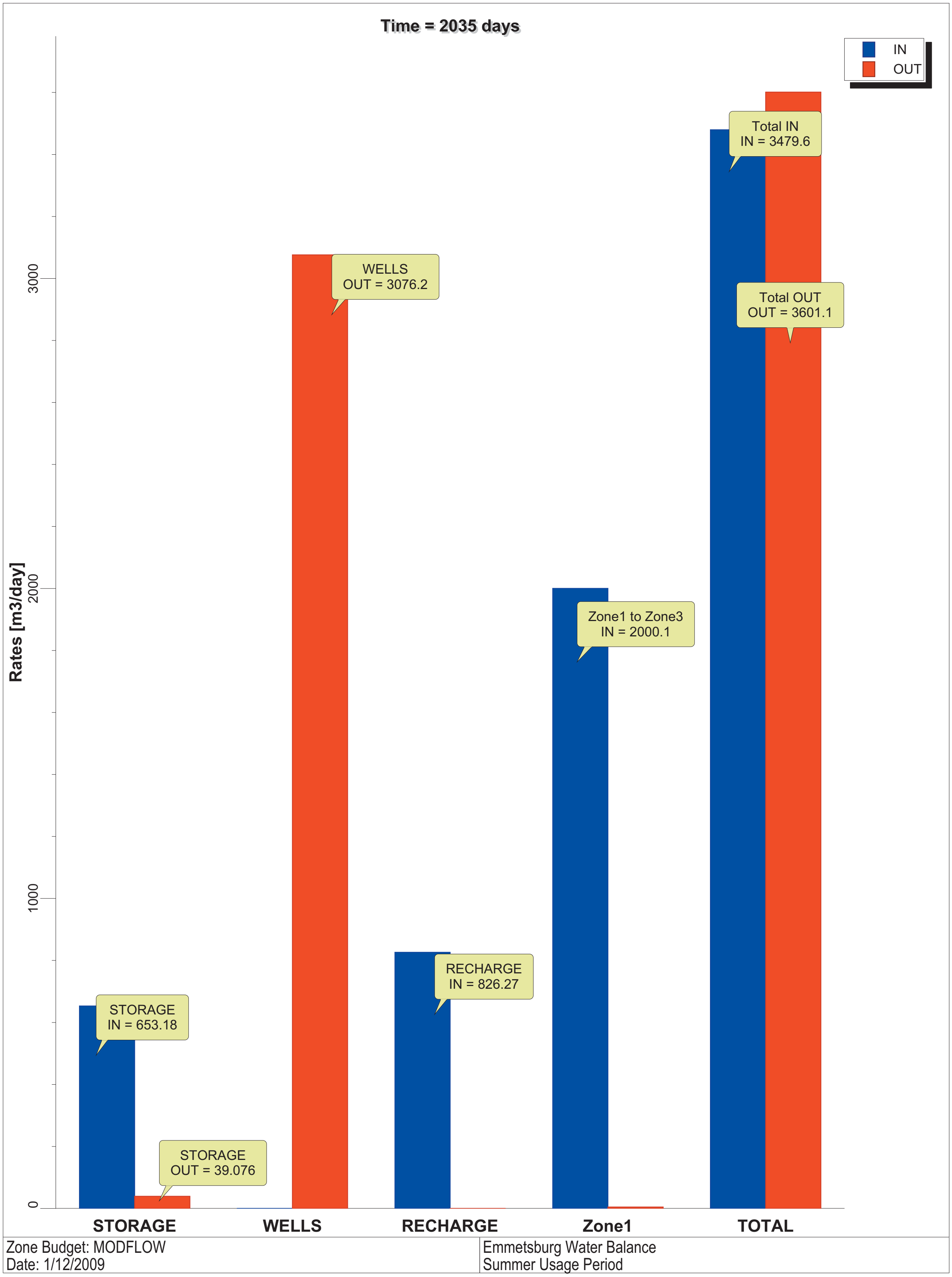

Time = 2035 days
IN
OUT
Rates [m3/day]
0
2000
4000
6000
STORAGE
IN = 1604
WELLS
OUT = 5013.2
RECHARGE
IN = 895.4
Zone1 to Zone4
IN = 5006.4
Zone4 to Zone1
OUT = 2536.8
Total IN
IN = 7505.7
Total OUT
OUT = 7580.4
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Cherokee Water Balance
Summer Usage Period

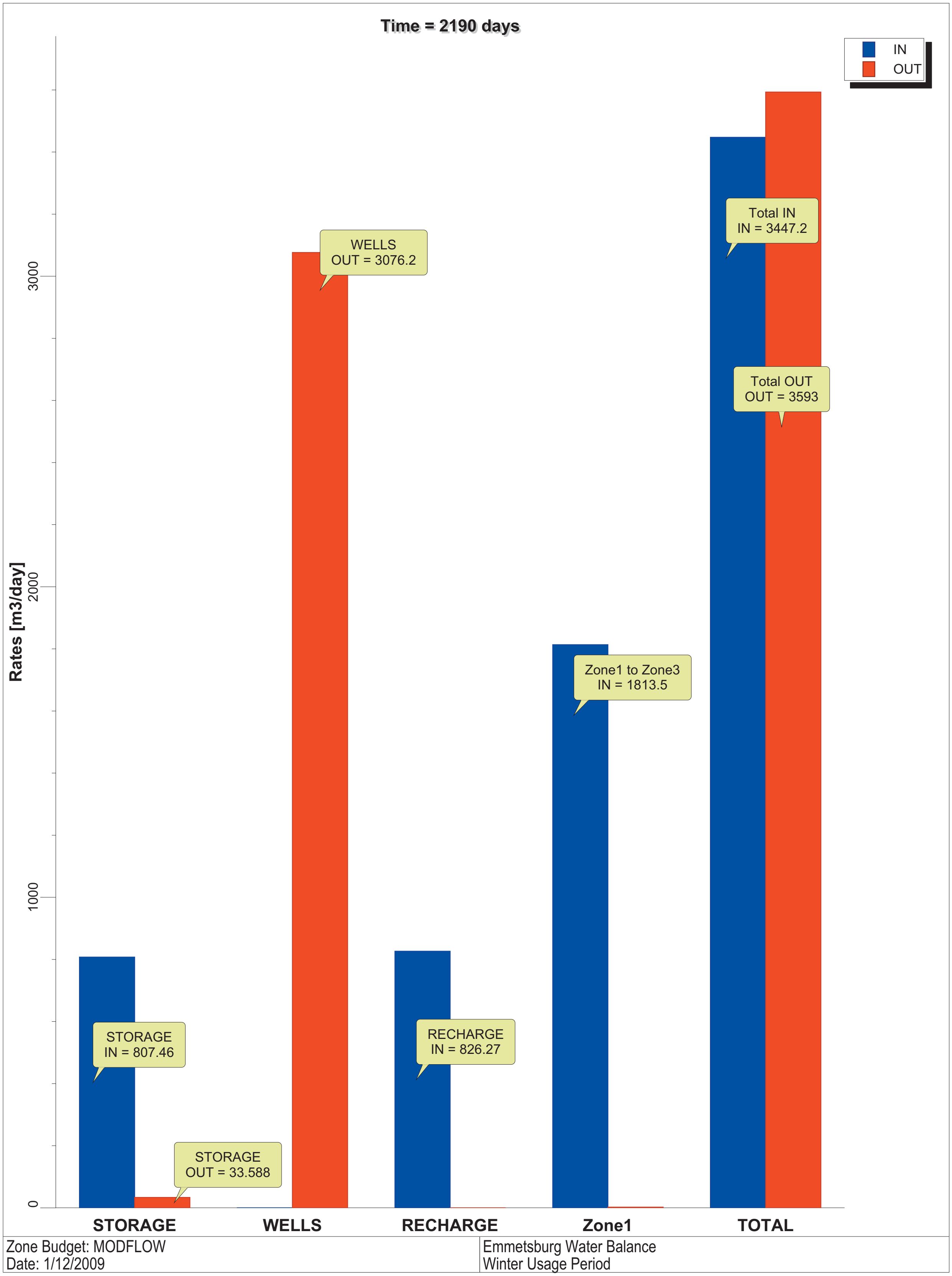

Time = 2190 days
IN
OUT
Rates [m3/day]
0
2000
4000
6000
STORAGE IN = 718.66
STORAGE OUT = 478.06
WELLS OUT = 3493.4
RECHARGE IN = 895.4
Zone1 to Zone4 IN = 4840.6
Zone4 to Zone1 OUT = 2584.8
Total IN IN = 6454.6
Total OUT OUT = 6556.3
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Cherokee Water Balance
Winter Usage Period

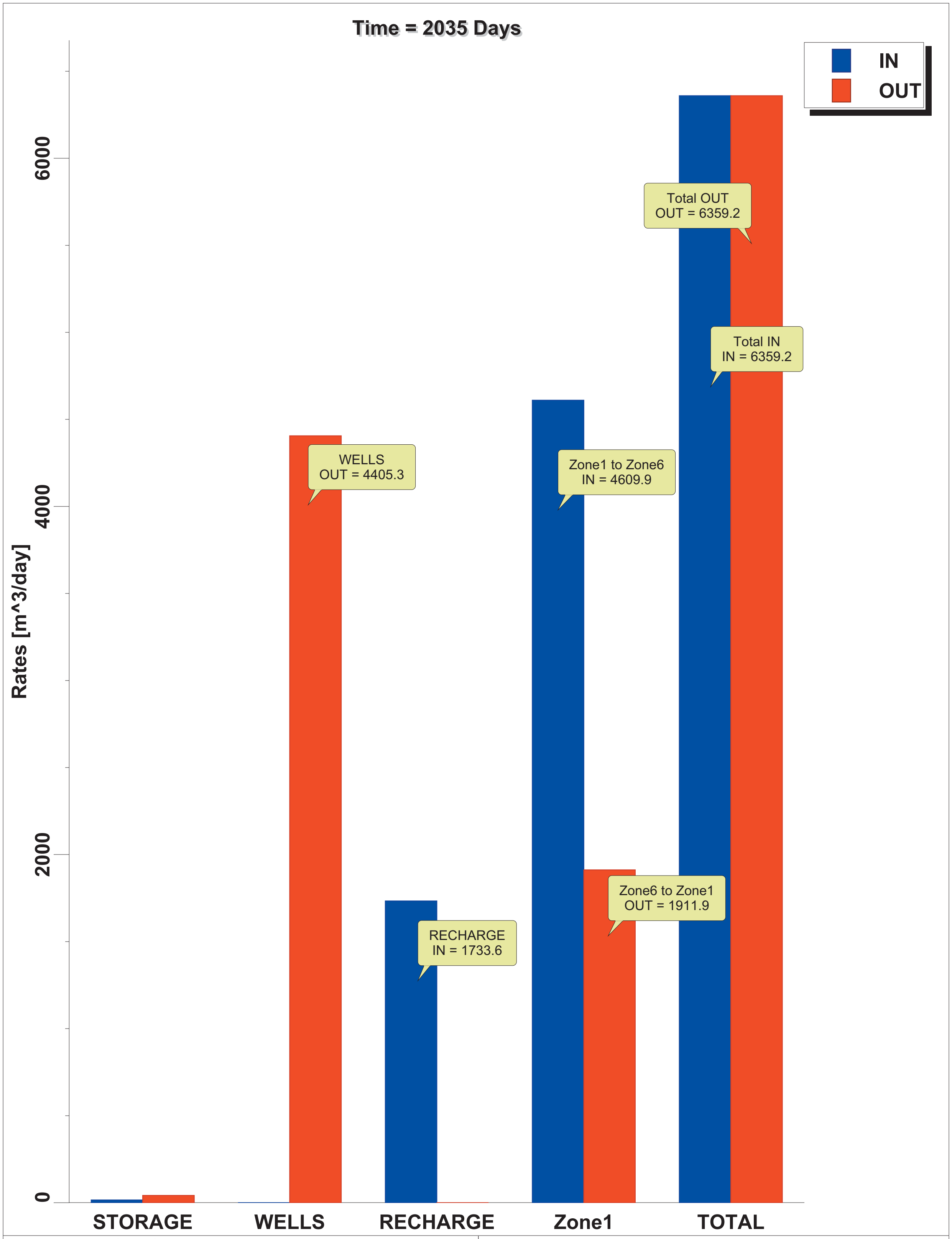

Time = 2035 days
IN
OUT
Rates [m3/day]
0
5000
10000
WELLS
OUT = 11569
Total IN
IN = 11836
Total OUT
OUT = 12005
STORAGE
IN = 8590.9
Zone1 to Zone12
IN = 1725.5
RECHARGE
IN = 1519.7
STORAGE
OUT = 123.71
Zone12 to Zone1
OUT = 312.77
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Clasing Water Balance
Summer Usage Period



Zone Budget: MODFLOW Date: 1/12/2009	Clasing Water Balance Winter Usage Period

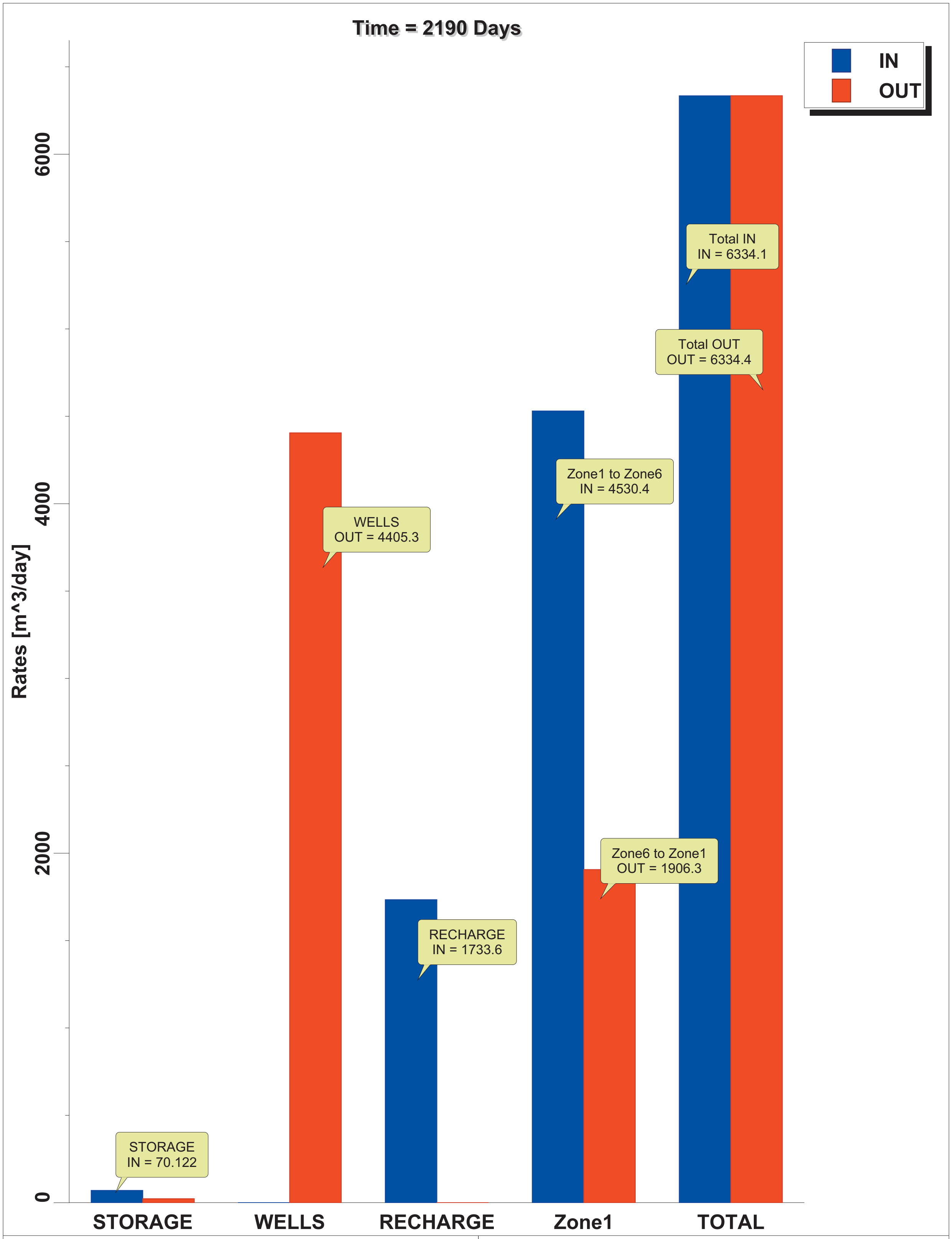

Time = 2035 days
IN
OUT
Rates [m3/day]
0
1000
2000
3000
STORAGE IN = 653.18
STORAGE OUT = 39.076
WELLS OUT = 3076.2
RECHARGE IN = 826.27
Zone1 to Zone3 IN = 2000.1
Total IN IN = 3479.6
Total OUT OUT = 3601.1
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Emmetsburg Water Balance
Summer Usage Period


Time = 2190 days
IN
OUT
Rates [m3/day]
0
1000
2000
3000
STORAGE
IN = 807.46
STORAGE
OUT = 33.588
WELLS
OUT = 3076.2
RECHARGE
IN = 826.27
Zone1 to Zone3
IN = 1813.5
Total IN
IN = 3447.2
Total OUT
OUT = 3593
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Emmetsburg Water Balance
Winter Usage Period

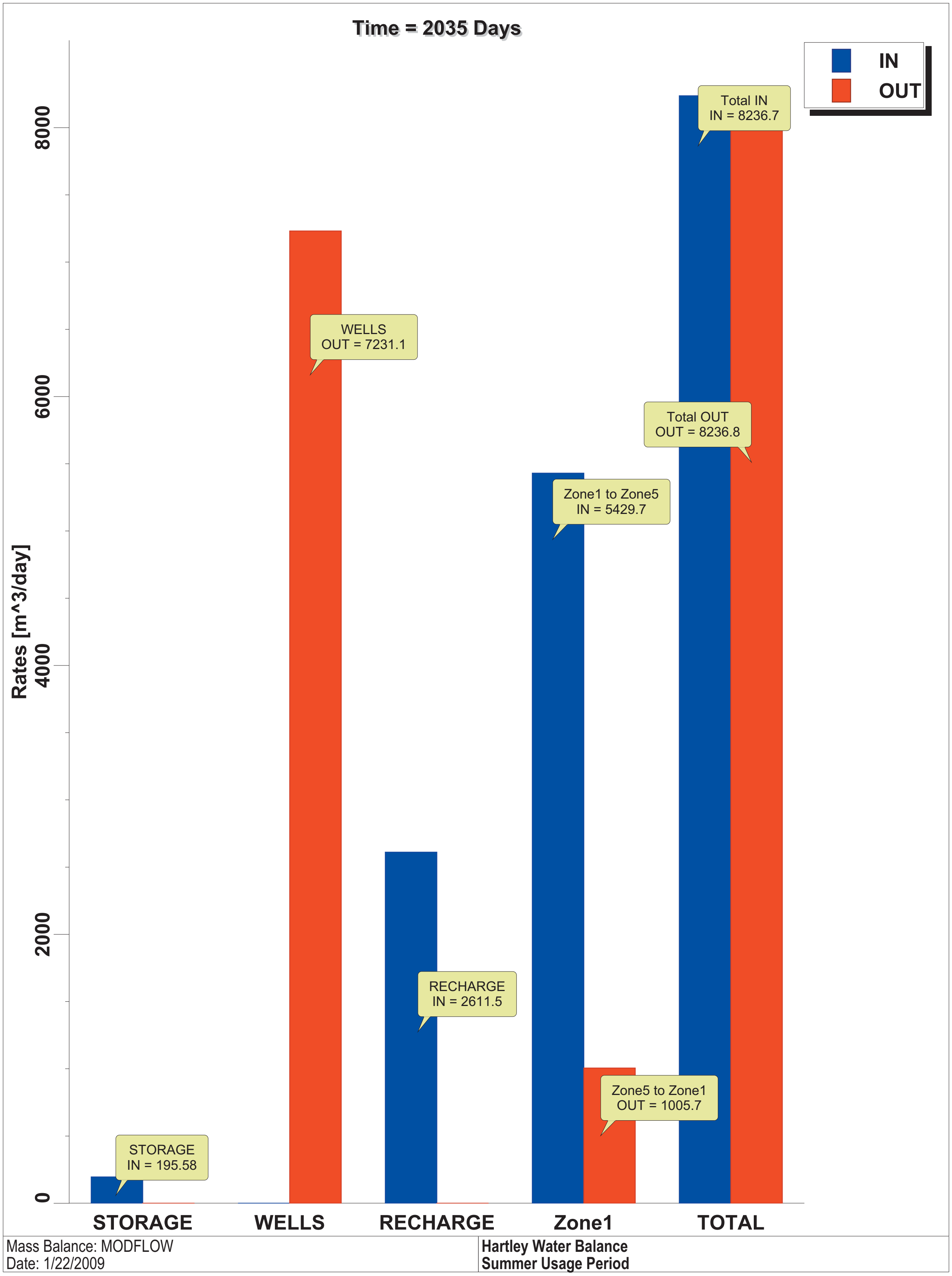


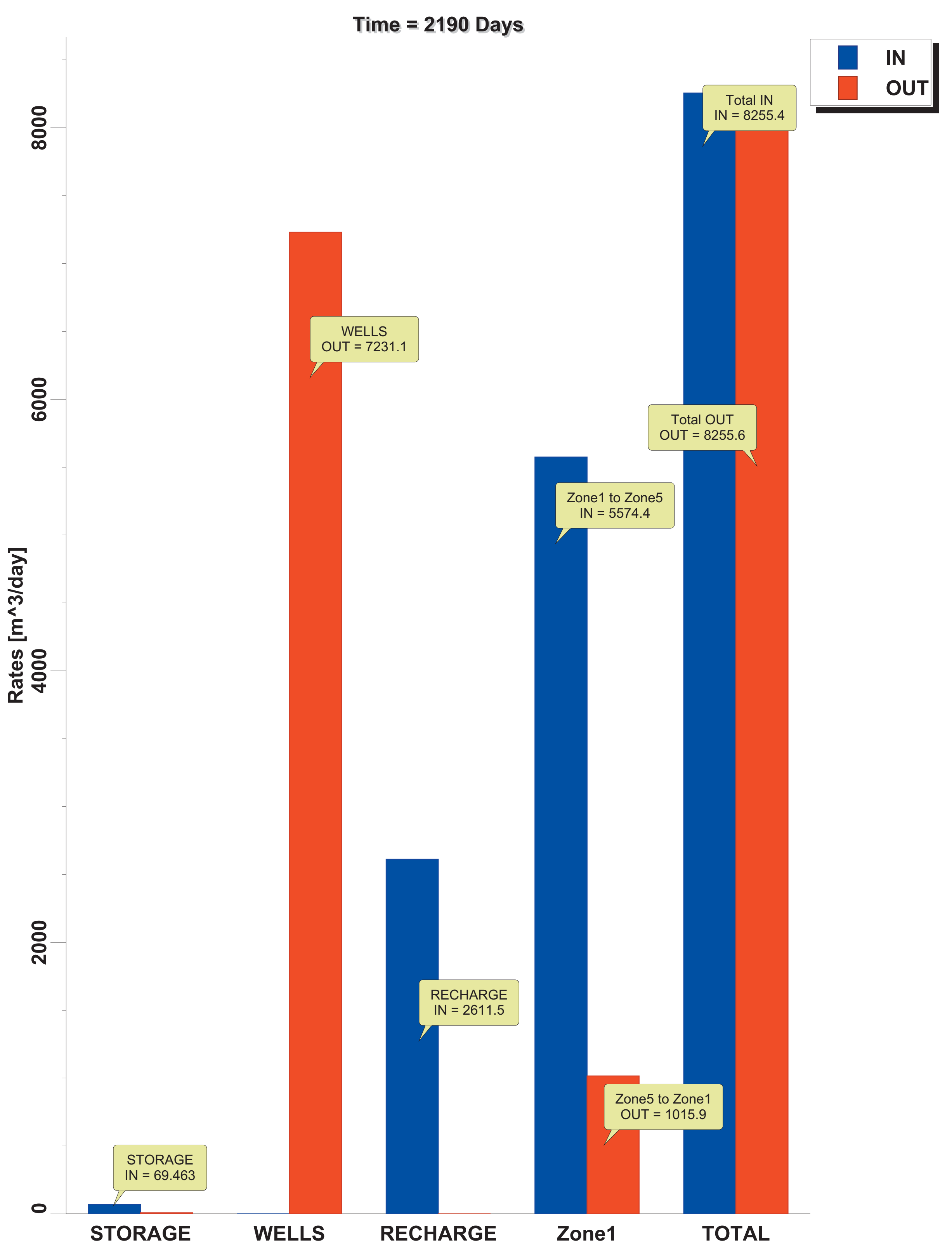
Mass Balance: MODFLOW
Date: 1/22/2009

Estherville Water Balance
Summer Usage Period

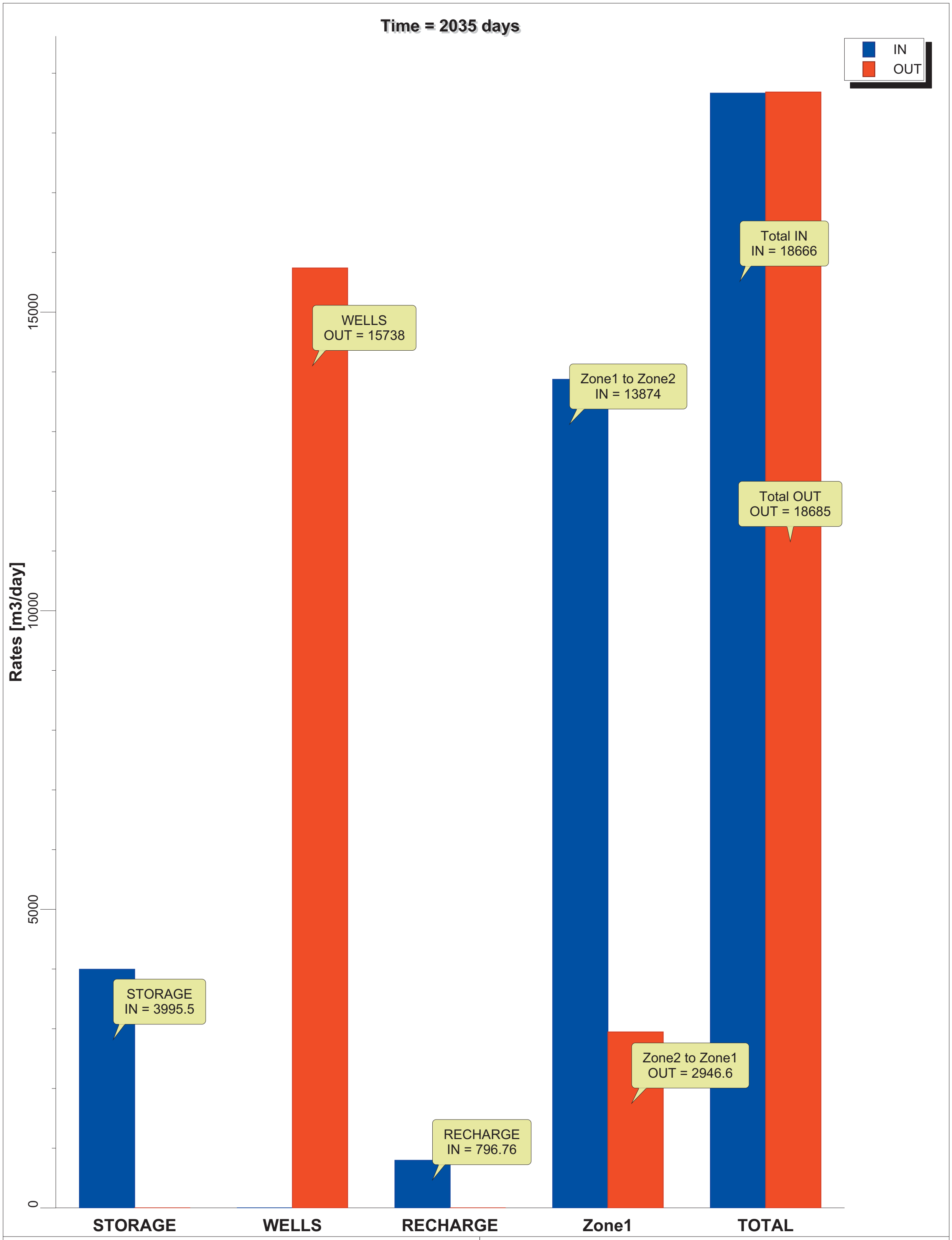


Mass Balance: MODFLOW Date: 1/22/2009	**Estherville Water Balance** **Winter Usage Period**

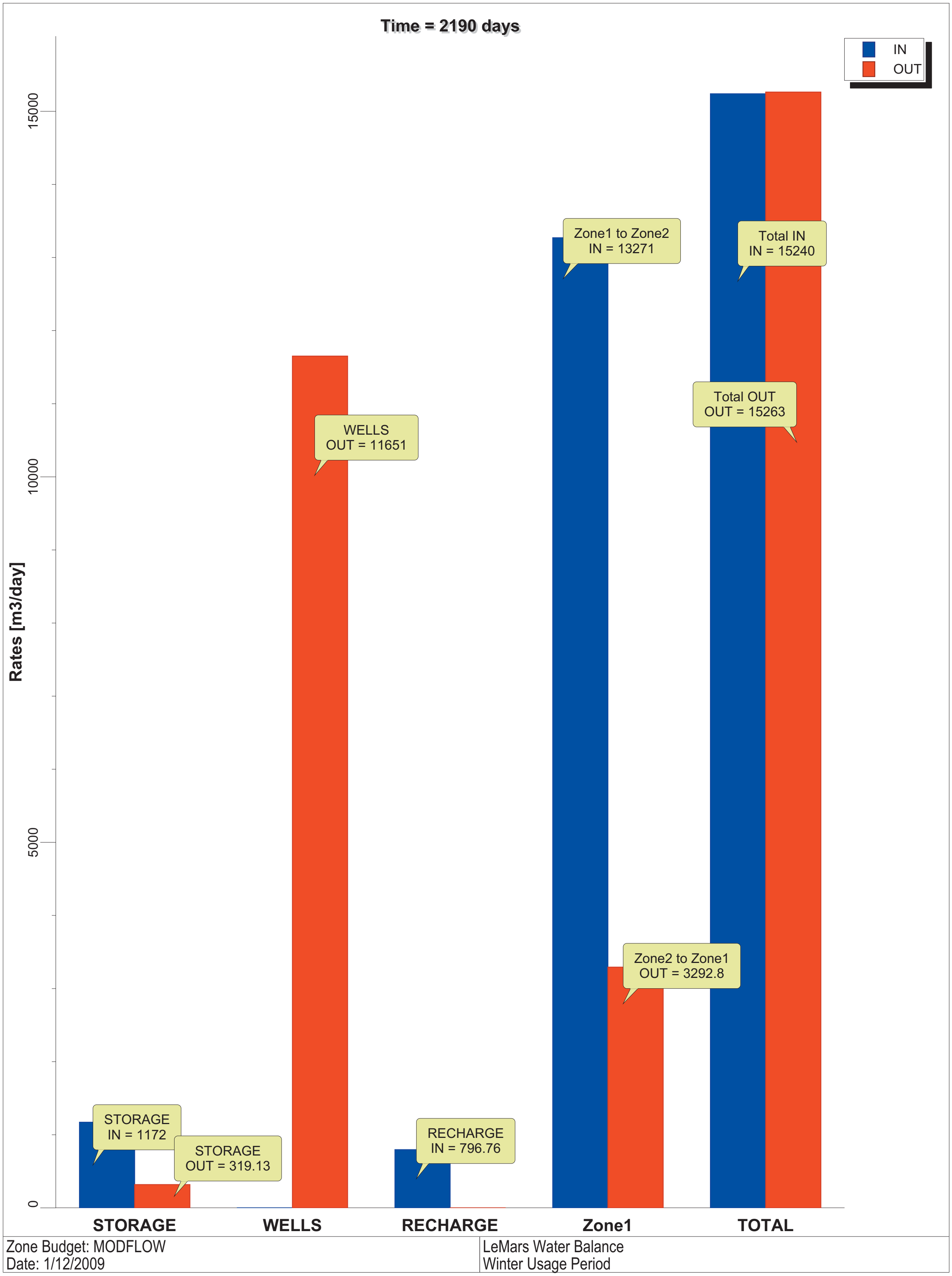

Time = 2035 Days
IN
OUT
Rates [m^3/day]
0
2000
4000
6000
8000
STORAGE
IN = 195.58
WELLS
OUT = 7231.1
RECHARGE
IN = 2611.5
Zone1 to Zone5
IN = 5429.7
Zone5 to Zone1
OUT = 1005.7
Total OUT
OUT = 8236.8
Total IN
IN = 8236.7
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Mass Balance: MODFLOW
Date: 1/22/2009
Hartley Water Balance
Summer Usage Period

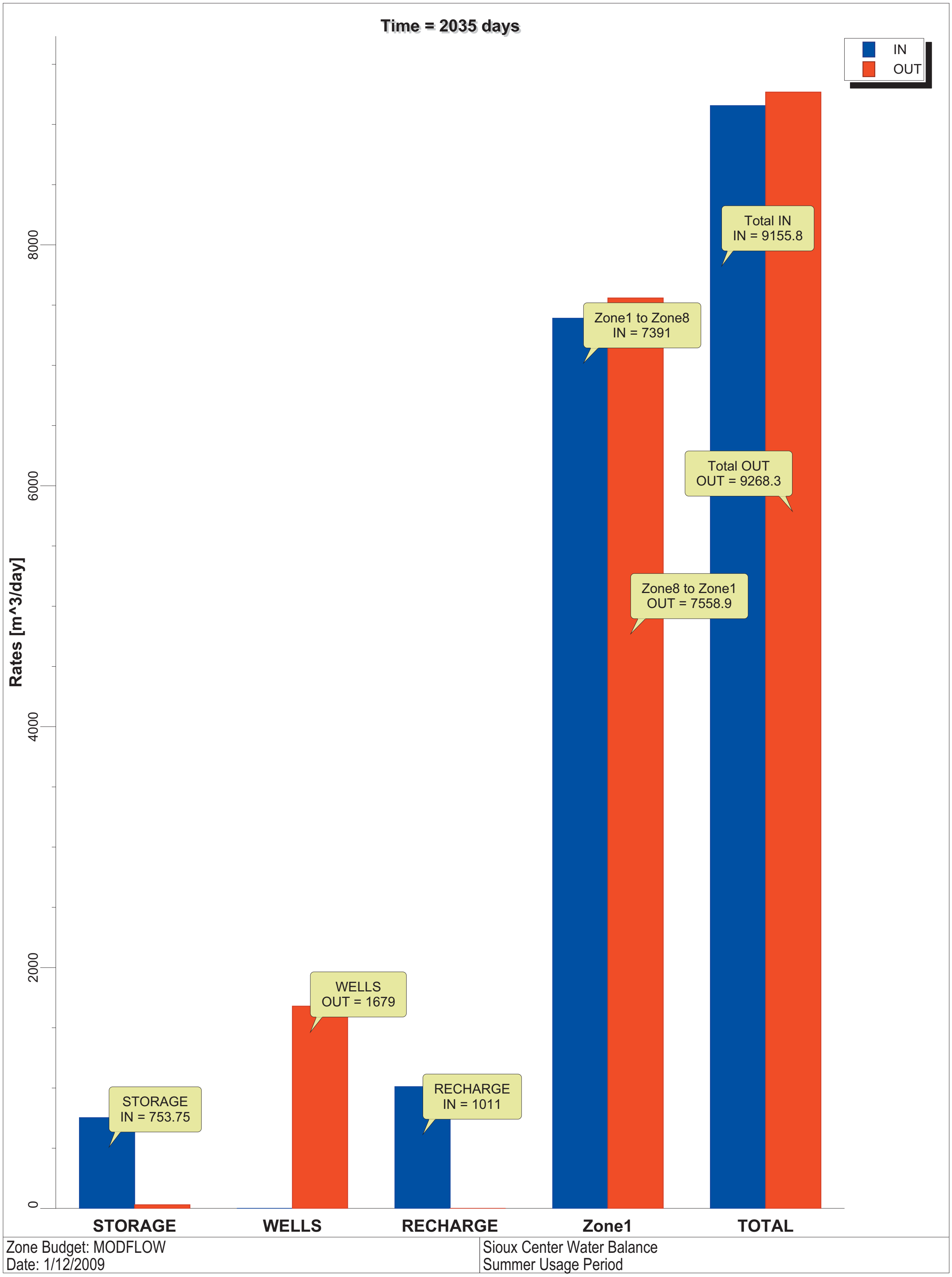


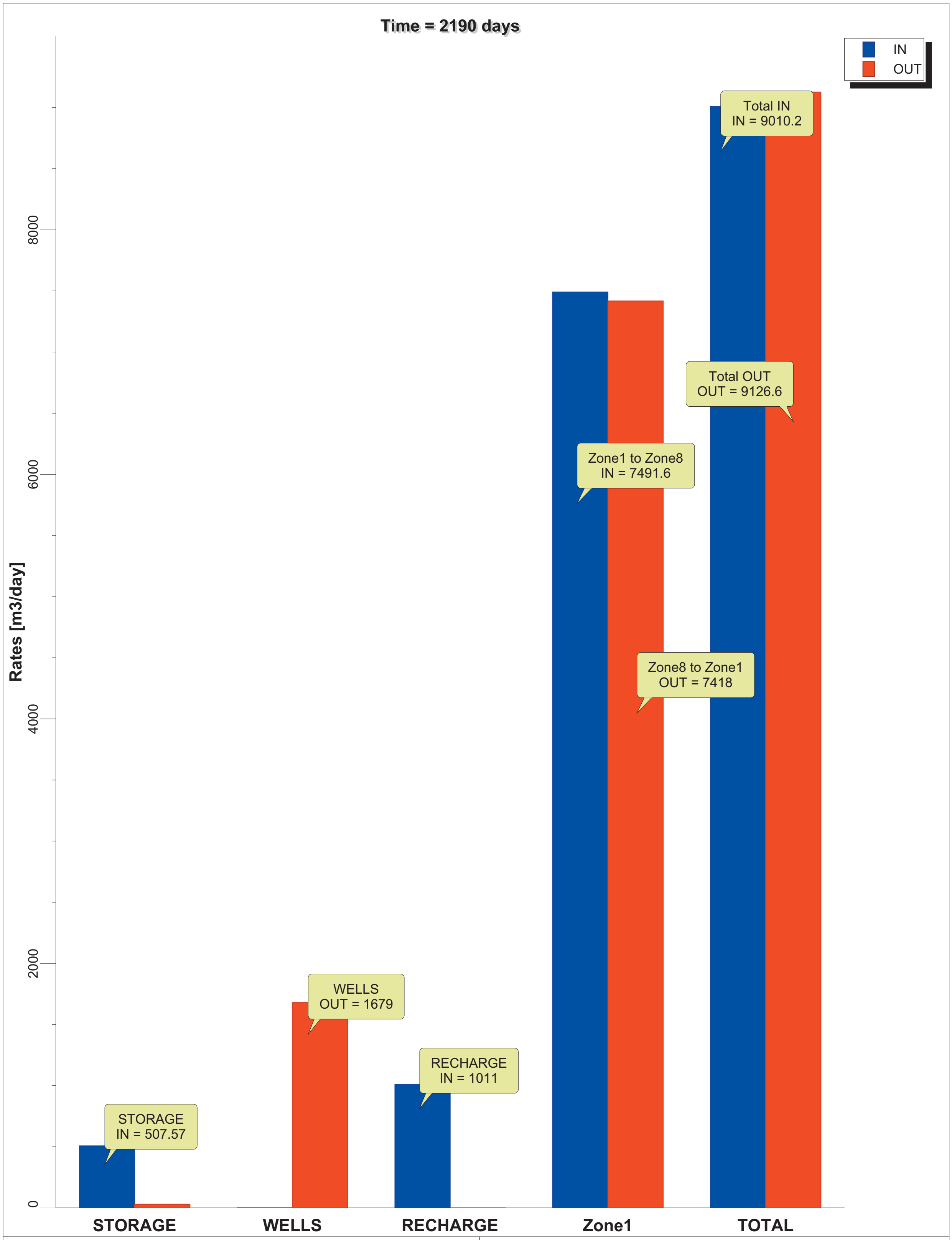
Mass Balance: MODFLOW Date: 1/22/2009	**Hartley Water Balance** **Winter Usage Period**



Zone Budget: MODFLOW Date: 1/12/2009	LeMars Water Balance Summer Usage Period

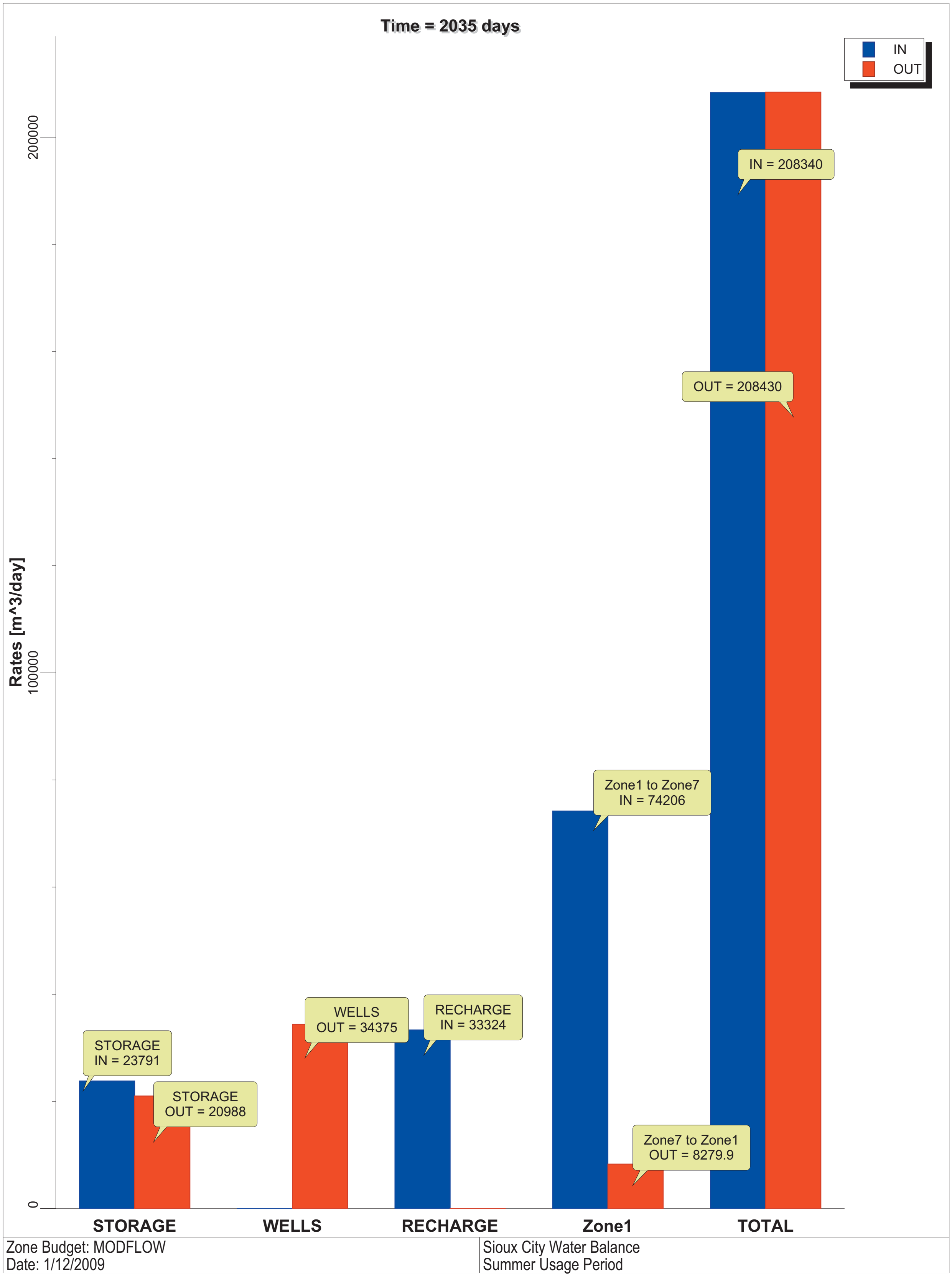
Time = 2190 days
🟦 IN
🟥 OUT
Rates [m3/day]
0
5000
10000
15000
STORAGE IN = 1172
STORAGE OUT = 319.13
WELLS OUT = 11651
RECHARGE IN = 796.76
Zone1 to Zone2 IN = 13271
Zone2 to Zone1 OUT = 3292.8
Total IN IN = 15240
Total OUT OUT = 15263
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
LeMars Water Balance
Winter Usage Period

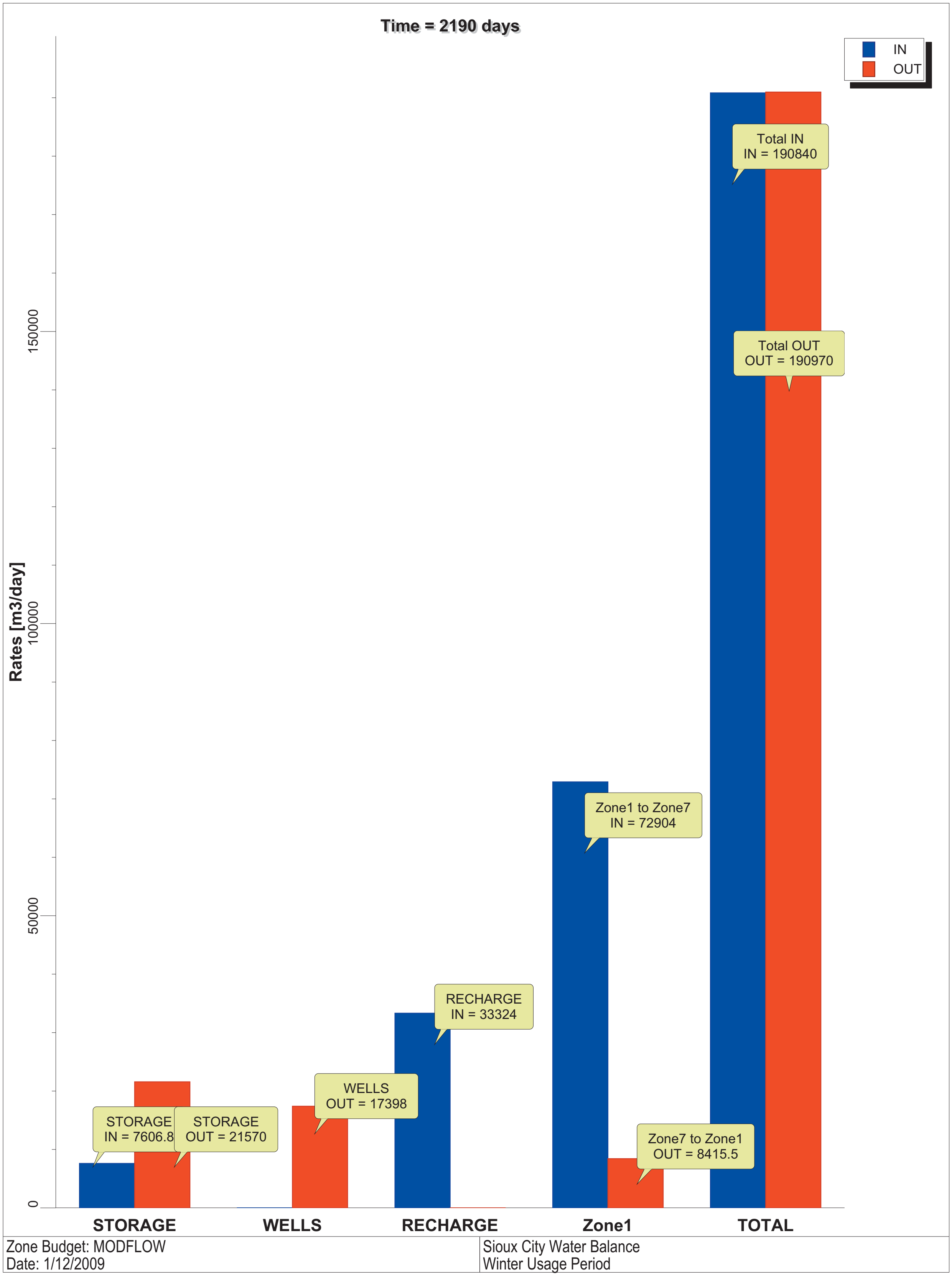

Time = 2035 days
IN
OUT
Rates [m^3/day]
0
2000
4000
6000
8000
Total IN
IN = 9155.8
Zone1 to Zone8
IN = 7391
Total OUT
OUT = 9268.3
Zone8 to Zone1
OUT = 7558.9
WELLS
OUT = 1679
RECHARGE
IN = 1011
STORAGE
IN = 753.75
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Sioux Center Water Balance
Summer Usage Period

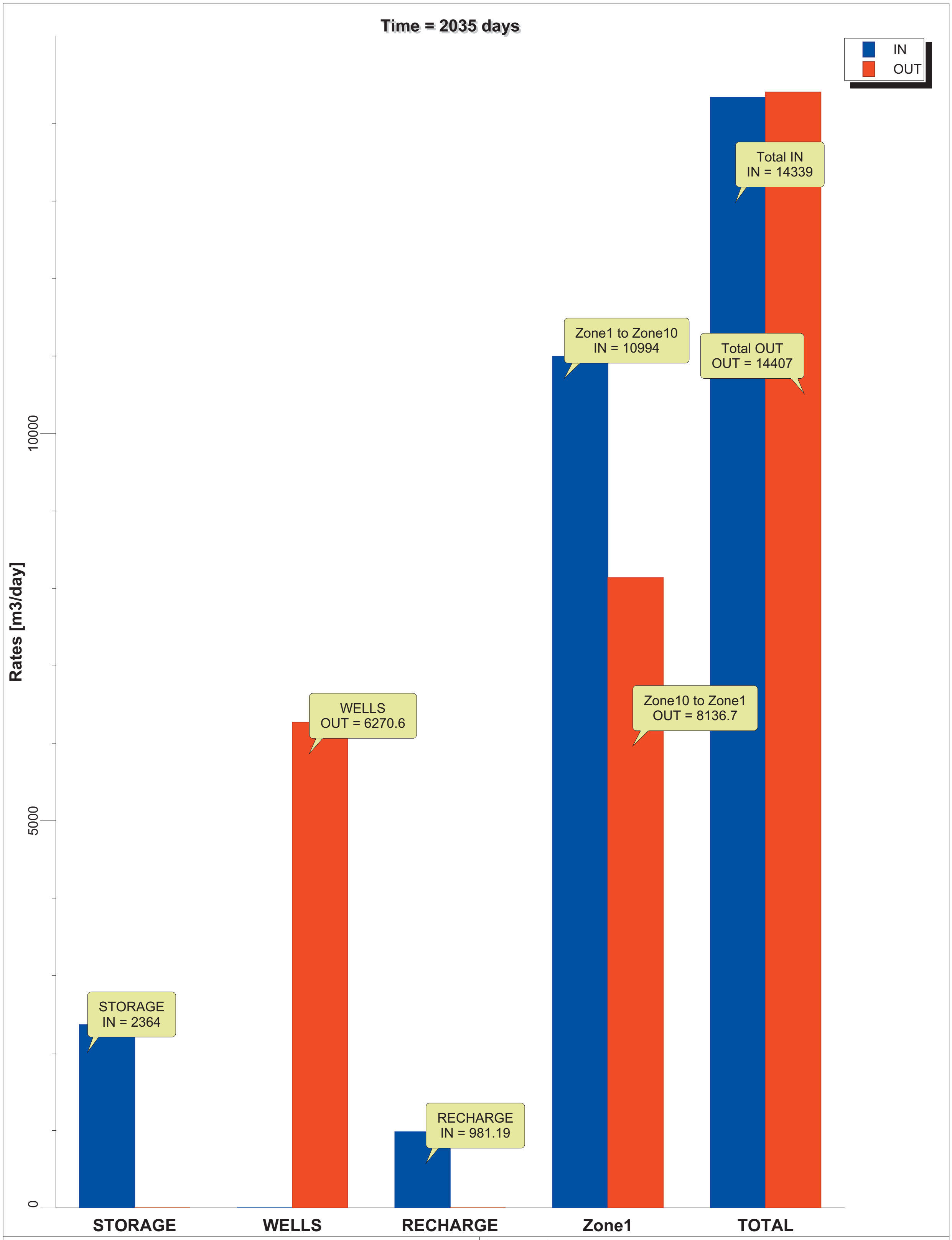


Zone Budget: MODFLOW
Date: 1/12/2009

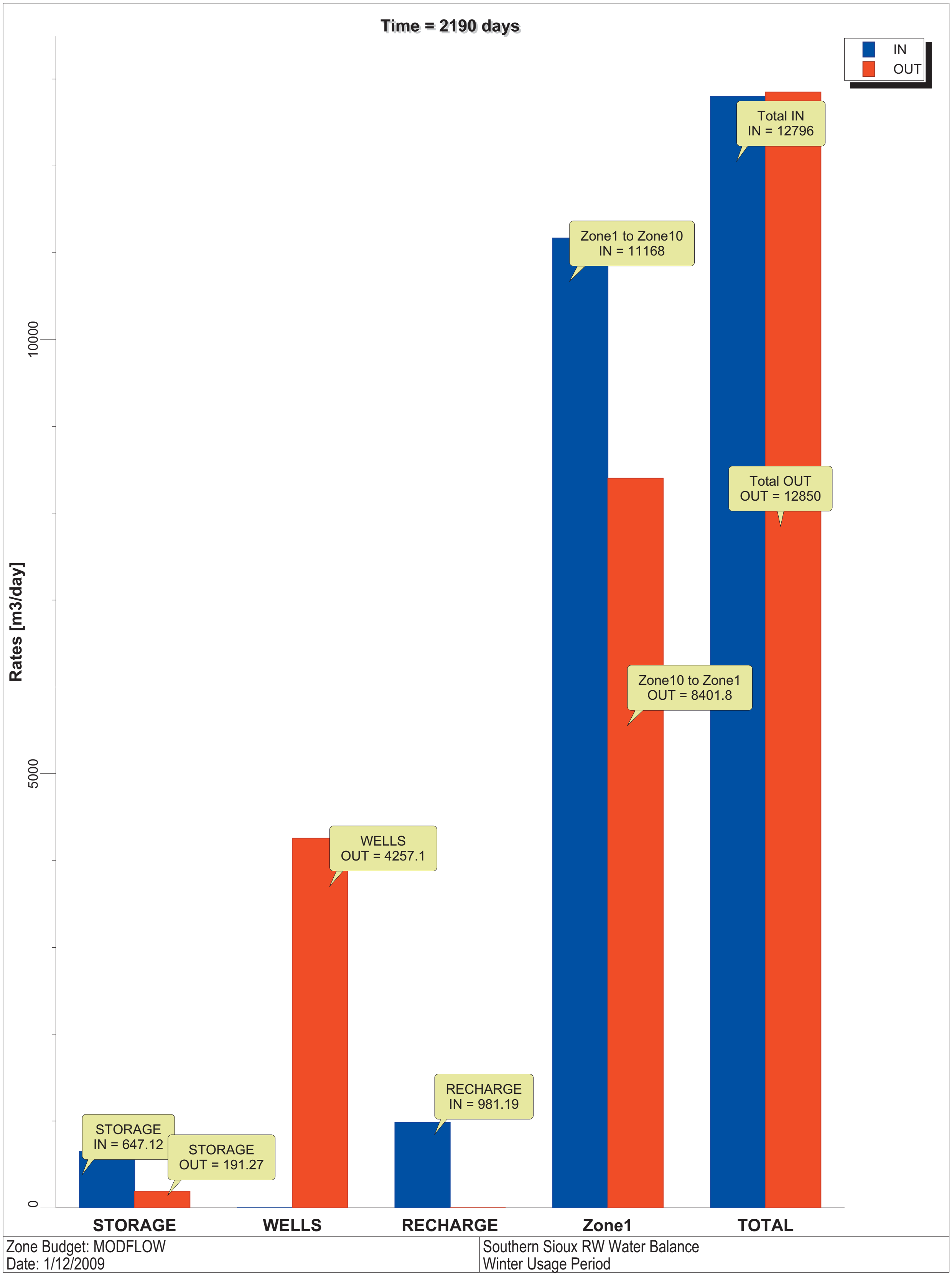
Sioux Center Water Balance
Winter Usage Period

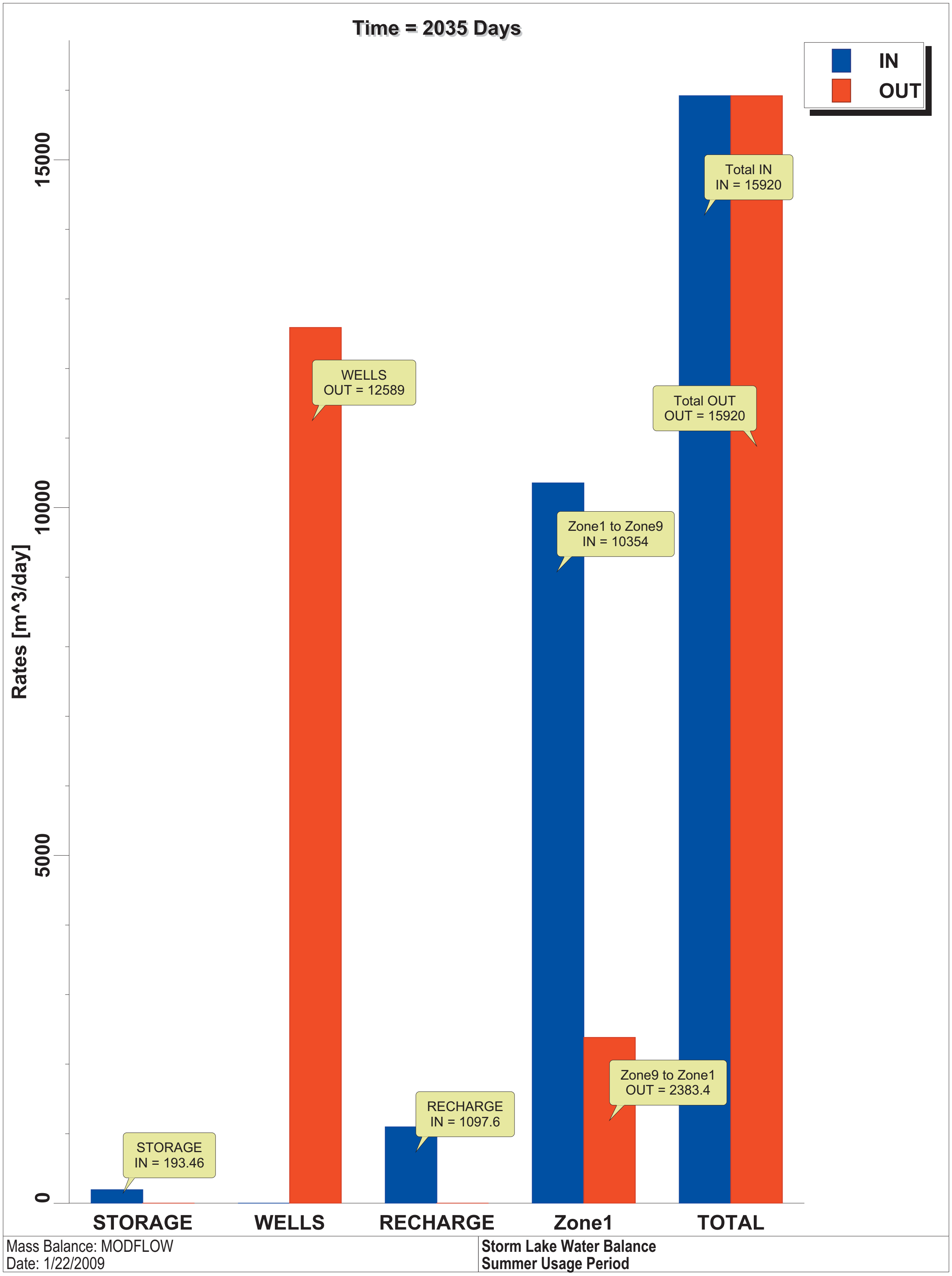

Time = 2035 days
IN
OUT
Rates [m^3/day]
200000
100000
0
IN = 208340
OUT = 208430
Zone1 to Zone7
IN = 74206
WELLS
OUT = 34375
RECHARGE
IN = 33324
STORAGE
IN = 23791
STORAGE
OUT = 20988
Zone7 to Zone1
OUT = 8279.9
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Sioux City Water Balance
Summer Usage Period

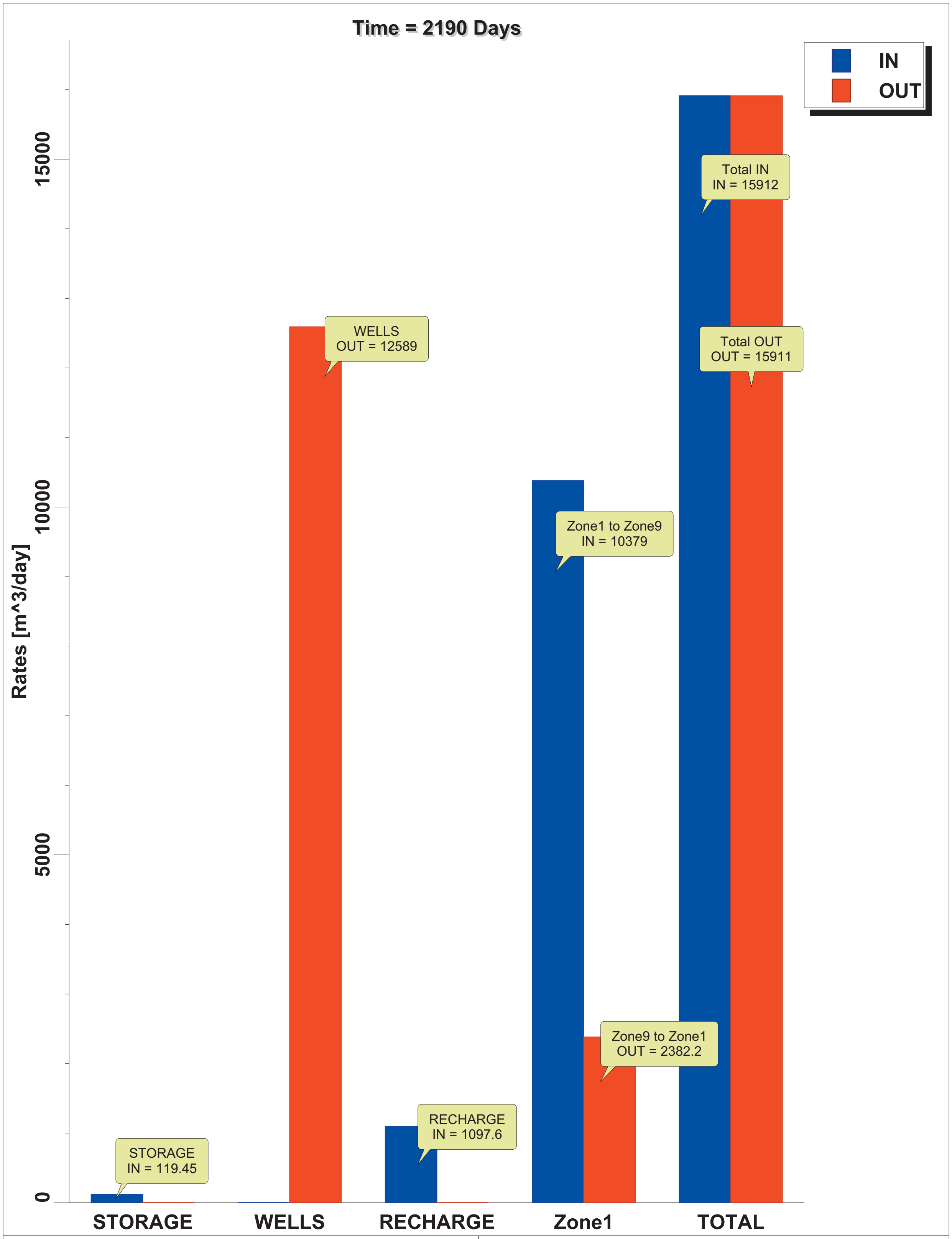

Time = 2190 days
IN
OUT
Rates [m3/day]
150000
100000
50000
0
Total IN
IN = 190840
Total OUT
OUT = 190970
Zone1 to Zone7
IN = 72904
RECHARGE
IN = 33324
WELLS
OUT = 17398
STORAGE
IN = 7606.8
STORAGE
OUT = 21570
Zone7 to Zone1
OUT = 8415.5
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Sioux City Water Balance
Winter Usage Period



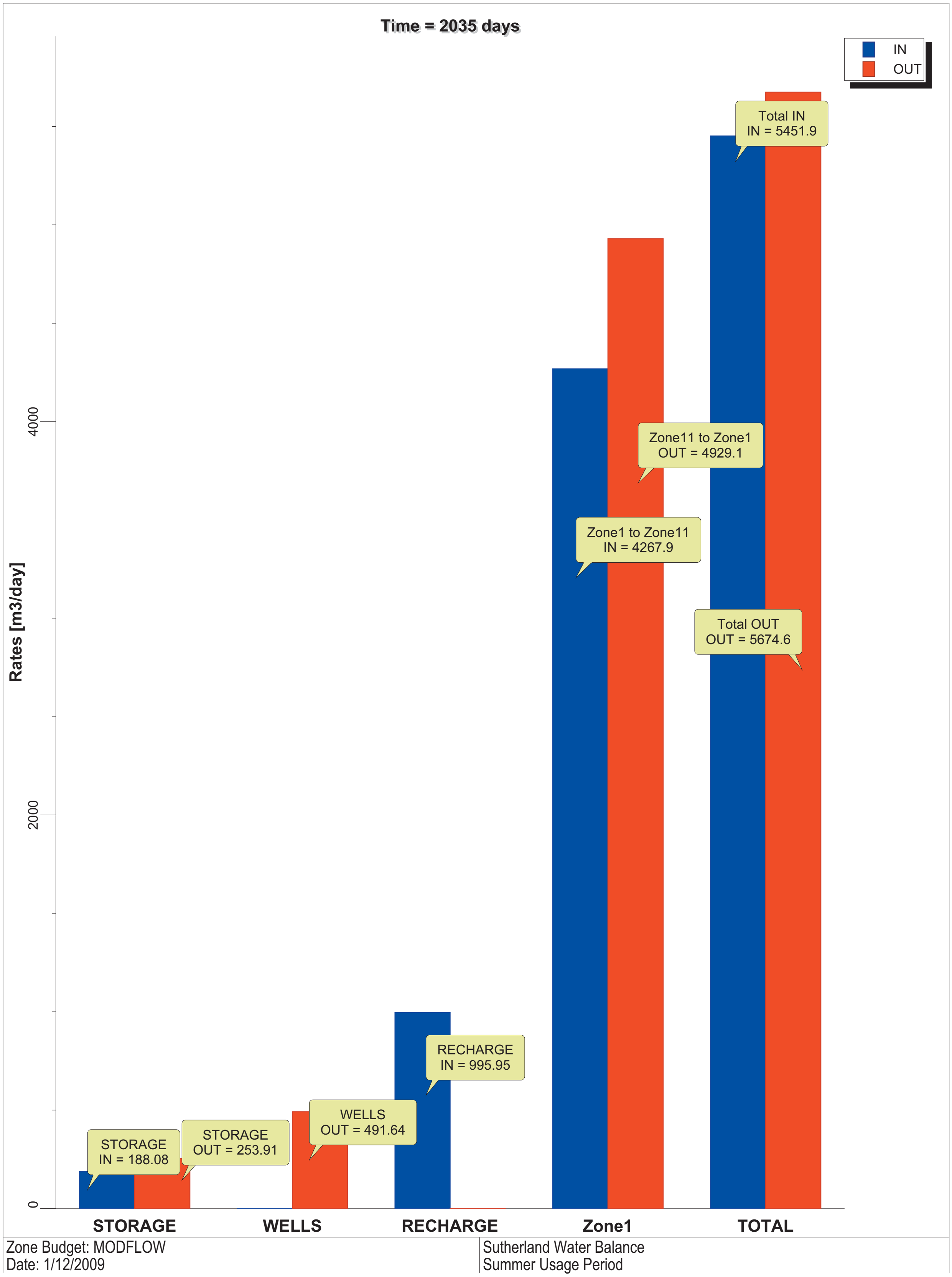
Zone Budget: MODFLOW Date: 1/12/2009	Southern Sioux RW Water Balance Summer Usage Period

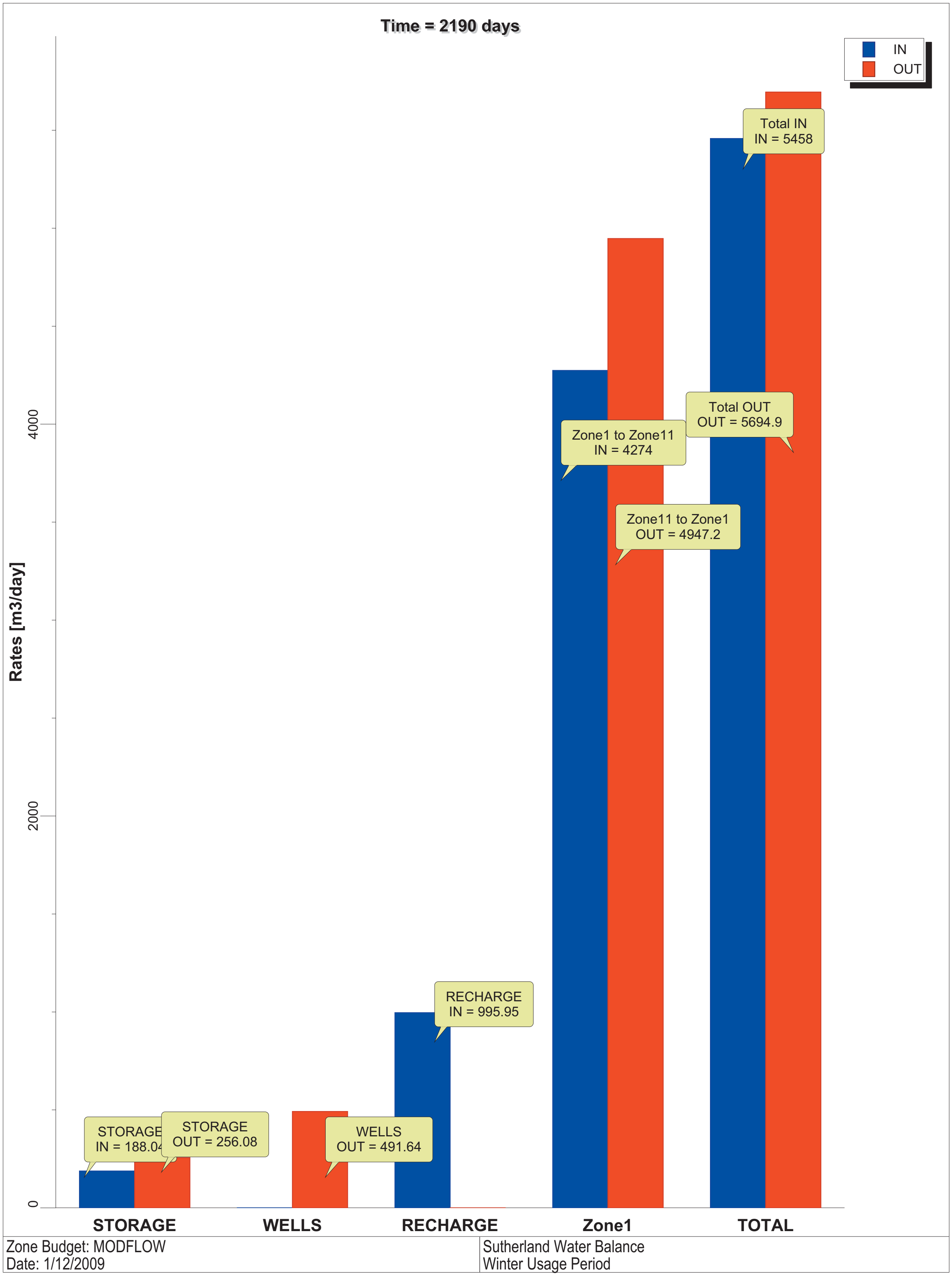

Time = 2190 days
IN
OUT
Rates [m3/day]
0
5000
10000
STORAGE IN = 647.12
STORAGE OUT = 191.27
WELLS OUT = 4257.1
RECHARGE IN = 981.19
Zone1 to Zone10 IN = 11168
Zone10 to Zone1 OUT = 8401.8
Total IN IN = 12796
Total OUT OUT = 12850
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Southern Sioux RW Water Balance
Winter Usage Period


Time = 2035 Days
IN
OUT
Rates [m^3/day]
0
5000
10000
15000
STORAGE
IN = 193.46
WELLS
OUT = 12589
RECHARGE
IN = 1097.6
Zone1 to Zone9
IN = 10354
Zone9 to Zone1
OUT = 2383.4
Total IN
IN = 15920
Total OUT
OUT = 15920
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Mass Balance: MODFLOW
Date: 1/22/2009
Storm Lake Water Balance
Summer Usage Period



Mass Balance: MODFLOW Date: 1/22/2009	**Storm Lake Water Balance** **Winter Usage Period**


Time = 2035 days
IN
OUT
Rates [m3/day]
0
2000
4000
Total IN
IN = 5451.9
Zone11 to Zone1
OUT = 4929.1
Zone1 to Zone11
IN = 4267.9
Total OUT
OUT = 5674.6
RECHARGE
IN = 995.95
WELLS
OUT = 491.64
STORAGE
IN = 188.08
STORAGE
OUT = 253.91
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Sutherland Water Balance
Summer Usage Period



Time = 2190 days
IN
OUT
Rates [m3/day]
0
2000
4000
Total IN
IN = 5458
Total OUT
OUT = 5694.9
Zone1 to Zone11
IN = 4274
Zone11 to Zone1
OUT = 4947.2
RECHARGE
IN = 995.95
STORAGE
IN = 188.04
STORAGE
OUT = 256.08
WELLS
OUT = 491.64
STORAGE
WELLS
RECHARGE
Zone1
TOTAL
Zone Budget: MODFLOW
Date: 1/12/2009
Sutherland Water Balance
Winter Usage Period

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