Attachment B

Groundwater Supply Evaluation

Big Stone II Project
Grant County, South Dakota

Prepared for
Otter Tail Power Company

March 27, 2007

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1.0 Introduction

1.1 Project Scope

This report describes the hydrogeologic evaluation of water-transmitting glacial drift deposits in northeastern Grant County, South Dakota for characterizing their use as a back-up water supply for a proposed 630-megawatt net capability coal-fired electric power generating station named Big Stone II. The proposed Big Stone II plant would be located adjacent to the existing Big Stone plant in Grant County, South Dakota, about eight miles northeast of Milbank and two miles northwest of Big Stone City, South Dakota.

The proposed Big Stone II plant would typically require withdrawal of an additional 7,500 acre-feet per year of fresh water from Big Stone Lake primarily to replace water losses due to evaporation in the power plant cooling system and the wet flue gas desulfurization system. Under extreme drought conditions, withdrawals from Big Stone Lake may be limited to preserve lake levels and plant cooling water may need to be supplemented by groundwater for short periods of time. As part of this hydrogeologic evaluation, a groundwater supply capable of supplying a maximum of 6,200 gallons per minute (gpm) (10,000 acre-feet per year) for a period of one year was assumed to be necessary to meet the cooling demands of the plant under extreme conditions.

This hydrogeologic evaluation consists of the following elements:

1. Installation of pilot borings to obtain continuous cores of unconsolidated deposits at potential sites for future water-supply wells;

2. Installation of test wells and observation wells at selected locations for the purpose of performing aquifer ("pumping") tests;

3. Aquifer testing at selected locations and water quality analysis of aquifer-samples; and

4. Groundwater flow modeling to predict the hydrogeologic effects of pumping of future water-supply wells.

1.2 Study Location

The hydrogeologic evaluation was performed in the area shown on Figure 1. Locations of pilot borings and wells are also shown on Figure 1. The nomenclature for the pilot borings and wells includes the phase number, a hyphen, and the boring/well number. For example, pilot hole 2-3 is the third pilot hole in Phase 2.

1.3 Investigation Schedule

The field investigation, which consisted of pilot borings, well installation, and aquifer testing, was performed in phases. A phased approach was used to make adjustments to the investigation approach as data were collected and evaluated. A work plan for installing five test wells on the Big Stone II Project Site, five monitoring wells, and aquifer testing of the wells was submitted in September 2006. The Western Area Power Administration (Western) and their consultant, R.W. Beck, provided comments and the Work Plan was revised. Western gave approval for drilling in early October 2006. Technical specifications for drilling were developed and bids for drilling were obtained. Boart Longyear Company of Little Falls, Minnesota was hired to drill pilot boreholes, and install the test and monitoring wells.

1.3.1 Phase 1 Pilot Holes

Drilling of the first pilot hole began on November 27, 2006. Pilot holes were drilled at locations 1-1, 1-2, 1-3, 1-4, and 1-5, shown on Figure 1. Based on the subsurface conditions encountered in these pilot holes, locations 1-2 and 1-4 were selected for installation of pumping wells. A 12-inch diameter pumping well was installed at the Well PW1-2 location on January 16 and 17, 2007 using mud rotary drilling method. A second 12-inch diameter pumping well was installed at the Well PW1-4 location on January 29 and 30, 2007. Along with each pumping well, a 2-inch diameter monitoring well was installed, approximately 400 feet from each pumping well for use in monitoring groundwater levels during aquifer testing.

1.3.2 Phase 1 Aquifer Tests

A step-drawdown test was conducted on January 26, 2007 in Well PW1-2 to estimate the approximate maximum sustainable pumping rate. The aquifer test of Well PW1-2 commenced at 9 pm on January 26, 2007, after aquifer recovery. The well was pumped continuously at 550 gallons per minute (gpm) for 82 hours, until the test was ended at 7 am on January 30th.

A step-drawdown test was conducted on February 27, 2007 in Well PW1-4 to estimate the approximate maximum sustainable pumping rate. The aquifer test of Well PW1-4 commenced, at 4:30 pm on February 27, 2007 after aquifer recovery. The well was pumped continuously at rates of 210 to 355 gpm until the test was ended at 4:30 pm on March 2, 2007.

1.3.3 Phase 2 Pilot Holes

A second phase of pilot-hole drilling took place February 6 through 14, 2007 in areas southwest of the Phase 1 pilot-hole locations. The locations of the Phase 2 pilot holes (designate as 2-"number") are shown on Figure 1. These pilot-hole locations were approved by Western on January 25, 2007, as an Interim Action Determination with drilling methods to follow the procedures outlined in the Work Plan for the Phase 1 drilling.

1.3.4 Phase 3 Pilot Holes

A third phase of pilot-hole drilling took place from March 6 through March 14, 2007 in the area encompassed by the Phase 2 pilot holes and in additional areas south of Phase 2 pilot-hole locations. The locations of the Phase 3 pilot holes (designate as "3-"number") are shown on Figure 1. The drilling activity was approved by Western on March 6, 2007, as an Interim Action Determination with drilling to conform with the procedures outlined in the Work Plan for the Phase 1 drilling. The March 6, 2007 letter from Western gave approval of up to 40 additional pilot holes. Pilot-hole drilling was terminated on March 14, 2007 when spring thaw conditions made access to the drilling sites extremely difficult. A fourth phase of drilling is planned for April 2007 to complete the Phase 3 pilot holes that could not be completed prior to spring thaw and to confirm the presence of aquifer material at these locales.

2.0 Regional Hydrogeology

2.1 Previous Studies

Previous studies with relevance to groundwater supply in northeastern Grant County include the following:

- *The Geology of Grant County, South Dakota, SD State Geological Survey, E.P. Rothrock, 1952.* This document details the geology in Grant County. Very little information is given on water in the area.

- *Groundwater Study for the City of Milbank, University of South Dakota, Barari, 1976.* The purpose of this study was to assist the city in locating a future water supply. Two areas are outlined. Some water quality and quantity data is given.

- *Groundwater Investigation for Big Stone City, South Dakota, University of South Dakota, Green and Gilbertson, 1987.* The purpose of this investigation was to identify alternative ground water supply for Big Stone City because of high total dissolved solid concentrations, particularly iron and manganese. Water quality data is given in this report.

- *Water Resources of Codington and Grant Counties, South Dakota, USGS, Hansen, 1990.* This document outlines the quantity and quality of both surface and groundwater in Codington and Grant Counties. Water quality is also is presented in this report.

- *ProGold, LLC water permit application and DENR report, 1995.* Water appropriations permit application for an fructose plant near the Big Stone plant (the fructose plant was not constructed).

- *Investigation of Groundwater Resources in Portions of Roberts County, SD, University of South Dakota, Gilbertson, 1996.* This document outlines both the geology and hydrogeology of Roberts County. Water quality data for the Veblen aquifer is provided.

- *Water Resources of the Lake Traverse Reservation, South and North Dakota, and Roberts County, USGS, Water-Resources Investigation Report 01-4219, Thompson 2001.* Addresses unconsolidated, water-bearing deposits primarily in Roberts County, SD.

- *First Occurrence of Aquifer Materials in Grant County, South Dakota, South Dakota Geological Survey, Aquifer Materials Map 17, Jensen, 2004.* Map of Grant County, showing approximate shallowest aquifer material, based on lithologic logs.

- *First Occurrence of Aquifer Materials in Roberts County, South Dakota, South Dakota Geological Survey, Aquifer Materials Map 22, Tomhave, 2006.* Map of Roberts County, showing approximate shallowest aquifer material, based on lithologic logs.

In addition to these studies, lithologic logs were examined and evaluated. Approximately 1,250 lithologic logs for wells in Roberts, Codington, Deuel, and Grant Counties were obtained from the South Dakota Geological Survey and 520 lithologic logs from the Minnesota County Well Index (CWI) were also included. From each log, the elevation of the top and bottom of the major water-transmitting units (if any) were recorded, along with the approximate saturated thickness (i.e. the total thickness of water-transmitting units). The elevations of the top and bottom of the water-transmitting units were contoured using kriging methods.

2.2 Overview of Regional Geology

The study area is located within the Coteau des Prairies plateau of the Central Lowlands physiographic province. The topography is characterized by rolling moraines, formed by deposition of glacial debris upon a bedrock highland during the Pleistocene. The Minnesota River lowlands is a somewhat flat ground moraine that consists of isolated areas of debris left by retreating glaciers (Thompson, 2001).

The geologic units in the area include, from oldest to youngest, (1) Precambrian-age crystalline bedrock, (2) Cretaceous sedimentary bedrock, and (3) Quaternary-age unconsolidated deposits. The unconsolidated deposits include alluvium, glacial till, glacial outwash deposits, and glacial lake sediments. Precambrian rocks rise to land surface at an elevation of 1,100 feet near Milbank, southwest of the study area but are deeper to the east, into Minnesota (Thompson, 2001).

The Cretaceous sedimentary rocks include sandstone with interbedded layers of shale and siltstone (Dakota Sandstone), interlayered beds of limestone (Niobrara and Greenhorn), and shales (Pierre, Carlile, and Graneros). The Dakota Sandstone directly overlies the Precambrian crystalline rocks. Depending upon the pre-glacial erosional surface, any of these three Cretaceous bedrock units may be the uppermost bedrock unit at a given locale in the study area. The depth to bedrock can vary from a few feet to over 300 feet, or more.

Glacial deposits or drift consist of till, glacio-fluvial, and glacio-lacustrine (lake) sediments were deposited in the area over bedrock. Glacial till is a heterogeneous mixture of clay, silt, sand, gravel, and boulders. Glacio-fluvial sediments include glacial outwash deposits of sand and gravel deposited by flowing glacial meltwaters. Glacial-outwash deposits may be stratified to semi-stratified, and consist of poorly sorted fine sand to coarse gravel. Glacio-lacustrine sediments are composed of layered deposits of clay, silt, and sand transported into Pleistocene lakes by glacial meltwaters. Alluvium may be found along recent flood plains or lake beds, and generally consists of semi-stratified deposits of silt, sand, and gravel (Thompson, 2001).

2.3 Unconsolidated Aquifers

An aquifer is a water-transmitting geologic unit capable of yielding usable quantities of water to awell. An unconsolidated aquifer refers to Pleistocene or younger water-transmitting units, mostly made up of sand and/or gravel. Unconsolidated aquifers typically were formed by glacial meltwaters or by recent fluvial activity (in the case of alluvial aquifers). Because of the complex nature of glacio-fluvial deposition, the lateral continuity and interconnectedness of unconsolidated aquifers in a setting such as the vicinity of the Big Stone II project is difficult to delineate precisely using existing lithologic information. It is for this reason that a site-specific boring program was undertaken as part of this evaluation.

Aquifers are typically given informal names. In Grant County, the aquifers named in Hansen (1990) are: the Big Sioux aquifer; the Antelope Valley aquifer; the Prairie Coteau aquifer; the Veblen aquifer; the Lonesome Lake aquifer; the Revillo aquifer; the Granite Wash aquifer; and the Altamont aquifer. Thompson (2001) identifies seven named aquifers in Roberts and northwestern Grant Counties: the Coteau Lakes aquifer system; the Big Sioux aquifer; the Altamont aquifer; the Revillo aquifer; the James aquifer; the Veblen aquifer system; and the Spiritwood aquifer. Thompson (2001) also describes "outwash" units, differentiating them from named aquifers by their qualitatively less defined aerial extent. These outwash units are: the Prairie Coteau outwash unit; the Lonesome Lake outwash unit; the Marday outwash unit; the Eden outwash unit; the Roslyn outwash unit, and the Wilmot outwash unit. The Wilmot outwash unit is closest to the Big Stone II project area.

The above-described unconsolidated aquifers and outwash units were considered in the planning process for the field investigation as part of this study as a guide to beginning the investigation. However, the "naming" of unconsolidated units is not particularly relevant to whether or not usable quantities of groundwater can be obtained from a particular local – this can only be confirmed by site-specific investigation. Contradictions in how various investigators have interpreted and named particular units can distract from the objective of this study, which is to identify a groundwater supply and to estimate the effects of withdrawals for the project.

For example, the Wilmot Outwash, as described in Thompson (2001), may be part of the Veblen Aquifer in Grant County, as described by Hanson (1990). The apparent contradiction seems to be a matter of different nomenclature used by Thompson (2001) for unconsolidated, water-transmitting materials in Roberts County, SD and the southeast corner of North Dakota, compared to the nomenclature used by Hanson (1990). The evaluation of Thompson (2001) did not include the area of the Big Stone II project or areas south of the project, whereas Hanson (1990) focused on these areas. Thompson (2001, p. 26) discusses the contradicting nomenclature:

> *The glacial history of the study area has led to a rather complex system of glacial aquifers. On the Coteau, especially, an uneven bedrock surface coupled with as many as seven sand and gravel layers in a single test hole can make aquifer delineation difficult. Additionally, localized ground-water investigations done in adjacent counties, and even specific locales within the study area, have given names to aquifers that may not match the naming convention assigned to the same aquifer in another study.* And.... *In some aquifers, the thickness of aquifer material at a specific test hole may not be the same as given in a previous report. This is either due to additional data and subsequent reinterpretation of cross sections, or not including adjacent outwash lenses as part of the aquifer.*

Thompson (2001, p. 33) specifically addresses the differences in the nomenclature of the Veblen aquifer in his report and in Hansen (1990):

> *Hansen (1990) proposed that the Veblen aquifer extended from northeast Marshall County across Roberts County and into Codington and Grant Counties. However, drilling and water-level data collected for this study indicate that it is not one continuous aquifer. Therefore, the Veblen aquifer mapped by Hansen in Codington and Grant Counties is not the same as the Veblen aquifer mapped by Koch in Marshall County. The Veblen aquifer mapped by Hansen does extend into southeast Roberts County, but it generally is very thin and may be discontinuous between test holes where it is found. For this reason, it is mapped as outwash deposits in this report.*

On page 56 of Thompson (2001), he notes that "the Wilmot outwash group may be what Hansen (1990) mapped as the Veblen aquifer. Test holes penetrating the Wilmot outwash had thicknesses ranging from 2 to 54 feet at depths from 2 to 78 feet below land surface." It is important to reiterate that the Thompson (2001) study does not evaluate conditions in eastern Grant County.

The subsurface investigations conducted for this evaluation have generally found sand and gravel deposits at two intervals in the pilot holes for the Big Stone II groundwater evaluation. The shallower sand and gravel is generally less than about 50 feet in depth. In many borings, deeper sand and gravel is found with thicknesses ranging from about 40 to 170 feet and depths ranging from about 80 to 250 feet below ground surface. Due to the complex glacio-fluvial depositional environment, some interconnection between the two sand units is likely in places. We hypothesize that the shallow sand is likely the equivalent of Thompson's Wilmont outwash and the deeper sand is the equivalent of Hansen's Veblen aquifer.

Jensen (2004) interprets that there is a shallow (less than 50 feet deep) alluvial aquifer approximately 0.5 miles wide that parallels the Whetstone River and that this alluvium consists of clay and silt with minor amounts of sand and gravel. Deeper water-transmitting units (generally greater than 100 feet below the ground surface) are also present in the vicinity of the proposed Big Stone II plant site (Jensen, 2004).

The Veblen aquifer of Hansen (1990) consists of unconsolidated coarse sand and gravel and likely underlies the portions of the proposed plant site. This water-transmitting unit has an approximate thickness of 150 feet near Milbank, South Dakota, southwest of the proposed project area, but thins to the north and east, with a thickness of 20 to 30 feet at the Grant County and Minnesota boundary (Hansen, 1990). It is likely that a thinner section of this unit underlies the remainder of the proposed project area. Hydraulic head in Hansen's Veblen aquifer indicate confined conditions. Municipal wells for Milbank and domestic and stock water wells are supplied by this aquifer. Recharge to the this unit is by direct infiltration and percolation of precipitation where the aquifer is at the land surface, and possibly by leakage through the till (Hansen, 1990). Water in the aquifer is of mixed chemistry, with calcium and sulfate predominating, but with significant concentrations of magnesium and bicarbonate. Total dissolved solids (TDS) concentrations average 1,300 milligrams per liter (mg/l).

Additional groundwater resources in the vicinity of the proposed Big Stone II plant site are the Milbank granite wash aquifer and the Dakota Sandstone (Hansen, 1990; Jensen, 2004). The granite wash aquifer is described by Hansen (1990) as consisting of uncemented coarse sand, derived from the weathering of the Milbank granite. The extent and water supply capability of this aquifer are relatively unknown; some stock watering and domestic wells use this unit. The thickness of this aquifer at the proposed plant site is approximately 40 feet. Depth to the granite wash aquifer varies widely. Water quality is dominated by sodium and sulfate.

The Cretaceous Dakota Sandstone is a regional aquifer that underlies much of South Dakota, western North Dakota, and Nebraska. It's easternmost extent is in the vicinity the proposed Big Stone II plant site. The Dakota Sandstone in this area generally consists of fine-grained sandstone and interbedded shale. Younger Cretaceous rocks that overlying the Dakota Sandstone are the Pierre Shale and Carlile Shale. The Dakota Sandstone is expected to have relatively poor water quality in this area, which makes it less attractive as a water supply.

2.4 Groundwater Use

All drinking water supplies in Grant County come from groundwater a portion of which is provided by a rural water system. According to Hansen (1990), the major withdrawals of groundwater come from gravel mining operations. The Big Sioux aquifer (in the western part of Grant County) is the major groundwater supply. The City of Milbank uses groundwater, presumably from the Granite Wash aquifer. In the vicinity of the proposed Big Stone II project, irrigation water is obtained from wells near the Whetstone River. Some of these wells are reported to have production rates of over 1,000 gpm with minimal drawdown in the pumping well.

Unconsolidated glacial aquifers vary in thickness and hydraulic conductivity (permeability). The greatest yields (wells with yields greater than 800 gallons per minute) are in the Big Sioux aquifer, the Antelope aquifer, and Prairie Coteau aquifer (Hansen, 1990). These higher yields have been attributed, in part, to the aquifers' good hydraulic connection with lakes and rivers, which provide rapid recharge.

3.0 Field Investigations

Field investigations as part of this hydrogeologic evaluation included: pilot borings to obtain core samples of unconsolidated deposits; installation of pumping wells and observation wells at two pilot-boring locations; and aquifer (pumping) tests in the two pumping wells. This section describes the methodologies and findings of the field investigations.

3.1 Site Access

Drilling activities were performed in accordance with a Work Plan developed by Barr Engineering Company in September 2006. The Western Area Power Administration (Western) and their consultant, R.W. Beck, provided comments and the Work Plan was revised. Western approved the field investigation procedures as described in the Work Plan with the following stipulations:

- No trees or shrubs shall be removed.
- All access shall be by rubber-tired vehicles.
- All access shall be accomplished when the ground is dry and firm (this was later modified to include frozen ground).
- Access shall be on existing roads or trails to the extent possible. Where there are no existing routes, access shall be along fence lines and field borders wherever possible. Access across grassland and pastureland shall be minimized.
- Access routes shall avoid all wetlands and streams. Drainages shall be avoided to the extent possible, except for existing access roads and where the drainage is under active cultivation. All incurred damage to drainages shall be repaired.
- The discovery of any Federally-protected species, including carcasses, requires that all work in the vicinity be stopped and the discovery shall be reported immediately to Western who will contact the Service.
- Drilling activities and site access shall be conducted so as to minimize any erosion. Drill cuttings from the boreholes shall be spread out in the vicinity of each well.

- Pumping must comply with the requirements of the temporary water appropriation permit issued by the State of South Dakota and the temporary water discharge permit.

- The drilling contractor shall develop and implement a hazardous materials safety protocol. All temporary storage of fuel, oil, hydraulic fluid, and other lubricants, fuels, oils and chemicals shall be positioned to prevent accidental spills from entering wetlands, streams or drainages.

- The contractor shall have hazardous materials spill clean-up and storage materials available at each activity location, and promptly clean up all spills. Personnel shall be trained in spill response and the use of the materials on hand.

- Prior to the completion of the hydrogeologic investigations, OTP shall reclaim disturbed ares to pre-drilling conditions in sonsultation with landowners. (Added at time of subsequent approval)

- Upon completion of the drilling activities, OTP shall provide Western with a report on the location of drilling sites and test results. (Added at time of subsequent approval)

All invasive activities included an archeological/cultural assessment by an archeologist. Access permission for all drilling locations were obtained from the land owners by Otter Tail Power Company. Technical specifications for drilling were developed and bids for drilling were obtained.

3.2 Pilot Holes

3.2.1 Methodology

Pilot holes were drilled at the locations shown on Figure 1. Pilot holes were drilled using Rotosonic methods, which provide a continuous core of unconsolidated materials and rock (where encountered). Drilling was performed by Boart Longyear of Little Falls, Minnesota. Drill core were logged on-site by a Barr Engineering Co. geologist. The drilling logs for each pilot hole are in Appendix A of this report. Each hole was advanced until it was determined by the on-site geologist that unconsolidated water-transmitting materials (namely sands and/or gravels) were unlikely to be encountered at deeper depths. Upon completion of each pilot hole, the borehole was filled with grout using a tremie pipe from the bottom of the hole to the ground surface. Cuttings and core were thin spread around the boring location.

3.2.2 Summary of Findings on Subsurface Conditions

Logs of pilot holes are in Appendix A. A total of 19 pilot holes were drilled, as of March 14, 2007. Table 1 summarizes the pilot holes' ground surface elevations, total depths, and depths at which relatively continuous water-transmitting zones (primarily sand, gravel and sandy silt) were encountered.

The shallowest pilot hole was PH3-9 (95 feet) and the deepest pilot hole was PH2-1 (260 feet). Pilot holes were advanced either into granitic or shaley bedrock or into a thick sequence of clay. Termination of each pilot hole was at the judgment of the on-site geologist.

Three of the 19 pilot holes (PH-2-2, PH2-4a, and PH2-4b) did not encounter any continuous sand and gravel layers greater than about 5 feet thick. Seven of the 19 pilot holes (PH1-4, PH1-5, PH-2-2, PH-2-7, PH3-1, PH3-3, AND PH3-9) encountered two zones of continuous sand and gravel. Samples from zones of relatively thick, continuous sand and/or gravel were retained for future grain-size analyses to design well screen in the event that a particular pilot hole will be over-drilled to install a production or test well.

Geologic cross sections were developed for the unconsolidated deposits in the study area using the pilot-hole logs and lithologic logs of wells obtained from the South Dakota Geological Survey website (http://www.sddenr.net/lithdb/). The location of the cross sections are shown on Figure 2. Cross-section A-A' and cross-section B-B' are on Figures 3 and 4, respectively.

3.3 Pumping and Observation Well Installation

3.3.1 Pumping Wells PW1-2 and PW1-4

Twelve-inch diameter wells were installed using mud-rotary drilling methods at the same locations as pilot holes PH1-2 and PH1-4. These pumping wells are designated as PW1-2 and PW1-4 and their locations are shown on Figure 1. Well construction logs for these wells are in Appendix B. The purpose of these wells was to perform aquifer (pumping) tests to evaluate the transmissivity and well yield. Samples were also collected and analyzed to assess water quality.. These wells were designed to be turned into production wells as part of a back-up water supply for the proposed Big Stone II project.

Well PW1-2 was installed on January 16 and 17, 2007. Well cuttings were contained within a portable steel mud recirculation container and were thin-spread around the well upon completion of well installation. Development was by jetting and pumping until well discharge appeared clear and free of sediment. The total depth of Well PW1-2 is 178 feet. The well consists of steel casing down to 143 feet below ground surface. A #40 slot wire-wound stainless steel screen, 35-feet in length, extends from 143 feet to 178 feet. The borehole annulus around the screen is filled with American Materials filter pack, sized for the #40-slot screen. Above the screen, the borehole annulus is filled with neat cement grout to ground surface.

Well PW1-4 was installed on January 29 and 30, 2007. Drilling procedures and equipment were identical to those used to install Well PW1-2. The well consists of steel casing down to 140 feet below ground surface. A #40 slot wire-wound stainless steel screen, 45-feet in length, extends from 140 feet to 185 feet. A tight-wind screen section was installed between 158 to 172 feet, where a clayey zone was encountered in drilling. The borehole annulus around the screen is filled with American Materials filter pack, sized for the #40-slot screen. Above the screen, the borehole annulus is filled with neat cement grout to ground surface. The total depth of PW1-4 is 185 feet below ground surface.

3.3.2 Observation Wells MW1-2 and MW1-4

Two-inch diameter observation wells were installed using mud-rotary drilling methods 400 feet from each of the two pumping wells for the purpose of collecting water-level data during aquifer tests. These wells are designated MW1-2 (located 400 feet south of PW1-2) and MW1-4 (located 400 feet south from PW1-4). Each well is constructed of 2-inch nominal diameter schedule 40, flush-threaded PVC riser/casing with 10-foot long, #10-slot PVC well screens. The borehole annuli around the screens is filled with a filter pack and the remainder of the borehole annuli to the ground surface is cement grout. Each observation well is fitted with a protective steel casing, equipped with a locking cap. Observation well MW1-2 is 180 feet deep and observation well MW1-4 is 185 feet deep. Construction logs for these two wells are in Appendix B.

3.4 Aquifer Testing

Separate aquifer tests (a.k.a. "pumping tests") were performed on wells PW1-2 and PW1-4 for the purpose of estimating aquifer parameters and well yield. Water levels in observations wells MW1-2 and MW1-4 were monitored, along with the water levels in the pumping wells, during the tests.

Both aquifer tests involve controlled pumping of one well close to the maximum sustainable rate and monitoring how groundwater levels in the pumping well and in the nearby observation well (located approximately 400 feet from the pumping well) change in response to the pumping. Conventional analytical methods are used to estimate two key aquifer parameters: storativity and transmissivity. These parameters are used in the groundwater flow model.

The maximum sustainable rate is estimated by a step-drawdown test prior to the controlled pumping test. The step-drawdown test systematically changes the pumping rate (typically from lower rates to higher rates) while monitoring water levels in the pumped well. Rates are increased until the water level in the pumping no longer reaches an equilibrium condition. The step-drawdown test is performed primarily because it is desirable to pump water at near maximum rates during the controlled pumping test in order to produce the highest degrees of drawdown.

Water levels in wells were monitored during the tests using a combination of *In Situ* Troll pressure transducer/data loggers and *Solonist* electronic measuring devices (for manual readings). The data loggers were set to read on a logarithmic scale during the early portion of the test (in order to collect water-level data during the period of the test when water levels change quickly) and arithmetically (at approximately 5-minute intervals) during the later portions of the test. The pressure transducers automatically adjust for changes in barometric pressure.

Groundwater samples were collected at approximately six-hour periods from the discharge end of the pump during the pumping phase of the aquifer test and analyzed for temperature, dissolved oxygen, pH and specific conductance. Daily, during the pumping phase of the aquifer test, groundwater samples were collected and submitted to a laboratory to be analyzed for analytes listed in Table 2. These analyses are for use in identifying water-treatment requirements for plant use. Results of the analyses are shown in Appendix B.

A totalizing flow meter was fitted to the discharge line of the pump to record pumping rates during the test period. The discharge line consisted of 100-feet of 6-inch nominal diameter, flexible hose connected to PVC pipe. At PW1-2, the total discharge length was 1,000 feet, with the effluent directed to a 5-foot diameter, 6-inch thick gravel pad to prevent erosion and drop the discharge velocities. From the gravel pad, the discharge flowed over a natural drainage in a farm field to a ditch along a County road. At PW1-4, the discharge was piped directly to the Big Stone plant cooling pond, located about 800 feet from the pumping well.

3.4.1 Aquifer Test of Well PW1-2

Well development of pumping well PW1-2 was completed on January 23, 2007. Well development is performed to remove residual drilling muds and assist in the development of gradational grain sizes in the filter pack, adjacent to the well screen, in order to minimize the infiltration of sand into the well (which can damage pumps) while maximizing the hydraulic connection between the well and the surrounding aquifer. Well development included a combination of jetting and "over-pumping".

A step-drawdown test was performed in well PW1-2 on January 26, 2007. A 1,000-gpm pump was temporarily installed in well PW1-2. Pumping rates for the step-drawdown test were selected based on: (1) conversations with the drillers from Boart Longyear who conducted the well development; (2) characteristics of the aquifer sand as measured in the core samples; and (3) past experience with similar wells. The well was pumped at stepped rates of 150 gpm, 300 gpm, 450 gpm, 550 gpm, 650 gpm, and 790 gpm for 30 to 45 minutes at each rate. Water levels at the end of the step-drawdown test reached 90 feet below casing, 14 feet lower than at the start of the test. The aquifer was then allowed to recover by turning the pump off for approximately 4.5 hours. Over that time, the aquifer recovered to a depth of 77 feet below casing, 0.65 feet lower than at the start of the test.

The pumping test commenced at 9 pm on January 26, 2007, after the well was allowed to recover. A pumping rate of 550 gpm was used. This rate was chosen based on the drawdown observed during the step-drawdown test. The objective was to use the highest sustainable pumping rate over the duration of the planned pumping period. A pumping rate that is too low may not "stress" the aquifer sufficiently, resulting in low measurable drawdowns in the observation well. Conversely, a pumping rate that is too high may draw the water level below the pump intake line, thereby ending the test prematurely and complicating the data analysis

The well was pumped continuously at 550 gpm for 82 hours, until the test was ended at 7 am on January 30, 2007. At that time the water level in the pumping well had dropped to a level of 83.95 feet below the top of the casing. The water level in the 2-inch diameter observation well MW1-2, located 400 feet to the south and screened at approximately at the same depth as the pumping well, was monitored continuously during the course of the test using a pressure transducer and automated data logger. Water levels in the observation well dropped from 83.25 feet below riser to 91.4 feet below riser (a total maximum draw down of 8 feet).

Observation well water-level data are generally preferred over pumping well water-level data in analyzing aquifer tests. This is because turbulence, cavitation, and small-scale pumping rate fluctuations in the pumping well result in short-term temporal fluctuations in water levels in pumping wells. Water levels in pumping wells are also subjected to "well losses" that are the result of less than 100% well efficiency (no well is 100% efficient). Observation well water-level data are generally not affected by these conditions.

Water-level data are collected to calculate drawdown and recovery. Drawdown is the change in water levels with respect to the pre-pumping, steady-state water level. Recovery is similar to drawdown but refers to the relative water level with respect to pre-pumping conditions after the pump is turned off. Drawdown and recovery are used in the analytic solutions to estimate aquifer parameters. Drawdown data for observation well MW1-2 are shown on Figure 5.

The observation-well data from MW1-2 were analyzed using the aquifer analysis program AQTESOLV (Hydrosolve, Inc., 2000). Attempts were made to match the drawdown data using the Theis solution for confined aquifers but only the early-time data could be satisfactorily matched. A good match, using the Theis solution (Theis, 1935), was obtained by including an image well and the method of superposition to simulate the effects of a nearby impermeable barrier, such as a thick clay sequence of low transmissivity. Logs for existing wells located about a mile to the north and northeast of site 1-2 were found to have encountered clay from land surface to bedrock, supporting the supposition that a relatively impermeable boundary is close to Well PW1-2. Image wells with pumping rates equal to Well PW1-2 were oriented from west-northwest to east-southeast at distances varying from 1,500 to 5,000 feet from the pumping well. A barrier located about 3,000 feet north of the site was found to best explain the high late-time drawdown at monitoring well MW1-2. The plot of the curve match, using the Theis equation and an image well, are shown on Figure 6.

The resulting solution yielded an estimated transmissivity of 1,200 m^2/day (96,600 gpd/ft) and a storativity value of 0.00047, which is indicative of a confined aquifer. The saturated thickness at Well PW1-2 is estimated to be 81 feet, based on the drilling information. Therefore, the estimated average hydraulic conductivity for this portion of the aquifer unit is 157 feet/day. This value of hydraulic conductivity is characteristic of gravelly sand – which is the type of material encountered in the boring for Well PW1-2. Therefore, in the absence of a nearby low-permeability barrier, the sustained yield from this well would be much higher – the low-permeability barrier reduces the overall ability of this well to produce at high rates.

The shape of the drawdown curve for monitoring well MW1-2 did not show any indication of leakage effects or the effects of a hydraulic barrier, such as a stream, lake or river. The results from this pumping test indicate that in this area, the aquifer unit is not in good hydraulic connection with the nearby Whetstone River. The thick layer of clay that overlies the aquifer unit likely acts as an aquiclude or very low permeability aquitard.

3.4.2 Aquifer Test of Well PW1-4

Well development of pumping well PW1-4 was completed on February 26, 2007. Well development is performed to remove residual drilling muds and assist in the development of gradational grain sizes in the filter pack, adjacent to the well screen, in order to minimize the infiltration of sand into the well (which can damage pumps) while maximizing the hydraulic connection between the well and the surrounding aquifer. Well development included a combination of jetting and "over-pumping".

A step-drawdown test was performed in well PW1-4 on February 27, 2007. A 1,000-gpm pump was temporarily installed in well PW1-4. Pumping rates for the step-drawdown test were selected based on: (1) conversations with the drillers from Boart Longyear who conducted the well development; (2) characteristics of the aquifer sand as measured in the core samples; and (3) past experience with similar wells. The well was pumped at stepped rates of 80 gpm, 110 gpm, 140 gpm, 200 gpm, 250 gpm, 300 gpm, 350 gpm, and 550 gpm for 15 to 45 minutes at each rate. Water levels at the end of the step-drawdown test reached 140 feet below casing, 18.7 feet lower than at the start of the test. The aquifer was then allowed to recover by turning the pump off for approximately 3.3 hours. Over that time, the aquifer recovered to a depth of 122.7 feet below casing, 1.6 feet lower than at the start of the test.

The pumping test commenced at 4:30 pm on February 27, 2007, after the well was allowed to recover. A pumping rate of 355 gpm was used. This rate was chosen based on the drawdown observed during the step-drawdown test. The objective was to use the highest sustainable pumping rate over the duration of the planned pumping period. A pumping rate that is too low may not "stress" the aquifer sufficiently, resulting in low measurable drawdowns in the observation well. Conversely, a pumping rate that is too high may draw the water level below the pump intake line, thereby ending the test prematurely and complicating the data analysis

The well was pumped continuously at 355 gpm for 5.5 hours. The pumping rate was reduced to 310 gpm at 10:02 pm on February 27, 2007 as drawdown in the well began to increase. The well was pumped at 310 gpm for 13 hours and the rate was dropped again to 210 gpm, where it remained for the remainder of the test until the test was ended at 4:30 pm on March 2, 2007. At that time the water level in the pumping well had dropped to a level of 14.67 feet below pre-pumping static water levels. The water level in the 2-inch diameter observation well MW1-4, located 400 feet to the south and screened at approximately at the same depth as the pumping well, was monitored continuously during the course of the test using a pressure transducer and automated data logger. Water levels in the observation well dropped from 115.7 feet below riser to 121.0 feet below riser (a total maximum draw down of 5.3 feet).

The data logger used to record the drawdown data in the monitoring well was found to have water in it and was sent to the manufacturer (In Situ Inc.) for data retrieval. Fortunately, these data were backed-up by roughly hourly manual measurements. Manual drawdown and data for observation well MW1-4 are shown on Figure 7.

The observation-well data from MW1-4 were analyzed using the aquifer analysis program AQTESOLV (Hydrosolve, Inc., 2000). Variable pumping rates were accounted for in the analysis, which used the Theis solution (Theis, 1935). A good curve match to the data was achieved using the Theis solution, which indicates negligible leakage was induced from overlying deposits, even though the Big Stone cooling pond was located less than 800 feet from the pumping well. The plot of the curve match, using the Theis equation and an image well, are shown on Figure 8.

The resulting solution yielded an estimated transmissivity of 1,2e m^2/day (9,874 gpd/ft) and a storativity value of 0.0147, which is indicative of a confined aquifer. The saturated thickness at Well PW1-2 is estimated to be 64 feet, based on the drilling information. Therefore, the estimated average hydraulic conductivity for this portion of the aquifer unit is 21 feet/day. This value of hydraulic conductivity is characteristic of fine to medium sand – which is the type of material encountered in the boring for Well PW1-2. The transmissivity of the aquifer materials at PW1-4 is about 10-times less than the transmissivity at PW1-2. This appears to be due to the finer-grained deposits at PW1-4 and the smaller saturated thickness.

4.0 Groundwater Flow Modeling

A numerical groundwater flow model was developed for the aquifer system in northeastern Grant County for the purpose of predicting the effects of pumping a groundwater supply for the proposed Big Stone II plant for a period of one year. The primary focus of the model is to predict drawdown, which can be used to evaluate the effects of pumping on existing groundwater users (i.e. wells) and surface waters.

4.1 Code Selection

The U.S. Geological Survey's code MODFLOW was used for the groundwater flow modeling (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). MODFLOW was selected for the following reasons:

- MODFLOW is widely used, extensively benchmarked, and widely accepted by scientific and regulatory entities;
- MODFLOW is capable of simulating non-uniform, unsteady flow in multi-aquifer systems and can simulate the interactions between surface water and groundwater in several ways; and
- MODFLOW is amenable to both regional groundwater flow simulations and detailed simulation of local areas through the method of telescoping mesh refinement (TMR).

The graphical user interface GMS Version 6.0 was used to prepare input files and evaluate results for groundwater flow.

4.2 Conceptual Hydrogeologic Model

The conceptual hydrogeologic model describes the hydrostratigraphic units that are included in the numerical model, the primary mechanisms for water to get into and out of the units (i.e. sources and sinks), and the general direction of flow of groundwater as it moves from sources to sinks. The conceptual hydrogeologic model also defines the problem that the numerical model is being designed to address. Different conceptual models may be required for different types of problems in the same area and the same groundwater flow system.

The conceptual model is shown on a schematic cross section on Figure 9. The aquifer system is defined in this evaluation as water-transmitting sands and gravels of glacial origin within a discontinuous matrix of low-permeability glacial tills. Some of these sand and gravel units have been named by others as aquifers or outwash. In general, there is shallow, discontinuous sand and gravel that is made up of outwash and/or alluvium and deeper, discontinuous sand and gravel that generally overlies bedrock (or is separated from the bedrock by till). Continuity of flow is dependent upon the interconnectedness of the sand and gravel units. There likely is flow in the till units, as well, but the quantity and rate of groundwater flow in the till units is much smaller than in the sand and gravel.

Recharge to the sand and gravel units is primarily by infiltrating precipitation where these units crop out or where there is a relatively thin cover of till. Much lesser amounts of recharge originate as vertical leakage of infiltrated precipitation through thicker till units.

Groundwater generally flows from west to east, discharging into the Minnesota River and Big Stone Lake. The Minnesota River is the major locale of regional discharge for the entire groundwater system. Wells pumping in the sand and gravel units are secondary discharge locales. Portions of the Whetstone River, where the stream is gaining, are secondary discharge locales.

This conceptual hydrogeologic model is a regional generalization that was developed in consideration of the problem at hand: namely, to predict (to the extent that data and information will allow) the hydraulic response of the aquifer system to pumping by a series of wells that serve as a back up water supply for the proposed Big Stone II project.

4.3 Model Domain and Discretization

The domain of the groundwater model covers an area approximately 40 miles across from east to west and about 30 miles across from north to south, as shown on Figure 10. The model is bordered on the east by Big Stone Lake and the Minnesota River; and on the west by the Prairie Coteau. The model domain extends approximately 10 miles north and 20 miles south of the Big Stone Plant site. The model domain was selected to accommodate the region's natural hydrologic boundaries to the extent feasible.

The model's discretization scheme was chosen in order to maximize the amount of numerical detail the model could simulate while also minimizing the time needed to run and calibrate the model. To meet both of these criteria, a varying grid discretization was used, with cells 250 m close to pumping well sites, and cells up to 2,500 m at the outermost boundaries of the model. This level of discretization was deemed satisfactory because particle tracking is not anticipated (avoiding weak sink problems) and the pumping rates that the model is intended to simulate are relatively high.

The model contains one layer to represent the deeper sand and gravel units (the Veblen aquifer of Hansen, 1990). The bottom of the model is delineated by extensive clay or bedrock. The top of the model is clayey till, where present.

4.4 Boundary Conditions

Big Stone Lake and similar lakes on the Minnesota River were assumed to act as constant head boundaries, which may act as either sources or sinks, depending on nearby groundwater levels. Big Stone Lake and the Minnesota River represent the primary mechanism for removing water from the aquifer system, through natural discharge of groundwater flow from west to east. The Whetstone River and Yellow Bank Rivers were simulated with the River Package, which accounts for the interaction between aquifer and surface-water feature, based on the relative water elevation and a conductance value to simulate the bottom sediments of the surface water.

Recharge from infiltrating rainfall is the primary mechanism for adding water to the aquifer system. There are no site specific data for recharge. Recharge was therefore conservatively estimated at 1 inch/year. It is likely that recharge rates are greater than 1 inch/year – in Minnesota, recharge values of 4 to 8 inches/year are commonly used for regional groundwater modeling. Conservatively estimating recharge is important because recharge limits the extent of the cone of depression that develops when a well is pumping.

4.5 Model Parameters

4.5.1 Aquifer Thickness and Elevation

To determine the thickness and depth of the modeled aquifer system, relevant U.S. Geological Survey reports were reviewed. It was concluded that the Veblen aquifer of Hansen (1990) is not as well-defined as suggested by Hansen (1990) and that a detailed review of the region's well logs would be useful. Approximately 1,500 well logs in Roberts, Grant, and Deuel Counties in South Dakota (from the South Dakota Geological Survey Well Database) and Lac qui Parle County in Minnesota (from the Minnesota County Well Index) were reviewed. Aquifer thickness and depth were recorded from each well log where available. Based on these known data, aquifer thicknesses and depths were interpolated throughout the entire model domain. The elevation of the top of the aquifer system was found to range from 275 to 602 meters elevation; the aquifer thickness ranges from 0 m thick (at places where the bedrock surfaces or a sand/gravel unit does not exist) to 272 m thick (along the margin of the Prairie Coteau, where there exist thick alluvial deposits). Information from the pilot holes drilled and logged in this evaluation where included in the interpolation.

The data were geostatistically interpolated over the model domain to define the top and bottom elevations of the aquifer unit in the model. The saturated thickness within the model is defined automatically as the difference between these two surfaces. Maps of the interpolated top elevations and the saturated thickness are shown on Figures 11 and 12, respectively

4.5.2 Hydraulic conductivity

Hydraulic conductivity was estimated from drawdown data at Monitoring Well MW1-2 measured during the pumping test. As previously discussed the data were fit to a Theis type-drawdown curve, which illustrates idealized drawdown in a perfectly confined aquifer. Assuming an aquifer thickness of 81 feet, a hydraulic conductivity of 157 ft/day (or 48 m/day) was calculated. This value was applied over the entire model domain. Though this is an oversimplification of actual conditions, the high variation in aquifer thickness makes it undesirable to use a high variation in hydraulic conductivity.

4.6 Model Calibration

The groundwater flow model was first run at a steady-state condition, in order to calculate the unstressed groundwater levels without the proposed wells pumping. The resulting simulated groundwater levels were compared to water levels reported for wells in the area as a check to ensure that water levels were approximately the same. An exhaustive calibration to existing head conditions was not performed for this study - what is of interest is the relative change (lowering) of groundwater levels in response to pumping of all of the wells.

The steady-state solution was used as the starting heads for a transient solution of one year duration with the wells pumping at constant rates (described in the next section).

4.7 Model Simulation of Well Fields

The groundwater flow model was used to predict drawdown (i.e. changes in the hydraulic head of the aquifer system) during one year of pumping of proposed wells. The drawdown is relative to the steady-state condition, previously described.

The following assumptions were used in assigning well locations and pumping rates in the simulation:

- The total withdrawal rate for all wells combined equaled 6,200 gpm. Pumping is distributed among the proposed wells uniformly, except for locations PW1-2 and PW1-4, where pumping test information provided data to further limit maximum sustainable rates. In addition, pumping rates were redistributed during preliminary simulation runs if at a particular well location drawdown was deemed to be to high to be sustainable – in these cases, pumping rates of these wells were reduced and pumping rates of other wells were increased.

- Pumping takes place for 365 days, beginning from a non-pumping condition.
- Wells are located only where pilot holes have been drilled and deeper unconsolidated, water-transmitting deposits were encountered or where future pilot borings are planned. Only approximately half of the future pilot borings are assumed to be at locations where water-transmitting sands and gravels are of sufficient thickness to warrant a well.

Transient simulations used a single stress period of 365 days and 100 time steps, with time-step increments increasing in length over the stress period (the largest time step is the last – 24 days). Internal convergence and numerical water-balance requirements were met within each time step. The model simulated the resulting drawdown at the end of each time step; however only selected time-step results are reported herein for purposes of brevity.

4.8 Results of Model Simulations

Two transient simulations of one-year in length were performed, each representing a slightly different set of pumping wells. Two different configurations were used because the results of the Phase 4 pilot borings are not yet available (these will be completed in April 2006). For the simulations, it was assumed that some of these Phase 4 pilot boring locations would be found to not be suitable for production wells.

The first configuration assumes seven wells will be capable of producing the requisite 6,200 gpm. The second configuration assumes that 14 wells will be needed to produce 6,200 gpm. These two configurations represent the minimum and maximum number of wells – the actual number of wells will likely be some number between 7 and 14. Additional field investigations should be able to verify this range and identify the actual number of wells.

4.8.1 Well Configuration 1

Well configuration 1 consists of seven well locations and pumping at the following rates:

Well Location	Pumping Rate (gpm)
1-2	300
1-4	150
2-1	1,353
2-6	1,353
3-1	1,353
3-5	1,353
3-9	1,353
Total	6,200

The seven well locations represent places where wells have been installed and tested (i.e. PW1-2 and PW1-4) or where geologic conditions encountered in the pilot holes showed favorable conditions. Locations in this scenario do not include planned pilot-hole locations that will be drilled in April 2006. While it is yet to be verified that locations 2-1, 2-6, 3-1, 3-9, and 3-5 are capable of yielding 1,313 gpm, the coarse-grained texture of the sands and gravel and their saturated thickness suggest that these locations would have high transmissivity. Within this area, an existing irrigation well has been shown to yield over 1,000 gpm with about 1-4 feet of total drawdown in the well – the performance of this well suggests that yields will be relatively high.

The model's prediction of drawdown (in feet) at 3 months, 6, months, and 1 year are shown on Figures 13 through 15. The maximum drawdown is approximately 40 feet after one year of pumping (in the vicinity of PH2-6 and PH3-9). Within the well field area, the typical maximum drawdown is predicted to be 20 to 30 feet. The 5-foot drawdown extent is predicted to be approximately 3 miles from the center of the well field.

4.8.2 Well Configuration 2

Well configuration 2 consists of seven well locations and pumping at the following rates:

Well Location	Pumping Rate (gpm)
1-2	300
1-4	150
2-1	300
2-6	495
3-1	495

3-5	495
3-7	495
3-9	495
4-1	495
4-3	495
4-5	495
4-7	495
4-9	495
4-11	495
Total	6,200

The 14 well locations represent places where wells have been installed and tested (i.e. PW1-2 and PW1-4), where geologic conditions encountered in the pilot holes showed favorable conditions (PH-2-6, PH-3-1, PH-3-5, PH-3-7, and PH3-9) and six locations that will be drilled in April 2007. This configuration represents a maximum-expected number of well and assumes no one well will produce sustainable yields greater than about 500 gpm.

The model's prediction of drawdown (in feet) at 3 months, 6, months, and 1 year are shown on Figures 16 through 18. The overall drawdown is very similar to Configuration 1 (this is likely because the total withdrawal rates are the same). The maximum drawdown is less (about 35 feet in the immediate vicinity of PH4-1). Most of the well field area is predicted to have drawdowns of between 15 and 25 feet. The 5-foot drawdown extent is predicted to be approximately 4 miles from the center of the well field.

5.0 Summary and Conclusions

5.1 Summary of Hydrogeologic Evaluation

A hydrogeologic evaluation of water-transmitting glacial drift deposits in northeastern Grant County, South Dakota was performed in order to characterizing their use as a back-up water supply for a proposed 630-megawatt net capability coal-fired electric power generating station named Big Stone II. The proposed Big Stone II plant would be located adjacent to the existing Big Stone plant in Grant County, South Dakota, about eight miles northeast of Milbank and two miles northwest of Big Stone City, South Dakota. As part of this hydrogeologic evaluation, a groundwater supply capable of supplying a maximum of 6,200 gallons per minute (gpm) (10,000 acre-feet per year) for a period of one year was assumed to be necessary to meet the cooling demands of the plant under extreme conditions.

This hydrogeologic evaluation consists of the following elements:

1. Installation of pilot holes (borings) to obtain continuous cores of unconsolidated deposits at potential sites for future water-supply wells;

2. Installation of test wells and observation wells at selected locations for the purpose of performing aquifer ("pumping") tests;

3. Aquifer testing at selected locations and water quality analysis of aquifer samples; and

4. Groundwater flow modeling to predict the hydrogeologic effects of pumping of future water-supply wells.

The field investigation was performed in three phases, with a fourth phase to be completed in April 2007. A phased approach was used to make adjustments to the investigation approach as data were collected and evaluated. The field activities were performed in accordance with a work plan for that was approved by the Western Area Power Administration (Western) and their consultant, R.W. Beck, in October 2006. Technical specifications for drilling were developed and bids for drilling were obtained. Boart Longyear Company of Little Falls, Minnesota was hired to drill pilot boreholes, and install the test and monitoring wells.

Two 12-inch diameter pumping wells and two 2-inch diameter monitoring wells were installed to perform aquifer tests at two locations. The tests provided data to estimate transmissivity, hydraulic conductivity, and storativity.

The pilot-hole data, the well installations, and the aquifer tests results were incorporated with existing data from well logs and regional groundwater studies to develop a numerical groundwater flow model using the code MODFLOW. Aquifer geometry (elevation and thickness) were geostatistically interpolated from over 1,000 lithologic logs, including logs of the pilot holes drilled in this study. The model was approximately calibrated to steady-state conditions and then used to predict the effects of pumping of the back-up groundwater supply for the proposed Big Stone II project.

5.2 Conclusions

The results of this hydrogeologic investigation indicate the following:

1. There are generally two sand and gravel units in the glacial deposits that overlie bedrock in the vicinity of the proposed Big Stone II project. They are typically separated by about 10 to 50 feet of glacial till. In some locations, they may be connected.

2. The sand and gravel units are not continuous throughout the study area and their thickness is variable. This lack of continuity reflects the complex glacio-fluvial environment in which they were deposited. More recent alluvium is likely also part of the shallow sand and gravel. However, the general occurrence of sand and gravel does appear to agree reasonably well with other regional studies for the area.

3. Aquifer testing at two sites indicates that the deeper sand and gravel unit is confined and does not display characteristics indicative of leakage through overlying till deposits. These results suggest that the overlying till is an effective confining layer and that there is not a good hydraulic connection between the deeper sand and gravel and surface waters (lakes, rivers, ponds, etc.).

4. Aquifer hydraulic conductivity values (i.e. permeability) of the sand and gravel evaluated in the study area is in the range of 21 feet/day (PW1-2 – a fine to medium sand) to 157 feet/day (PW1-2, a sand and gravel). These value corresponds to the types of material encountered in the pilot holes and the type of material described in many of the logs for wells in the area. Storativity values agree with well logs for the area the unit is confined.

5. Even though the transmissivity of the aquifer can be relatively high (e.g., 96,600 gpd/ft at Well PW1-2), sustained pumping (i.e. pumping for a period of 1 year) from Well PW1-2 is likely limited to the 150-250 gpm range, although yields of 550-650 gpm would be realized for periods of pumping of 1 to 2 weeks. The sand and gravel deposits are likely in discontinuous lenses and stringer, bounded by clay till that can function as an impermeable boundary that limits sustained yields.

6. The groundwater flow model that was developed for this evaluation includes the variable thickness and continuity of the sand and gravel to the level allowable by both the newly collected data and pre-existing data. This model was used to simulate two well configurations with withdrawal rates equal to 6,200 gpm for a period of one year – one configuration with 7 wells and one configuration with 14 wells.

7. The maximum drawdown is predicted to be between 35 feet (14 well configuration) and 40 feet (7 well configuration) below existing static water level at the end of one year of pumping. Within the well-field area, the drawdown is predicted to be approximately 15 to 35 feet. The 5-foot drawdown is predicted to extend 3 miles (7 well configuration) to 4 miles (14 well configurations) from the approximate center of the well field.

8. The aquifer system is confined and recovery of groundwater levels will be approximately the inverse of pumping – i.e. water-levels will rebound quickly and then slowly approach pre-pumping conditions after approximately a year.

In summary, the field investigations and the groundwater-flow modeling indicate that the aquifer system should be capable of yielding 6,200 gpm for at least 1 year of pumping without significant regional drawdown. The connect of the aquifer to the surface (and therefore, to streams, such as the Whetstone River) was found to be negligible. The total number of wells required to produce 6,200 gpm will likely be in the range of 7 to 14.

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Tables

Table 1

Summary of Continuous Sand and Gravel Layers in Pilot Borings

Pilot Boring	Approximate Ground Surface Elevation (ft, MSL)	Total Depth (ft)	Depth (ft) to top of first continuous sand/gravel	Depth (ft) to bottom of first continuous sand/gravel	Depth (ft) to top of second continuous sand/gravel	Depth (ft) to bottom of second continuous sand/gravel
PH1-1	1122	215	152	181	NA	NA
PH1-2*	1079	196	81	196	NA	NA
PH1-3	1089	198	96	104	NA	NA
PH1-4*	1102	200	67	75	121	185
PH1-5	1112	208	85	94	145	184
PH2-1	1102	260	85	95	104	254
PH2-2	1067	185	NA	NA	NA	NA
PH2-4a	1085	175	NA	NA	NA	NA
PH2-4b	1053	140	NA	NA	NA	NA
PH-2-5	1064	130	35	99	NA	NA
PH2-6	1106	155	5	151	NA	NA
PH2-7	1129	155	20	43	78	84
PH3-1	1064	115	7	37	61	98
PH3-2	1047	173	11	20	35	40
PH3-3	1050	182	7	20	NA	NA
PH3-4	1122	210	15	57	NA	NA
PH3-5	1102	225	15	202	NA	NA
PH3-8	1073	153	0	40	NA	NA
PH3-9	1079	95	4	19	53	82

PH1-2 and PH1-4 were completed as pumping wells PW1-2 and PW1-4, respectively
NA: not applicable – zone not present

Table 2

Analytical Parameters – Groundwater

Alkalinity
Aluminum (dissolved)
Aluminum (pH 6.5-9.0)
Arsenic
Arsenic (III) (dissolved)
Barium
Beryllium (dissolved)
BOD_5
Boron
Boron (dissolved)
Cadmium
Cadmium (dissolved)
Calcium
Chloride
Chromium
Chromium (Hex) (dissolved)
Chromium (III) (dissolved)
Cobalt
Cobalt (dissolved)
COD
Color
Copper
Copper (dissolved)
Cyanide
DOC (Dissolved Organic Carbon)
Fecal Coliforms
Fine Sediments
Fluoride
Hardness, Non-Carbonate
Hardness, Total
Iron
Iron (dissolved)
Lead
Lead (dissolved)
Lithium
Lithium (dissolved)
Magnesium
Manganese
Manganese (dissolved)
Mercury
Mercury (II) (dissolved)
Molybdenum
Molybdenum (dissolved)
N, (dissolved)
NH_4 (dissolved)
Nickel (dissolved)
NO_3, (dissolved)
Ortho-Phosphate
P, (dissolved)
pH
Phosphate
Phosphorus, Total
PO4, (dissolved)
Potassium
Potassium (dissolved)
Selenium
Selenium (dissolved)
Silica, Colloidal
Silica, Reactive
Silica, Total
Silicon
Silt Density Index
Silver
Silver (dissolved)
Sodium
Sodium (dissolved)
Strep
Strontium
Strontium (dissolved)
Sulfate
TDS - Evaporation
TDS - Sum of ions
TKN, (dissolved)
TKN, Total
TOC
TSS
Turbidity
Vanadium
Vanadium (dissolved)
Zinc
Zinc (dissolved)

Figures

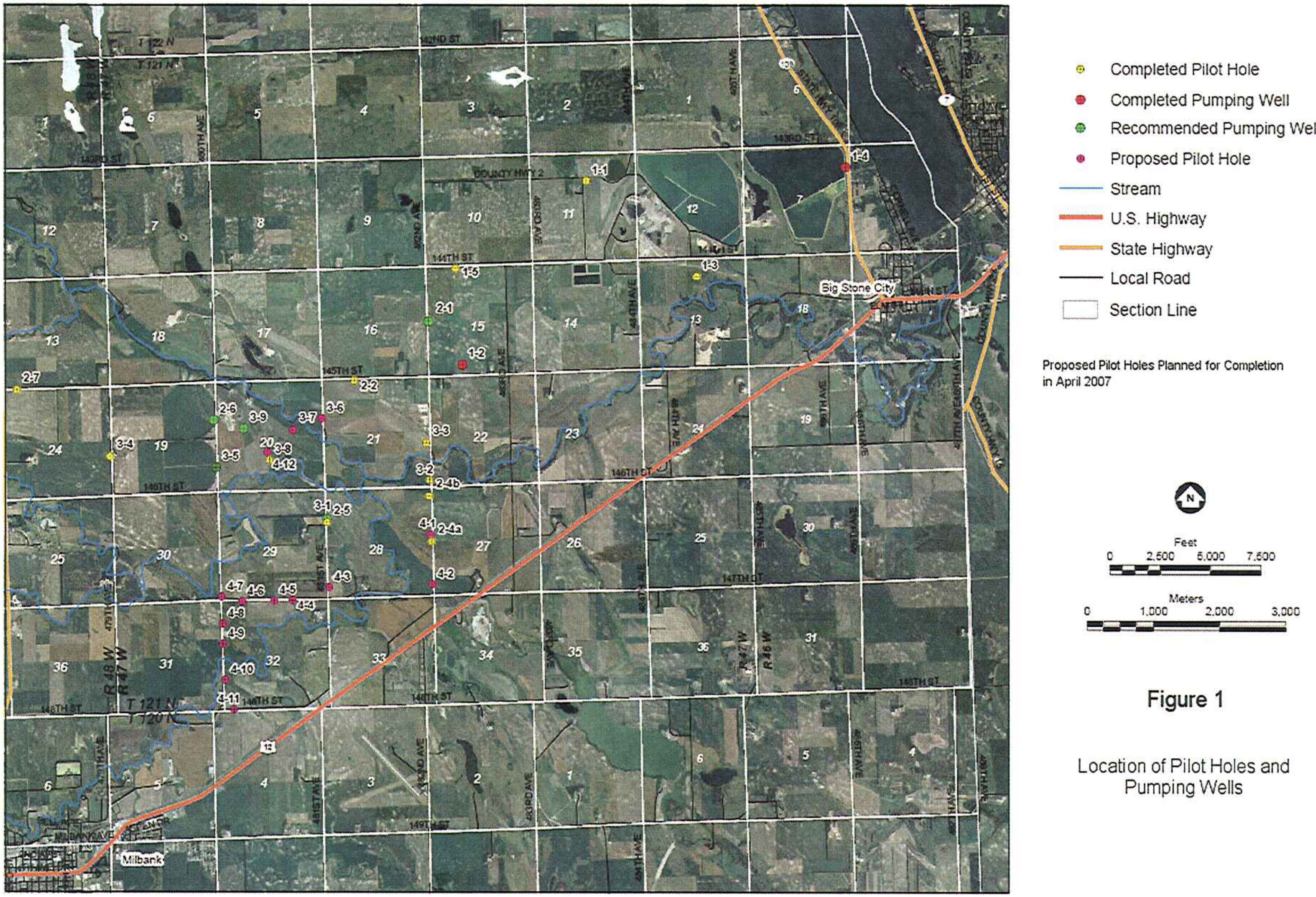

Figure 1

Location of Pilot Holes and Pumping Wells

Figure 2

Locations of Cross-Sections
A-A' and B-B'

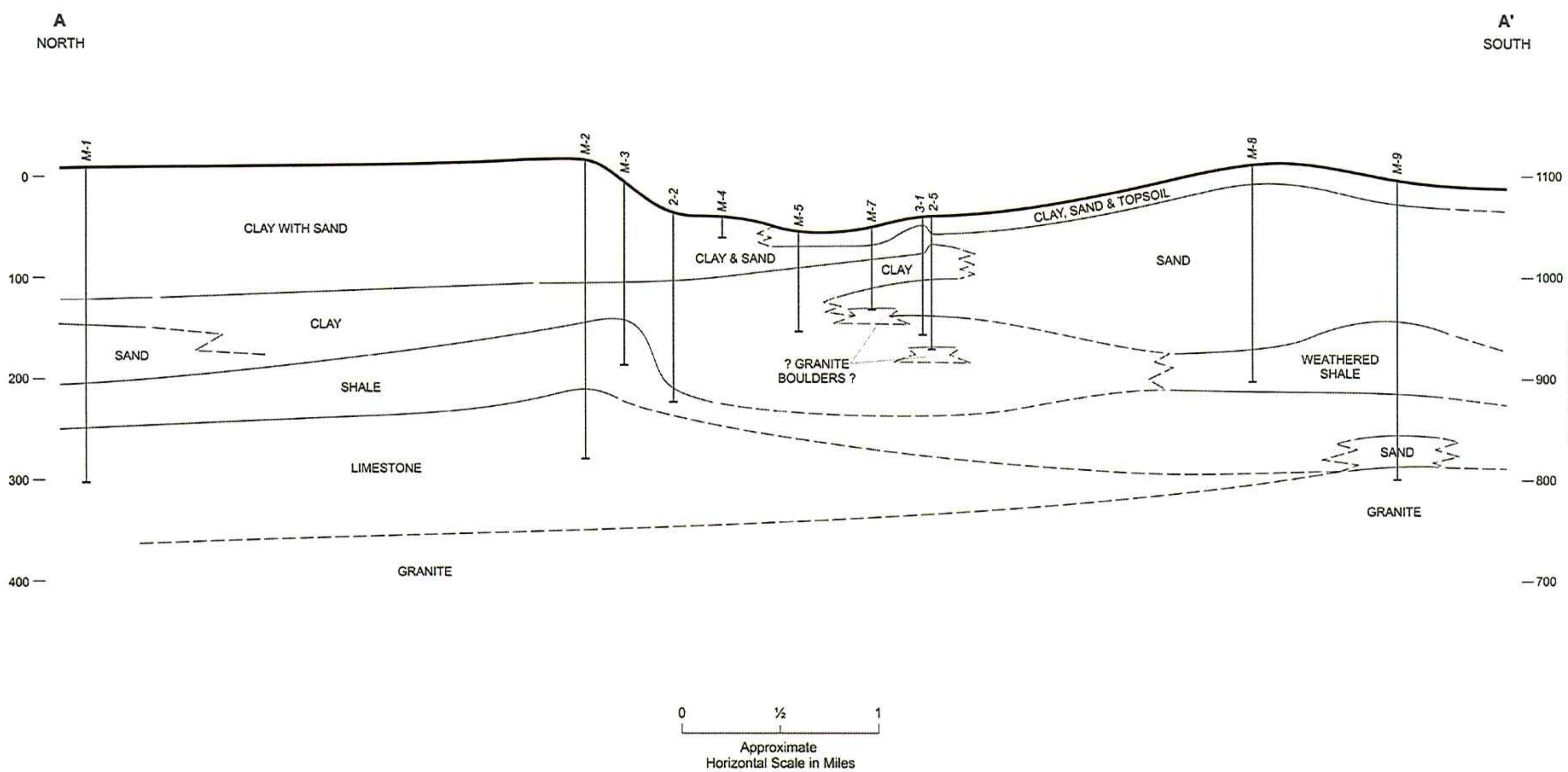

Figure 3

CROSS SECTION A-A'

P:\Mpls\41\SD\25\41125003\Work Files\Figures_Graphics\Cross Section AA CDR RLG 03-23-07

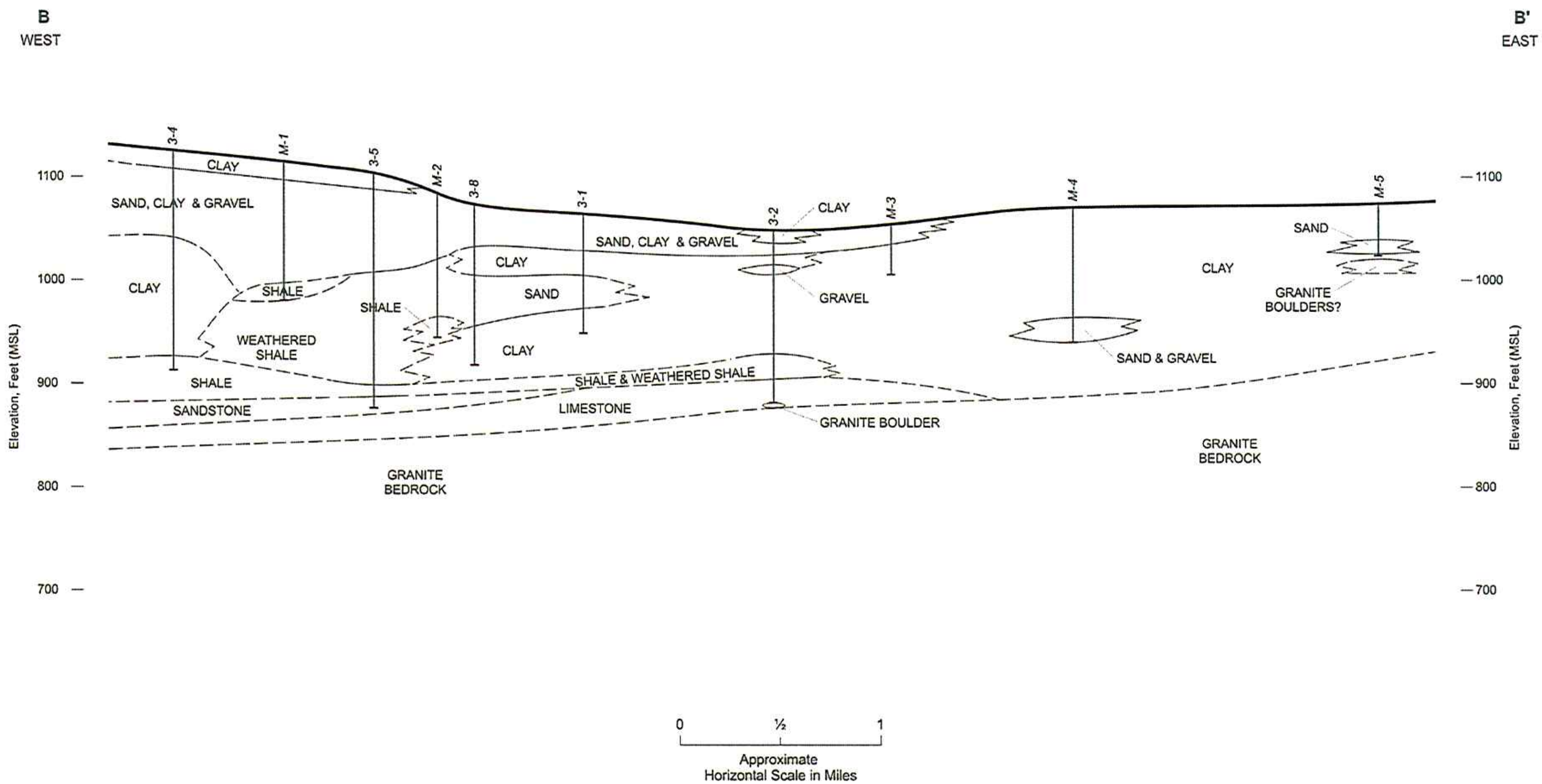

Figure 4

CROSS SECTION B-B"

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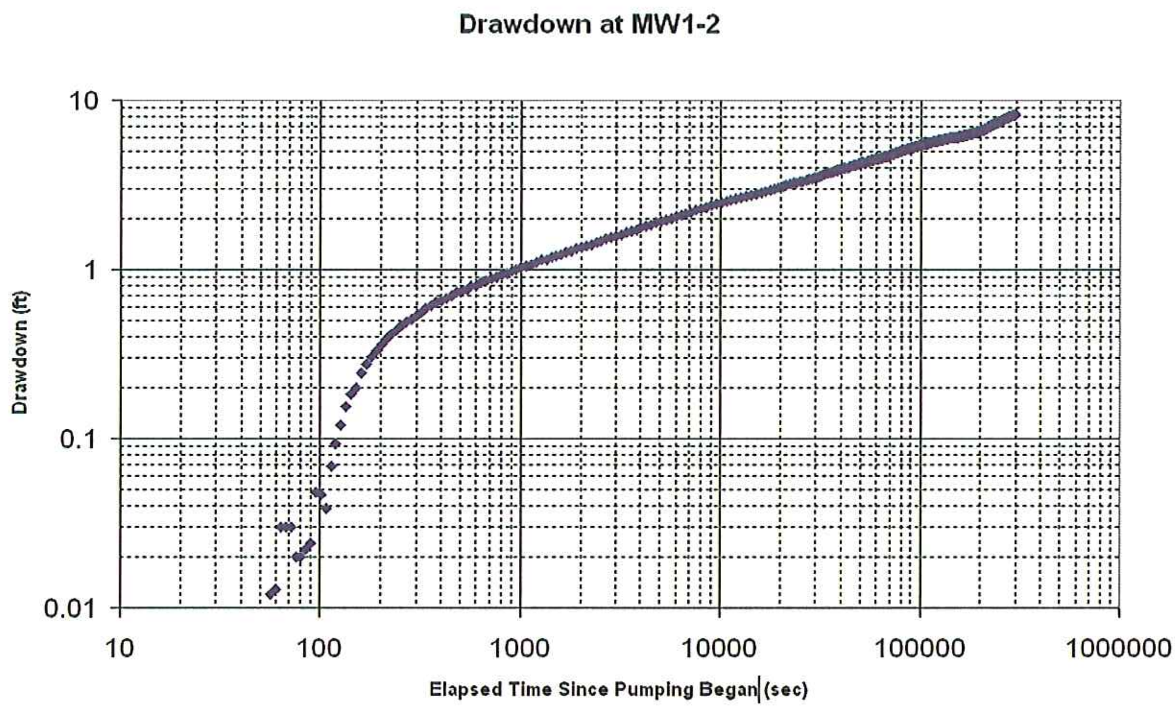

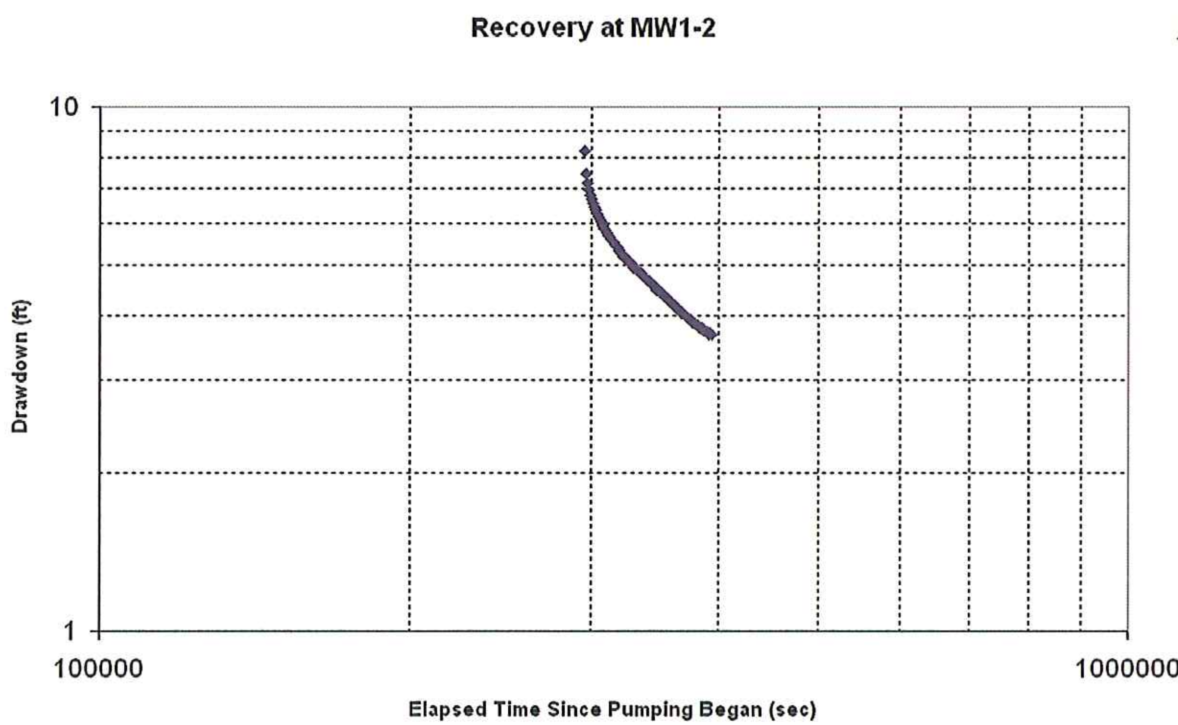

Figure 5

Drawdown and Recovery Plots for Observation Well MW1-2

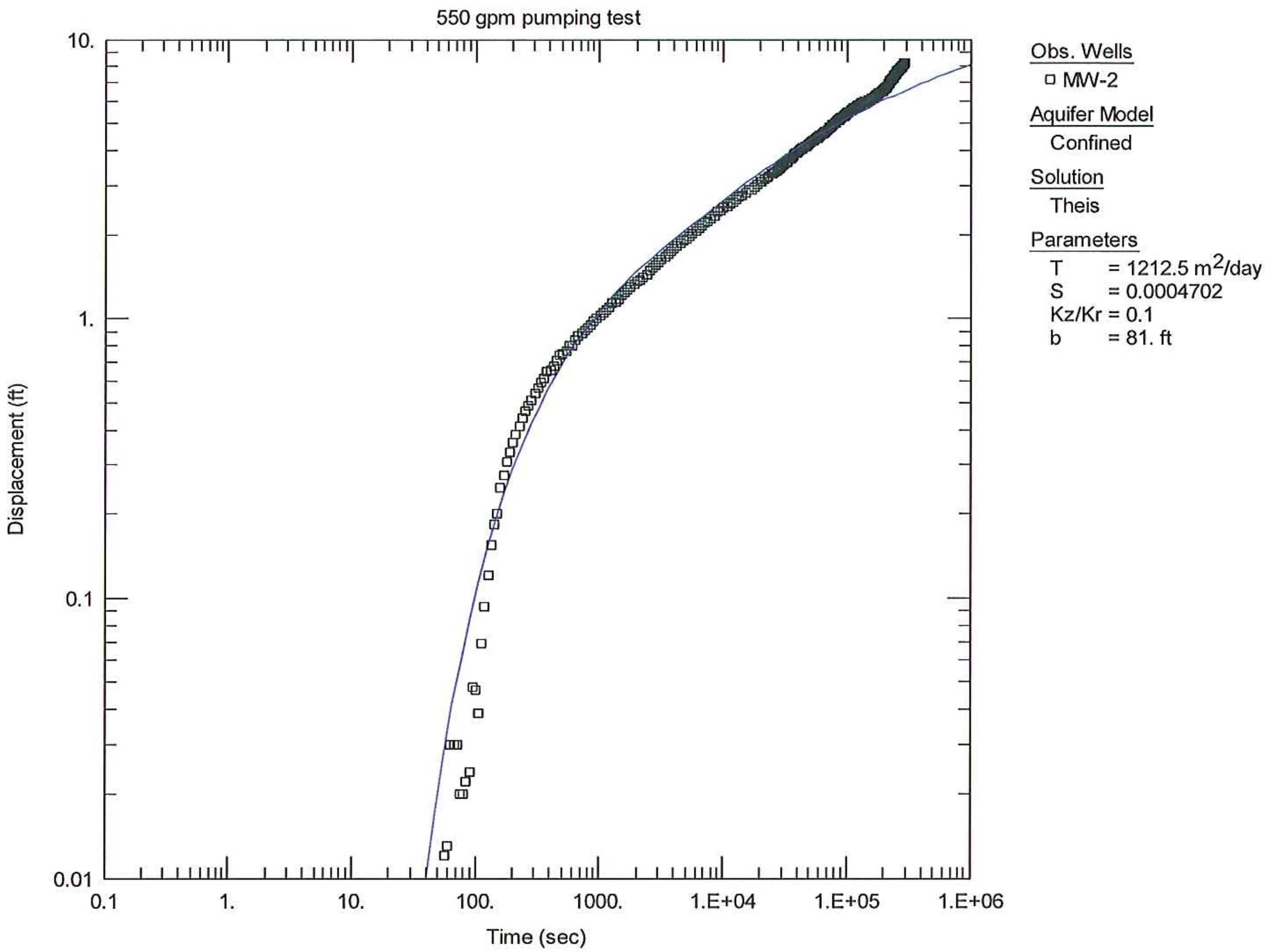

Figure 6

Curve-Match Plot of Drawdown Data from Observation Well MW1-2, With Resulting Aquifer Parameter Estimates

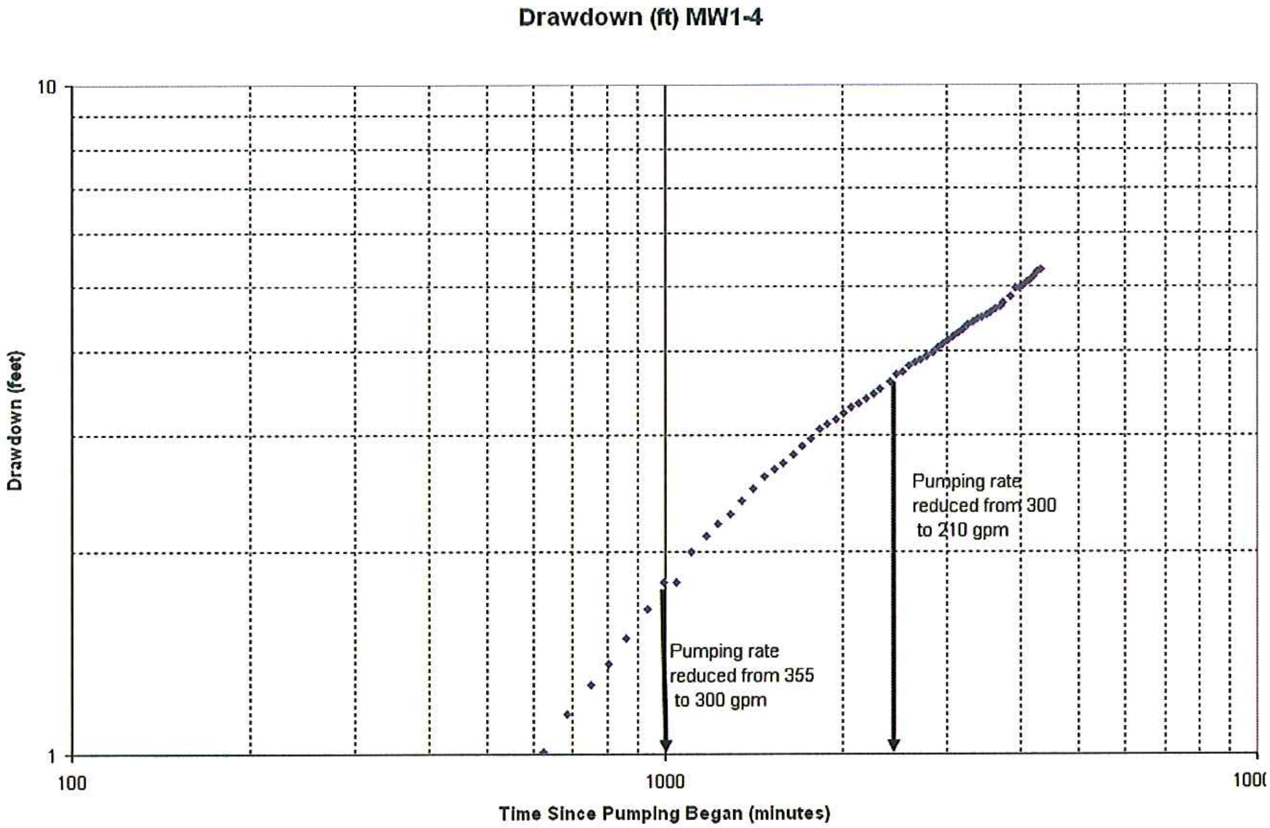

Figure 7

Drawdown for Observation Well MW1-4 (Manual Measurements)

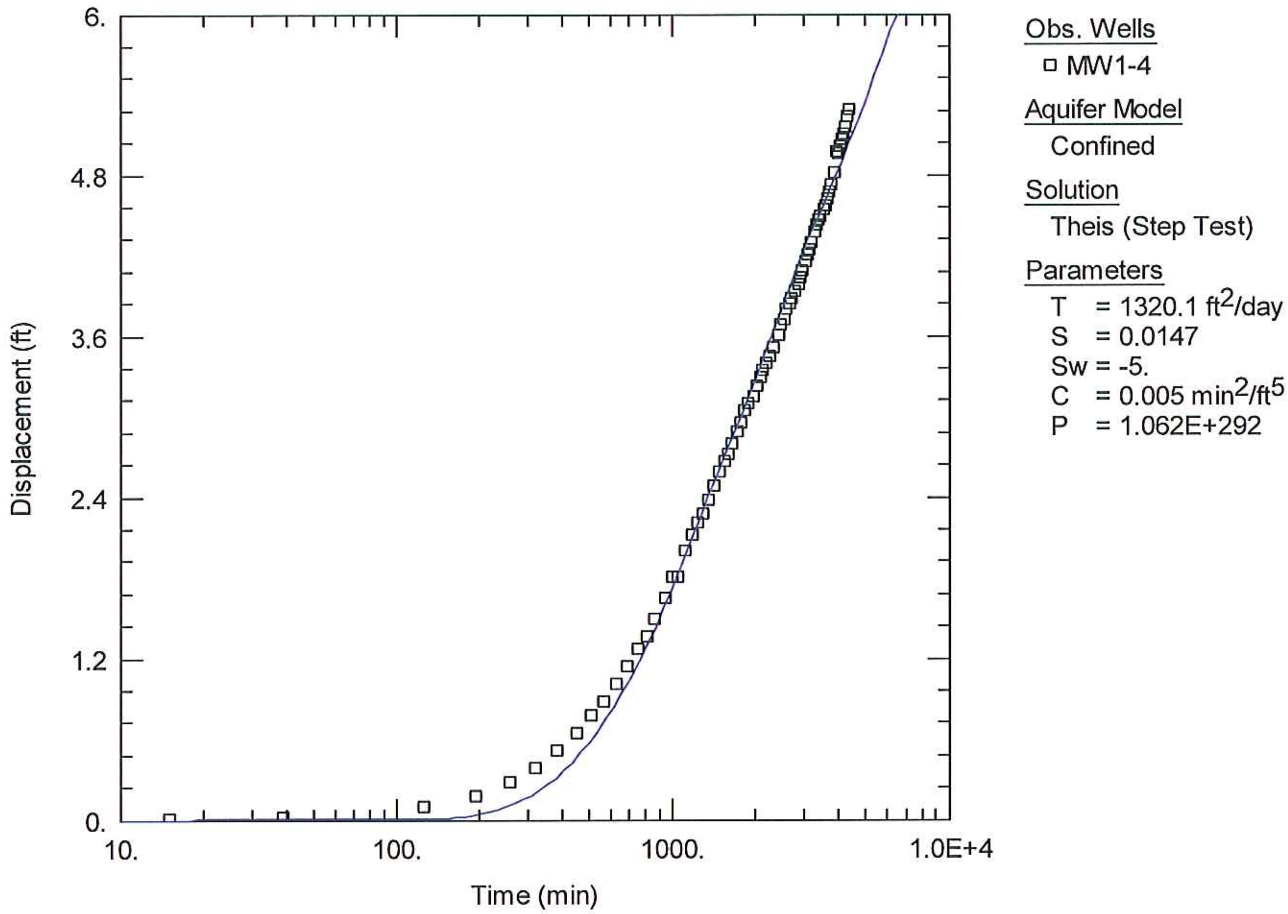

Figure 8

Curve-Match Plot of Drawdown Data from Observation Well MW1-4, With Resulting Aquifer Parameter Estimates

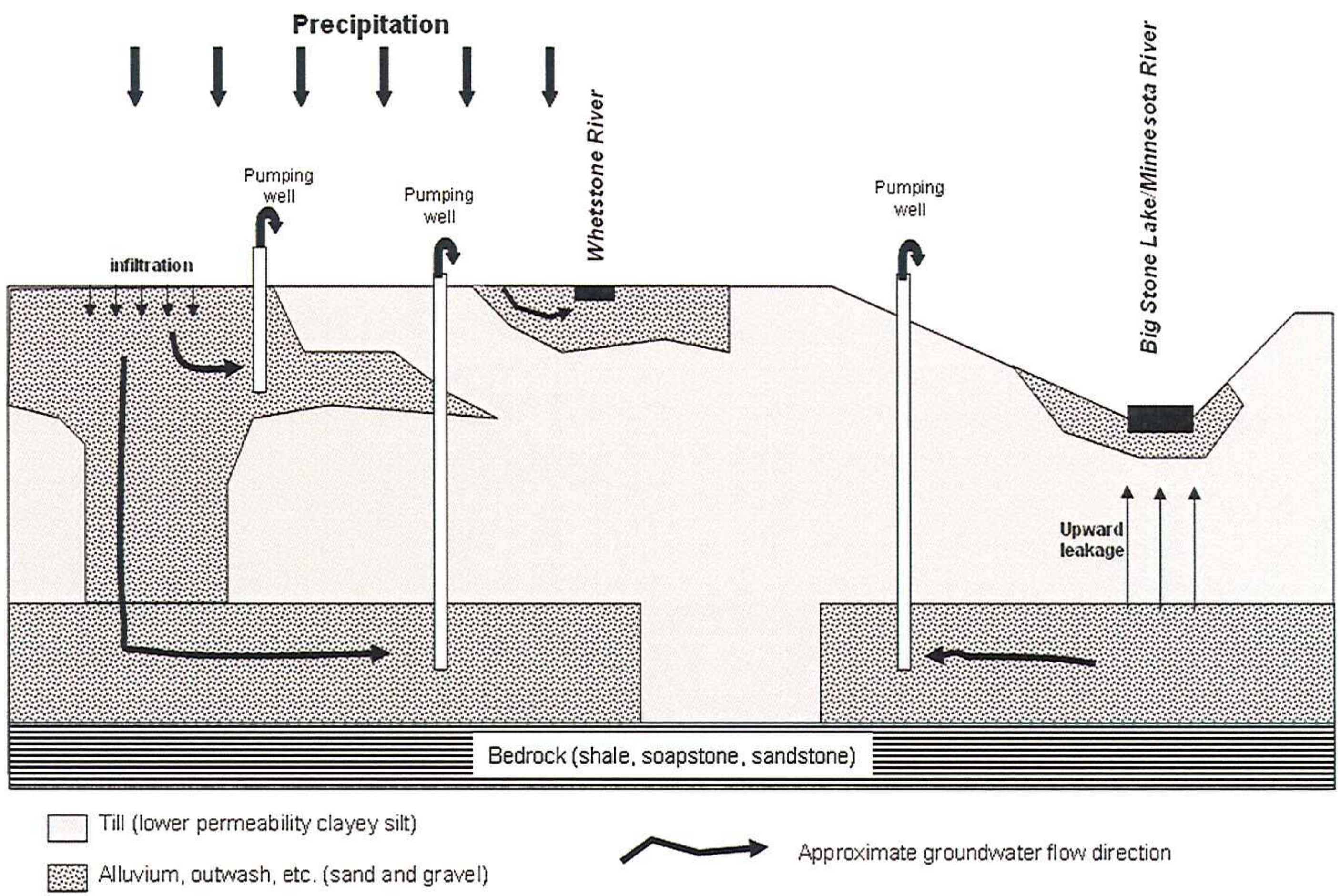

Figure 9

Conceptual Hydrogeologic Model of Groundwater Flow

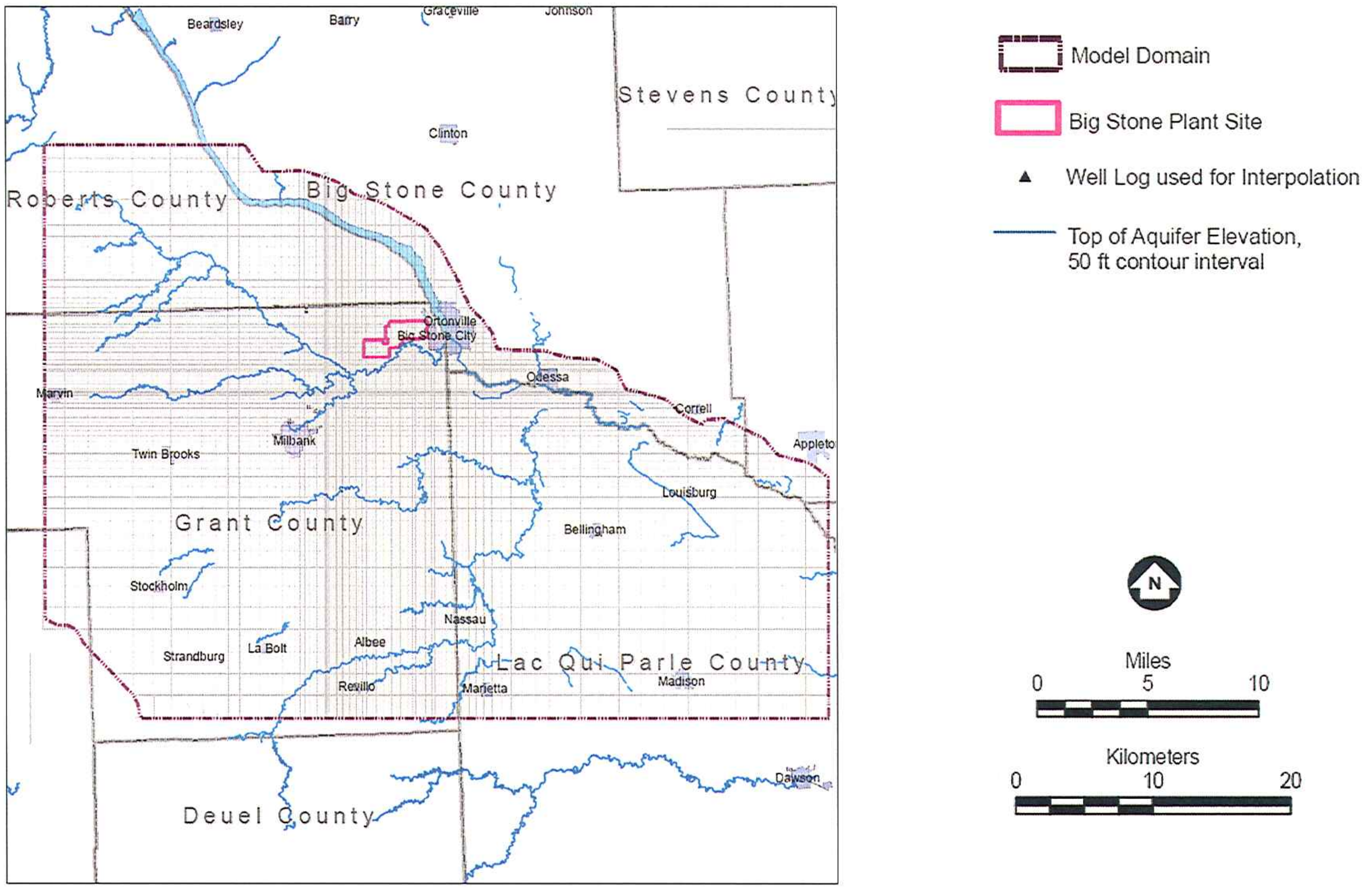

Figure 10

Model Domain and Grid Discretization

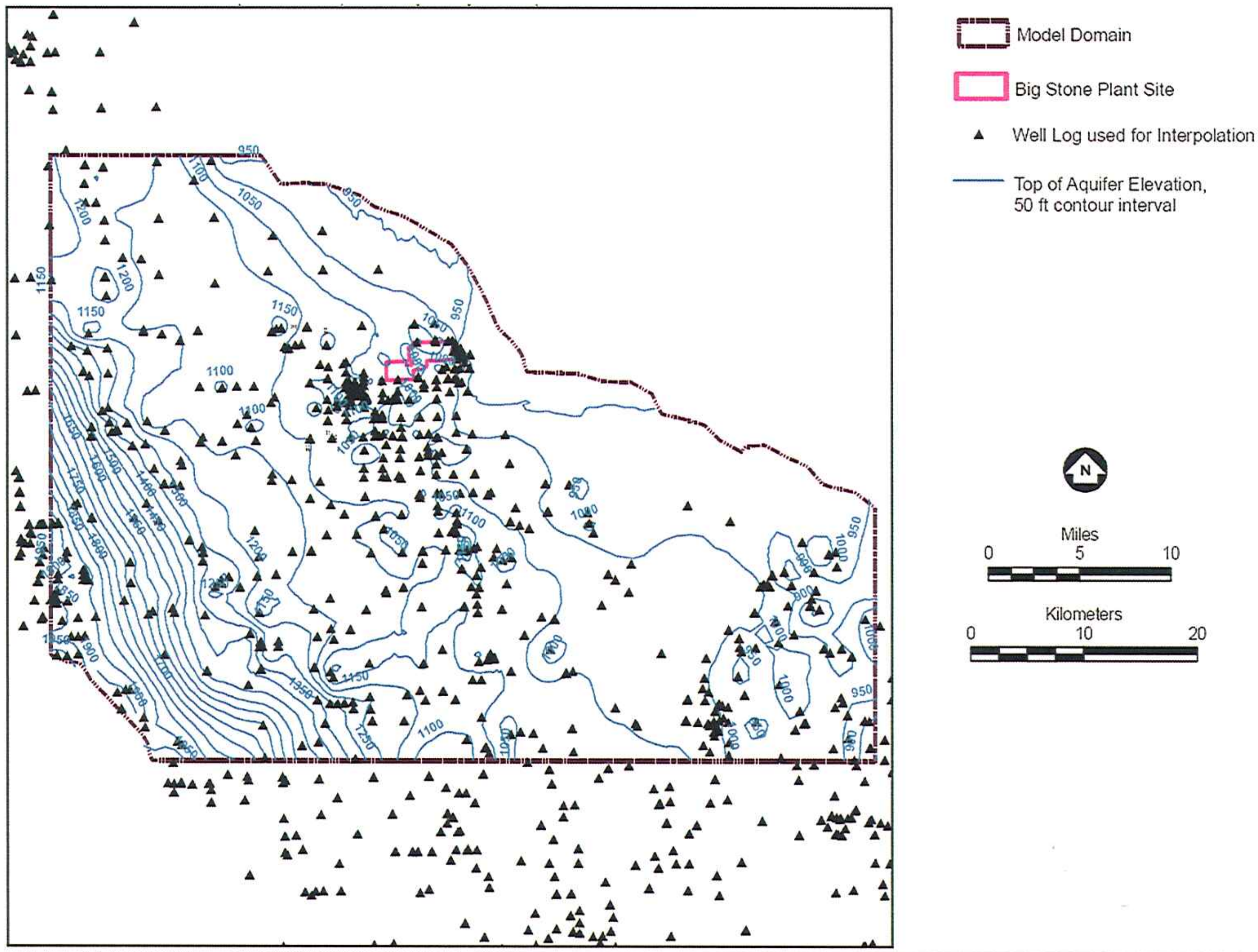

Figure 11

Interpolated Elevation of Top of Aquifer Unit

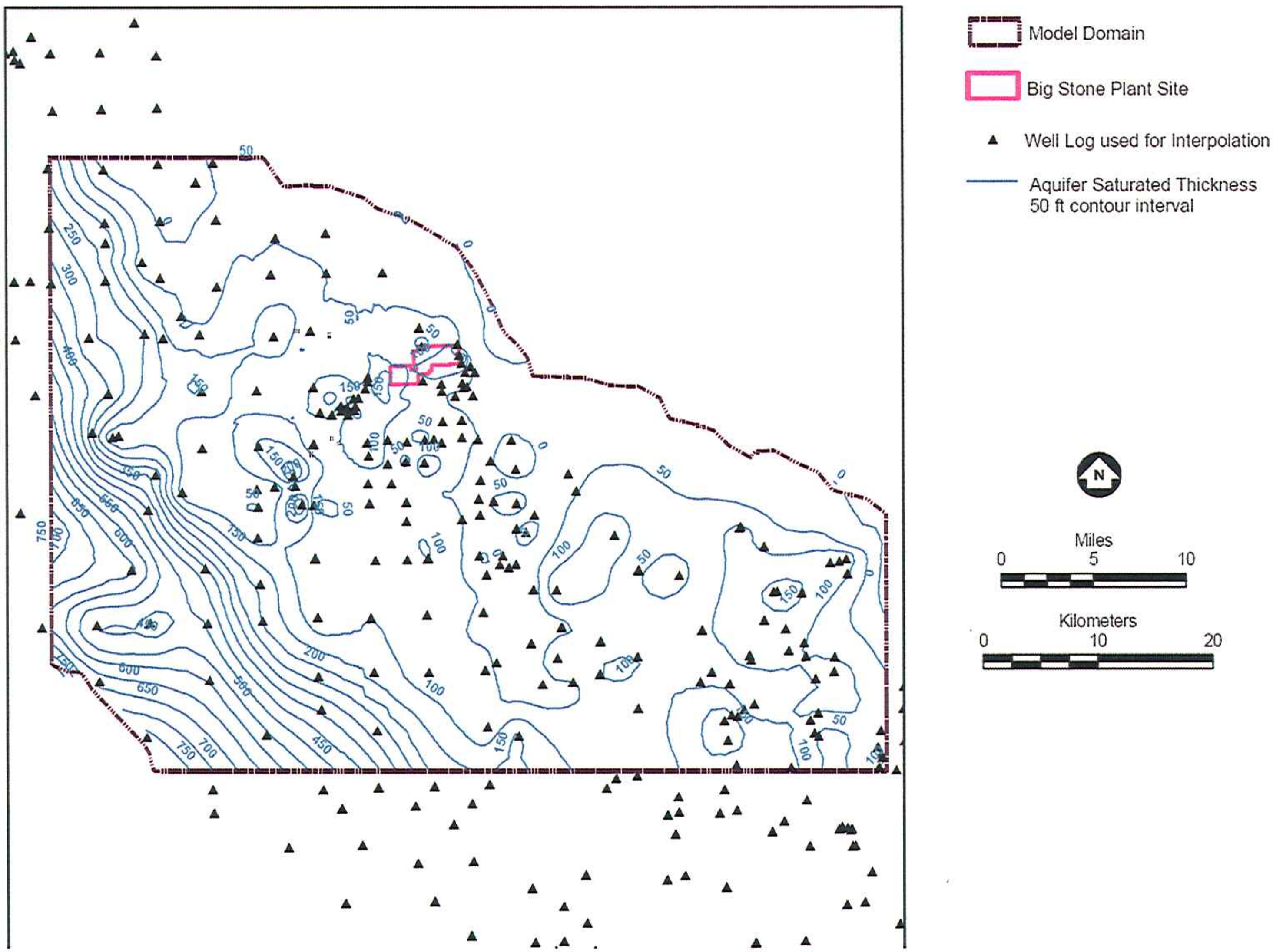

Figure 12

Interpolated Saturated Thickness of Aquifer Unit

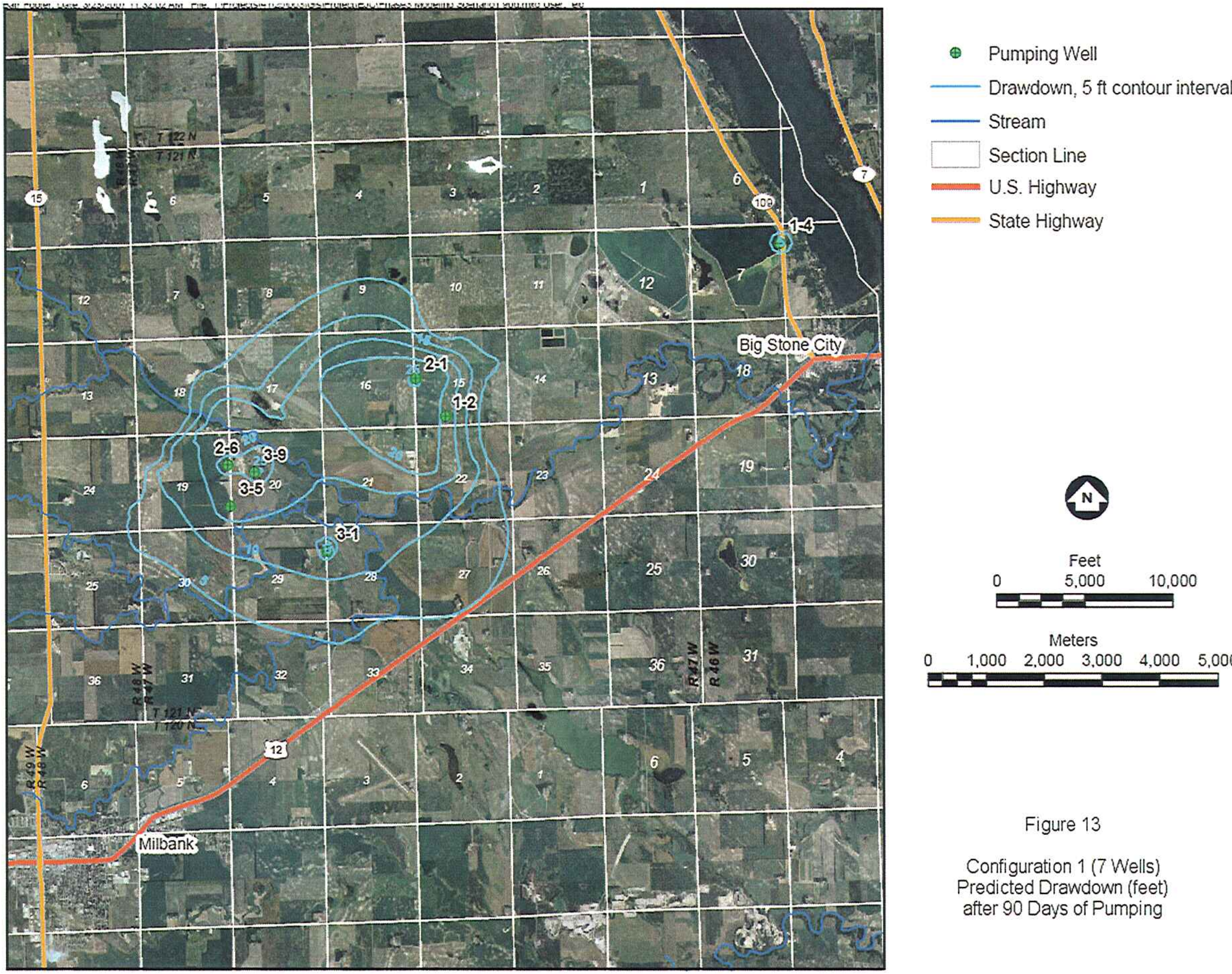

Figure 13

Configuration 1 (7 Wells)
Predicted Drawdown (feet)
after 90 Days of Pumping

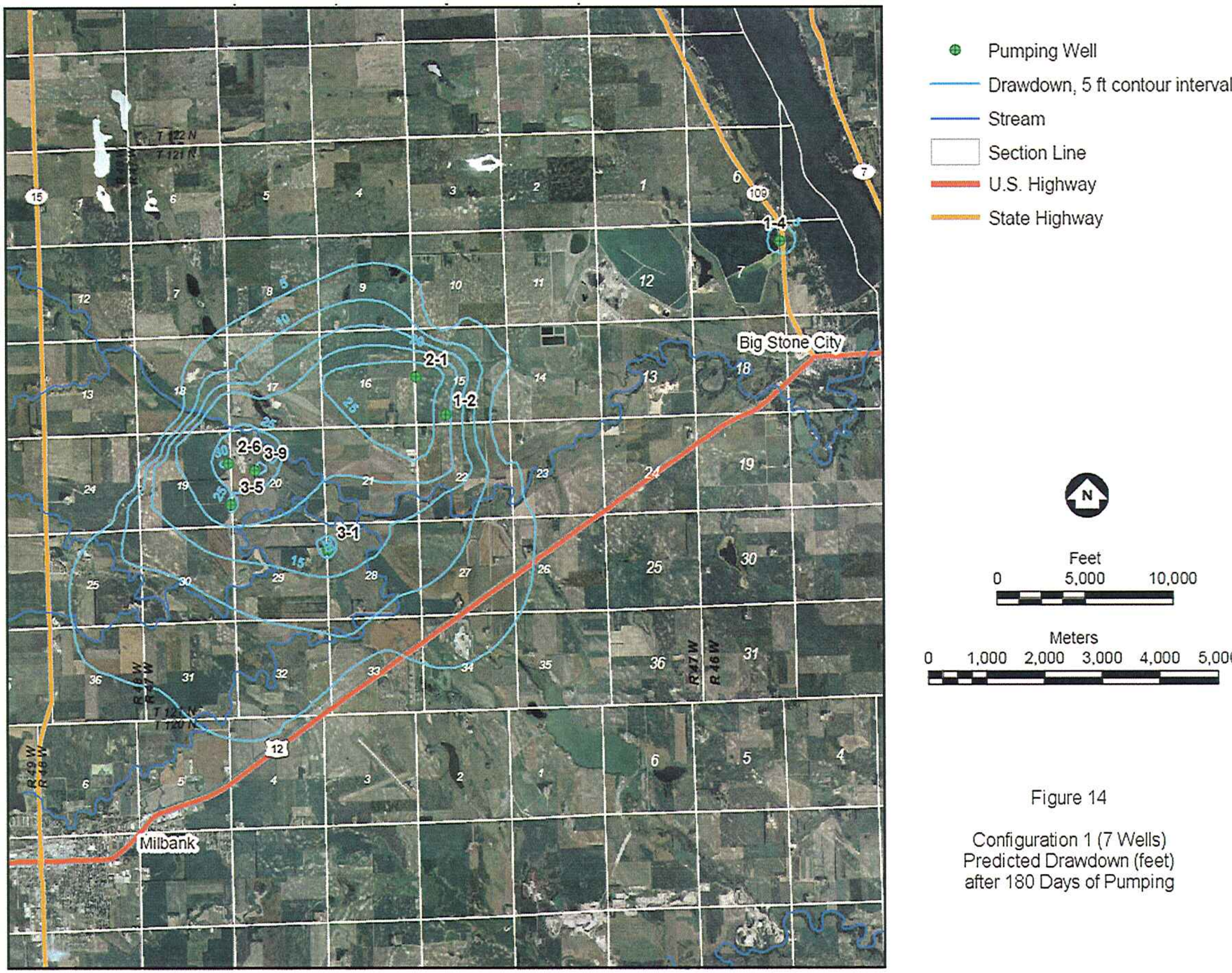

Figure 14

Configuration 1 (7 Wells)
Predicted Drawdown (feet)
after 180 Days of Pumping

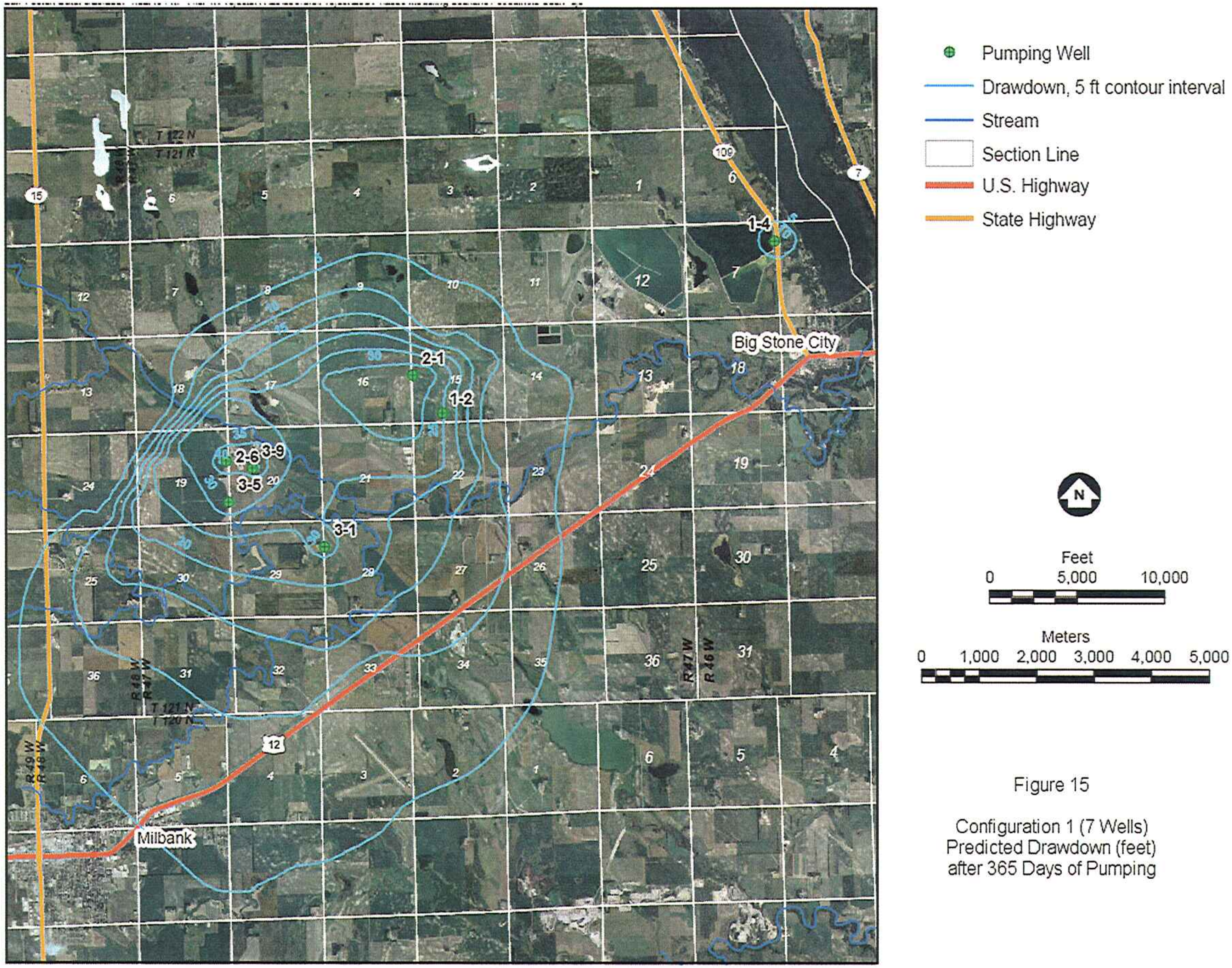

Figure 15

Configuration 1 (7 Wells)
Predicted Drawdown (feet)
after 365 Days of Pumping

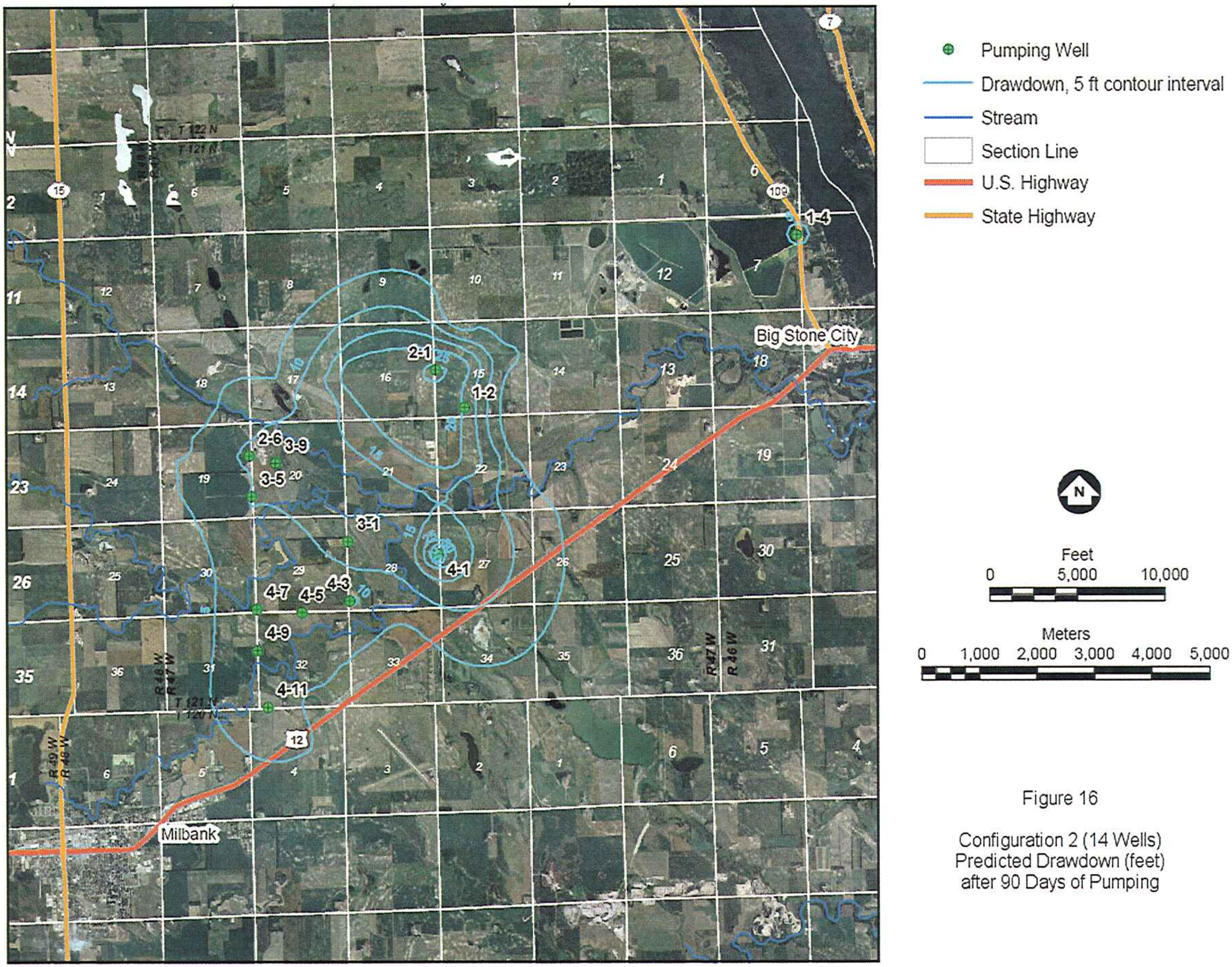

Figure 16

Configuration 2 (14 Wells)
Predicted Drawdown (feet)
after 90 Days of Pumping

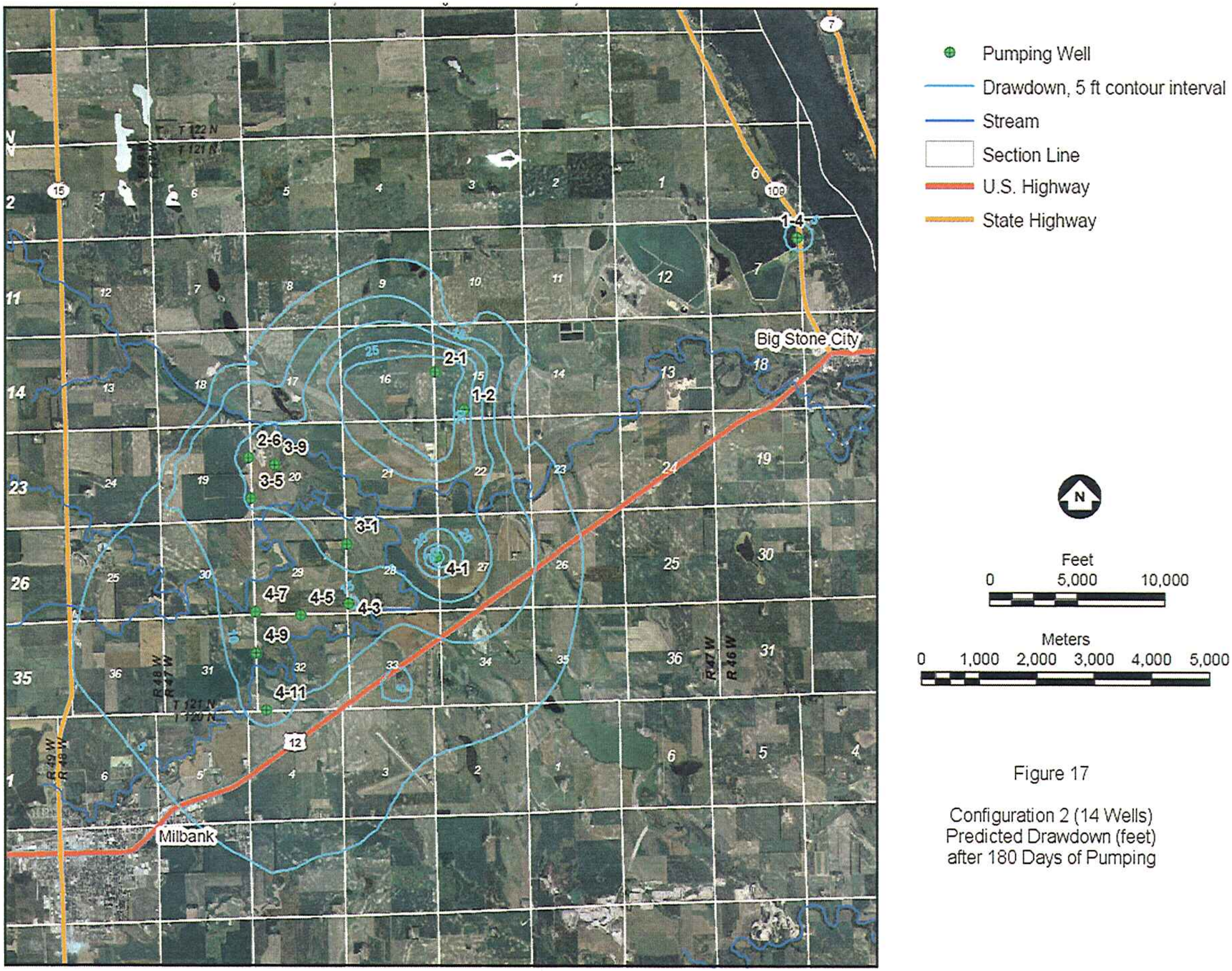

Figure 17

Configuration 2 (14 Wells)
Predicted Drawdown (feet)
after 180 Days of Pumping

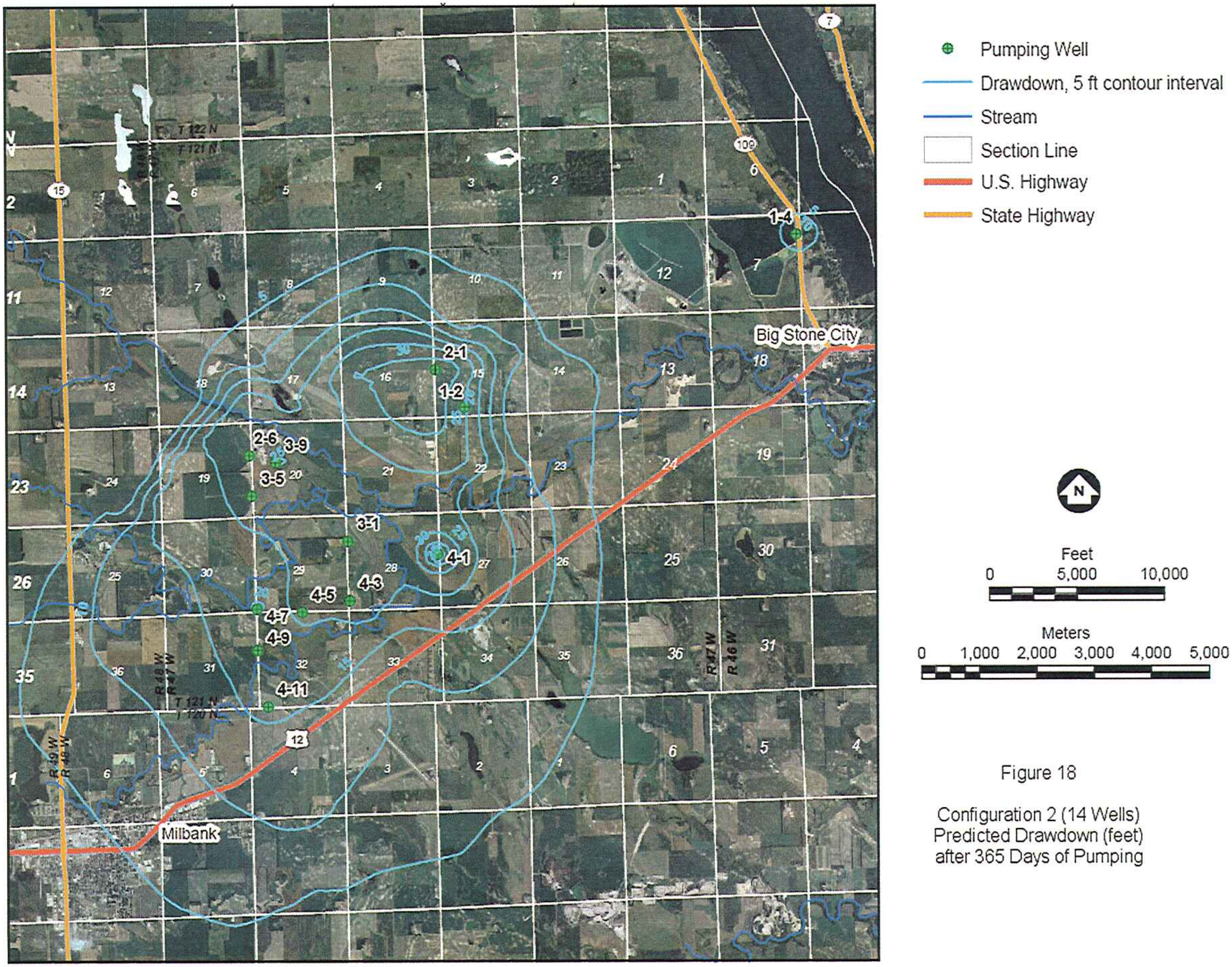

Figure 18

Configuration 2 (14 Wells)
Predicted Drawdown (feet)
after 365 Days of Pumping