Prepared in cooperation with the Ho-Chunk Nation

Ground-Water Flow in the Vicinity of the Ho-Chunk Nation Communities of Indian Mission and Sand Pillow, Jackson County, Wisconsin

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Scientific Investigations Report 2008–5121

U.S. Department of the Interior
U.S. Geological Survey

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By Charles P. Dunning, Gregory D. Mueller, and Paul F. Juckem

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Conversion Factors, Vertical Datum, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day (m/d)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Elevation, as used in this report, refers to distance above the vertical datum.

*Hydraulic conductivity: The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area [$(ft^3/d)/ft^2$]. In this report, the mathematically reduced form, foot per day (ft/d), is used for convenience.

Particle sizes and weights of sediment particles are given in micrometers (μm) and grams (g), respectively.

Ground-Water Flow in the Vicinity of the Ho-Chunk Nation Communities of Indian Mission and Sand Pillow, Jackson County, Wisconsin

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Abstract

An analytic element ground-water-flow model was constructed to help understand the ground-water-flow system in the vicinity of the Ho-Chunk Nation communities of Indian Mission and Sand Pillow in Jackson County, Wisconsin. Data from interpretive reports, well-drillers' construction reports, and an exploratory augering program in 2003 indicate that sand and gravel of varying thickness (0–150 feet[ft]) and porous sandstone make up a composite aquifer that overlies Precambrian crystalline rock. The geometric mean values for horizontal hydraulic conductivity were estimated from specific-capacity data to be 61.3 feet per day (ft/d) for sand and gravel, 6.6 ft/d for sandstone, and 12.0 ft/d for the composite aquifer.

A ground-water flow model was constructed, the near field of which encompassed the Levis and Morrison Creeks Watershed. The flow model was coupled to the parameter-estimation program UCODE to obtain a best fit between simulated and measured values of ground-water levels and estimated Q_{50} flow duration (base flow). Calibration of the model with UCODE provided a ground-water recharge rate of 9 inches per year and a horizontal hydraulic conductivity of 13 ft/d for the composite aquifer. Using these calibrated parameter values, simulated heads from the model were on average within 5 ft of the measured water levels. In addition, these parameter values provided an acceptable base-flow calibration for Hay, Dickey, and Levis Creeks; the calibration was particularly close for Levis Creek, which was the most frequently measured stream in the study area.

The calibrated model was used to simulate ground-water levels and to determine the direction of ground-water flow in the vicinity of Indian Mission and Sand Pillow communities. Backward particle tracking was conducted for Sand Pillow production wells under two pumping simulations to determine their 20-year contributing areas. In the first simulation, new production wells 6, 7, and 8 were each pumped at 50 gallons per minute (gal/min). In the second simulation, new production wells 6, 7, and 8 *and* existing production well 5 were each pumped at 50 gal/min. The second simulation demonstrated interference between the existing production well 5 and the new production wells when all were pumping at 50 gal/min.

Introduction

In cooperation with the Ho-Chunk Nation, the U.S. Geological Survey initiated in 2003 a ground-water study in the vicinity of the Indian Mission and Sand Pillow communities in central Jackson County, Wis. (fig. 1). The Ho-Chunk Nation expects considerable growth in these communities in the coming years, including additional housing and expansion of their casino and hotel. As a result, the projected demand for ground water will increase from a total of 60,000 gallons per day (gal/d) for the communities to 114,000 gal/d in 5 years (Indian Health Service, 2002). Projected demand in 20 years is 216,000 gal/d (Indian Health Service, 2002). An understanding of the ground-water-flow system is necessary for water-resources managers to meet the anticipated water demand in the most efficient and sustainable way. A ground-water-flow model is presented in this study that provides a tool for simulating the effects of pumping on water resources and delineating the areas contributing ground water to wells.

Purpose and Scope

This report describes the ground-water hydrology in the vicinity of the communities of Indian Mission and Sand Pillow, Jackson County, Wis. Geologic and hydrologic data used during this study consisted of interpretive maps, previously published reports, well-construction reports, and historical streamflow measurements. These data, plus new data collected at eight exploratory augering sites in the vicinity of Sand Pillow, form the basis for development of a computer model to simulate regional ground-water levels and determine the direction of ground-water flow in the vicinity of Indian Mission and Sand Pillow. The development and calibration of the model are discussed, and the calibrated model is used to simulate areas of contribution for selected production wells near Sand Pillow.

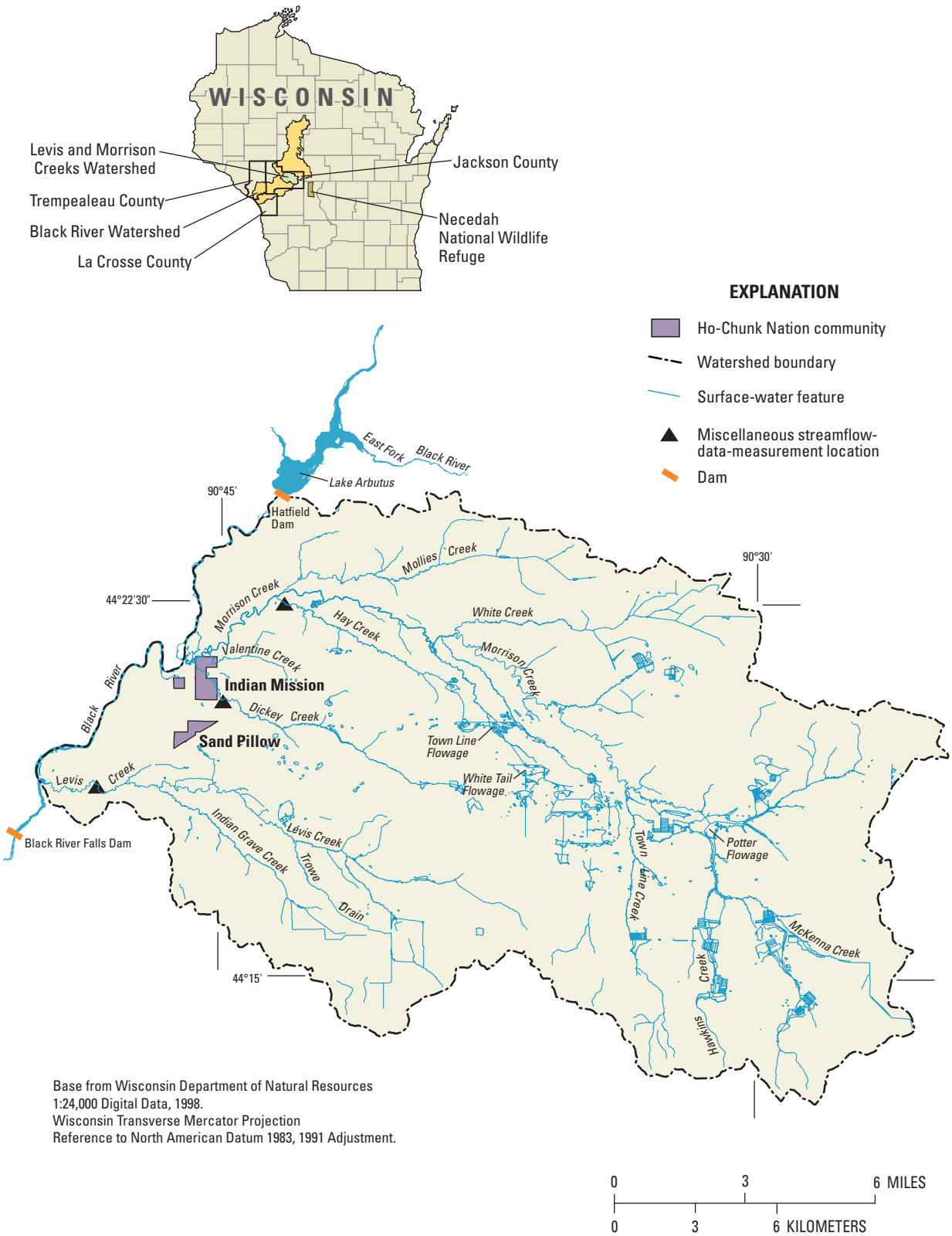

Figure 1. Location of the Black River, Levis and Morrison Creeks watershed, and the Ho-Chunk Nation communities of Indian Mission and Sand Pillow, Jackson County, Wis.

Methods

The hydrogeology of the study area was investigated by means of a stepwise approach. In this approach, existing data were first interpreted and used in conceptualizing the hydrologic setting. The conceptual hydrologic model was the basis for development of the numerical ground-water-flow model. Subsequent field investigations were conducted based on simulations of the calibrated flow model. The final version of the model incorporated the results of the collected field data.

Data from 184 existing well-construction reports (WCRs) for the vicinity of Indian Mission and Sand Pillow provided specific-capacity values that were used to estimate hydraulic conductivity using the algorithm TGUESS (Bradbury and Rothschild, 1985). WCRs data were also used to assess the variability in saturated thickness across the area. No WCRs were available for areas in the upper parts of the Levis and Morrison Creeks Watershed. Wells documented in the WCRs are generally located only to the nearest quarter/quarter section; no attempt was made to locate these wells in the field. Fifty-seven WCRs, a subset of the 184, were selected (based on data quality) as the source for ground-water-level calibration targets for the ground-water-flow model (fig.2). Ground elevation of these wells and elevation of surface-water features were estimated from USGS topographic maps (1:24,000 scale). The potential inaccuracy of the estimated ground elevation for any well is the combined inaccuracy of the well location (center of nearest quarter/quarter section) and estimate of ground elevation at that location based on the topographic map.

Because the ground-water-flow model of this study simulates *steady-state* ground-water flow, the appropriate streamflow calibration targets are base flow. Stream base flow is the portion of streamflow attributed to ground-water discharge, and is assumed to be between the Q_{50} and Q_{80} flow duration (the stream discharge equaled or exceeded 50 percent or 80 percent of the time) for Wisconsin streams (Krohelski and others, 2000). The best streamflow data available for this area are historical streamflow measurements for Levis Creek and two tributaries to Morrison Creek—Hay and Dickey Creeks (fig. 1). Streamflow measurements were made in the late 1960s to early 1970s as part of a USGS study; streamflows were measured once each in Hay and Dickey Creeks and 15 times in Levis Creek (Holmstrom, 1979). These measurements were not necessarily taken during baseflow conditions so were adjusted based on their relation to measured streamflow on the same dates at a long-term discharge station in the Trempealeau River at Dodge, Trempealeau County, Wis. (USGS streamgage 05379500). However, an additional adjustment was made because there was an approximately 30% increase in baseflow observed for the Trempealeau River at Dodge, Wis. between the late 1960's and the 1993–2003 time period (fig. 3). This adjustment was made for each discharge measurement on Hay, Dickey, and Levis Creeks to estimate Q_{50} and Q_{80} discharges that represented the period from 1993 to 2003 for Hay, Dickey, and Levis Creeks.

Eight boreholes were augered to depths between 70 and 110 ft to determine lithologic properties, water-table elevation, and saturated thickness of the sand and gravel part of the composite aquifer in the area around Sand Pillow and Indian Mission. Water was encountered in 6 of the 8 boreholes; levels measured in those 6 boreholes were used as targets, along with other level data, for calibration of the ground-water-flow model.

Monitor wells were installed at the three auger sites (sites 1, 2, and 4) with the most favorable characteristics (proximity to Sand Pillow, greater saturated thickness, and greater proportion of clean sand) (fig. 2). Monitoring wells at sites 1 and 2 were constructed using 2 inch (in.) polyvinyl chloride (pvc) pipe with 9.9-ft screens. The bottom of the screen of the monitoring well at site 1 was set at 77 ft below ground level (bgl). The bottom of the screen of the monitoring well at site 2 was set at 97 ft bgl. The monitoring well at site 4 was constructed using 1-in. pvc pipe with a 5.0-ft screen; the bottom of the screen was set at 82 ft bgl. For each of the monitoring wells, collapsed native material filled the annular space around the screen and riser pipe below the water table. Auger returns were shoveled into the annular space above the water table followed by bentonite chips or quick grout to the surface (Appendix).

An analytic element (AE) ground-water-flow model was constructed by use of the computer program GFLOW (Haitjema, 1995) to simulate the ground-water-flow system and its interaction with surface-water features. A brief description of the analytic element method is given below. The reader is referred to Strack (1989) and Haitjema (1995) for detailed discussions of this method.

Unlike traditional modeling methods, the analytic element method assumes an infinite aquifer and does not use a grid or involve interpolation between grid cells. To construct an analytic element model, the hydrologic features important to ground-water flow are identified and represented by analytic elements or strings of elements. Important features include surface-water bodies such as rivers and streams, lakes, pumping wells, and zones of differing hydrogeologic properties. Each analytic element is a mathematical equation with a solution to the ground-water-flow equation. The effects of these individual solutions are superposed, or added together, to arrive at a solution for the larger ground-water-flow system. Unlike finite-difference modeling wherein the solution is calculated only at grid nodes, analytic-element modeling allows for computation of heads and flows without nodal averaging anywhere in the model domain. Comparisons of analytic element to finite-difference numerical modeling techniques have been discussed by others (Hunt and Krohelski, 1996; Hunt and others 1998). The GFLOW model used here is two dimensional and designed to simulate steady-state conditions (that is, water levels (heads) do not vary with time). The GFLOW model was calibrated by use of UCODE (Poeter and Hill, 1998) which systematically varies values for input parameters such as recharge rate, hydraulic conductivity, and stream resis-

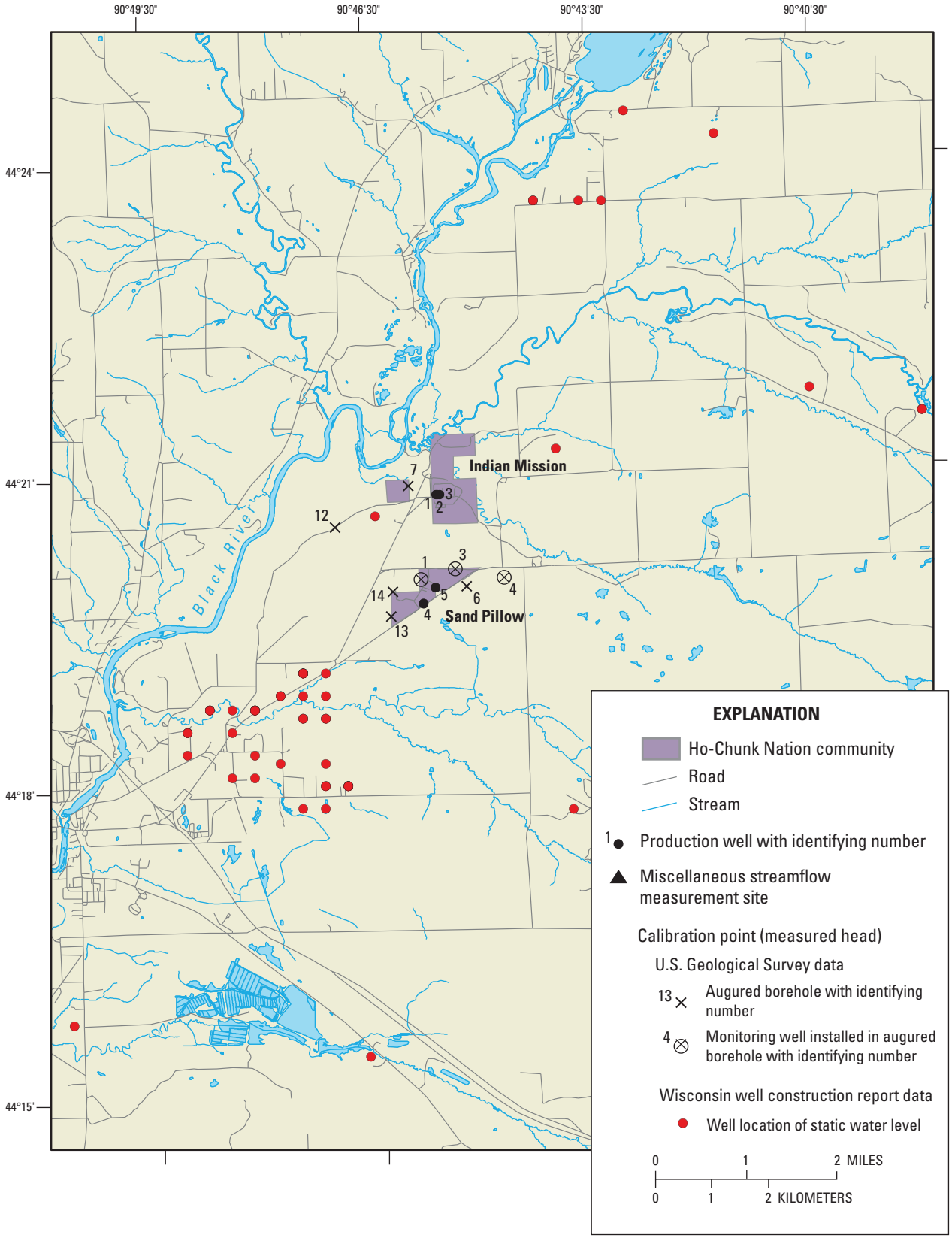

Figure 2. Indian Mission and Sand Pillow production wells and augered borehole sites, Jackson County, Wis. Well locations from Wisconsin well construction reports are reported and plotted to the nearest quarter/quarter section; consequently, all 57 of the observations are represented in the 34 plotted locations.

tance until there is a statistical best fit between measured and simulated calibration targets, such as heads and streamflows.

Defining the area of recharge for ground water flowing to pumping wells is important for the protection of the wells and for making land-management decisions. This area of the ground surface where recharge flows to a well is commonly called its contributing recharge area. Contributing areas for existing wells were simulated by use of backward particle tracking in the AE model. Simulated water particles were placed at the open intervals of wells and mathematically tracked backward in time for 20 years. The rate of movement of a particle depends on the hydraulic properties input to the model representing the aquifer, including porosity (assumed), and the geometry of the surface-water features.

Hydrogeologic Setting and Conceptual Model of Ground-Water Flow

Precambrian crystalline rock underlies the Indian Mission and Sand Pillow communities. The Precambrian rock is overlain by permeable Cambrian Mount Simon Sandstone which is in turn overlain by geologically recent outwash deposits. The outwash deposits are described as “Mainly well sorted and stratified sand and/or sand and gravel” by Hadley and Pelham (1978). Other sources report that the communities are situated on alluvial deposits of sand and gravel, and silt and clay (Earth Tech, 2000). In a few areas the Cambrian sandstone is absent, in which case the outwash lies directly on the crystalline bedrock.

The three existing production wells in the Indian Mission community and the two wells in the Sand Pillow community (fig. 2) produce water from the Mount Simon Sandstone. Although the maximum thickness of sand and gravel reported on the reviewed WCRs is 150 ft, thickness varies considerably. For example, sand and gravel are absent at Indian Mission production well 1, less than 5 ft thick at well 2, and 45 ft thick at well 3, which are all within 100 ft of each other. Although the thickness of the sandstone in the Indian Mission area is about 100 ft, the sandstone thickness in the surrounding area is generally unknown because most private wells with available WCR data do not penetrate the entire sequence of sandstone. Because no WCRs could be located for the upper parts of the Levis and Morrison Creeks Watershed, the thickness of both the sand and the sandstone is unknown. The Precambrian crystalline rock, which forms the base of the aquifer system, has an irregular surface; therefore, the sandstone thickness is expected to vary (Young and Borman, 1973). A lithologic description of the sand and gravel, as well as particle-size analysis from selected samples collected during exploratory augering, is given in the Appendix. These particle-size analyses are the basis of estimates of horizontal hydraulic conductivity (using the Hazen equation) ranging from 10.2 to 20.5 ft/d (feet per day).

Estimates of horizontal hydraulic conductivity determined from specific capacity reported on the WRCs range over several orders of magnitude and exhibit no apparent spatial zonation. The estimates of hydraulic conductivity have a geometric mean value of 6.6 ft/d (135 wells) for wells finished in sandstone, 61.3 ft/d (48 wells) for wells finished in sand and gravel, and 12.0 ft/d when combined (184 wells).

Studies in the vicinity of Indian Mission and Sand Pillow provide estimates of a recharge rate. Hunt and others (2000, 2003) indicate that recharge rate can vary considerably but averages around 9.5 in./yr for the Necedah Wildlife Area and 8.5 in./yr for LaCrosse County (fig. 1).

The Indian Mission/Sand Pillow communities are within of the Morrison Creek watershed, which is part of the larger Black River watershed (fig. 1). The closest streamgage with an adequate period of record to estimate base flow is Trempealeau River at Dodge, Wis. (fig. 1), approximately 65 mi to the southwest of these communities. Base flow at this streamgage has increased from approximately 250 cubic feet per second (ft^3/s) to 400 ft^3/s (about 30 percent) since the late 1960s and early 1970s when measurements were made at Hay, Dickey, and Levis Creeks (Gebert and Krug, 1996) (fig. 3). Similar increases in base flow have been documented nearly statewide and have been attributed to increases in ground-water recharge resulting from changes in land-use practices (Gebert and Krug, 1996) or climatic variability (Magnuson and others, 2003).

Prior to construction of the ground-water-flow model, a conceptualization of the system was developed to form the framework for model development. The conceptualization reduces the physical flow system into its essential component parts. Steps in the development of the conceptual model include (1) definition of aquifers and confining units, (2) identification of sources and sinks of water, and (3) identification and delineation of hydrologic boundaries. A cross-sectional conceptualization of the ground-water/surface-water system in the vicinity of the communities of Indian Mission and Sand Pillow is shown in figure 4.

The ground-water system consists of laterally extensive deposits of sand and gravel over sandstone (fig. 4). Both the sand and gravel and the sandstone are sources of the water to wells in the area and are considered a single composite aquifer for the purposes of this study. Because the AE GFLOW model requires a single-layer representation of the flow system, this is a convenient conceptualization. Porosity of the composite aquifer was assumed to be 20 percent on the basis of reported values for medium-grained sandstone and unconsolidated sand and gravel (Freeze and Cherry, 1979). Because of the unconsolidated nature of the sand and gravel deposits and the porous nature of the sandstone, the composite aquifer is considered to be relatively vulnerable to contamination by point-source contamination or private septic systems. This vulnerability is lessened by the presence of silt and clay layers penetrated in some bore holes during the auger investigation (Appendix), although the spatial distribution of these lower conductivity layers is unpredictable. The conceptual model assumes a homogeneous composite aquifer; therefore, these silt and clay layers

have not been explicitly represented. In addition, preferential flow pathways (such as high-hydraulic-conductivity channels within the sand and gravel) that could potentially allow rapid transport of contaminants are not represented in the model.

The source of water to the ground-water system is precipitation, specifically that portion of precipitation that does not run off, evaporate, or transpire. That portion, called recharge, is depicted by the sub-vertical arrows above the water table in figure 4. Once recharge reaches the water table, ground water moves from higher to lower potentials (or heads), that is, typically from areas of recharge (sources) to areas of discharge (sinks). As a result, ground water generally moves toward, and discharges to, lower-lying surface-water features, as indicated by the flow-direction arrows in figure 4. Because of the generally high permeability of the sand, gravel, and sandstone that comprise the aquifer in the study area, a good hydraulic connection between the aquifer and the streams and other surface-water features is assumed. The depth of the water table in the vicinity of the Indian Mission and Sand Pillow communities varies from near land surface close to surface-water features (lakes, streams, wetlands) to more than 50 ft below land surface in areas of increased topographic relief. Pumping from the composite aquifer is another type of discharge (sink) that removes water from the ground-water system. Pumping near surface-water features intercepts ground water that would likely otherwise discharge to those streams or rivers; the end result is a reduction of stream base flow.

Major hydrologic boundaries provide a natural extent to the conceptual model of ground-water flow. The Black River is a major hydrologic boundary on the west side of the study area; it is a major boundary because of its size and flow, and because it has cut down near, or to, the “impermeable” crystalline bedrock. Ground water within the Levis and Morrison Creeks Watershed flows to the Black River or its tributaries; ground water is not expected to flow underneath the Black River to a more distant hydrologic boundary. The ground-water divide of the Levis and Morrison Creeks Watershed provide the major hydrologic boundary on the remaining sides of the study area.

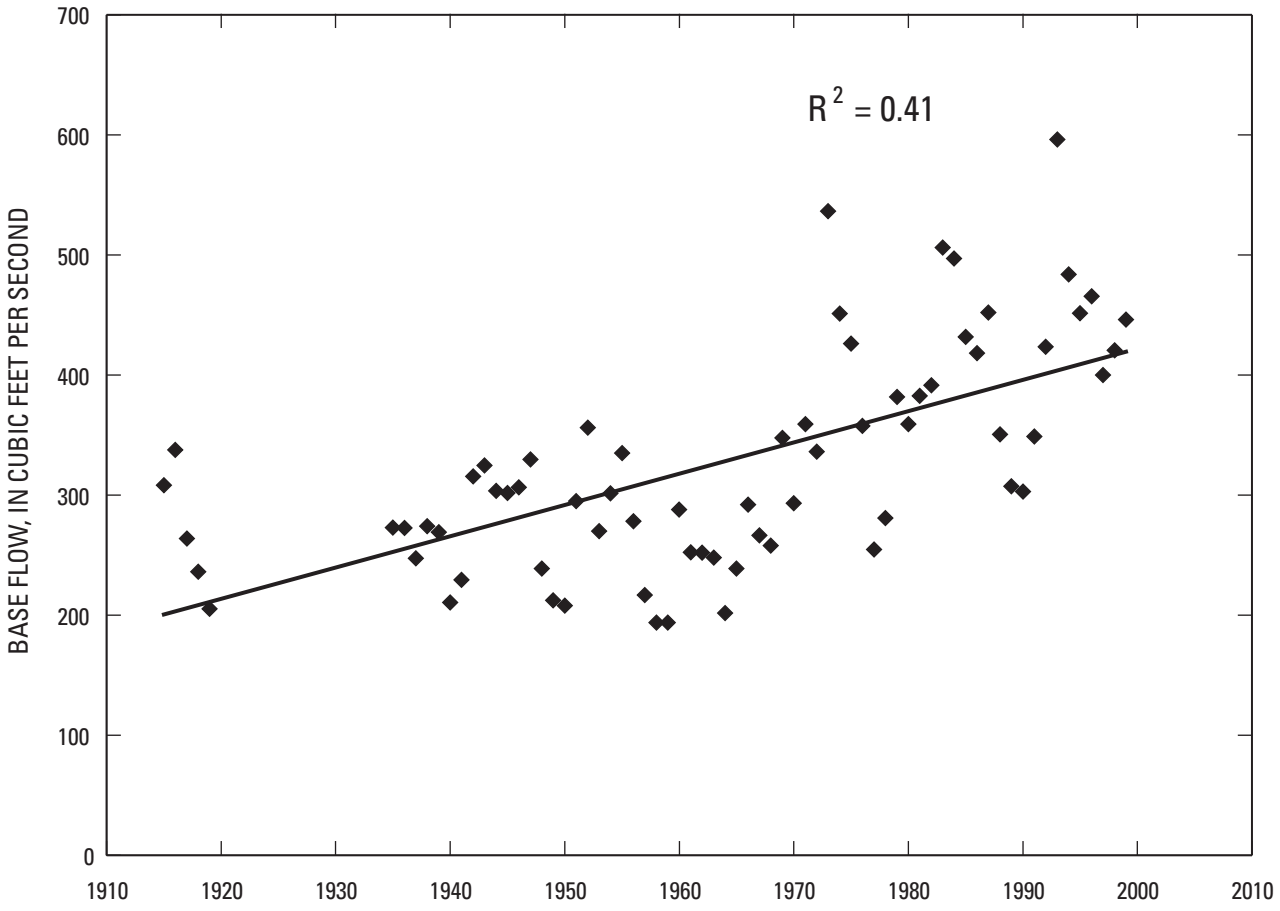

Figure 3. Trend of base flow in the Trempealeau River at Dodge from 1915 to 1999, Trempealeau County, Wis.

Simulation of Ground-Water Flow

The GFLOW model in the Sand Pillow area incorporated available hydrogeologic and water-use data. Model calibration was accomplished using UCODE (Poeter and Hill, 1998), an automated trial-and-error approach that calculates parameter values that are a statistical best fit between simulated model output and measured data. Ground-water levels and flow were simulated by use of the calibrated GFLOW model. Model output included simulated water-table altitudes and delineation of contributing areas to production wells.

Development of the GFLOW Model

Model development includes estimating (1) the elevation of the base of the composite aquifer system, (2) streambed resistance, (3) a global recharge rate, and 4) a horizontal hydraulic conductivity. The base of the model was set to an altitude of 700 ft on the basis of WCRs and geologic reports (Young and Borman, 1973). Streambed resistance was set to 0.5 day (reduced form of streambed thickness, in ft, divided by hydraulic conductivity, in ft/day) for all streams tributary to the Black River. The Black River streambed resistance was set to 2 day. Because streambed-sediment resistance in analytic element modeling is calculated by dividing the streambed sediment thickness by the vertical hydraulic conductivity, a smaller value represents a better connection between aquifer and stream. In this model, the value of 0.5 day corresponds to a 0.5-ft sediment thickness with a vertical hydraulic conductivity of 1 ft/d, which is representative of a good connection between the ground-water and surface-water systems. A streambed resistance of 2 day indicates a relative fourfold increase in resistance to flow across the Black River streambed due to proximity to the impermeable Precambrian crystalline rock. The width of the tributaries to the Black River was assigned according to stream order and ranged from 10 to 25 ft. The width of the Black River was set to 250 ft.

The recharge rate and horizontal hydraulic conductivity of the aquifer each had a uniform value across the model. However, in this model, the recharge rate and horizontal hydraulic conductivity were considered calibration parameters and, thus, were varied during calibration with UCODE.

On the basis of the conceptual model, crystalline bedrock defines the GFLOW model base and the model extent is defined by the hydrologic boundaries of the Black River to the northwest and regional ground-water divides in all other directions. The model near-field area was defined to be the area of the Levis and Morrison Creeks Watershed—the region beyond the near-field area is considered the far field (fig. 5). Far-field features are distant rivers and lakes that are simulated with coarse line sinks that are assigned no resistance between the surface-water features and the ground-water system. The purpose of simulating the far field is to have the model explicitly define the regional ground-water-flow field that surrounds the near-field area of interest.

The near field encompasses most surface-water features in the Indian Mission/Sand Pillow area and includes the Levis and Morrison Creeks Watershed (fig. 5). The Black River forms the prominent hydrologic boundary to the near field on its west side. Near-field streams are simulated with a sophisticated type of line sink, called a “stream element” (Mitchell-Bruker and Haitjema, 1996). This element consists of linked line sinks that route water from high-elevation line sinks to low-elevation line sinks. During the routing through the stream network, the amount of water captured by the stream (base flow, overland flow) and lost by the stream (infiltration) is tabulated. Model output includes the flux from any line sink in

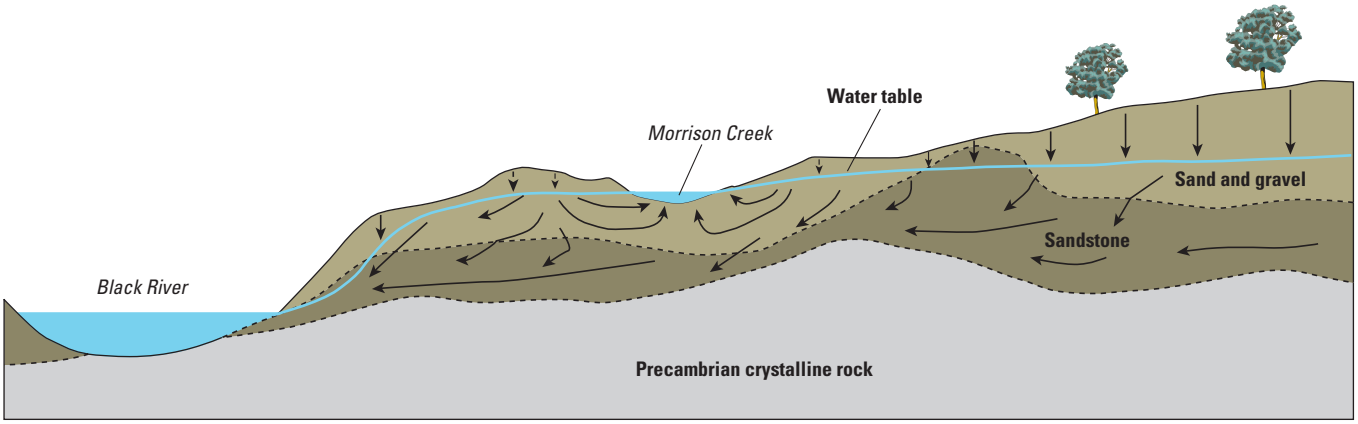

Figure 4. Conceptual model of the hydrologic system in the vicinity of the Ho-Chunk Nation communities of Indian Mission and Sand Pillow, Jackson County, Wis. Vertical arrows indicate recharge to the ground-water system and sub-horizontal arrows indicate direction of ground-water flow.

the stream network that includes flows from all the upstream line sinks. More importantly, the accounting also ensures that the amount of stream water lost to the ground-water system is restricted to the amount of water available (that is, captured from upgradient line sinks in the network). Streams and lakes in the far field are not used for flux calibration and are modeled as individual line sinks with a constant stage.

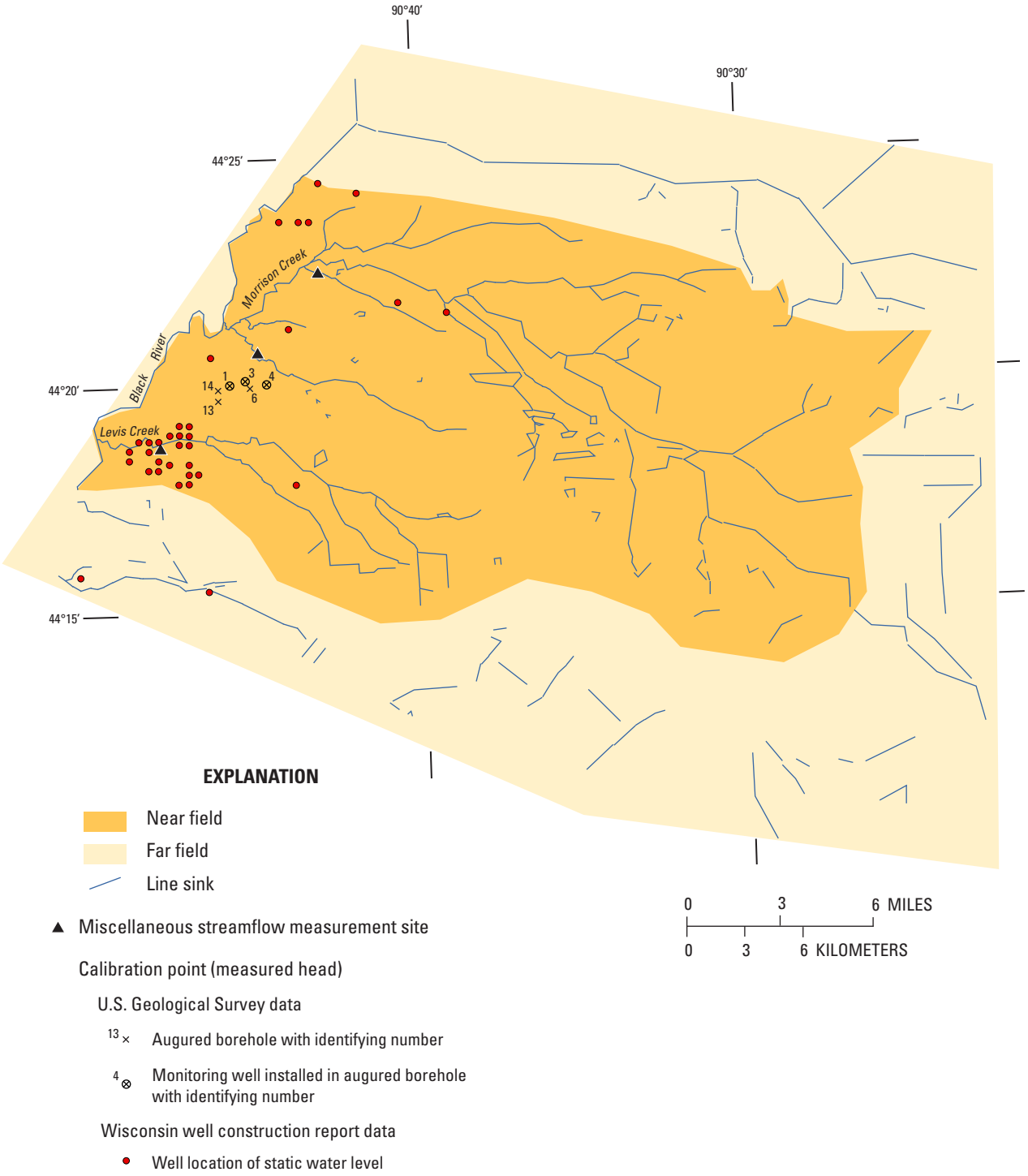

Figure 5. Analytical element model line sinks, near field, far field, and the location of wells, augered boreholes, and streamflow measurement sites used in calibration, Jackson County, Wis.

Calibration

Calibration consists of producing a statistical best fit between measured and simulated heads (ground-water levels) and measured and simulated fluxes (routed stream base-flow). Using an automated trial-and-error approach, UCODE calculates parameter values that provide this statistical best fit between simulated model output and measured data. One of the most important operations in automated parameter estimation is the selection of observations and associated weights given to these observations in the calibration routine. Weights for ground-water-level calibration targets that reflect the uncertainty associated with the target value are input as standard deviations; greater uncertainties (higher standard deviations) place less emphasis on fitting the simulated value to the measured value for the calibration target. Measured ground-water elevations from the subset of 57 WCRs were assigned a 10-ft standard deviation; ground-water elevations from the six auger holes which encountered the water table were assigned a standard deviation of 2 ft. Therefore, more weight (less uncertainty expressed as a smaller standard deviation) was assigned to water levels measured in the auger holes which were located with a Global Positioning System; more accurate locations result in more accurate estimates of ground level altitude.

Estimated Q_{50} flow durations (the median discharge from 1993 to 2003) of 2.2, 3.4, and 29.4 ft^3/s for Hay, Dickey, and Levis Creeks, respectively, were used to calibrate the model. Streamflow target weights are defined as the coefficient of variation (the standard deviation divided by the target value) and have no measurement units. The estimated Q_{50} values for the period 1993–2003 were assigned weights of 0.2 for Hay and Dickey Creeks and 0.05 for Levis Creek. Levis Creek was given more weight (smaller uncertainty) because it was measured 15 times, whereas the other two creeks were only measured once each.

During calibration, UCODE adjusted horizontal hydraulic conductivity and recharge in the GFLOW model to obtain the best fit of simulated to observed heads and streamflows. The optimized model used a horizontal conductivity of 13 ft/d and a recharge rate of 9 in/yr. A comparison between measured and simulated heads is shown in figure 6, along with a summary table of the calibration statistics based on the 63 head targets, including the 6 auger holes in which a water level was measured. The table in figure 6 illustrates that the calibrated model more closely matches the water levels at the auger holes

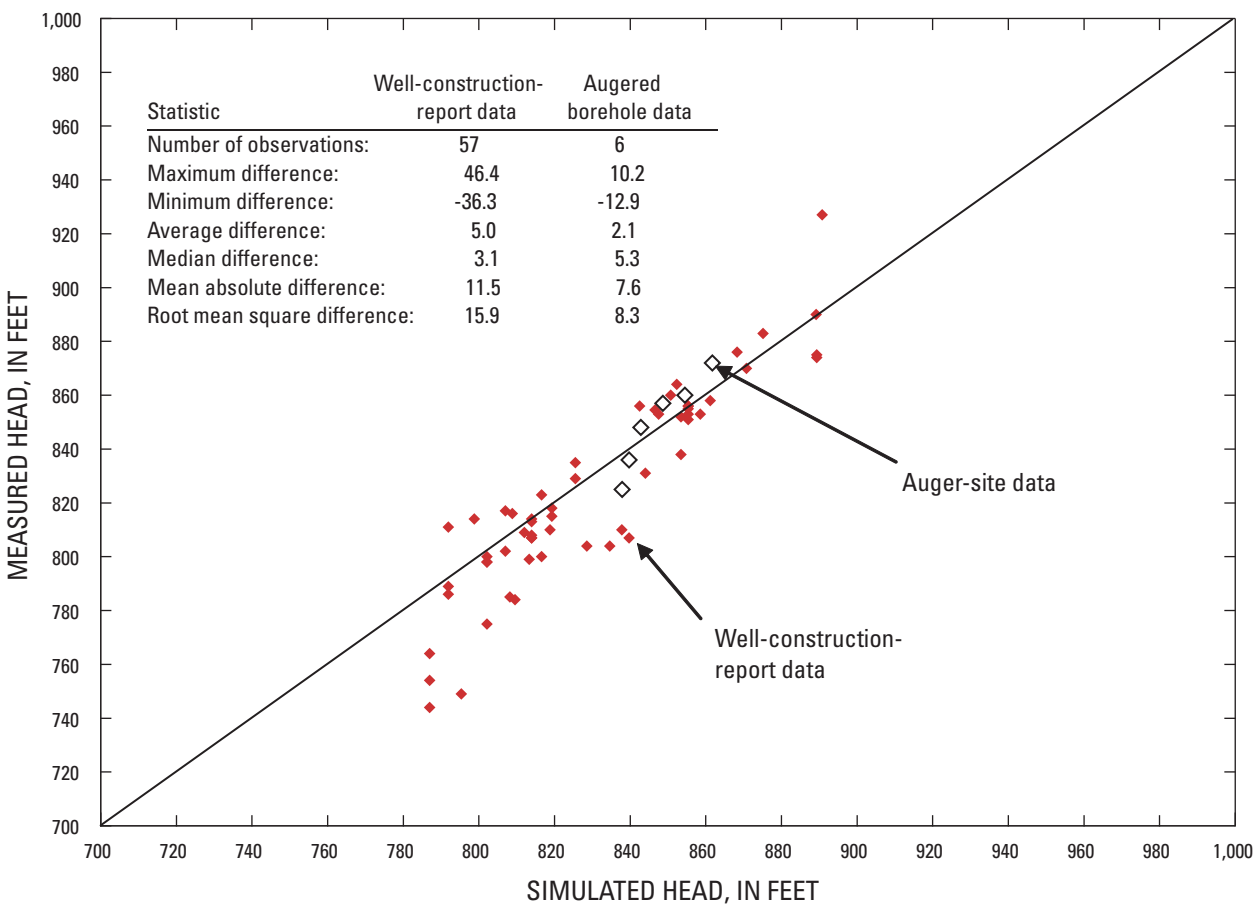

Figure 6. Model-calibration statistics, and model-simulated heads versus observed heads from well construction reports and augered boreholes, Jackson County, Wis.

than at the WCR targets. This is to be expected as the water levels measured in the auger holes were assigned a higher weight than those of the WCR targets. The head calibration is generally better in the Indian Mission/Sand Pillow area and poorer along the lower part of the Levis Creek watershed. This may be because of the inability of the model to simulate the steep vertical gradients close to the Black River or because of the recognized inaccuracy in the location of WCR head targets. Estimates of horizontal hydraulic conductivity based on grain-size profiles of returns from auger holes 1 and 3 range from about 10 to 20 ft/d (Appendix); this range includes the model calibrated value of horizontal conductivity (13 ft/d).

Calibrated simulated streamflows for Hay and Levis Creeks were between their estimated Q_{50} and Q_{80} targets (fig. 7); however, the simulated streamflow for Dickey Creek is greater than its estimated Q_{50} flow duration. The Q_{50} flow duration was assigned low weight in the calibration for Hay and Dickey Creeks, owing to the single target measurement they are based on. Undocumented water transfers between headwaters of Dickey and Morrison Creeks due to irrigation ditches also may contribute to model inaccuracies for Dickey Creek. However, the flux calibration for Levis Creek, which was measured on 15 occasions, falls intermediate to the estimated Q_{50} and Q_{80} flow durations even though the head calibration is poor along the lower part of Levis Creek.

Model Simulations and Particle Tracking

The calibrated model has been used to simulate the water-table elevation in the near field (fig. 8). The model simulates the composite aquifer (sand and gravel and sandstone) with a saturated thickness of between 100 and 150 ft in the vicinity of Indian Mission and Sand Pillow. The arrows indicate that ground-water flows from high ground-water elevation to lower elevation, eventually discharging to streams. The model simulates the interaction of ground water and surface water and allows estimation of the ground-water contribution to streamflow.

The contour map and arrows show that the source of ground water to wells in the vicinity of Sand Pillow is up gradient from the wells and recharges locally in an area between Levis and Dickey Creeks. Backward particle tracking, a feature of the GFLOW model, was used to delineate the contributing area for existing production well 5 and three newly constructed production wells (wells 6, 7, and 8). Ten water particles were tracked backwards for 20 years from the open interval of each simulated well. Thus, the particle paths delineate the 20-year contributing recharge areas for each well.

In the first simulation, production wells 6, 7, and 8 were each pumped at 50 gal/min (fig. 9A). In the second simulation, production wells 6, 7, and 8 *and* well 5 were each pumped

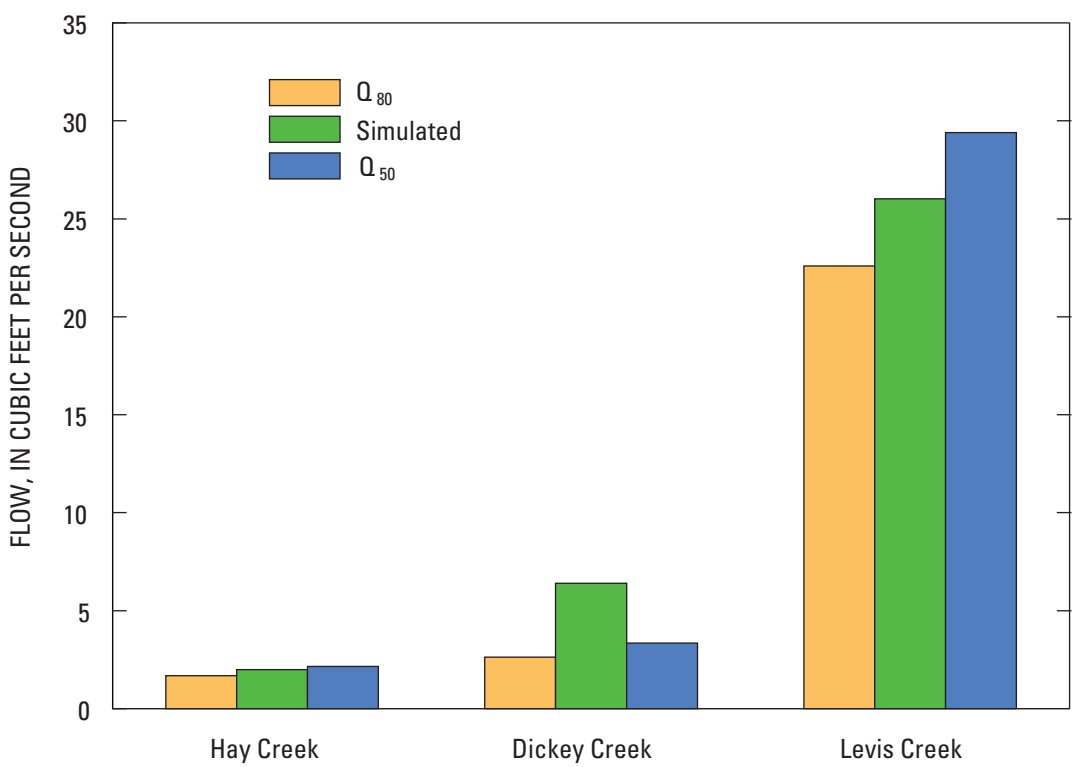

Figure 7. Estimates of flow-duration values and simulated flow for Hay, Dickey, and Levis Creeks, Jackson County, Wis.

at 50 gal/min (fig. 9B). The second simulation shows interference between contributing areas for well 5 and the new production wells; this underscores the importance of proper well placement and pumpage rates to avoid excessive drawdown from interference. This type of assessment is useful for wellhead-protection programs designed to protect drinking-water resources by controlling land-use activities within the contributing areas.

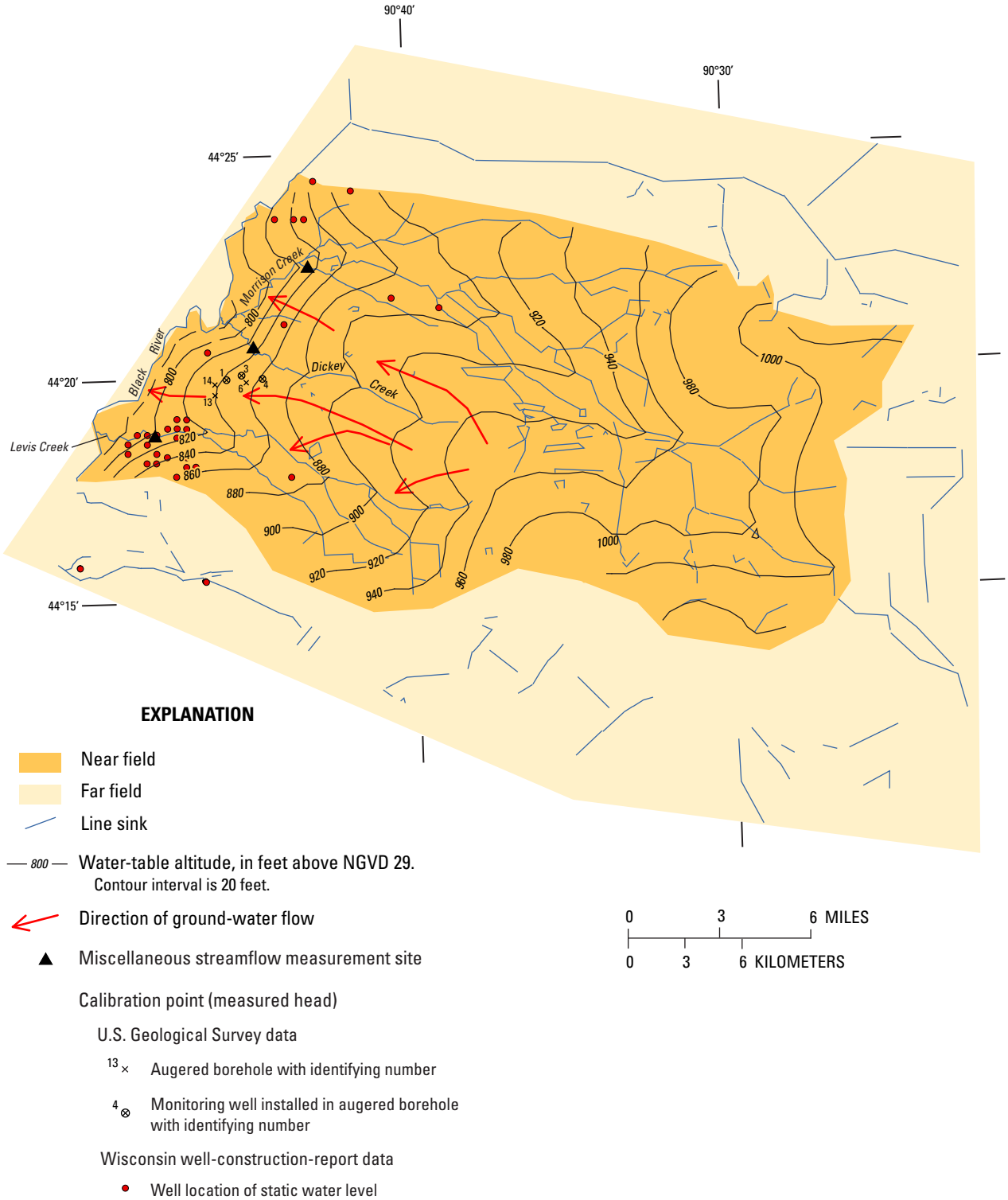

Figure 8. Simulated water-table surface and direction of ground-water flow, Jackson County, Wis. Also shown are analytical element model line sinks, near field, far field, and the location of wells, augered boreholes, and streamflow measurement sites used in calibration.

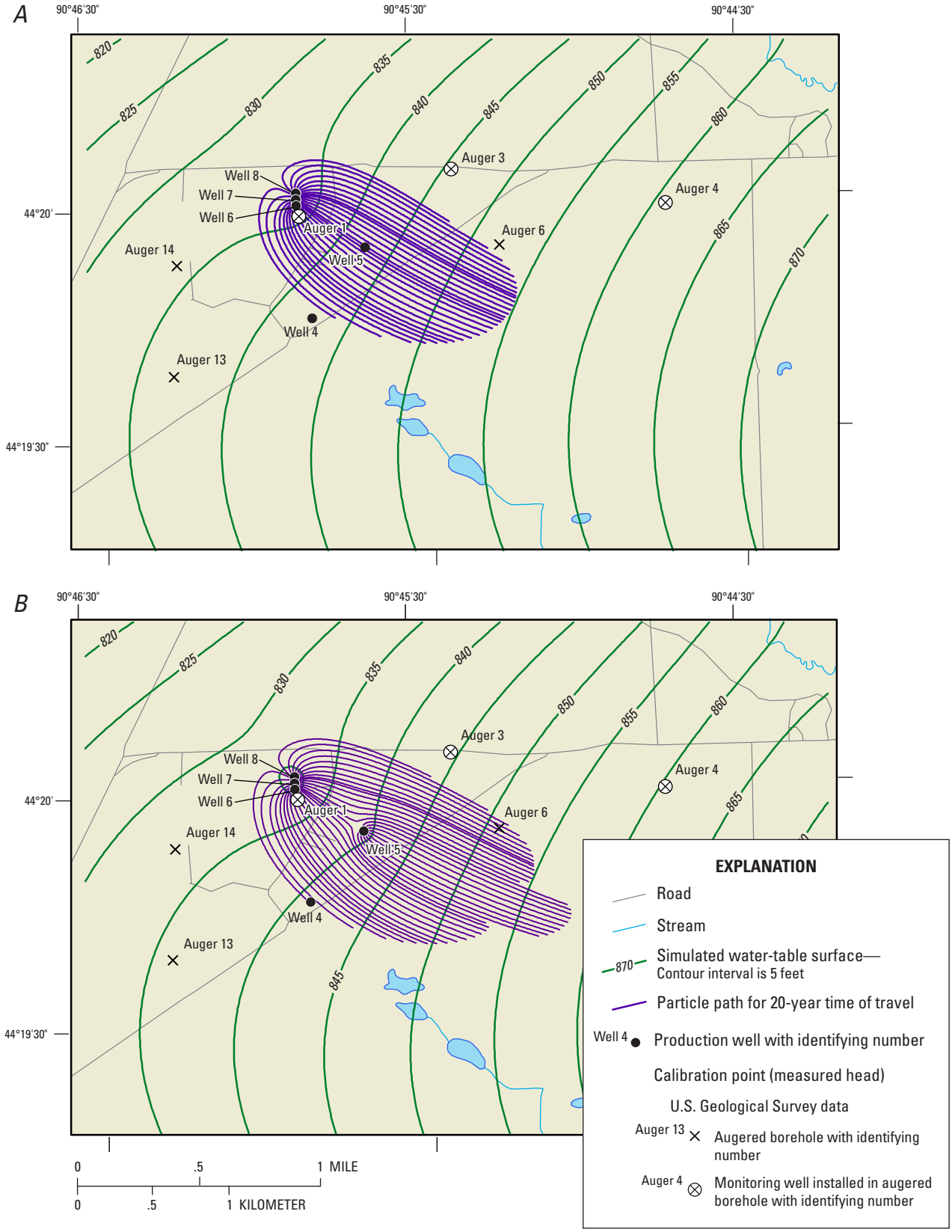

Figure 9. Twenty-year zones of contribution for new production wells 6, 7, and 8 pumping at 50 gallons per minute, Jackson County, Wis. (A, Without well 5 pumping. B, With well 5 pumping at 50 gallons per minute)

Model Limitations

As with any ground-water-flow model, the AE model constructed for the Indian Mission and Sand Pillow communities is a simplification of local hydrogeology, with proportional limitations on model precision and application. For instance, the AE model employs the Dupuit-Fochheimer approximation that assumes ground-water flow is horizontal; therefore, the model will not accurately represent the water table in areas where strong vertical gradients and/or flow are present, such as very near creeks and rivers. This is not believed to present a problem in addressing the questions of the Ho-Chunk Nation in the vicinity of the Indian Mission and Sand Pillow communities. The single-layer construct of the GFLOW model is an additional simplification; however, substantial additional lithologic data in the area of interest would be required to reasonably represent two aquifers (sand and gravel, and sandstone) of variable thickness.

In this single-layer model, the aquifer has been assigned uniform horizontal hydraulic conductivity, though significant variations in conductivity are suggested by the range of specific capacity reported in the WCRs. However, the spatial variability of specific capacity (and estimates of horizontal hydraulic conductivity) was not sufficiently defined to be incorporated into the model. Therefore, this model provides a basis for only general conclusions about ground-water flow across the area. The evaluation of site-specific questions would likely require additional hydrogeologic information and refinement of the model.

The available calibration data set (water levels and streamflow) was relatively modest. Only six of 63 water levels used during calibration were collected as part of this study. These six were the six of eight auger boreholes that encountered the water table; these levels were located by GPS and measured by USGS scientists specifically in the area of interest over just a few-day period. Hence, these six water-level targets were given greater weight during calibration. The remaining 57 water levels were given lesser weight during calibration because each measurement was taken at a different time over a period of many years, and because of lower confidence in the location and ground elevation datum of the wells. The topographic relief in the area of the ground-water-level measurements is about 100 feet; hence, location uncertainty (nearest quarter/quarter section for the Well Construction Reports) can result in greater uncertainty in ground-level, and water-level elevations. Flows measured in local creeks during the late 1960s to early 1970s had to be adjusted for use as calibration targets based on flow data at a long-term USGS streamgage 65 miles away. The adjustments made were to account for measurements taken during non-base-flow conditions and the observed increase in base flow over the last 35 years (regional and state-wide). Model uncertainty could be reduced by collecting synoptic, local base-flow data to provide calibration flow targets with a higher degree of confidence.

The porosity value assumed for the composite aquifer is a controlling factor in the simulated traveltime for the (mathematical) water particles tracked backward from well locations to define the ground-water contributing areas. An assumed porosity greater than 20 percent would decrease the distance traveled by particles over a given time, and an assumed porosity less than 20 percent would increase the distance traveled. However, over the range of reasonable porosity values (15–25 percent), the difference in distance traveled is small (plus or minus 25 percent of the distance traveled at 20 percent porosity).

Summary

Ground-water demand is expected to increase for the Ho-Chunk Nation Communities of Indian Mission and Sand Pillow, Jackson County, Wis. The U.S. Geological Survey, in cooperation with the Ho-Chunk Nation, completed a ground-water study that included review of published interpretive reports, review of well-construction reports and historical streamflow measurements, and an exploratory augering program. On the basis of the reviewed and new data, a conceptual model was formed of the ground-water system and was incorporated into an analytic element ground-water-flow model constructed using the GFLOW code. The near field of the analytic-element model includes the watersheds of Morrison and Levis Creeks. The model was used to simulate ground-water levels and to determine the directions of ground-water flow in the vicinity of Indian Mission and Sand Pillow.

The conceptualized ground-water system includes a composite aquifer of sand and gravel, and Cambrian sandstone that overlies Precambrian crystalline rock. On the basis of the review of 184 well-construction reports, the thickness of sand and gravel is thought to be highly variable. In the Indian Mission and Sand Pillow area, the maximum thickness of sand and gravel is 150 ft, but sand and gravel are absent or very thin at sites such as Indian Mission wells 1 and 2. The geometric mean value of horizontal hydraulic conductivity estimated from specific-capacity data is much higher for wells open to sand and gravel (63.1 ft per day) than for wells open to sandstone (6.6 ft per day). The geometric mean horizontal hydraulic conductivity for the composite aquifer is 12.0 ft per day. Ground-water levels are close to land surface near surface-water features such as lakes and streams and more than 50 ft below land surface in areas of increased topographic relief.

The model was calibrated to ground-water levels and streamflow. Well-construction reports provided 57 ground-water levels, and the exploratory augering provided 6 additional water levels. Streamflow measurements made in the late 1960s to early 1970s were available for Levis Creek (15 measurements) and Hay and Dickey Creeks (1 measurement each); the latter two are tributaries of Morrison Creek. These measurements were correlated to a continuous-recording streamgage to estimate flow duration for the period 1993–2003.

Estimated Q_{50} flow durations (the median discharge from 1993 to 2003) of 2.2, 3.4, and 29.4 ft^3/s for Hay, Dickey, and Levis Creeks, respectively, were used to calibrate the model.

The ground-water-flow model was coupled to the parameter-estimation program UCODE to obtain a best fit between simulated and measured values of ground-water levels and estimated Q_{50} flow duration (base flow). On average, simulated heads from the model were within 5 ft of the measured water levels. The base-flow calibration for Hay, Dickey, and Levis Creeks was acceptable and was particularly close for Levis Creek, which was the most frequently measured stream in the study area. Calibrated model results indicate a ground-water recharge rate of 9 inches per year and a horizontal hydraulic conductivity of 13 ft per day for the composite aquifer.

The model was used to simulate ground-water levels and to determine the direction of ground-water flow in the vicinity of Indian Mission and Sand Pillow. Backward particle tracking was conducted for existing production well 5, and three new production wells (well 6, 7, and 8) to determine contributing areas for each. Ten particles were placed at the bottom of each simulated well and tracked backwards for 20 years. In the first simulation, production wells 6, 7, and 8 were each pumped at 50 gal/min (fig. 9A). In the second simulation, production wells 6, 7, and 8 *and* well 5 were each pumped at 50 gal/min (fig. 9B). The second simulation demonstrated interference between well 5 and the new production wells; this underscores the importance of proper well placement to avoid excessive drawdown from well interference.

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References

Bradbury, K.R., and Rothschild, E.R., 1985, A computerized technique for estimating the hydraulic conductivity of aquifers from specific capacity data: Ground Water, v. 23, no. 2, p. 240–246.

Earth Tech, Inc., 2000, Wellhead protection area study, Indian Mission-Sand Pillow, Jackson County, Wisconsin: 5 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N. J., Prentice-Hall, 604 p.

Gebert, W.A. and Krug, W.R., 1996. Streamflow trends in Wisconsin's Driftless Area: Water Resources Bulletin, v. 32, no. 4, p. 733–744.

Hadley, D.W., and Pelham, J.H., 1978, Glacial deposits of Wisconsin: sand and gravel resource potential, State Map 10, Scale 1:500,000.

Haitjema, H.M., 1995, Analytic element modeling of groundwater flow: San Diego, Calif., Academic Press, 394 p.

Hunt, R.J., Graczyk, D.J., and Rose, W.J., 2000, Water flows in the Necedah Wildlife Refuge: U.S. Geological Survey Fact Sheet FS–068–00, 4 p.

Hunt, R.J., Saad, D.A., and Chapel, D.M., 2003, Numerical simulation of ground-water flow in La Crosse County, Wisconsin, and into nearby pools of the Mississippi River: U.S. Geological Survey Water-Resources Investigations Report 03–4154, 36 p.

Hunt, R.J., Anderson, M.P., and Kelson, V.A., 1998, Improving a complex finite difference groundwater-flow model through the use of an analytic element screening model, Ground Water, v. 36, no. 6, p.1011–1017.

Hunt, R.J., and Krohelski, J.T., 1996, The application of an analytic element model to investigate groundwater-lake interactions at Pretty Lake, Wisconsin, Journal of Lakes and Reservoir Management, v. 12, no. 4, p. 487–495.

Holmstrom, B.K., 1979, Low-flow characteristics of Wisconsin streams at sewage-treatment plants and industrial plants: U.S. Geological Survey Water-Resources Investigations 79–31, 123 p.

Indian Health Service, Rhinelander District Office, 2002, Preliminary engineering report, Improvements to the Indian Mission–Sand Pillow Water System, Ho-Chunk Nation, WI.

Krohelski, J.T., Bradbury, K.R., Hunt, R.J. and, Swanson, S.K., 2000, Numerical simulation of groundwater flow in Dane County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 98, 31 p.

Magnuson, J.J., Krohelski, J.T., Kunkel, K.E., and Robertson, D.M., 2003. Wisconsin's waters and climate—Historical changes and possible futures: Wisconsin Academy of Arts, Science, and Letters Transactions, v. 90, p. 23–36.

Mitchell-Bruker, Sherry, and Haitjema, H.M., 1996, Modeling steady state conjunctive groundwater and surface water flow with analytic elements: Water Resources Research, v. 32, no. 9, p. 2725–2732.

Poeter, E.P., and Hill, M.C., 1998, Documentation of UCODE, a computer code for universal inverse modeling: U.S. Geological Survey Water-Resources Investigations Report 98–4080, 116 p.

Strack, O.D.L., 1989, Groundwater mechanics: Englewood Cliffs, N.J., Prentice Hall, 732 p.

Young, H.L., and Borman, R.G., 1973, Water resources of Wisconsin, Trempealeau-Black River Basin: U.S. Geological Survey Hydrologic Investigations Atlas HA–474, 4 sheets.

Appendix. Supplemental Data From Exploratory Augering

A program of exploratory augering was conducted to help water-resources managers determine the best sites for future community wells. Fourteen sites were chosen for augering; however, after field reconnaissance, six of these sites were eliminated because of poor access or other reasons such as proximity to crystalline bedrock. The eight sites at which exploratory augering was conducted are shown on appendix figure 1-1. The stratigraphic descriptions from auger returns and depth to water are provided in appendix table 1-1. Note that at auger locations 7 and 12, water levels could not be determined. Monitor wells were installed at auger sites 1, 3, and 4. The details of construction of the monitor wells are listed in appendix table 1-1. Particle-size analysis was conducted at selected intervals from auger returns at auger sites 1 and 3 (appendix table 1-2).

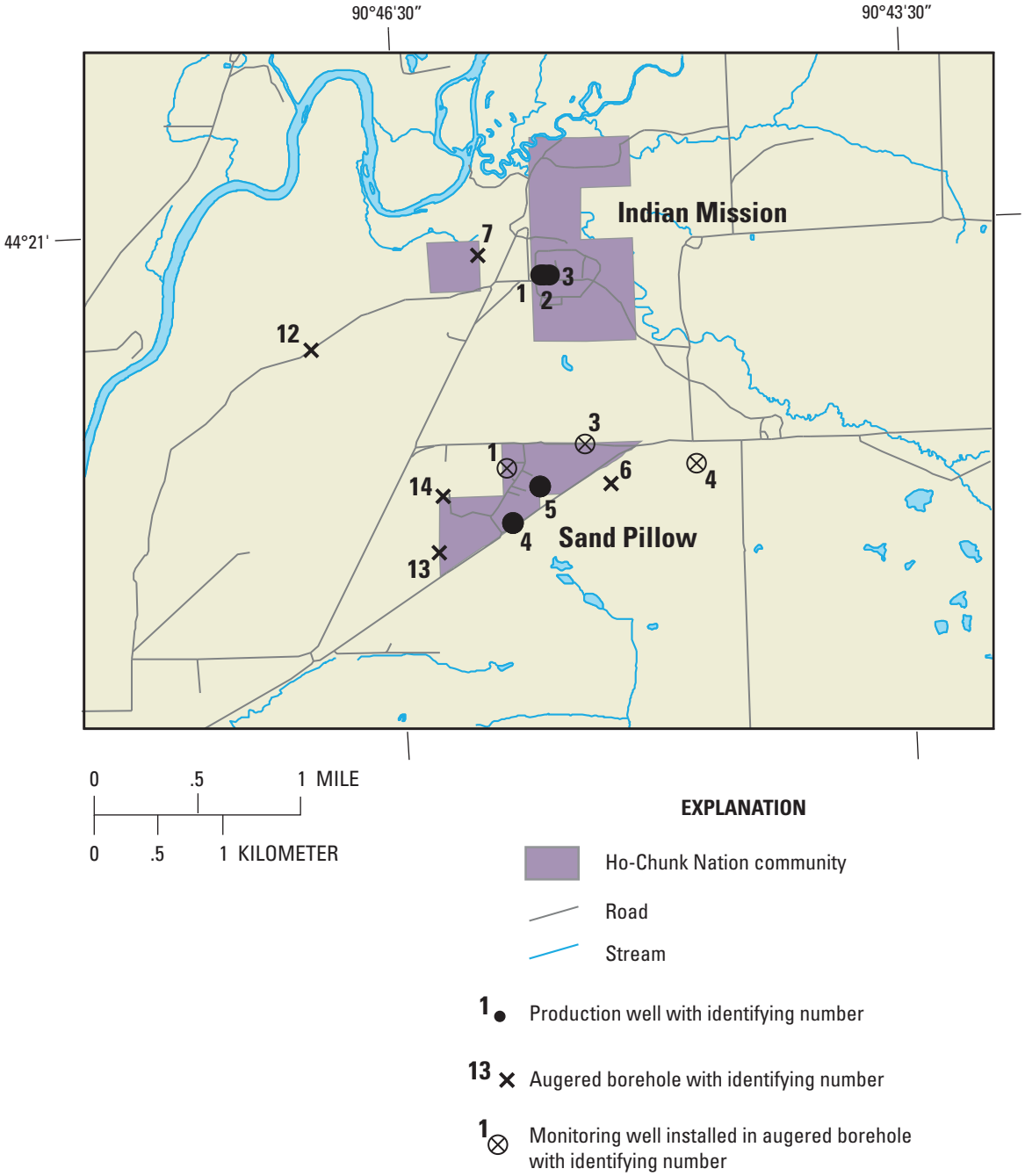

Figure A1. Location of Indian Mission and Sand Pillow production wells and augered boreholes, Jackson County, Wisconsin.

Appendix table 1-1. Summary of data collected at auger locations on Ho-Chunk Nation land in Jackson County, Wis.

Auger Location 1 (off Low Cloud Road)	N 44° 19' 59.6" W 90° 45' 53.4"
Auger investigation 10/14/03	
Total depth of hole	105 ft below ground level (bgl)
Static water-level	37.3 ft bgl
Auger returns	
0–5 ft	No soil, very light brown sand, sucrosic, fine- to medium-grained, uniform, well-sorted, no pebbles.
5–10 ft	Same uniform sand, slightly darker brown (still light) with bit of red, some darker grains, well-sorted.
10–35 ft	Medium-dark brown sand, fine- to coarse-grained sand, common dark grains, common igneous pebbles up to 0.5 in, 15-35 ft a little darker than 10-15 ft, sand-sized fraction is moderately well sorted.
35–105 ft	Fine- to medium-grained sand, medium dark red brown at 35 ft, lightens in color progressively to about 65 ft, below 65 ft no red color, clean sand, no pebbles or dark grains.
Sediment on pulled augers 85–105 ft	
Indications that clay was being cut the last 20 ft of the auger hole. Soft plastic gray clay upper 10 ft. Very hard whitish clay with red and green streaks lower 10 ft. Sand returns appear to have largely been coming from above 90 ft.	
Installation of monitoring well 10/16/03	
Total depth of hole	77 ft below ground level (bgl)
Total depth of monitoring well	77 ft bgl
Diameter of monitoring well	2 in.
Length of screen	9.9 ft
Material surrounding screen	Collapsed native material – fine- to coarse-grained sand, possibility of some silty sand in the screen interval
Up-hole completion	Collapsed native material to water table, shoveled native backfill, then 7 bags 3/8 in. bentonite chips, 10 bags quick grout, ½ bag chips to about 2 ft bgl. Sand fill added to seat protective casing. Locking well cap under flush-mount protective casing.
Static water-level	38.1 ft bgl.
Top of PVC	Top of PVC is 0.3 ft bgl.

Appendix table 1-1. Summary of data collected at auger locations on Ho-Chunk Nation land in Jackson County, Wis.—Continued

Auger Location 3 (along Sand Pillow Road) N 44° 20' 04.7" W 90° 45' 25.0"

Auger investigation 10/14/03

Total depth of hole	80 ft below ground level (bgl)
Static water-level	23.4 ft bgl
Auger Returns	
0–5 ft	Clean, light brown sand, fine- to medium-grained, well-sorted, sucrosic, no soil, no pebbles.
5–10 ft	Clean, darker brown sand, fine- to medium-grained, presence of darker grains, well-sorted, no pebbles.
10–15 ft	Sand as above, with abundant dark/igneous pebbles up to 1.0 in.
15–20 ft	Sand as above, larger pebbles not present, abundant smaller pebbles and coarse-sand-sized igneous grains, modrately well-sorted.
20–25 ft	Clean, orange-brown sand, fine- to medium-grained, abundant mafic/igneous pebbles up to 0.75 in.
25–40 ft	Orange brown, medium- to coarse-grained sand, abundant igneous pebbles up to 0.5 in. and coarse grains.
40–80 ft	Medium-light brown, fine- to medium-grained sand, uniform, well-sorted, occasional small (0.1 in) igneous pebbles; color lightens with depth to very-light brown sand with rare igneous grains.

Sediment on pulled augers 75-80 ft

Very clean, fine to medium sand, well-sorted, abundant pebbles up to 0.5 in., very light brown, no sign of iron staining, no indication of fines or clay.

Installation of monitoring well 10/16/03

Total depth of hole	97 ft below ground level (bgl)
Auger returns	
80–97 ft	Very light brown, fine- to medium-grained sand, uniform, well-sorted, rare mafic grains.

Sediment on pulled augers 95–97 ft

Very- to medium-light brown sand, fine- to medium-grained, some silt/clay

Total depth of monitoring well	97 ft bgl
Diameter of monitoring well	2 in
Length of screen	9.9 ft
Material surrounding screen	Collapsed native material – fine to coarse-grained sand
Up-hole completion	Collapsed native material to water table, fill with 16 bags 3/8 in bentonite chips to about 2 ft bgl. Sand fill added to seat protective casing. Locking well cap under flush-mount protective casing.
Static water-level	23.3 ft bgl
Top of PVC	Top of PVC is 0.35 ft bgl

Appendix table 1-1. Summary of data collected at auger locations on Ho-Chunk Nation land in Jackson County, Wis.—Continued

Auger Location 4 (off of State Highway 54)	N 44° 19' 59.3" W 9° 44' 45.3"
Auger investigation 10/15/03	
Total depth of hole	110 ft below ground level (bgl)
Static water-level	14.5 ft bgl
Auger returns	
0–20 ft	Fine- to medium-grained sand, very light brown (5-10 ft slight orange tint, 15-20 ft slightly darker brown), well-sorted, sucrosic texture.
20–30 ft	Fine- to coarse-grained sand, medium-brown, red and black coarser grains common, moderately well sorted.
30–50 ft	Fine- to coarse-grained sand, medium-dark brown, well-sorted, abundant red and black coarse grains, small red and black igneous pebbles, uniform over the 20 ft.
50–110 ft	Fine- to coarse-grained sand, color lightens from medium brown to very light brown, rare small black igneous pebbles.
Sediment on pulled augers 100–110 ft	
Dark gray clay with abundant sand, common small igneous pebbles, clay becomes greenish at bit end.	
Installation of monitoring well 10/15/03	
Total depth of hole	110 ft below ground level (bgl)
Total depth of monitoring well	82 ft bgl
Diameter of monitoring well	1 in
Length of screen	5 ft
Material surrounding screen	Collapsed native material – fine- to coarse-grained sand
Up-hole completion	Collapsed native material to wate table, shoveled native backfill, then bentonite to 2 ft bgl. Sand fill added to seat protective casing. Locking well cap under flush-mount protective casing.
Static water-level	13.4 ft bgl
Top of PVC	Top of PVC is 0.40 ft bgl

Appendix table 1-1. Summary of data collected at auger locations on Ho-Chunk Nation land in Jackson County, Wis.—Continued

Auger Location 6 (South of Hwy 54)	N 44° 19' 54.6" W 90° 45' 15.8"
Auger investigation 10/13/03	
Total depth of hole	70 ft below ground level (bgl) Believe sandstone bedrock was hit – auger refusal and hard drilling
Static water-level	19.9 ft bg
Auger Returns	
0–5 ft	Medium- to coarse-grained sand, light brown, no soil, moderately well sorted, sucrosic texture.
5–15 ft	Fine- to medium-grained sand, very light-brown, well-sorted, sucrosic texture.
15–20 ft	Fine- to medium-grained sand, light-brown, well to moderately well sorted, sucrosic texture.
20–30 ft	Medium- to coarse-grained sand, med-brown sand, occasional igneous pebbles up to 1.0 in.
30–50 ft	Medium- to coarse-grained sand, medium brown, abundant black and red sand grains, occasional igneous pebbles up to 1.0 in.
50–70 ft	As above, some silt-sized fraction, abundant black and red sand grains, occasional small igneous pebbles.
Sediment on pulled augers 50–70 ft	
50–65 ft - generally reddish sand with lots of silt and clay, some significant clay layers. 65–70 ft - plastic green/red/brown clay, very stiff and hard with reddish sand, abundant small black pebbles; clay at bottom contains sandstone fragments.	

Appendix table 1-1. Summary of data collected at auger locations on Ho-Chunk Nation land in Jackson County, Wis.—Continued

Auger Location 7 (Lot in new development)	N 44° 20' 50.5" W 90° 46' 11.2"
Auger investigation 10/15/03	
Total depth of hole	110 ft below ground level (bgl) Resistance and harder drilling beginning about 107 ft.
Static water-level	Could not push piezometer below 75 ft, no water in piezometer, on pulled augers, indication of water beginning at 95 or 100 ft bgl.
Auger returns	
0–5 ft	Medium brown sand, fine- to medium-grained, very uniform, well-sorted, sucrosic, no pebbles.
5–20 ft	Same texture as above, but lighter brown in color.
20–25 ft	Brown sand, darker than 0-5 ft, fine- to coarse-grained (coarse is less common fraction), some silty fraction.
25– 45 ft	Same sand as 20-25 ft with abundant pebbles 25-30 ft up to 1.0 in. Pebble size and abundance decreasing to 45 ft, abundant dark grains in medium to coarse-grained fraction and small pebbles.
45–55 ft	Fine- to coarse-grained brown sand, skewed toward coarse fraction, abundant dark and red coarse grains, small pebbles.
55–95 ft	Fine- to coarse-grained sand, coarse fraction decreasing with depth, black and red fraction decreasing with depth, color changing from medium brown to light brown with depth.
95–110 ft	Continued lightening in color to very light brown. Sucrosic texture, medium-grained, some coarse fraction, common black sand grains.
Sediment on pulled augers	
Plastic greenish clay scraped from bit.	

Appendix table 1-1. Summary of data collected at auger locations on Ho-Chunk Nation land in Jackson County, Wis.—Continued

Auger Location 12 (Along West Bottom Road) N 44° 20' 30.1" W 90° 46' 59.9"

Auger investigation 10/15/03

Total depth of hole	110 ft below ground level (bgl)
Static water-level	Could not push piezometer below 56 ft, no water in piezometer after 30 minutes, water level > 56 ft bgl.
Auger returns	
0–25 ft	Fine- to medium-grained sand, very light brown (blond), well-sorted, no pebbles, sucrosic texture, slight orange tint 5-10 ft.
25–30 ft	Fine- to medium-grained sand, darker orange brown, abundant pebbles, generally rounded, igneous, up to 1.0 in, sand fraction generally well sorted.
30–50 ft	Fine- to coarse-grained sand, medium-brown, moderately well sorted, abundant red and black coarse grains, common pebbles, small up to 1.5 in.
50–65 ft	Fine- to coarse-grained medium-brown sand, progressively lighter in color with a bit more orange, pebbles still present though mostly larger, fewer small pebbles, common black coarse grains.
65–110 ft	Medium- to coarse-grained sand, light brown. Common red, black coarse grains, well-sorted, progressively lighter color to 110 ft becoming very light brown (blond), no pebbles.

Sediment on pulled augers

Last two or three (107–110) ft held very coarse sand that was very orange in color.

Auger Location 13 (SW of Majestic Pines Casino) N 44° 19' 35.2" W 90° 46' 13.8"

Auger investigation 10/13/03

Total depth of hole	80 ft below ground level (bgl)
	Driller estimates sandstone bedrock at about 72 ft bgl
Static water-level	35.8 ft bg
Auger returns	
0–5 ft	Light-brown, fine- to medium-grained sand, sucrosic texture, no soil, very uniform, no apparent fines, well-sorted.
5–20 ft	Darker brown sucrosic sand, fine- to medium-grained, abundant igneous pebbles up to 1.0 in., angular to rounded.
20–25 ft	Slightly lighter brown, slightly reddish, sand, well-sorted, sucrosic, fine- to medium-grained, none of the larger pebbles, rare smaller pebbles.
25– 65 ft	Similar to 20-25 ft but becomes progressively lighter in color though maintaining reddish tint. Rare small igneous pebbles.
65– 80 ft	Same fine- to medium-grained sand, well-sorted, slightly more orange color. Increasing fines to 80 ft, no clay encountered.

Sediment on pulled augers

Almost the entire length of auger string carrying orange-brown sand with minor silt and clay, not sticking to augers. Last flight (75-80 ft) has very light colored sand and sandstone incorporated in orange, rusty-colored sand.

Appendix table 1-1. Summary of data collected at auger locations on Ho-Chunk Nation land in Jackson County, Wis.—Continued

Auger Location 14 (NW of Majestic Pines Casino)	N 44° 19' 51.9" W 90° 46' 12.4"
Auger investigation 10/14/03	
Total depth of hole	100 ft below ground level (bgl)
	Tighter drilling beginning at 93 ft
Static water-level	46.9 ft bgl
Auger returns	
0–5 ft	Fine- to medium- sand, well-sorted, light brown, slightly orange, uniform, no pebbles, some soil.
5–10 ft	Sand as above, but very light brown (blond), not orange brown as above.
10–15 ft	Medium-dark brown sand, hint of orange, fine- to medium-grained, abundant igneous pebbles up to 1.0 in. Small mafic clasts, coarse sand-sized grains.
15–30 ft	Medium-dark-brown sand, no hint of orange, occasional pebbles up to 1.0 in., fine- to coarse-grained, moderately well sorted.
30–45 ft	Transition to more uniform, fine- to medium-grained sand, medium-dark brown, no pebbles, well-sorted.
45–70 ft	Same fine- to medium-grained sand, uniform, well-sorted, medium-dark brown at 45 ft, progressive lightening of color with depth.
70–90 ft	Fine- to medium-grained sand, continued lightening of color to very light brown.
90–100 ft	Fine- to medium-grained sand, very light brown sand to blond, no pebbles, well-sorted.
Sediment on pulled augers 95–100 ft	
Clay present on lower auger and bit.	
Abandonment	Collapsed native material to water table, shoveled native backfill to about 5 ft bgl, then 1+ bag of quick grout to surface.

Appendix table 1-2 Particle-size analysis from samples collected at auger sites 1 and 3.

		Particle Size Distribution, divisions in micrometers, Weight in grams								*Hazen Estimate of K**		
Description	**Depth**	**2000**	**1000**	**500**	**250**	**125**	**63**	**pan**	**TOTAL**	***D_{10} cm***	***K cm/s***	***K ft/d***
Sand Pillow Auger Location 1	80-85	3	2	35	92	50	10	1	193	0.0085	0.0072	20.5
Sand Pillow Auger Location 1	75-80	1	3	55	130	61	16	2	268	0.0075	0.0056	15.9
Sand Pillow Auger Location 1	70-75	3	5	66	114	58	17	3	266	0.0080	0.0064	18.1
Sand Pillow Auger Location 1	65-70	1	5	90	121	70	28	5	320	0.0060	0.0036	10.2
Sand Pillow Auger Location 3	95-100	1	8	121	173	69	22	5	399	0.0075	0.0056	15.9
Sand Pillow Auger Location 3	90-95	1	13	146	163	62	28	7	420	0.0065	0.0042	12.0
Sand Pillow Auger Location 3	85-90	0	13	144	200	79	25	7	468	0.0075	0.0056	15.9
Sand Pillow Auger Location 3	80-85	1	7	88	151	68	23	5	343	0.0065	0.0042	12.0

* Hazen Equation to estimate horizontal hydraulic conductivity from Particle Size Distribution

$$K = C(D_{10})^2$$

where:
K = hydraulic conductivity (cm/sec)
C = 0.4 to 1.2, typically 1.0 in sands
D_{10}= particle size of 10% passing (cm)

Hazen A, 1893, Some physical properties of sands and gravels, Massachusetts State Board of Health, 24th Annual Report.

Prepared by the Wisconsin Water Science Center:
U.S. Geological Survey
Wisconsin Water Science Center
8505 Research Way
Middleton, WI 53562
tel: (608) 828-9901
fax: (608) 821-3817

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