Evaluation of Groundwater and Surface Water Conditions in the Vicinity of Well PW-101, Osceola County, Michigan

Σ²Π S.S. PAPADOPULOS & ASSOCIATES, INC.
Environmental & Water-Resource Consultants

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7944 Wisconsin Avenue, Bethesda, Maryland 20814-3620 • (301) 718-8900

Table of Contents

Page

Figures

Tables

List of Figures

List of Tables

REPORT

Section 1
Introduction

This report describes an evaluation of the effects of increasing the withdrawal rate of well PW-101 at the White Pine Springs Site in Osceola County, Michigan. Well PW-101 is operated by Nestlé Waters North America (NWNA) and the water withdrawn from the well is used by NWNA for bottled water production. An increase in the maximum withdrawal rate from a baseline of 150 gpm to 250 gpm was registered with the Michigan Department of Environmental Quality (MDEQ) in April 2015, and an increase in the maximum withdrawal rate from 250 gpm to 400 gpm was registered by the MDEQ in January 2016[1].

Since the total authorized increase in the withdrawal rate above the baseline is greater than 200,000 gallons per day (increase from a baseline of 150 gpm to 400 gpm), NWNA is submitting an application under Section 17(3) of the Safe Drinking Water Act (SDWA) that contains an evaluation of environmental, hydrological and hydrogeological conditions that exist and the predicted effects of the intended increase in withdrawal. This report describes in detail the surface water and groundwater conditions in the vicinity of PW-101; describes a groundwater model that was developed to evaluate the effect of the increase in withdrawal on surface water flows, springs flows, and groundwater levels; and describes the potential effects of the increase in withdrawal on surface water and groundwater resources.

Extensive site-specific surface water and groundwater data are available in the vicinity of PW-101 from the hydrological and hydrogeological investigations which have been conducted by NWNA. Thirty-nine groundwater monitoring wells and 54 drive points have been installed, and a stream-gaging system was established. Monitoring of groundwater levels and surface water flows and levels began in 2000 and continues to date. A nine-day aquifer test was conducted at PW-101 in June 2001. These extensive data provide the foundation for the description of the hydrological and hydrogeological conditions in the vicinity of PW-101 in this report.

The conceptual model of the groundwater and surface water systems in the vicinity of PW-101 is described in the next section. The groundwater flow model structure and model parameters are described in Section 3 and model calibration is described in Section 4. Section 5 describes the sensitivity of model parameters and Section 6 describes the groundwater basins for the upper portions of Twin Creek and Chippewa Creek. The results of the surface water and groundwater assessments that were conducted using the groundwater flow model are described in Section 7, and references cited in the report are listed in Section 8.

[1] The Michigan Water Withdrawal Registration ID for PW-101 for a capacity of 400 gpm is #4125-201512-31. This withdrawal was registered following a Site-Specific Review (SSR) by the MDEQ. The SSR is summarized in a letter from James F. Milne, MDEQ, to Arlene Anderson-Vincent, NWNA, dated January 5, 2016.

Section 2
Conceptual Model of Groundwater and Surface Water System

This section describes the regional setting and groundwater and surface water systems in the vicinity of PW-101 and the relationship between groundwater and surface water flows in the vicinity of PW-101.

Regional Setting

Well PW-101 is located in south-central Osceola County, Michigan, approximately 2.5 miles northwest of the city of Evart. The location of this well is shown on Figure 1. This well is screened from 94 to 181 feet below ground surface (BGS). The area surrounding the well is forested or agricultural land with a few residences. The area is characterized by gently rolling terrain at elevations between 1,000 feet above mean sea level (MSL) along the Muskegon River to about 1,500 feet above MSL in the upland areas north of PW-101, and by a number of springs and seeps that occur in the headwaters of Twin Creek and Chippewa Creek.

The study area for this analysis, which is also referred to as the model area, encompasses a 50-square mile area that includes the recharge areas and discharge areas for groundwater that flows in the vicinity of production well PW-101 (Figure 1). The model area was defined on the basis of surface watershed boundaries and it encompasses the entire Twin Creek and Chippewa Creek watersheds as well as adjacent watersheds of small tributaries of the Muskegon River. The reasonableness of the model area was verified by developing a groundwater level map of the area (Figure 2a). Water level data were obtained from static-water level measurements from the MDEQ Statewide Groundwater Database for water supply wells in Osceola County. The groundwater level map illustrates that groundwater flow is approximately parallel to watershed boundaries, indicating that it is appropriate to use watershed boundaries in defining an area that includes both the recharge and discharge areas for groundwater in the vicinity of well PW-101.

The southern boundary of the model area is the Muskegon River, a regional groundwater discharge area. The western and northern boundaries of the model area follow watershed boundaries. The southern part of the western boundary is along a ridge east of Cat Creek, a tributary of the Muskegon River, and the rest of the western boundary corresponds to the western extent of the Twin Creek watershed. The western portion of the northern boundary corresponds with the northern boundary of the Twin Creek watershed and the remainder of the northern boundary corresponds with the boundaries of the watersheds of several small tributaries of the Muskegon River. The eastern boundary of the model area is a small-unnamed tributary of the Muskegon River that enters the river approximately 2.5 miles northeast of Evart. Beyond the model area to the northwest is the watershed of the Pine River, a tributary of the Manistee River. To the north of the model area is the watershed of the Middle Branch River, a tributary of the Muskegon River.

In the entire northwestern half of the model area, which is at an elevation of greater than about 1,150 feet above MSL, there are no perennial streams. Perennial streams are limited to Twin Creek, Chippewa Creek and a few other unnamed creeks near the Muskegon River with headwater elevations at about 1,150 feet above MSL or less. Numerous springs and seeps occur in the headwaters of each of these drainages. Most of the northwestern portion of the model area is forested and is a part of the Pere Marquette State Forest.

Geologic Setting

Osceola County lies near the center of the Michigan Basin. The Michigan Basin is an intracratonic synclinal structure, that is roughly circular in plan view and that underlies Michigan's Lower Peninsula. The sedimentary fill of the Michigan Basin exceeds 17,000 feet in thickness and ranges in age from Precambrian to Jurassic (Westjohn and Weaver, 1998). Glacial deposits overlie much of the Michigan Basin, and Pleistocene glaciofluvial deposits are the largest reservoir of fresh groundwater in Michigan (Westjohn and Weaver, 1998). In the southern portion of Osceola County, the glacial deposits overlie Jurassic "red beds", which act as a confining layer to the underlying Saginaw Aquifer (Westjohn and Weaver, 1998). North of the subcrop of the Jurassic "red beds" in Osceola County, the glacial deposits directly overlie the Pennsylvanian-age Grand River-Saginaw Formations.

In south-central Osceola County, the glacial drift is dominated by coarse-grained glacial till deposits and glaciofluvial deposits associated with outwash from two Wisconsinian-age glacial lobes: one to the east (the Saginaw), and one to the west (the Michigan). In the vicinity of PW-101, sand and gravel represent about 50 to 75 percent of the glacial deposits (Westjohn and Weaver, 1998).

In general, the glacial deposits of the Michigan Basin area thicken toward the north. Total thickness ranges from 0 feet (in areas of the Saginaw Lowlands) to ~900 feet in the northwestern part of the Lower Peninsula. The thickness of glacial deposits in the vicinity of PW-101 is about 500 to 600 feet (Michigan State University, 1981). The glacial deposits thicken towards the northwestern corner of Osceola County where they are greater than 800 feet thick. Most of the glacial deposits in Osceola County and the surrounding area are primarily glaciofluvial sediments not associated with terminal moraines, although their morphology suggests a morainal origin. Their deposition is likely associated with stagnation zone retreat rather than true end-moraines (Westjohn, et al., 1994).

The glacial deposits in the vicinity of PW-101 have been mapped as glacial outwash and postglacial alluvium, end moraines of coarse-textured glacial till, undifferentiated coarse-textured glacial till, and fine-textured glacial till (Farrand and Bell, 1982). The character and extent of the glacial deposits were evaluated further for this study by means of lithologic information from water supply wells in Osceola County, in combination with monitoring wells constructed in the vicinity of PW-101, and topographic features.

In the vicinity of PW-101, the more permeable glacial deposits generally occur within about 150 feet of the water table. Below these permeable deposits, a clay of glaciolacustrine or glacial origin exists that appears to be areally extensive at elevations of about 900 to 980 feet above MSL. Other permeable glacial fill deposits occur below this clay unit; however, this clay forms the base of the modeled aquifer system.

Four geologic units were identified within the model area as shown in Figure 3. Generalized geologic cross sections through the vicinity of PW-101 are presented in Figure 4. These geologic units were defined based upon site-specific and regional geologic and hydrogeologic information including lithologic, geologic, and hydrologic data, and topographic morphology. The data set was limited by the variability inherent in the lithologic descriptions provided in the driller's logs; however, general lithologic trends could be identified on a regional scale.

The geologic units that were defined are the following:

Eastern fine-grained sediments – The Eastern fine-grained sediments are located in a broad region along the eastern margin of the model area. The unit is characterized by thick sequences of clay or clayey deposits, some up to 200-feet thick, sometimes overlain by a thin mantle of 20 to 30 feet of sand or sand and gravel. The Eastern fine-grained sediments generally correlate with the fine-textured glacial till of Farrand and Bell (1982).

Fine-grained sediments of Twin and Chippewa Creeks – The fine-grained material underlying the valleys of Twin and Chippewa Creeks is characterized by a mixture of clayey and sandy deposits. The fine-grained material that extends into the Twin and Chippewa Creek valleys does not appear to be as thick as the unit to the east; however, the extent of the unit is distinguished by the presence of interlayered clayey and coarse-grained or sandy deposits, rather than thick sequences of clay within the upper 50 feet of sediments. The fine-grained sediments of Twin and Chippewa Creeks are mapped within the coarse-textured glacial till unit by Farrand and Bell (1982).

Undifferentiated Sands – The Undifferentiated Sand deposits are primarily sand, or sand and gravel, interlayered with varying thicknesses of clayey materials. The unit is defined based on the general absence of thick sequences of clay, and an abundance of sand or sand and gravel; however, due to the nature of the drillers' logs and variability in the sediments, the lithologic descriptions are highly variable. The unit is also characterized by an absence of spatial trends in the character of the sediments, and in places, the unit resembles the Coarse-grained Gravel and Sand deposits, described below. The Undifferentiated Sands also include the sandy deposits associated with the Muskegon River in the central and western portion of the model area. The Undifferentiated Sands generally correlate with the coarse-textured glacial till mapped by Farrand and Bell (1982). These sediments were deposited in the interlobate region between the Michigan and Saginaw lobes and consist of coarse-grained glacial till, that has been washed relatively free of fine-grained sediments.

Coarse-grained Gravel and Sand – These sediments are located in an elongated band north of the Muskegon River near Evart and they are characterized by gravel and sand sometimes exceeding 100 feet thick with very little or no clayey material. The deposits are in places similar to the Undifferentiated Sand deposits and the precise extent of this region is difficult to establish due to the lack of deeper wells and the brief lithologic descriptions provided in the drillers logs. The area outlined consists of thick sequences of gravel and sand; however, the unit may be more extensive than indicated on Figure 3. The majority of this unit is likely associated with glaciofluvial gravel deposits; however, the westernmost extent includes an upland area of coarse-grained glacial till not of glaciofluvial origin.

Groundwater Setting

The water table at PW-101 occurs at a depth of about 35 feet below the ground surface. The depth to groundwater increases to the northwest, and in the far northwestern portion of the model area the water table is estimated to be at a depth of over 200 feet. Groundwater recharge occurs from precipitation and discharge occurs at surface water features including springs, seeps, creeks, and the Muskegon River. Static water levels measured for individual wells in the region obtained from the MDEQ's Statewide Groundwater Database are shown in Figure 2a. The general direction of regional groundwater flow is from the upland areas, southeast towards the Muskegon River. The regional ground water levels and direction of groundwater flow also demonstrate that the model area, as shown on Figure 2a, captures the groundwater flow system that contributes to the Twin and Chippewa Creek drainages and the associated spring and seep discharge areas.

Groundwater flow in the water-table aquifer in the vicinity of PW-101 is generally toward the south. A water-table map developed from groundwater level measurements taken on August 7, 2012 is shown on Figure 2b. This water-table map is representative of water-table conditions that have been observed since monitoring began in the vicinity of PW-101. Also shown on Figure 2b are hydrographs of two representative monitoring wells, MW-107d and MW-110d, showing water level fluctuations during the period 2001 through October 2015. Water levels at both of these monitoring wells fluctuated over a range of about three feet during this 15-year period. The hydraulic gradient between MW-107d and MW-110d, which are located about 2,300 feet apart, has been relatively constant during this time period at about 0.0058 feet/feet (range of 0.0057 to 0.0059). The water level differences between MW-107d and MW-110d during the 15-year monitoring period are shown on the upper insert graph on Figure 2b. The groundwater flow rate in the water-table aquifer, based on this estimate of the hydraulic gradient and an aquifer transmissivity of 8,100 ft^2/day (discussed below), is about 1,300 gpm per mile width of the aquifer.

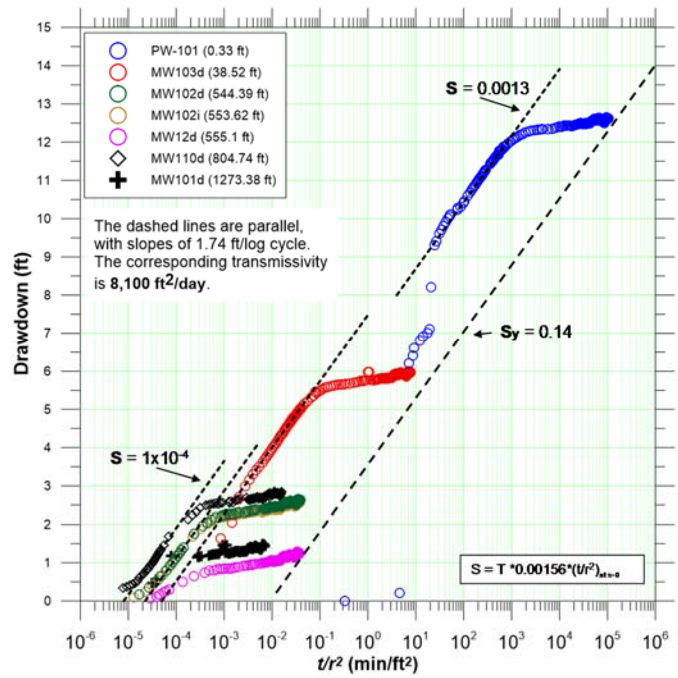
Groundwater within the region usually occurs under water-table conditions; however, confined conditions do exist, as evidenced by the presence of artesian conditions in wells installed near the Muskegon River (Leverett, et al., 1907) and in a few wells and drive points along the Twin Creek drainage (monitoring wells MW-107, MW-101s, and abandoned well MW-109). The artesian wells described occur in isolated cases where sand units overlain by fine-grained sediments yield flows at elevations above the land surface. The sporadic location of the artesian conditions, and the depth at which they are encountered, are evidence for the great variability in the characteristics of the glacial sediments that are encountered over short distances in the area.

In the vicinity of PW-101, the springs discharge at sporadic locations along the contact between the Fine-grained Sediment of Twin and Chippewa Creeks and the Undifferentiated Sands unit. Groundwater flows from the upland areas, which are underlain by the Undifferentiated Sands, and discharges along the break in slope where the Undifferentiated Sands are in contact with the Fine-grained Sediments of Twin and Chippewa Creeks. Although the finer-grained materials control the discharge location of springs and seeps in the area, continuous clay layers are difficult to identify. The clayey sediments are not simply continuous units, but rather a complex interlayered network that effectively serves as a low permeability barrier to groundwater flow. Based on the lithologic description in the boring logs, the subsurface materials are highly variable over short distances and consist of discontinuous clay and sand lenses with a low effective permeability.

Aquifer Parameters

Estimates of aquifer parameters in the vicinity of PW-101 were made from data collected during the aquifer test conducted at PW-101 in 2001. For the aquifer test, PW-101 was pumped at a constant rate of 400 gpm for eight days and then at a constant rate of 700 gpm for an additional day. Water levels were measured and drawdowns computed at 32 monitoring wells and the pumped well.

The drawdowns observed during the pumping test indicate that the water-table aquifer in the immediate vicinity of PW-101 is relatively uniform. The uniformity of aquifer properties in the vicinity of PW-101 is illustrated on the graph to the right which is a plot of drawdown versus scaled time[2] for many of the monitoring wells in the vicinity of PW-101 during the eight day 400 gpm aquifer test. With a graph of this type, the drawdowns in many monitoring wells can be easily compared on a single plot. On this graph, the slopes of early time drawdown data from nearby monitoring wells are similar, indicating that the transmissivity at these nearby monitoring wells is similar. As noted on the graph, the estimated transmissivity is 8,100 ft^2/day as derived by the Cooper-Jacob analysis method (Cooper and Jacob, 1946).



The straight lines fitted to the drawdown data on the graph above intercept the x-axis at different x-values; this indicates that the effective storativity is variable. The effective storativity is estimated using the formula shown in the lower right corner of the graph above which is a function of the x-intercept. The effective storativity is estimated as $1x10^{-4}$ from early time drawdown data from MW-110d, 0.0013 from early time drawdown data from PW-101 and MW-103d, and late time drawdown data from PW-101 and MW-12d suggest a specific yield of 0.14. The relevant storage parameter is the specific yield as the storativity in a water table aquifer is approximately equal to the specific yield. The specific yield of 0.14 estimated from the test data is consistent with the expected specific yield of a fine to coarse grained sand but at the lower end of the expected range McWhorter and Sunada, 1977).

Surface Water, Springs and Seeps

The predominant surface water feature in the model area is the Muskegon River, located approximately three miles southeast of production well PW-101 (Figure 1). Perennial streams in the area include Twin Creek, Chippewa Creek and several unnamed creeks located near the Muskegon River. Twin Creek is an approximately 5-mile-long drainage feature extending from

[2] Time is scaled by the inverse of the squared distance from a monitoring well to PW-101.

its headwaters near Strawberry Lake, and flowing southeast through Evart to the Muskegon River. The East Branch of Twin Creek extends from two unnamed ponds near Nine Mile Road and joins with the main stem of Twin Creek just west of Decker Ponds. Chippewa Creek flows from the area of Decker Ponds east-southeast to the Muskegon River northeast of Evart.

Major spring areas in the vicinity of PW-101 consist of the Northern Ridge Spring, Northern Boomerang Springs, Southern Boomerang Springs, White Pine Springs, Chippewa Springs, and Decker Springs. These spring areas are shown on Figure 5. These named springs, with the exception of the Northern Ridge Spring, consist of a large number of seeps and vents where groundwater discharges at the surface. The Northern Ridge Spring consists of a single vent. In addition to the named springs, there are numerous other seeps along Twin Creek, along the ponds in the upper portion of Chippewa Creek, and along Chippewa Creek and along its northern tributaries.

The U.S. Geological Survey (USGS) has operated a gaging station on the Muskegon River at Evart since 1930. The average annual flow at Evart, for the baseline period 1971 to 2000, was about 510,000 gallons per minute (gpm). For the sixteen-year period 2000 through 2015, the average flow was about 483,000 gpm and the median flow was 389,000 gpm (http://waterdata.usgs.gov/mi/nwis/uv?04121500). Water year 2003 (October 2002 to September 2003) had the lowest flows ever recorded at Evart; the average flow during this water year was only 272,000 gpm. The average base flow, that component of flow that originates from groundwater discharge, of the Muskegon River at Evart is estimated, on the basis of analyses conducted by Holtschlag (1997) and on the basis of analyses conducted for this report, to be between 80 and 84 percent of the total flow in the Muskegon River at Evart.

A surface-water monitoring system was established in the vicinity of PW-101 in the summer of 2000, and surface-water flows have been monitored periodically from then until the present. The locations of the main gaging stations on Twin Creek and Chippewa Creek are shown on Figure 1 and the main gaging stations in the vicinity of the named springs are shown on Figure 5. These data have been used to estimate stream flow characteristics including the median annual flow and the median August flow. The median annual flow provides an approximation of the average annual stream base flow and the median August flow provides an approximation of average flow conditions during the late summer.

Stream flow characteristics were calculated from the measured flow data for gaging locations on Twin Creek, Chippewa Creek and various springs in the Twin Creek and Chippewa Creek watersheds in the vicinity of PW-101 based on available data from October 2000 through December 2015. Flow hydrographs for gaging locations on Twin Creek, Chippewa Creek, springs in the Twin Creek watershed and springs in the Chippewa Creek watershed are shown on Figures 6, 7, 8, and 9, respectively. All available flow data are plotted except for outliers that exceed the maximum y-value on the graphs.

Twin Creek originates as a perennial stream just upstream of where the stream crosses Nine Mile Road (Figure 1). Approximately one and one-half miles downstream at Eight Mile Road the base flow of Twin Creek is approximately 3,000 gpm (SF-9), and the base flow increases slightly in the next three miles to about 3,800 gpm where the creek enters the Muskegon River (SF-13). The measured flows in Twin Creek are shown on Figure 6.

Chippewa Creek originates from a number of springs and seeps, that are referred to as Chippewa Springs, that flow into the man-made Decker Ponds north of Eight Mile Road (Figure 5). The measured flows in Chippewa Creek are shown on Figure 7. The average base flow of Chippewa Creek just downstream of the Decker ponds on 95th Avenue is estimated to be 1,038 gpm (SF-16). Approximately one-half mile downstream the average base flow is estimated to be about 2,058 gpm (SF-20), which represents a doubling of the base flow within this one-half mile reach as a result of significant groundwater discharge.

Within approximately a one-mile radius of PW-101, groundwater discharge to seeps and springs averages about 3,350 gpm; approximately 2,300 gpm to seeps and springs in the Twin Creek drainage (SF-9) and 1,050 gpm to seeps and springs in the Chippewa Creek drainage (SF-16). This includes seeps and springs in the Chippewa Creek drainage upstream of 95th Avenue and springs and seeps in the Twin Creek drainage upstream of Eight Mile Road.

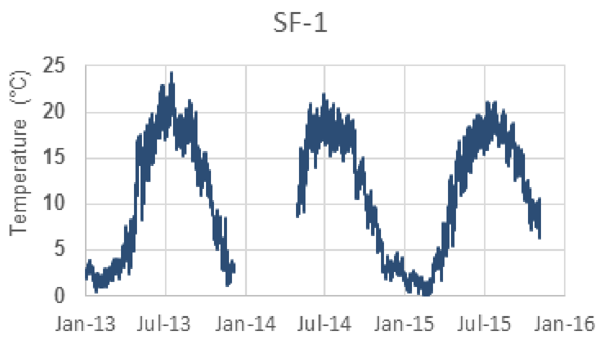
Plots of the measured flows of selected seep/spring areas in the Twin Creek watershed are shown on Figure 8. The flow of these springs are relatively constant with time, though flow appears to vary with long-term climatic trends. In addition there is variability that is related to changes in the drainage patterns in the main seep areas. The drainage patterns change as the result of tree falls, vegetative growth, and migration of the seeps.

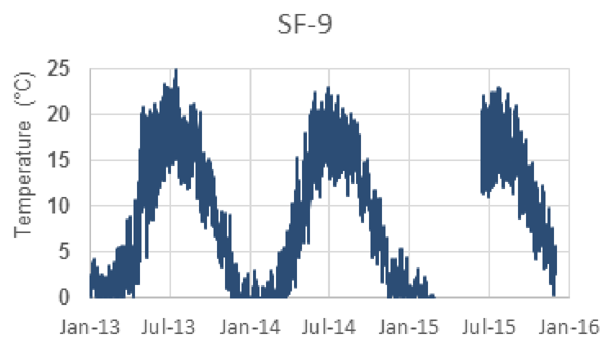
The total flow of the spring area known as White Pine Springs was gaged historically at SF-6 but only limited data are available as this gaging location generally has backwater conditions due to beaver activity. The average base flow at SF-6 is estimated to be about 300 gpm based on the data collected in 2003. The measured flows at Weirs 2, 3 and 4 account for about 40 percent of the flow at SF-6. Plots of the measured flows of seeps in the Chippewa Springs watershed are shown on Figure 9. Two small streams emanate from Chippewa Springs and flow into a pond. These streams are monitored at Weir 5 and SF-8, respectively, and the combined estimated base flow of these two streams is about 185 gpm. The hydrologic characteristics of the White Pine Springs and the Chippewa Springs are described in detail in Section 3.

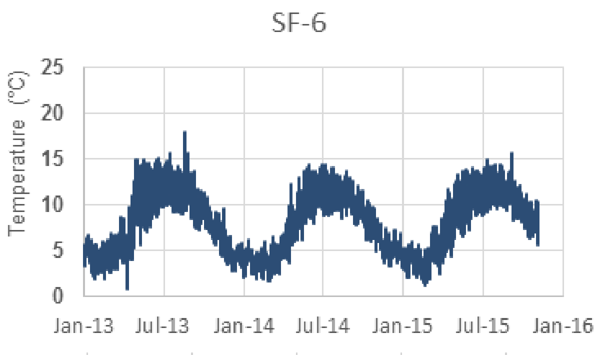
Surface-water level measurements are taken at the stream gaging locations at the same time that groundwater levels are measured. As is expected, surface water levels do not fluctuate significantly. To obtain a measure of stream level variability, the 25th percentile and 75th percentile levels and flows were calculated at each stream gaging location for the period 2003 through 2015. These results are discussed for the three gaging locations nearest to PW-101 (SF-1, SF-9 and SF-16). At SF-1, on Twin Creek, the difference between the 25th and 75th percentile level is 0.12 feet and the difference between the 25th and 75th percentile flow is 173 gpm. This indicates that the creek level at SF-1 varies only about 0.12 feet as a result of a flow change of 173 gpm. At SF-9, on Twin Creek, the differences between the 25th and 75th percentile levels and flows are 0.32 feet and 712 gpm; indicating that a flow change of 712 gpm results in a creek water level change of 0.32 feet. At SF16, on Chippewa Creek, the differences between the 25th and 75th percentile levels and flows are 0.11 feet and 174 gpm; indicating that a flow change of 174 gpm results in a creek water level change of 0.11 feet.

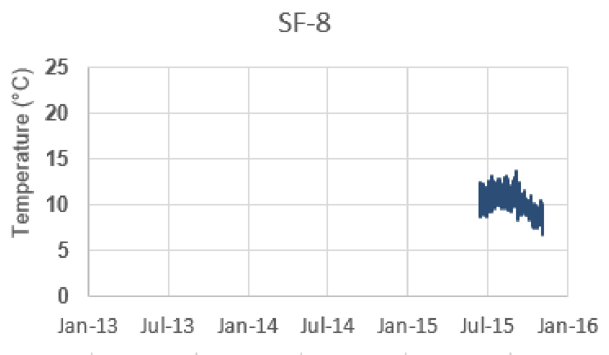
Surface water temperatures have been measured hourly since December 2012 at SF-1 on the East Branch of Twin Creek approximately 2,000 feet west of PW-101, at gaging location SF-6 in the White Pine Spring area, and at SF-9 on Twin Creek approximately 3,000 feet south of PW-

101. In addition, surface water temperatures have been measured hourly at SF-8 in the Chippewa Springs area since January 2015. Plots of these data are shown below.









Stream temperatures in the warmest part of the summer are often used as a metric for assessing the suitability of stream reaches for fish populations. The temperatures measured in July, the warmest summer month, in surface water at the four locations described above are summarized on the table below. The table lists the average July temperature, the average daily minimum temperature, the average daily maximum temperature, and the average diurnal range of temperature in the month of July.

	July Temperature (°C)									
	SF-6			**SF-1**			**SF-9**			**SF-8**
	2013	**2014**	**2015**	**2013**	**2014**	**2015**	**2013**	**2014**	**2015**	**2105**
Average	11.62	10.96	11.37	19.90	18.09	18.54	18.17	16.82	16.85	10.57
Avg Daily Minimum	10.41	9.67	9.96	18.91	16.98	17.38	15.87	14.48	13.61	8.13
Avg Daily Maximum	13.44	12.85	13.48	20.84	19.20	19.57	20.97	19.38	20.67	12.51
Avg Diurnal Range	3.03	3.18	3.52	1.93	2.22	2.19	5.10	4.79	7.06	4.38

Summer flows in Twin Creek, for the most part, are the result of discharge of groundwater at seeps and springs along the course of the stream. The temperature of the discharging groundwater is about 9.5°C. The summer stream temperatures reflect the heating of the discharging groundwater, with the coolest stream temperatures at SF-6 which is immediately downstream of an area with numerous seeps and springs (White Pine Springs). The magnitude of diurnal stream temperature changes primarily reflects the density of vegetation shading of the stream; the higher the density of shading the smaller the diurnal temperature changes.

Wetlands

The wetlands mapped in the vicinity of the production well are shown on Figure 10. From a groundwater perspective, these wetlands fall into three broad categories, as shown schematically in Figure 11; wetlands that are perched above the regional groundwater table, wetlands that occur in depressions in the land surface and are in contact with the regional water table, and wetlands that occur in stream valleys and are in contact with the water table.

Perched wetlands are wetlands in which the regional water table is sufficiently lower than the wetland water level such that a zone with unsaturated conditions exists between the base of the wetland and the regional water table. Some wetlands that are perched above the regional water table receive groundwater discharge from a perched groundwater system. A perched groundwater system is a saturated zone that is separated from the water table in the regional aquifer by a zone of unsaturated materials. The presence of fine-grained materials, such as a clay, that impede the vertical flow of groundwater is the cause of perched groundwater conditions.

Eight of the mapped wetlands are most likely hydraulically connected to the regional water table (Wetlands A, G, H, R, CC, FF, OO and PP on Figure 10). The hydrology of these wetland is described in detail in a report by ECT (2016). The other wetlands are perched on top of clay layers within the glacial deposits. These wetlands are probably formed in glacial kettle deposits and are not hydraulically connected to the regional water table, since the base elevation of the saturated portion of the wetland is most likely above that of the regional water table.

Large wetlands occur in groundwater discharge areas along Twin Creek and its tributaries and in headwaters of Chippewa Creek that are in contact with the water table. These large wetland areas have been mapped as Wetland R, which is located adjacent to Twin Creek, and wetlands A, CC, FF, OO and PP which are located in the headwaters of Chippewa Creek. Water levels in these wetlands are primarily a function of direct precipitation, surface-water run-on, and groundwater discharge that occurs as springs and seeps primarily on the perimeter of the wetlands. The water level in these wetlands is technically an expression of the groundwater table, but the shallow groundwater beneath the wetlands has limited hydraulic connection with groundwater in deeper permeable units as the result of fine-grained materials near the surface. This limited hydraulic connection is reflected in the strong upward hydraulic gradients measured in monitoring wells in the vicinity of the wetlands.

Two small mapped wetlands, Wetlands G and H, occur in depressions where the water table intersects the land surface. These wetlands are in direct contact with the water table, but fine-grained materials that occur beneath the wetland surface limit the hydraulic connection with the more permeable, deeper materials beneath the water table.

Precipitation and Recharge

The average annual precipitation in the vicinity of PW-101 is estimated to be about 36.6 inches based on data from the weather station in Big Rapids, which is located about 20 miles to the southwest, from 1981 to 2010. Recharge is that portion of precipitation that infiltrates into the subsurface and reaches the water table. Studies conducted by the U.S. Geological Survey (Holtschlag, 1997) indicate that about 25 percent of precipitation on average recharges groundwater in Osceola County and vicinity. These studies analyzed stream flow data and determined the portion of stream flow that results from groundwater discharge to the streams.

Groundwater recharge for the base period 1951-1980 used in the analyses by Holtschlag (1997) was estimated to be 8.4 inches per year for the Muskegon River watershed above Evart (1450 square miles) and 8.7 inches per year for the Pine River watershed near Le Roy (a 118 square mile watershed located immediately to the northwest of the model area). Recharge in the model area is greater than these average rates as the result of the generally coarse-grained soils in the model area, as explained below and higher precipitation in recent decades. Holtschlag (1997) developed a relationship for recharge in an area based on soil type and forest cover. Based on this relationship after adjusting for differences in precipitation between Holtschlag's base period of 1951 to 1980 and the period 1981 and 2010, the calculated average annual recharge rate in the model area is about 10.4 inches per year using the method developed by Holtschlag.

Groundwater Usage

Groundwater usage within the model area consists of pumping for municipal, commercial and domestic uses. The City of Evart obtains its municipal water supply from seven wells; Wells 1 through 4 and Well 6 are located between Twin Creek and West 5th Street (Twin Creek Wellfield) and Wells 8 and 9 located approximately 5000 feet west of the city center near Highway 10 (Figure 1). The City also owns two wells in the Twin Creek Wellfield used for commercial purposes; wells 7 and 13[3]. The average monthly pumping rate for municipal uses in 2015, as reported by the City, was about 700 gpm with approximately 33 percent of the water supplied by Wells 8 and 9. The average pumping rates of wells 7 and 13 in 2015 was about 180 gpm. In 2001, the total pumping by the City averaged 1,540 gpm with approximately 20 percent pumped from Well 8 (well 9 was not in existence in 2001). Other groundwater uses in the model area are small relative to the water use by the City of Evart. Water supply wells at Spring Hill Camp pump approximately 4 million gallons annually, with approximately half of the total pumped between June and August[4]. The highest production is from a well located approximately 1000 feet northeast of Decker Ponds; however, the average pumping rate for this well was only 2.4 gpm.

[3] Well 13 was constructed as a replacement wells for Well 5, which is located nearby, in 2014.

[4] Estimates of Spring Hill Camp pumping based on 2002 data.

Section 3
Groundwater Model

The groundwater flow model was developed using MODFLOW-2000, a finite difference flow simulation code developed by the USGS (Harbaugh et al., 2000). The input data sets for the model were prepared using Groundwater Vistas (Rumbaugh, 2002). The groundwater model was calibrated to average annual groundwater conditions based upon data generally collected between October 2000 and September 2003. The structure of the flow model is described in this section.

Finite-Difference Grid

The finite-difference model grid encompasses an area of approximately 50 square miles that represents the shallow aquifers within the Twin Creek-Chippewa Creek sub-basin of the Muskegon River, as shown on Figure 12. The model grid extends for approximately 8 miles in a north-south direction and eight miles in an east-west direction. The model grid is aligned north-south. The model grid has 176 columns and 174 rows. Row and column spacing is variable. In the vicinity of the proposed production well and the major springs, the grid cells are approximately 50-foot squares. Elsewhere, grid cells have a maximum size of 500 feet by 500 feet. The grid spacing is sufficiently fine to allow an accurate calculation of changes in groundwater levels and groundwater discharges to surface water from groundwater withdrawals at PW-101.

The finite-difference grid has five layers to represent the glacial deposits in the shallow aquifers of the Twin Creek-Chippewa Creek sub-basin of the Muskegon River. The model layers have, with the exception of the upper model layer, uniform thickness throughout the model domain, as it was determined that the known geologic information can be incorporated in the model with this structure. The upper layer was defined as all saturated deposits above an elevation of 1,060 feet above MSL. The saturated thickness of this layer is as great as 140 feet in the northwest portion of the model area. The other model layers were defined as follows:

- Layer 2 – thickness of 30 feet from 1,030 feet to 1,060 feet MSL;
- Layer 3 – thickness of 30 feet from 1,000 to 1,030 feet MSL;
- Layer 4 – thickness of 40 feet from 960 to 1000 feet MSL; and
- Layer 5 – thickness of 60 feet from 900 to 960 feet MSL.

Recharge

The groundwater recharge rate for the model area was estimated through model calibration. In the model calibration process, two different recharge distributions were investigated; a uniform recharge distribution and a non-uniform recharge distribution in which the groundwater recharge was specified as a function of soil type and forest cover according to the method developed by Holtschlag (1997). Recharge rates in the non-uniform distribution were specified for ten different combinations of soil type and forest cover:

- Open water – Zone 1;
- Upland areas with no forest cover – Zone 2;

- Upland areas with soils developed on coarse-grained till with no forest cover – Zone 3;
- Upland areas with soils developed on outwash sands with no forest cover –Zone 4;
- Upland areas with deciduous forest – Zone 5;
- Upland areas with soils developed on coarse-grained till with deciduous forest –Zone 6;
- Upland areas with soils developed on outwash sands with deciduous forest—Zone 7;
- Upland areas with coniferous forest – Zone 8;
- Upland areas with soils developed on coarse-grained till with coniferous forest –Zone 9; and
- Upland areas with soils developed on outwash sands with coniferous forest—Zone 10.

The areal extent of soil types and forest cover was specified on the basis of digital land-cover data from the Geographic Data Library, Michigan Center for Information Technology, State of Michigan. The distribution of the various recharge zones is shown on Figure 13.

Rivers, Creeks, and Ponds

Twin Creek, Chippewa Creek and other tributaries to the Muskegon River were simulated using the MODFLOW Drain package with the exception noted below. The Drain Package simulates only the discharge of groundwater to a surface-water body, and not the seepage of water from a surface-water body to the water table. The Drain Package is appropriate for simulating surface-water bodies that do not lose significant amounts of water to the groundwater table by seepage.

The Muskegon River was simulated using the MODFLOW River Package. The River Package simulates both the discharge of groundwater to a surface-water body and the seepage of water from a surface-water body to the water table. Twin Creek in the vicinity of the Twin Creek Wellfield was also simulated with the River Package as operation of the wellfield has the potential to induce infiltration from Twin Creek into the groundwater system.

The ponds located along Twin Creek and in the headwaters of Chippewa Creek were also simulated with the Drain Package. These ponds are all located within groundwater discharge areas and the Drain Package is an appropriate means of simulating changes in groundwater inflow into the ponds as the result of groundwater production. When the ponds are simulated with the Drain Package, the groundwater model does not explicitly calculate the change in pond levels that occurs as the result of changes in groundwater discharge to the ponds. For these ponds, the calculated changes in groundwater inflow are sufficiently small that ponds levels are not quantifiably altered as the result of changes in groundwater inflow. All of the ponds that were simulated with the Drain Package are man-made impoundments with outlet control structures that control the water level in the ponds, and these control structures are the primary controls on pond levels.

Four input parameters are required in using the MODFLOW Drain and River packages: the water level in the stream or pond, the area of the stream or pond within a model grid cell, the vertical hydraulic conductivity of the deposits at the base of the stream or pond, and the thickness of the deposits. For simplicity, the latter two parameters were lumped into a single parameter referred to as the normalized conductance. The normalized conductance is defined as the vertical hydraulic conductivity of the stream or pond bed deposits divided by the thickness of the deposits. The normalized conductances were determined in the model calibration process with the procedures described in the next section.

The surface elevations of the creeks and ponds in the vicinity of PW-101 were defined on the basis of a topographic map prepared with 2-foot contour intervals. The elevations of the Muskegon River and creeks outside of the vicinity of PW-101 were specified on the basis of digital elevation model (*DEM*) data from the Michigan Geographic Information Library (2003). DEM data are arrays of regularly spaced elevation values referenced to a geographic coordinate system. The grid cells are spaced at regular intervals along south-to-north profiles that are ordered from west to east. The DEM data used in the groundwater model were the 7.5-minute, 30-meter data for the Evart and Sears 7.5-minute quadrangles. The area of a stream or pond within a model cell was estimated on the basis of available maps.

Springs

The mapped seeps in White Pine Springs, Northern and Southern Boomerang Springs, Chippewa Springs, and Decker Springs and the Northern Ridge Spring were simulated with the MODFLOW Drain Package. The elevations of the seeps were specified as the average water level measured in an adjacent drive point (for example, the elevation at Seep-1 was specified as the average water level measured in the drive point identified as "Seep-1"), or if there was not a nearby drive point, on the basis of land-surface elevation.

Wetlands

All wetlands within the model area were simulated implicitly. Implicit simulation means that water levels in wetlands were not directly simulated. For wetlands in contact with the regional water table, implicit simulation implies that water levels in the wetlands are directly correlated with the regional water table. This is seldom the case, as most wetlands are underlain by fine-grained materials that limit the hydraulic communication with the underlying regional aquifer. As a result, implicit simulation of wetland water levels tends to over predict the changes in wetland levels that will occur as a result of changes in the regional water table.

In selecting the implicit method for simulating wetland water levels, an analysis was made of the relationship between groundwater levels and water levels in Wetland R, and an analysis was made of the relationship between spring flow and wetland water levels. An analysis of wetland water levels and seep flow rates at White Pine Springs, Northern Ridge Spring and Decker Springs has indicated that there is not a meaningful correlation between wetland water levels and seep flows. Water levels in the wetlands located at a break in slope appear to be controlled by the morphology of the land surface rather than by groundwater discharge rates; therefore, an implicit simulation of these wetlands is appropriate.

The water levels in perched wetlands are not a function of the regional water table, as changes in the level of the regional water table do not affect the flux from this type of wetland to the regional water table. Perched wetlands were modeled as a source of recharge to the regional water table that is not affected by the level of the regional water table. All wetlands in the vicinity of PW-101, except for those in or adjacent to the valleys of Twin and Chippewa Creeks, are perched wetlands.

Groundwater Use

Groundwater production from the City of Evart's wells in the Twin Creek and Western wellfields was simulated in the groundwater model as occurring at a steady-state rate of approximately 1,500 gpm, which was the reported groundwater production rate in 2001. Groundwater production at residential wells and the Spring Hill Camp wells was not simulated in the groundwater model because production from these wells averages less than 5 gpm per individual well. The production rates from these wells are sufficiently small that they do not have a quantifiable effect on groundwater flow conditions, and much of the water that is produced from these wells is returned to the subsurface via infiltration from septic tanks.

Parameters

Horizontal Hydraulic Conductivity

A uniform horizontal hydraulic conductivity distribution was specified initially within each mapped geologic unit. To begin the calibration process, hydraulic conductivity was specified as 50 feet per day in the undifferentiated sands, 150 feet per day in the coarse-grained gravel and sand, 10 feet per day in the Eastern fine-grained sediments and 5 feet per day in fine-grained sediments of Twin and Chippewa Creeks. Outside of the valley of the Muskegon River in model layer 5, a horizontal hydraulic conductivity of one foot per day was specified. The initial values were estimated on the basis of the lithologic characteristics of the materials.

Vertical Hydraulic Conductivity

A uniform vertical hydraulic conductivity distribution was also specified initially within each mapped geologic unit. To begin the calibration process, a vertical hydraulic conductivity of 1 foot per day was specified throughout the model domain. This initial value was chosen to represent the effective vertical hydraulic conductivity of fine-grained lenses within the subsurface environment.

Conductance

The normalized conductance for the streams, ponds, and seeps simulated with either the Drain Package or the River Package was initially specified as one per day, a typical value for the normalized conductance of stream bed deposits.

Storage Parameters

A steady-state simulation does not require the specification of any storage parameters. In simulating the aquifer tests, a specific yield of 0.14 and a storage coefficient of 5×10^{-4} were specified initially in each model layer. These values are consistent with storage parameters estimated from aquifer tests conducted at PW-101 and at the test wells TW-1, TW-2 and TW-3.

Section 4
Groundwater Model Calibration

The groundwater model was calibrated using the automated computer program "PEST - Model Independent Parameter Estimation" (*PEST*) (Doherty, 2002). A groundwater model is deemed calibrated when the difference between model outputs and field observations, referred to as calibration targets, has been reduced to a minimum in the weighted least squares sense [i.e., the sum of squared differences between model outputs and measurements, termed the objective function or PHI (Φ)]. Model calibration is an iterative process that seeks to reduce PHI by determining the sensitivity of the model parameters to the calibration data. When the calibration process can no longer reduce PHI (i.e., $\Phi = \Phi_{min}$), the parameters are considered optimal with respect to the measured data set and may be used to make predictions under conditions comparable to the calibration conditions. The computer program PEST automates the procedure of determining the minimum value of PHI.

The first step in the model calibration process is the identification of measured hydrologic data that can be used as calibration targets. Two sets of formal calibration targets were identified: average water levels in monitoring wells in the vicinity of PW-101, and average measured stream flows and spring flows. A total of 42 monitoring-well targets; 9 stream-flow targets and 5 spring targets were used in the model calibration process. These calibration targets are listed on Table 1. In addition, water levels at eighteen residential wells distributed widely over the model area were utilized in the model calibration process.

The monitoring well water-level targets were based on average water levels during the period January 2001 through December 2002. The stream-flow and spring-flow targets were also based on average base flows between January 2001 and December 2002. All calibration targets that were identified represent average, baseline hydrologic conditions. As a result, the calibration process consisted of the development of a groundwater model to simulate average, baseline conditions. This type of model is commonly referred to as a steady-state model. In this steady-state groundwater model, the variable parameters are the distribution of hydraulic conductivity, the magnitude of hydraulic conductivities, and the recharge rate.

The second step in the model calibration process is the selection of model parameters that can be varied in the model calibration process. In setting up the PEST input files for the model, a very flexible approach was adopted such that the sensitivity of a large number of parameters could be investigated and, in theory, a large number of parameters could be estimated. The parameters and parameter groups that were specified in the PEST input files were the following:

- Horizontal and vertical hydraulic conductivities – Seventeen zones were defined in the PEST input files in which the horizontal and vertical hydraulic conductivities could be estimated. Zones were specified for each of the major geologic units in each of the model layers, with the following exceptions. In model layer 5 one zone was specified that encompassed all areas outside of the valley of the Muskegon River, and only one zone was specified for the coarse-grained gravel and sand unit and this zone was specified in both model layers 4 and 5. In addition, two sets of zones were defined for the fine-grained sediments of Twin and Chippewa creeks – a set of zones for the area adjacent to the East Branch of Twin Creek and a set of zones for everywhere else.

- Normalized Conductance – Twenty-seven zones in which the normalized conductance could be estimated were defined in the PEST input files. One zone was specified for each mapped seep, major stream reach, and major ponds.
- Recharge – one recharge parameter was defined in the PEST input files. This parameter was the recharge rate when the model was calibrated for a uniform recharge distribution and was a multiplier for the initial recharge estimates derived from the Holtschlag (1997) method when the model was calibrated for a non-uniform recharge distribution.

The third step in the model calibration process is the identification of conditioning information on model parameters. Two types of conditioning information were identified: estimates of aquifer transmissivity from an aquifer test conducted at the production well, and geologic information. The transmissivity of the glacial aquifer at well PW-101 is estimated from the aquifer test to be about 8,100 ft^2/day. This information was incorporated in the calibration process as a constraint on the estimated transmissivity in the vicinity of the tested well. The known geologic information was incorporated into the calibration processes by the use of the geologic zones shown on Figure 3.

The fourth step in the calibration process is automated calibration using the computer program PEST. The result of this step is the calibrated groundwater model. In this step, the groundwater model was calibrated using both uniform and non-uniform recharge distributions. The model calibrated equally well to both distributions, and since the uniform recharge distribution is based on fewer assumptions, a uniform recharge distribution was used to develop the final calibrated model. The hydraulic conductivities estimated by this process were the following:

- Undifferentiated sands -- layer 1 – horizontal hydraulic conductivity (K_h) of 47 feet per day and vertical hydraulic conductivity (K_v) of 3 feet per day; layer 2 – K_h of 30 feet per day and K_v of 0.4 feet per day; layer 3 – K_h of 25 feet per day and K_v of 0.4 feet per day; layer 4 – K_h of 140 feet per day and K_v ranging from 10^{-3} feet per day to 0.1 foot per day; and layer 5 – K_h of 50 feet per day near the Muskegon River and K_h of 1 foot per day elsewhere with K_v of one foot per day.
- Eastern Fine Grained Sediments -- K_h of 15 feet per day layers 1 through 4, this unit not defined in layer 5; K_v of one foot per day.
- Coarse-grained gravel and sand -- K_h of 150 feet per day in layers 4 and 5, this unit not defined in other layers; K_v of one foot per day.
- Fine-grained sediments of Twin and Chippewa Creeks (with exception of area near East Branch of Twin Creek) -- layer 1 - K_h of 28 feet per day and K_v of $3x10^{-2}$ feet per day; layer 2 - K_h of 15 feet per day and K_v of $3x10^{-2}$ feet per day, layers 3 and 4 – K_h of 10 feet per day and K_v of 0.1 foot per day. This unit is not defined in layer 5.
- Fine-grained sediments near the East Branch of Twin Creek – K_h of 1 foot per day and K_v of 1 foot per day.

The recharge rate was calibrated at 14 inches per year. This calibrated recharge rate is approximately 25 percent greater than the rate estimated using the Holtschlag method that is based on regional conditions. The calibrated recharge rate is consistent with the observation that much of the model area has poorly developed surface drainages indicating that surface-water runoff is insignificant over much of the model area. In addition, the calibrated recharge rate is consistent with the observed base flows of Twin Creek and Chippewa Creek.

The calculated steady-state water levels in the calibrated model in the vicinity of production well PW-101 in model layer 2 are shown on Figure 14 along with calculated residuals for monitoring wells screened in models layers 2 and 3. Calibrated steady-state water levels in the entire model area are shown on Figure 15. These calculated water levels are similar to the water levels shown on Figure 2a that were estimated on the basis of drillers' logs from residential wells.

Quantitative evaluation of the model calibration consisted of examining the residuals between the 42 measured and calculated average water levels from the monitoring wells, the residuals from the 9 stream-flow targets, and the residuals from the five spring-flow targets. The residual is defined as the target minus the calculated water level, stream flow or stage. The calculated water levels, stream flows, and spring flows are listed on Table 1 along with the residuals.

The automated calibration process minimized the sum of the square of the residuals for the 42 monitoring wells to 218 ft^2. To quantify the model error for the water levels in the calibrated model with easier-to-understand metrics, three statistics were calculated for the residuals: the mean of the residuals, the mean of the absolute value of the residuals, and the standard deviation of the residuals. The mean of the residuals is 0.3 foot, the mean of the absolute value of the residuals is 1.7 feet, and the standard deviation of the residuals is 2.3 feet. The near-zero value of the mean residuals demonstrates that there is no systematic bias in the calibration. The absolute mean residual of 1.7 feet is considered acceptable since the observed water-level measurements applied as calibration targets have a total range of 40 feet. The standard deviation of 2.3 feet is also acceptable given the range of water-level values.

As shown on Table 1, there is good agreement between the stream-flow targets and the calibrated model-calculated stream flows, and there is good agreement between spring flow targets and measured spring flows.

The calibrated model was used to simulate the eight-day aquifer test conducted at production well PW-101 between June 12 and June 20, 2001. During this test, the well was pumped at a relatively constant rate of 400 gpm, and water levels were measured in nearby monitoring wells. In simulating this test, a specific yield of 0.15 and a storage coefficient of 5×10^{-4} were specified in all geologic zones. Simulated drawdowns reasonably match measured water levels in nearby monitoring wells as shown on Figure 16.

The calibrated model was also used to simulate the 7-day pumping test conducted at wells TW-1, TW-2 and TW-3 from August 23 to August 30, 2001. TW-1 was started first at a rate of 200 gpm, followed one hour later by TW-2 at a rate of 227 gpm, followed one hour later by TW-3 at a rate of 296 gpm. Pumping continued for seven days. Flows at the weirs were measured during the test, and significant changes in flow were observed. The calculated changes in water levels in monitoring wells and flow at the weirs closely match observed changes as shown on Figure 17.

Section 5
Model Sensitivity

Model calibration is a process of determining the sensitivity of model results to changes in model parameters and using this information in an iterative manner to produce a model in which there is good correspondence between observed and calculated values. The parameter estimation program used in this study, PEST, calculates sensitivities to parameters during model calibration, and PEST uses these sensitivities in its search for optimal solutions. The sensitivities to parameters are calculated by the method of perturbation: a base run of the model is made and the sum of squares of the residuals is computed and then one of the parameters is changed by a fractional amount and the model is rerun and the sum of squares of the residuals is recomputed. The difference in the sum of squares of the residuals between the two runs is a measure of the sensitivity to that parameter. The program PEST works by computing sensitivity to each parameter, and then uses the information on the sensitivities to adjust parameter values to minimize the sum of squares of the residuals.

The sensitivity of the model results to 44 parameters was computed by PEST, and only a very few of the model parameters were identified as having a significant effect on model results. The most sensitive and the relative sensitivity of the model results to these parameters are listed below

Parameter	**Relative Sensitivity**
Horizontal Hydraulic Conductivity – Undifferentiated Sands -Layer 4	1.0
Horizontal Hydraulic Conductivity – Undifferentiated Sands -Layer 2	0.30
Horizontal Hydraulic Conductivity – Undifferentiated Sands -Layer 3	0.26
Horizontal Hydraulic Conductivity – Fine-Grained Sediments of Twin and Chippewa Creeks –Layer 3	0.17
Horizontal Hydraulic Conductivity – Undifferentiated Sands near the Muskegon River – Layer 5	0.13
Horizontal Hydraulic Conductivity – Undifferentiated Sands -Layer 1	0.11
Recharge Rate	0.10
Horizontal Hydraulic Conductivity – Fine-Grained Sediments of Twin and Chippewa Creeks –Layer 2	0.10

The relative sensitivity is a measure of the change that occurs in the computed sum of squares of the residuals for a fractional change in the value of the parameter. A larger relative sensitivity indicates that a fractional change in the given parameter will result in a larger change in model outputs. Therefore, the relative sensitivities are a useful measure of the effect different model parameters have on model results.

The model is most sensitive to the hydraulic conductivity of the undifferentiated sands in model layers 1 through 4. The transmissivity (hydraulic conductivity multiplied by thickness of aquifer unit) of these sands, as estimated from the aquifer test of PW-101, is about 8,100 ft^2/day. The transmissivity of these sands in the model, which represents the thickness-weighted hydraulic conductivities of layers 1 through 4, is 8,070 ft^2/day. The close correspondence between the estimated transmissivity and the model transmissivity for these sands and the fact that the hydraulic conductivities of these sands are the more sensitive model parameters, provide strong evidence that the parameters in the calibrated groundwater model are consistent with observed conditions.

The model is also relatively sensitive to recharge. In the groundwater model, recharge equals discharge from the model, and since discharge from the model to Twin Creek and Chippewa Creek are targets in the model calibration process, it is expected that recharge would be a sensitive parameter. Since good estimates of stream flows are available, the calibration process provides a reliable estimate of recharge. The estimate is considered to be reliable as the groundwater model is fundamentally a water balance model, and at steady state input (recharge) must equal discharge (stream flow and pumping). Since good estimates of streamflow and total pumping are available from measurements, it follows that there is also a good estimate of recharge.

Section 6
Groundwater Basins

The calibrated groundwater model was used to calculate the groundwater basins upgradient of gaging location SF-9 on Twin Creek and upgradient of SF-17 on Chippewa Creek (Figure 18). The groundwater basins include those areas upstream of SF-9 and SF-17 where the groundwater component of stream flow originates as precipitation infiltrating into the subsurface. The groundwater basins were calculated using the computer program MODPATH (Pollock, 1994). With this program, water particles were traced from the water table at the center of every grid node in the model domain to the location where they discharge to a surface water body or well. The groundwater basin upgradient of SF-9, as shown on Figure 18, was defined to include the starting locations of all particles that discharge to Twin Creek upstream of SF-9. Likewise, the groundwater basin upgradient of SF-17 was defined to include the starting locations of all particles that discharge to Chippewa Creek upstream of SF-17.

The groundwater basin upgradient of SF-9 on Twin Creek differs markedly from the surface watershed upstream of SF-9 as shown on Figure 18. The area of the groundwater basin is 7.2 square miles whereas the area of the surface watershed is 17 square miles. This groundwater basin is smaller than the surface watershed, in part, because there are no perennial streams in much of the watershed and as a result groundwater flow is toward the Muskegon River and other watersheds rather than toward Twin Creek. Because the groundwater basin upgradient of SF-9 is much smaller than the surface watershed, the base flow at SF-9 is smaller than is predicted using generalized techniques that are based on the area of the surface watershed.

The groundwater basin upgradient of SF-17 on Chippewa Creek also differs markedly from the surface watershed upstream of SF-17 as shown on Figure 18. In this case, the area of the groundwater basin is much larger than the area of the surface watershed (2.8 square miles and 5.6 square miles, respectively). Because the groundwater basin upgradient of SF-17 is much larger than the surface watershed, the base flow at SF-17 is larger than is predicted using generalized techniques that are based on the area of the surface watershed.

Section 7
Assessment Results

The calibrated groundwater model was used to calculate the changes in baseline groundwater levels, spring flows and stream flows that would occur if the groundwater withdrawal from PW-101 was increased from an average rate of 150 gpm to 400 gpm. The calculated water-level changes that result from this simulated increase in withdrawal are shown on Figure 19 and the calculated changes in spring and stream flows are listed on Table 2.

Most of the stream flow reduction occurs as the result of decreased groundwater discharge to the main stem and tributaries of Twin Creek and Chippewa Creek. The calculated flow reduction in Twin Creek is about 127 gpm and the calculated flow reduction in Chippewa Creek is 90 gpm on an average annual basis. The calculated changes in flow in Twin Creek and Chippewa Creek represent a decrease of less than four percent of the average base flows in the streams.

The calculated change in the flow of White Pine Springs is about 27 gpm and the calculated change in flow of Chippewa Springs is about 20 gpm. White Pine Springs has an estimated average base flow of 300 gpm and Chippewa Springs has an average base flow of 185 gpm. Therefore, the calculated changes in flow represent a decrease of approximately 9 percent and 11 percent from the average base flows in these springs, respectively.

Water level changes in the East Branch of Twin Creek at SF-1, in Twin Creek at SF-9, and in Chippewa Creek at SF-16 are estimated to be on the order of 0.01 feet, a very small change. The average water level, and water level change, were calculated from stream flow rating curves that were developed for these streams. With time, it is expected that the channel form will adjust by a decrease in average width of the stream and an increase in the average depth after the flow reduction.

The drawdown that will result from an increase in the withdrawal from PW-101 is less than two feet beyond the immediate vicinity of PW-101 as shown on Figure 19 in the main aquifer unit. At all nearby private wells the calculated drawdown is less than two feet, and only at two wells is the calculated drawdown greater than one foot. These water level changes should have no material effect on the yield of the private wells.

As noted in Section 2, all wetlands except for A, G, H, R, CC, FF, OO, and PP in the vicinity of PW-101 are perched (wetland locations are shown on Figure 10). Water levels in the perched wetlands are unaffected by withdrawals from PW-101. The intended increase in the withdrawal rate from PW-101 from 150 gpm to 400 gpm is calculated to reduce water levels in the regional aquifer by more than 0.5 feet only in the vicinity of wetlands A, G, H, and R. At Wetland CC, which borders Decker Pond, the reduction in the water level in the regional aquifer is greater than 0.5 feet at the northern extremity of the wetland, but beneath most of the wetland the reduction in the water level in the regional aquifer is less than 0.5 feet.

Estimated water level changes in Wetland R along Twin Creek and in Wetland A in the headwaters of Chippewa Creek are very small as the water levels in these wetlands are primarily controlled by the level of Twin Creek and its tributaries as though these wetland are in contact with the water table, they have limited hydraulic connection with the regional aquifer as a result of the fine-grained materials underlying these wetlands. Groundwater does discharge along the perimeter of these wetlands, and as noted above small changes in groundwater discharge will occur. An analysis of the relationship between flow at the springs and wetland water levels indicate that there is only a weak correlation between flow and wetland water levels. This means that water levels in Wetland R appear to be little affected by small changes in flow from the seeps and springs at White Pine Springs and water levels in Wetland A appear to be little affected by small changes in flow from the seeps and springs in Chippewa Springs.

Water level changes in the regional aquifer beneath the two wetlands that occur in depressions where the water table intersects the land surface are calculated to be about one foot (Wetlands G and H). The average change in the wetland water levels will be less than the changes in the regional aquifer water levels, but how much less is not known. During the spring and early winter water levels in these wetlands are likely to be little affected by groundwater production as during these seasons the wetland water budget is dominated by surface water run-on. During the latter part of the summer and in the fall, the water level change in the wetlands may approach the water level change in the regional aquifer water levels.

Stream Temperature Changes

Potential temperature changes in streams in the vicinity of PW-101 were evaluated using the computer program SSTEMP developed by the U.S. Geological Survey[5]. The calculated changes in stream temperature from increasing the groundwater withdrawal from PW-101 from 150 gpm to 400 gpm are very small in the summer months relative to normal diurnal temperature variations. The calculated stream temperature change at SF-6 at White Pine Springs (Figure 5) on a hot summer day is less than 0.2°C as the result in the increase of the intended increase in the withdrawal rate of PW-101. The temperature change is small because the flow change is not large enough to significantly change the heating rate in the small streams near the source springs within the White Pine springs group (Figure 5).

The analyses conducted with the stream temperature model SSTEMP suggest that temperature changes will be small in the streams in the vicinity of PW-101 as the result of the intended increase in the withdrawal rate of PW-101 from 150 gpm to 400 gpm. Calculated temperature changes in one of the more sensitive stream segments indicates that potential stream temperature changes are less than 0.2°C.

Degree of Uncertainty of Calculated Changes

There is some uncertainty associated with the calculated effects of the intended increase in the withdrawal from PW-101 as a result of imperfect knowledge of subsurface conditions. This uncertainty was quantified by an iterative process similar to model calibration using PEST in which the structure of the groundwater model was altered iteratively in a trial and error manner. Using PEST, a small increment was added to the calibration objective function, termed $\Phi_{min} + \delta$

[5] Bartholow, J., 2002. Stream Segment Temperature Model (SSTEMP) Version 2.0: Fort Collins, CO, U.S. Geological Survey, 29p.

— where δ is typically about 5% of Φ_{min} — under which conditions the model is deemed to satisfactorily match measured field data. An automated, iterative process was then undertaken, which minimized (or maximized) the key model prediction while maintaining the calibration sum of squared differences below $\Phi_{min} + \delta$. The process is achieved by determining the sensitivity of the model parameters with respect to both the model calibration outcomes and the model prediction. In this manner, the minimum and maximum values of the model prediction were determined while ensuring that the model meets calibration constraints, or simply stated, matches the existing measured data. The results of the uncertainty analysis indicate that the uncertainty associated with the calculated effects of the intended increase in the withdrawal from PW-101 is small.

Section 8
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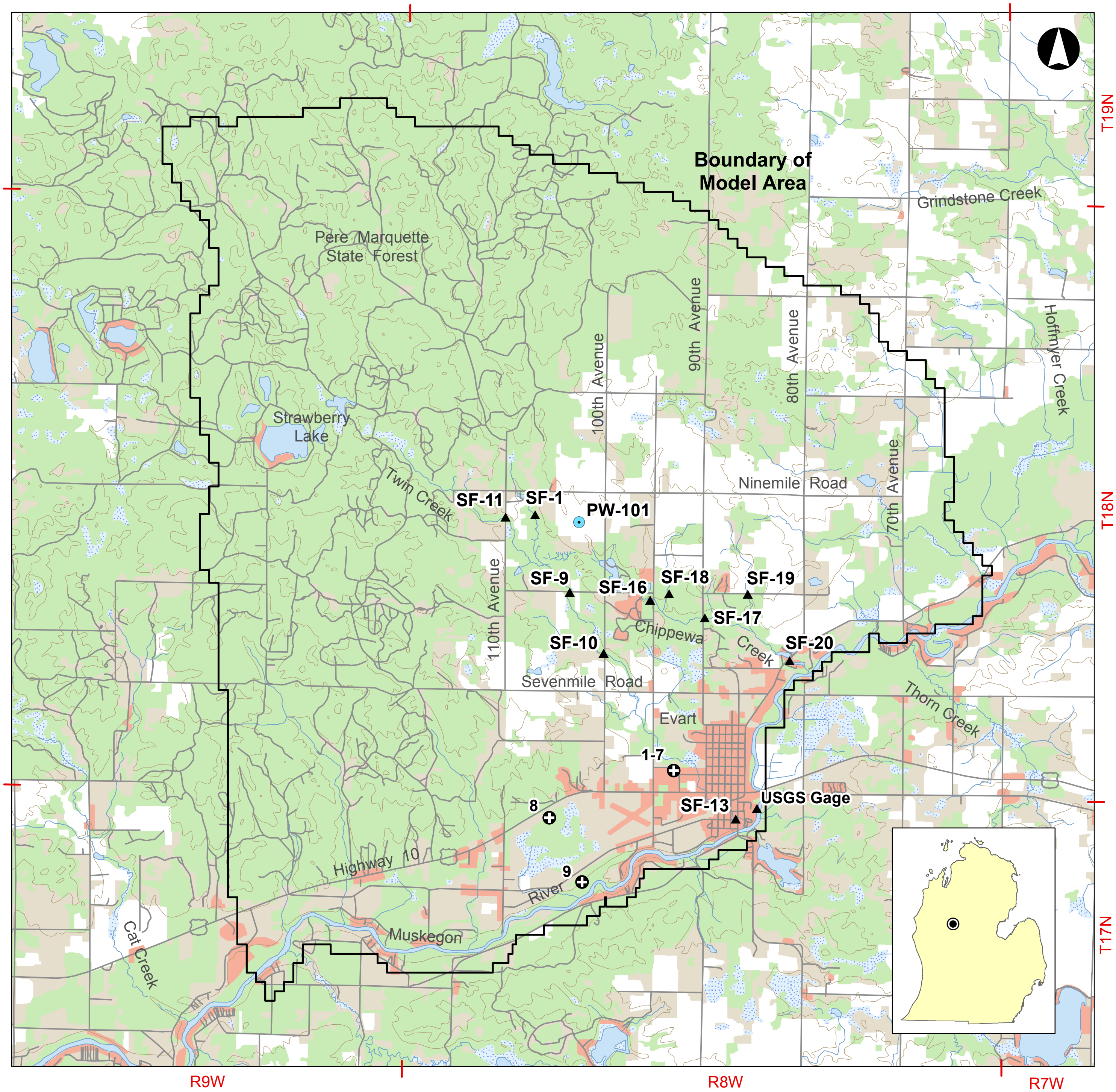
FIGURES



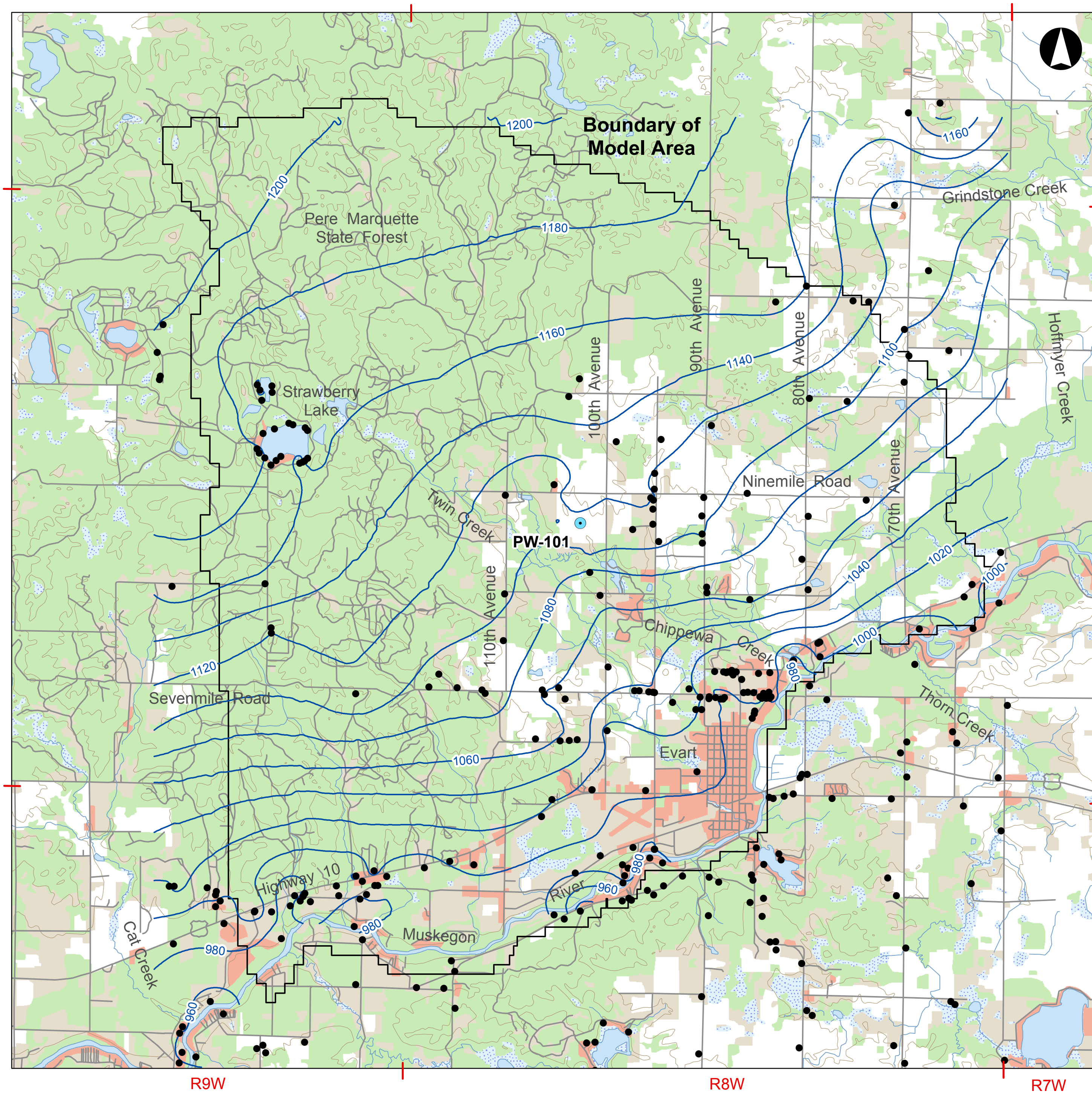
PW-101 Production well

8 Stream gaging locations

SF-10 Evart municipal wells and well number

0 7,500 15,000 Feet

Figure 1 Regional Model Area



PW-101 Production well

Residential and supply well location with water- level data

— 980 — Contour of elevation of water-table surface (feet, MSL)

0 7,500 15,000 Feet

Figure 2a Regional Groundwater Levels from Water Well Records

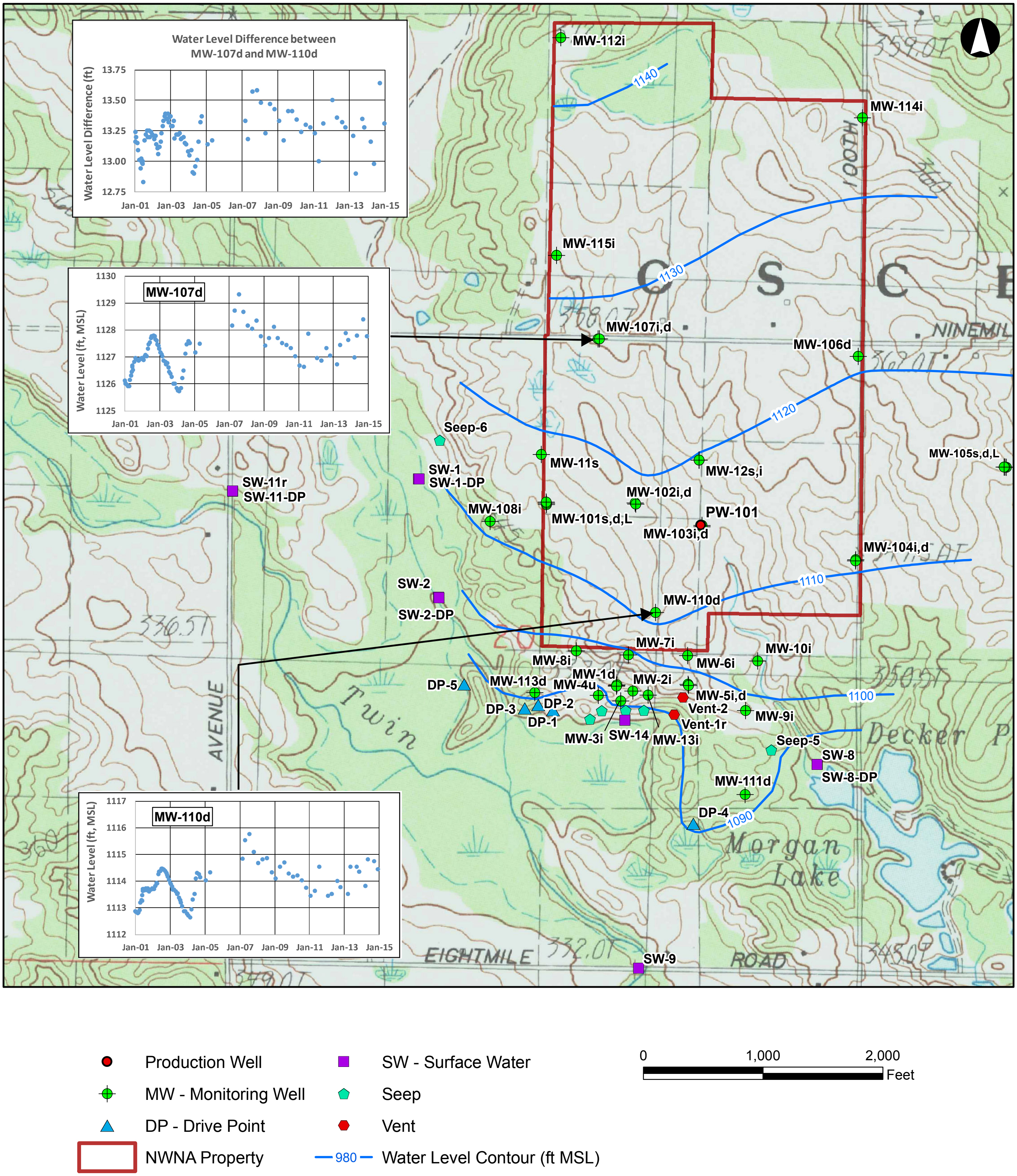
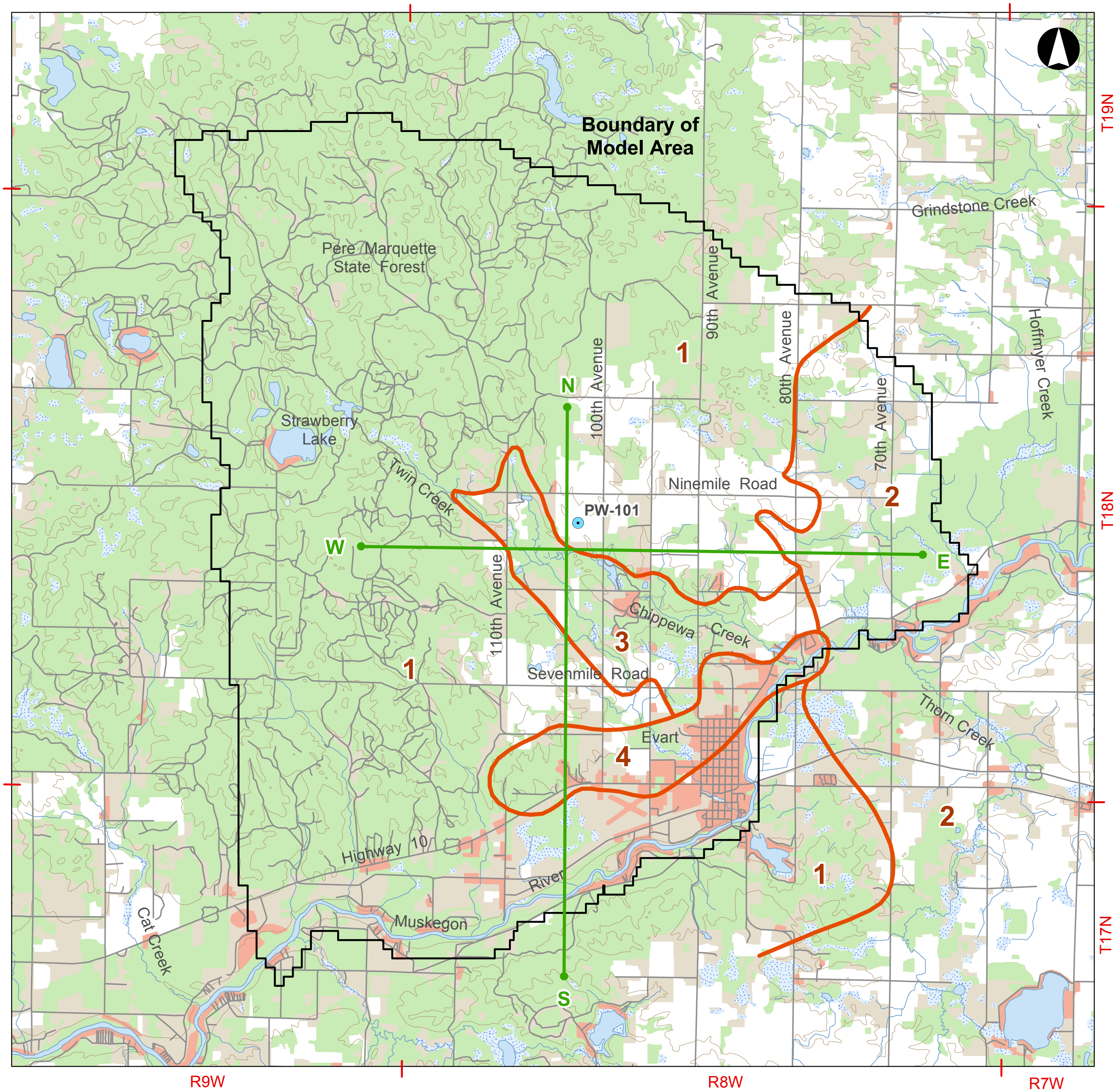


Figure 2b Groundwater Levels on July 7, 2012 in Vicinity of PW-101



1 Undifferentiated Sands

2 Eastern Fine-grained Sediments

3 Fine-grained Sediments of Twin and Chippewa creeks

4 Coarse-grained Sand and Gravel

Geologic cross section trace

Figure 3 Regional Geologic Zones and Cross Section Traces

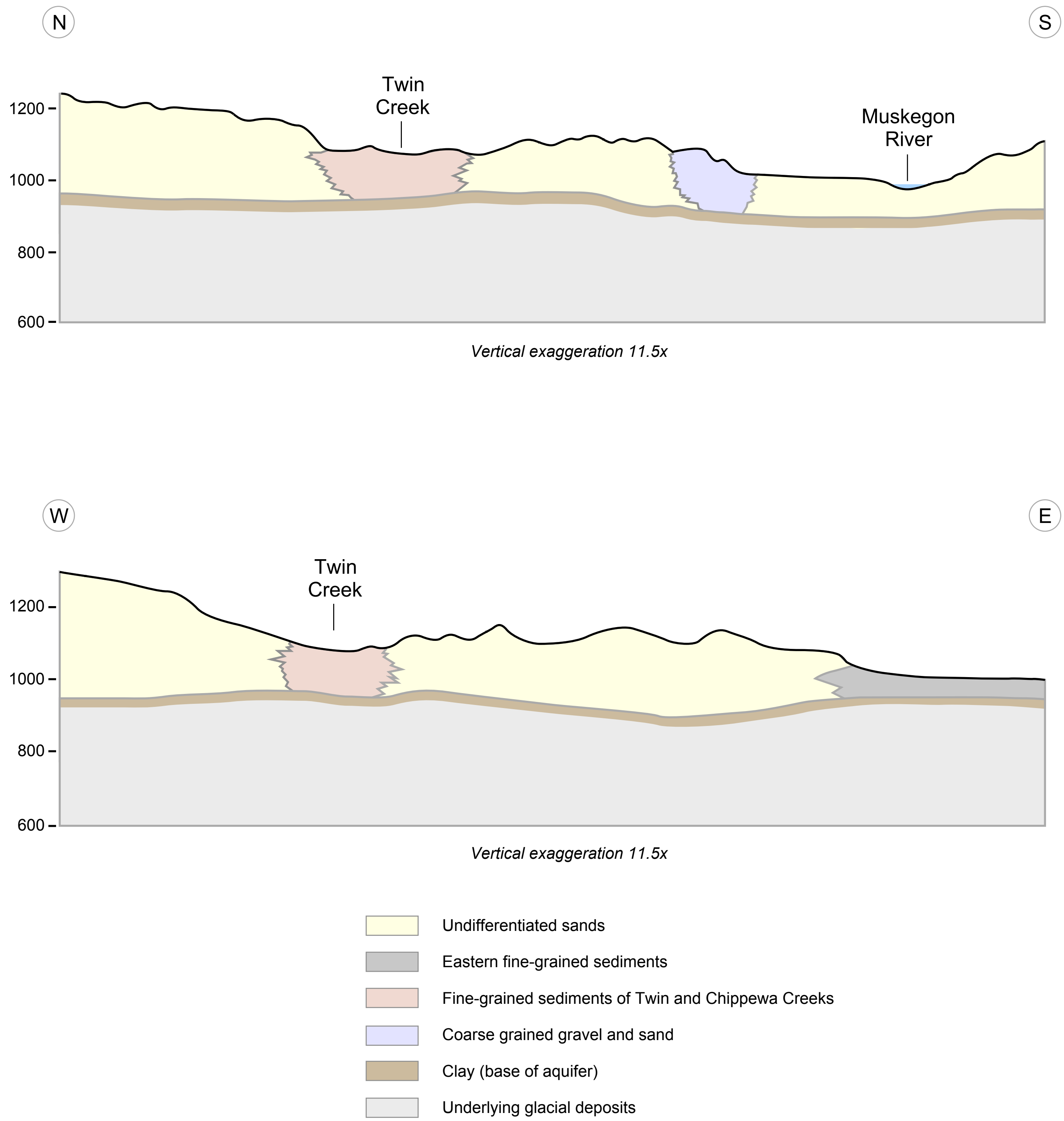


Figure 4 Regional Geologic Cross Sections

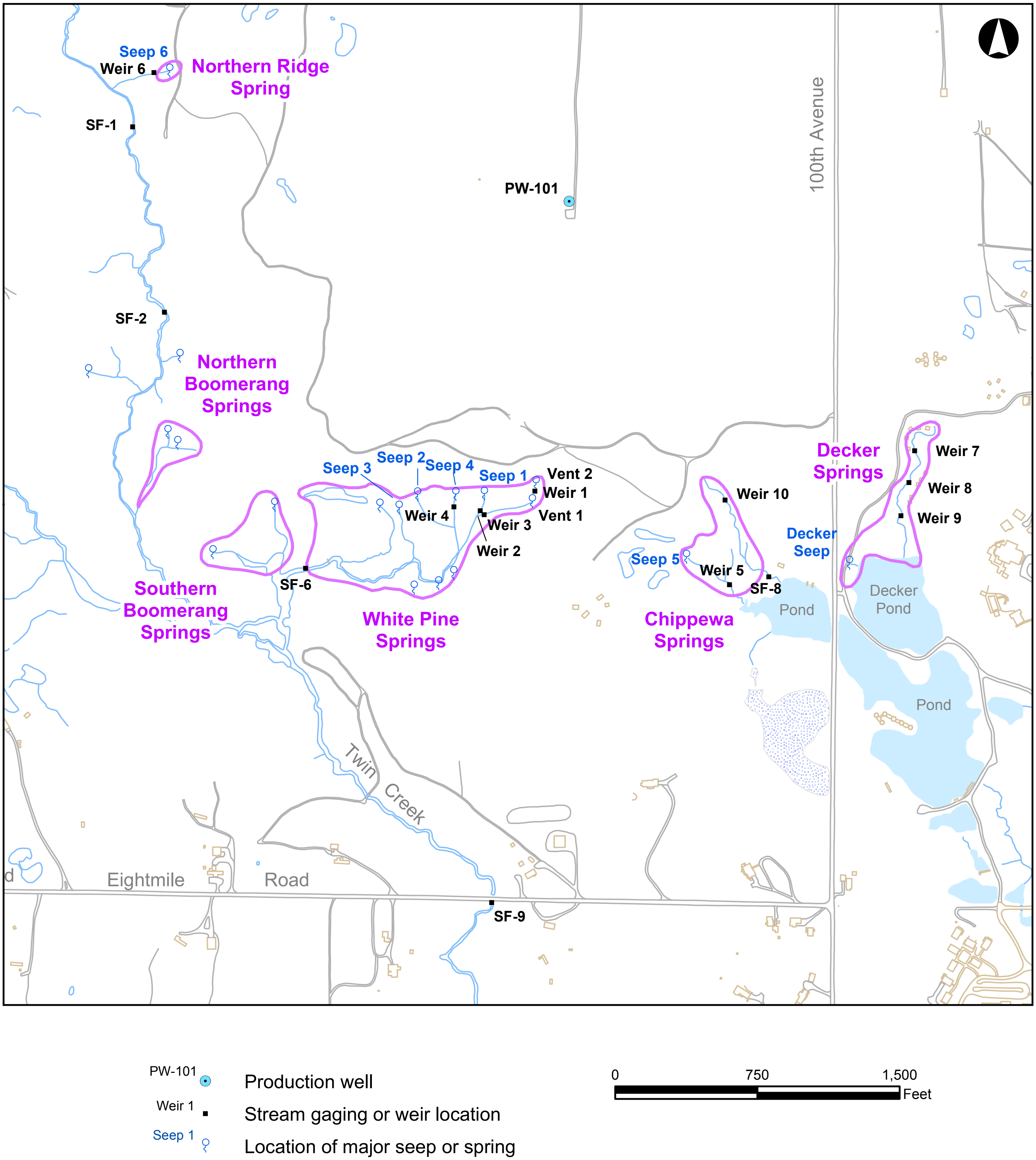


Figure 5 Springs and Streams in the Vicinity of PW-101

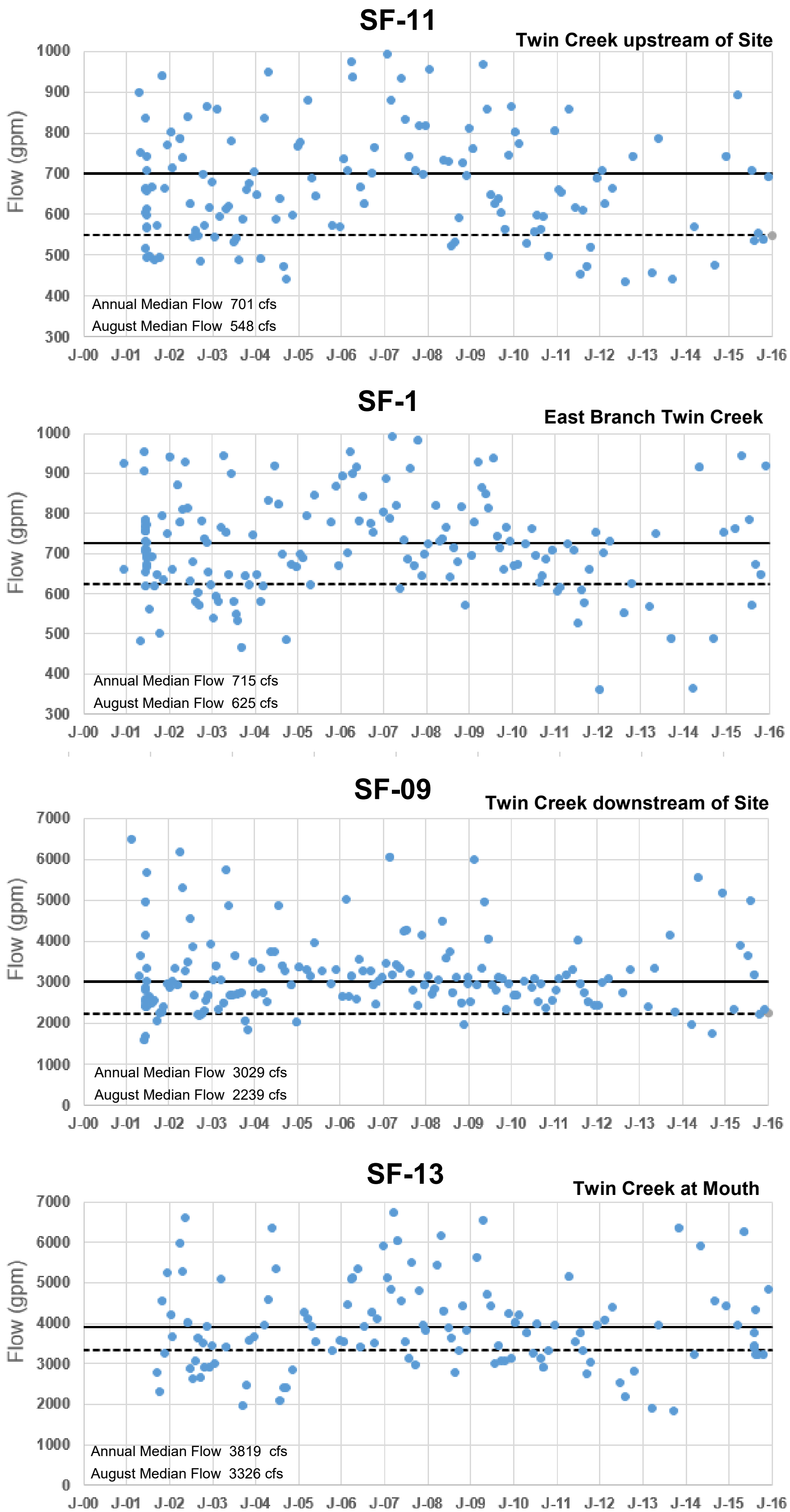


Figure 6 Measured Flows in Twin Creek

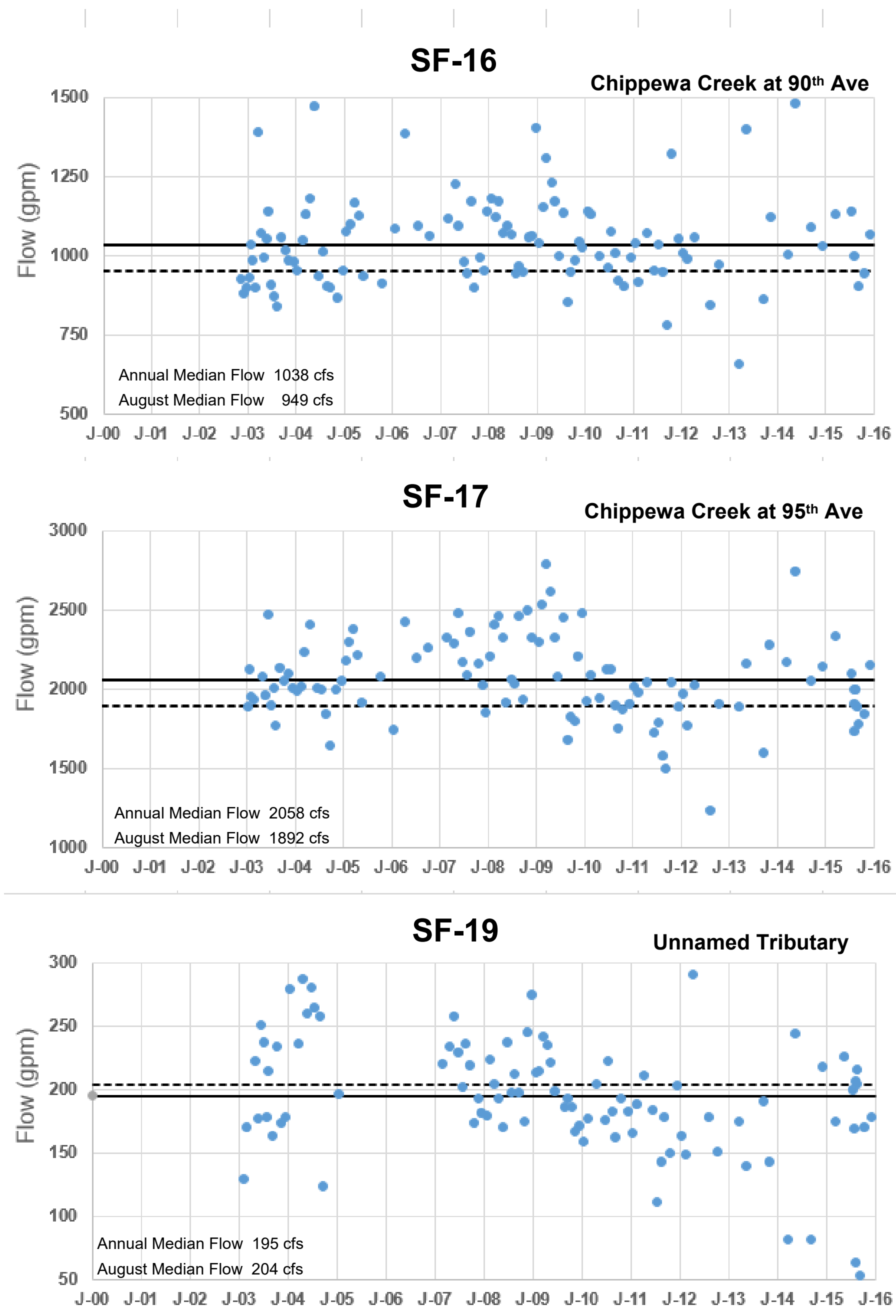


Figure 7 Measured Flows in Chippewa Creek

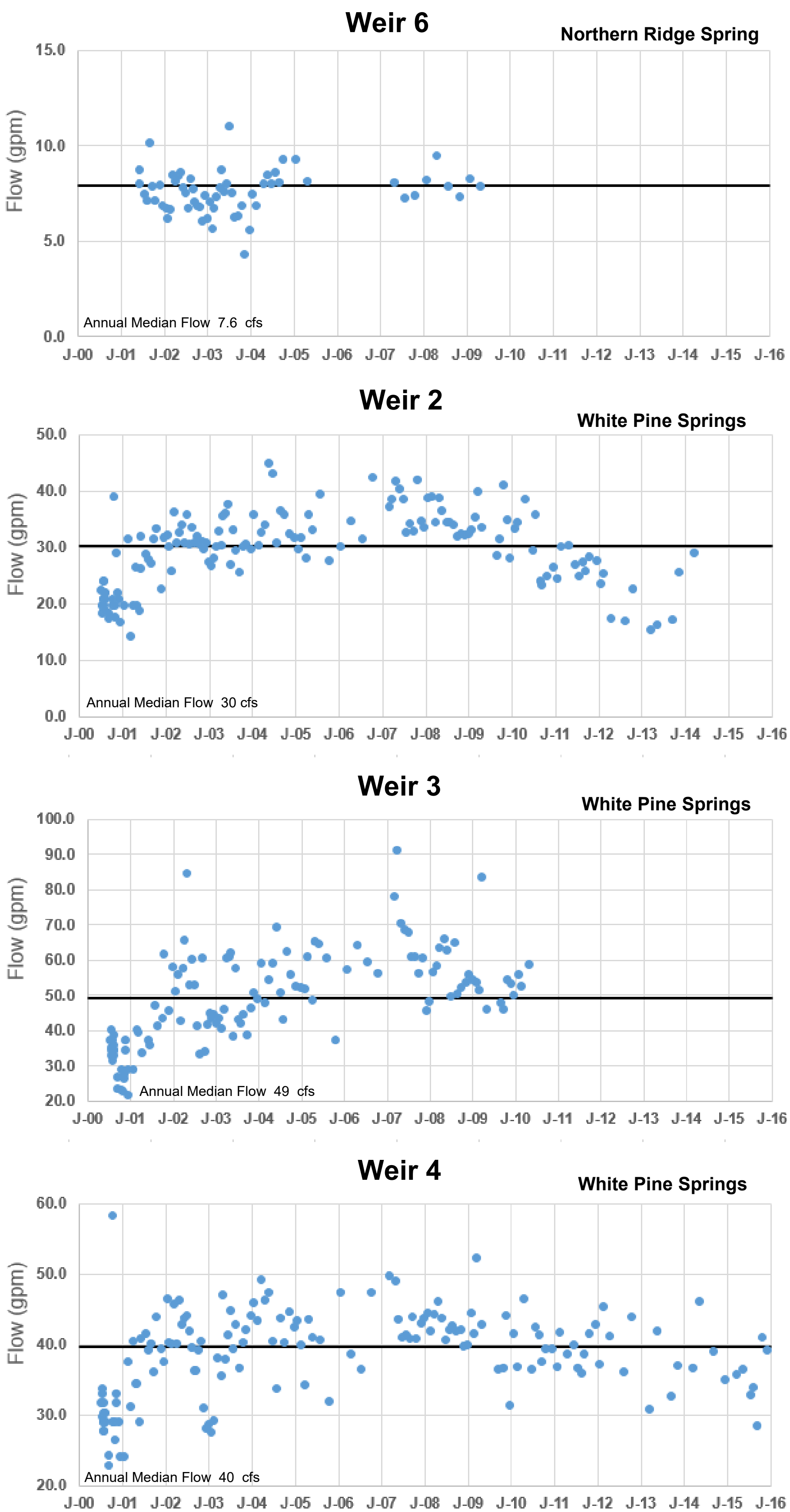
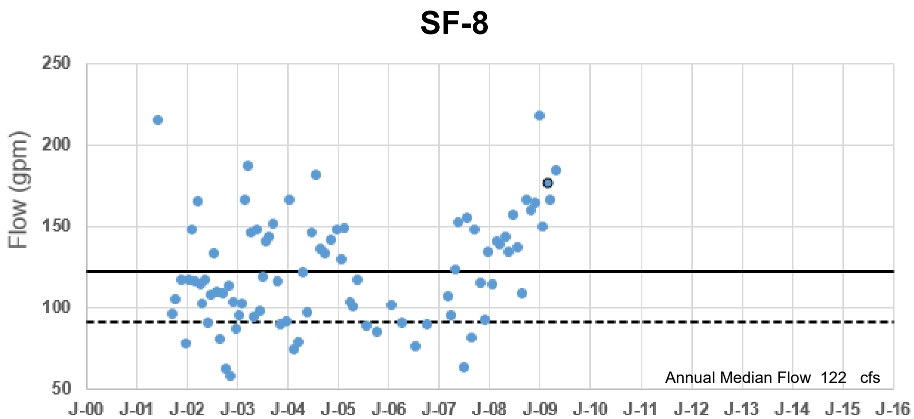


Figure 8 Measured Flows in Twin Creek Springs



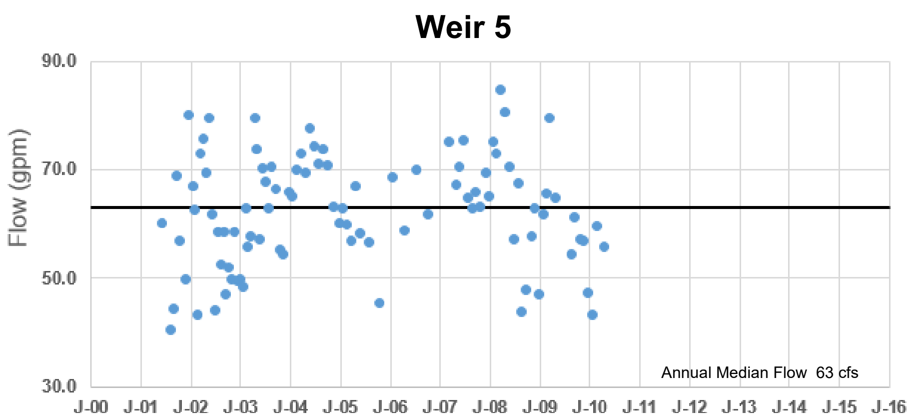


Figure 9 Measured Flows in Chippewa Creek Springs

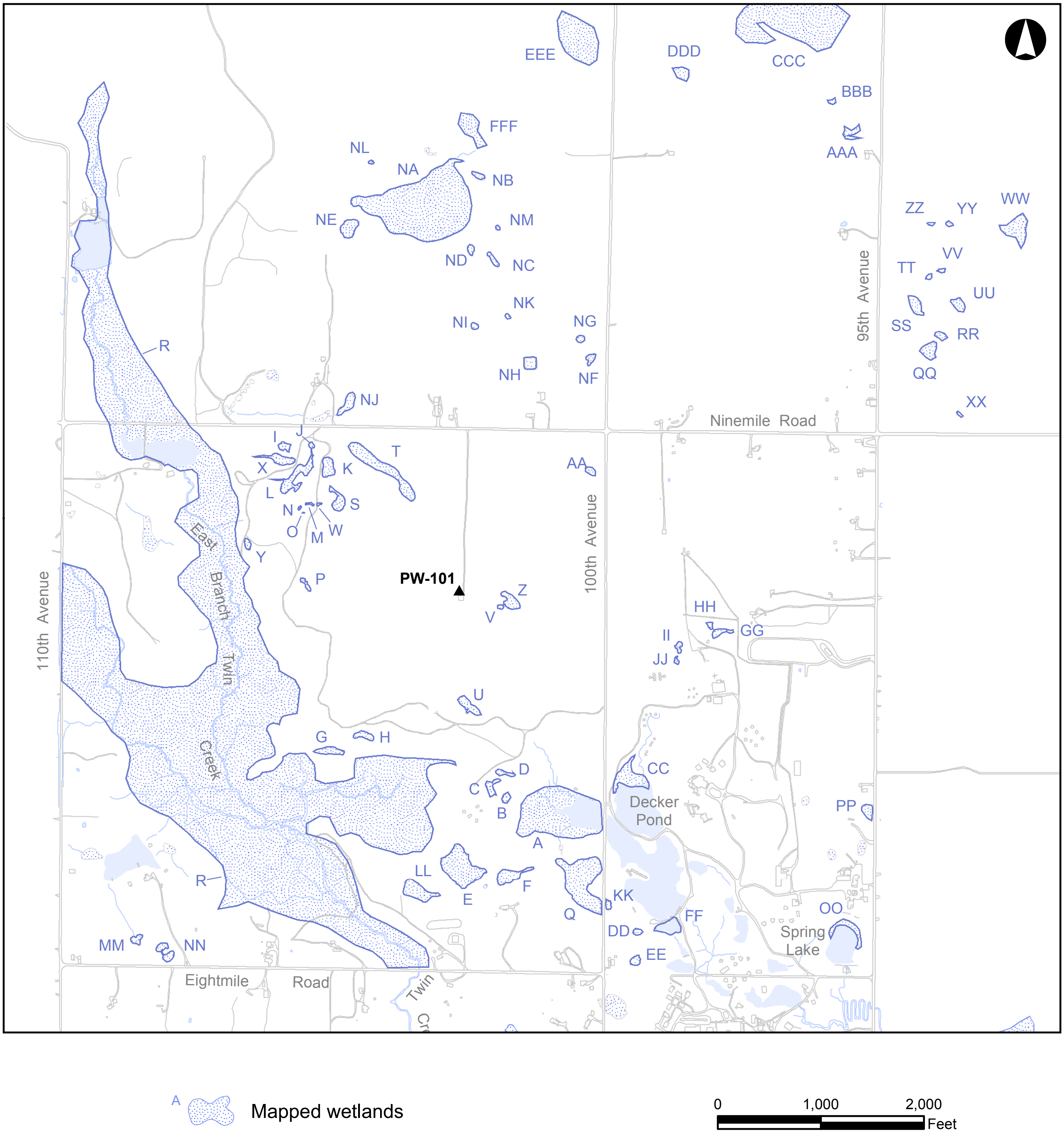


Figure 10 Location Map of Wetlands

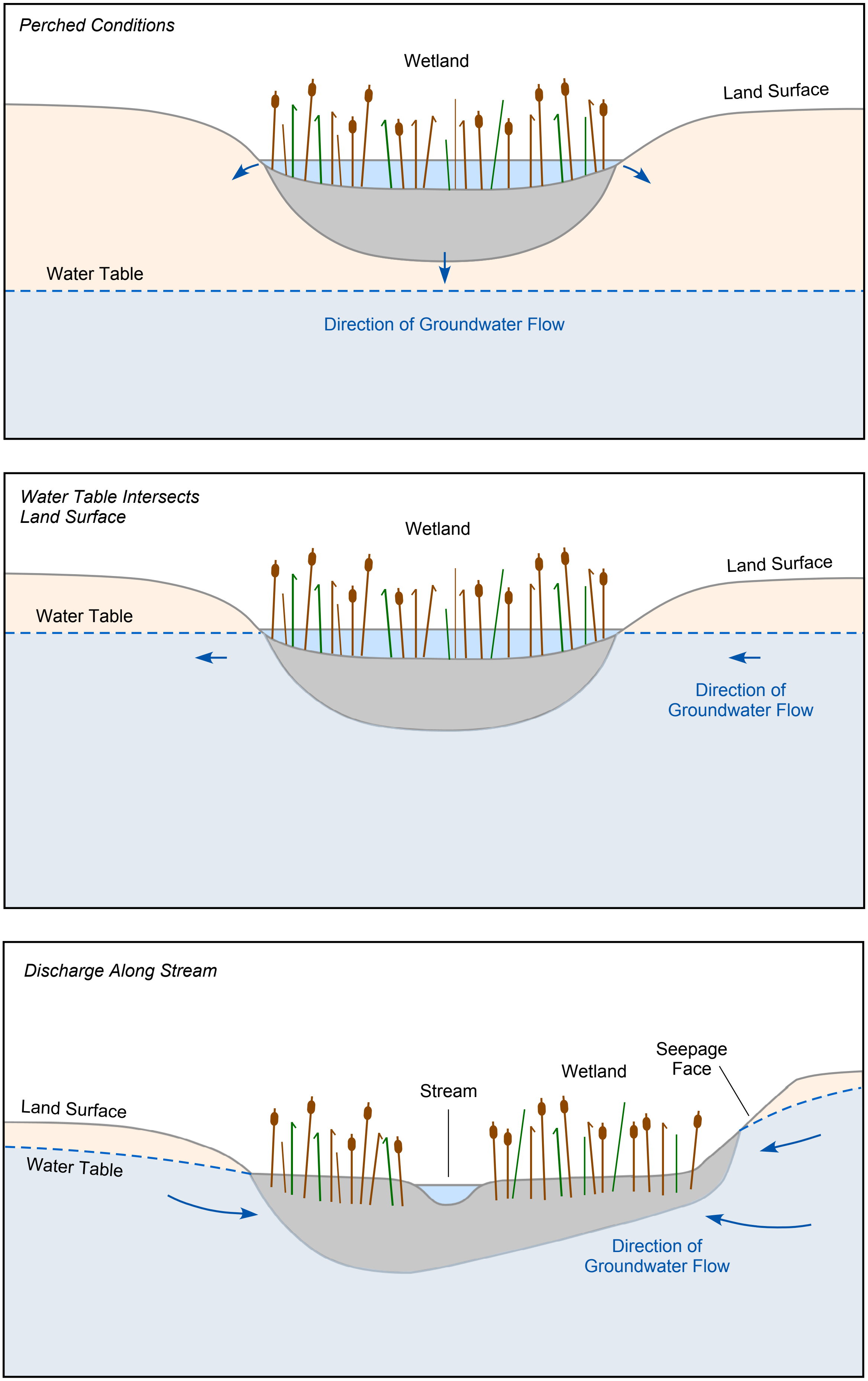


Figure 11 Schematic Diagrams of Wetland Systems

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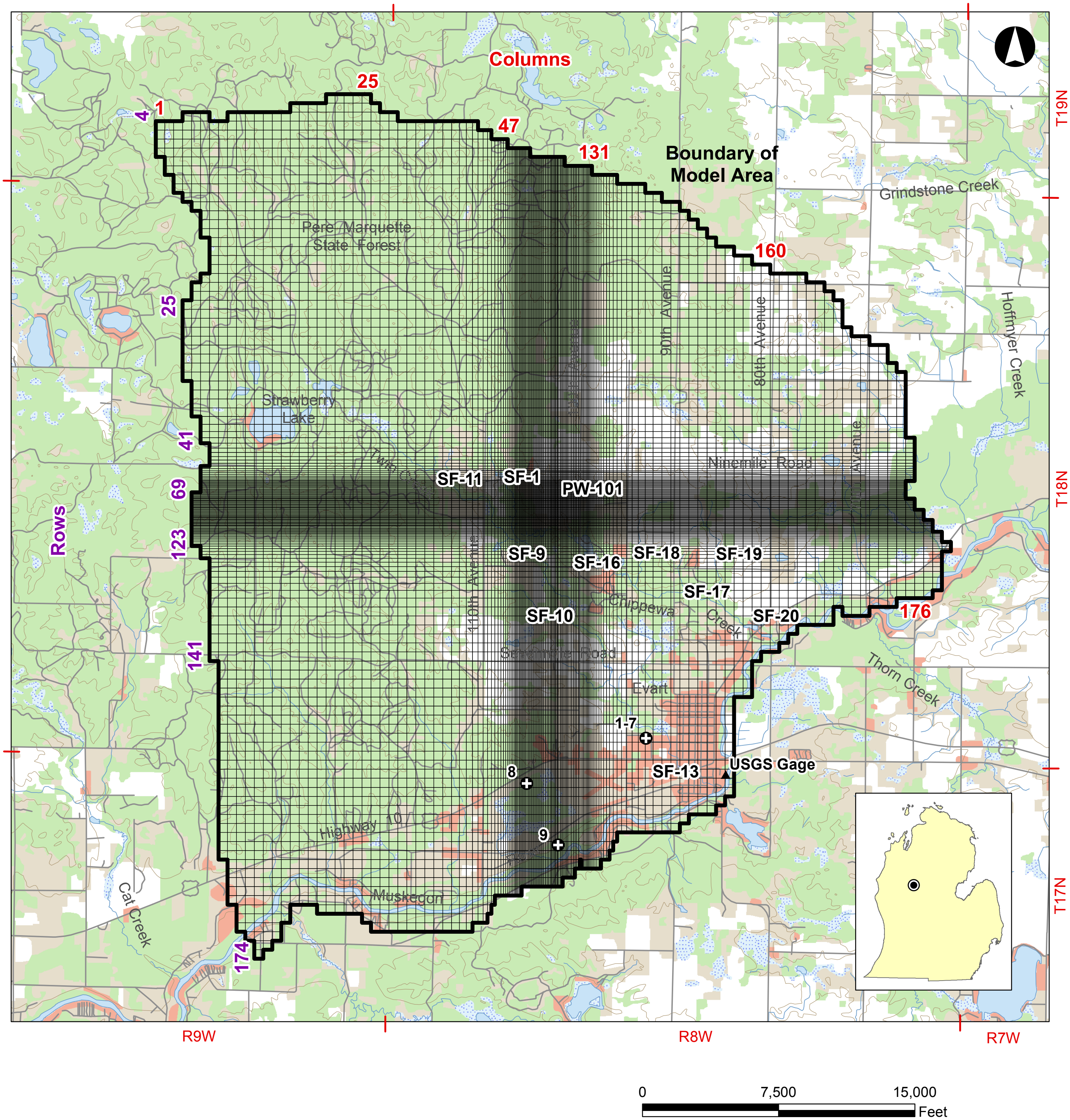


Figure 12 Regional Groundwater Model Grid

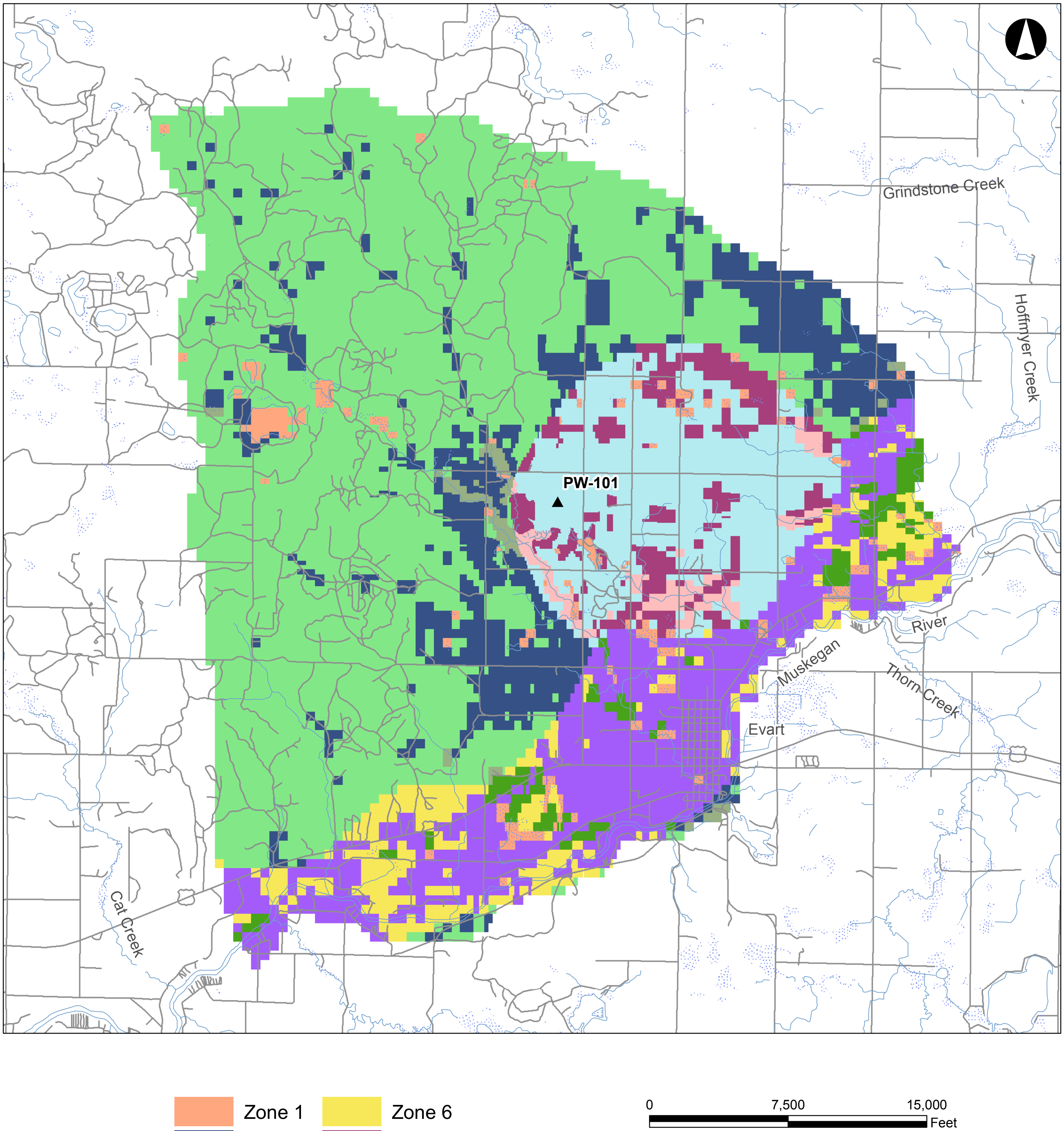


Figure 13 Recharge Zones in Model Area

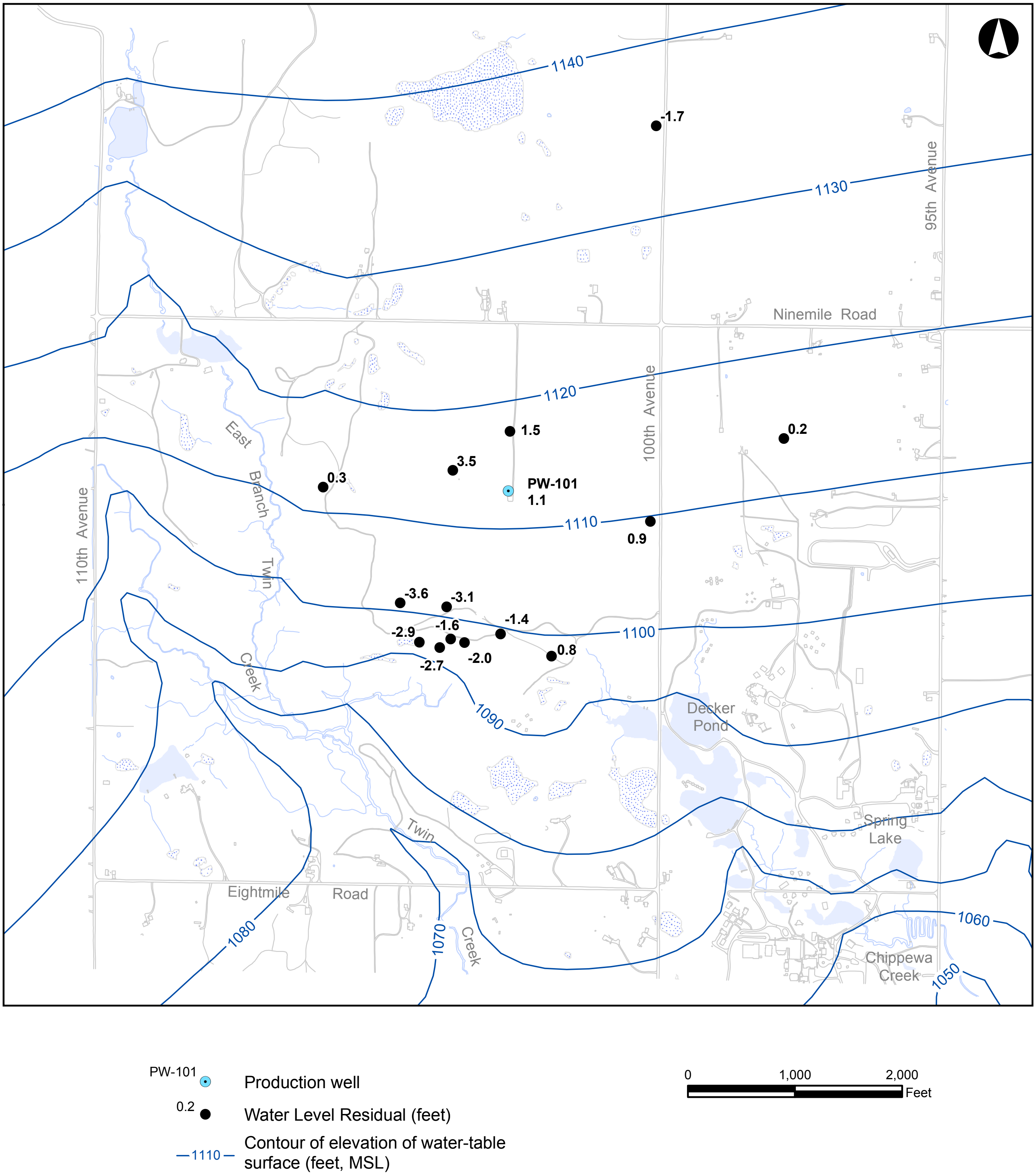


Figure 14 Calculated Steady-State Groundwater Levels in Vicinity of PW-101

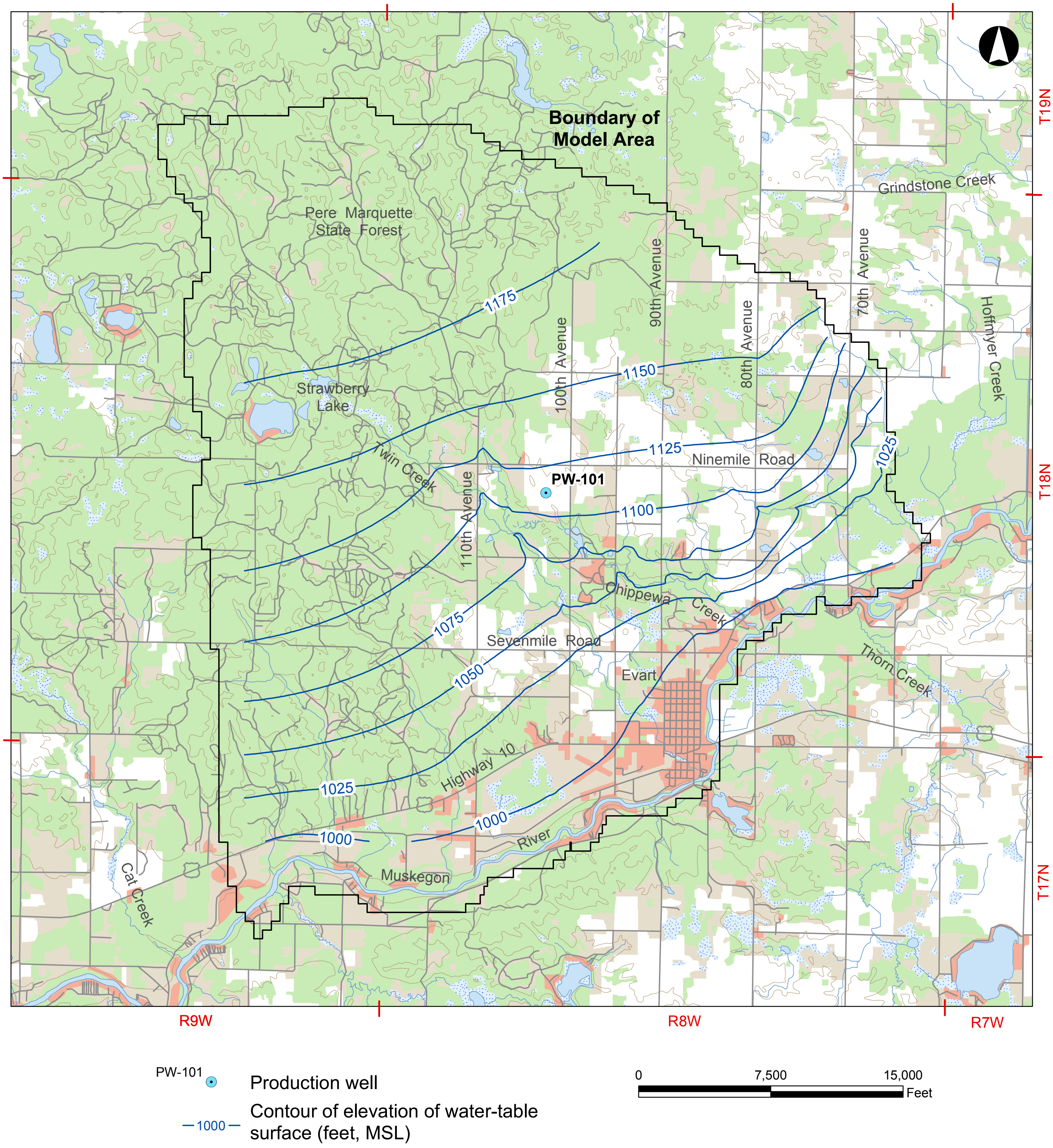
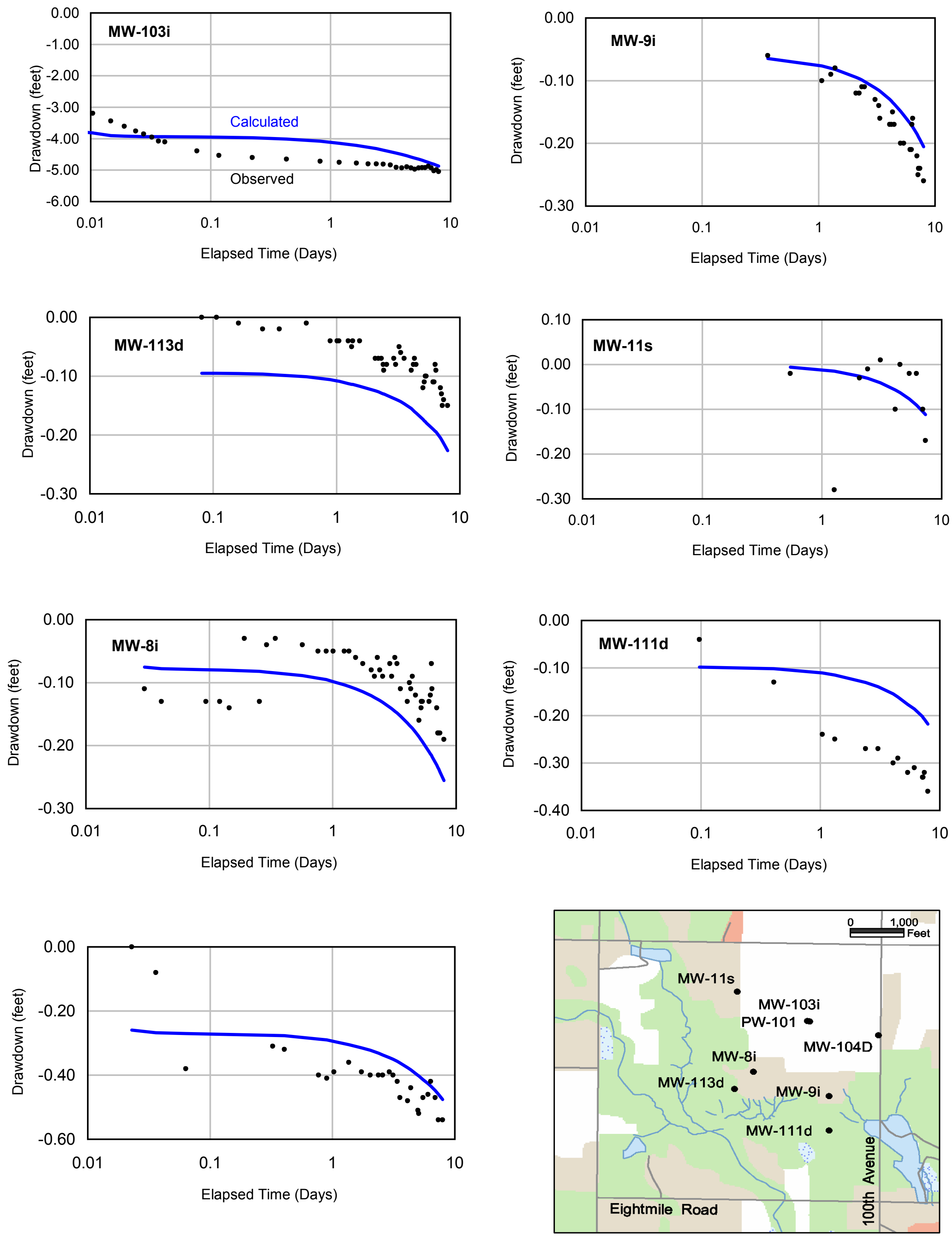
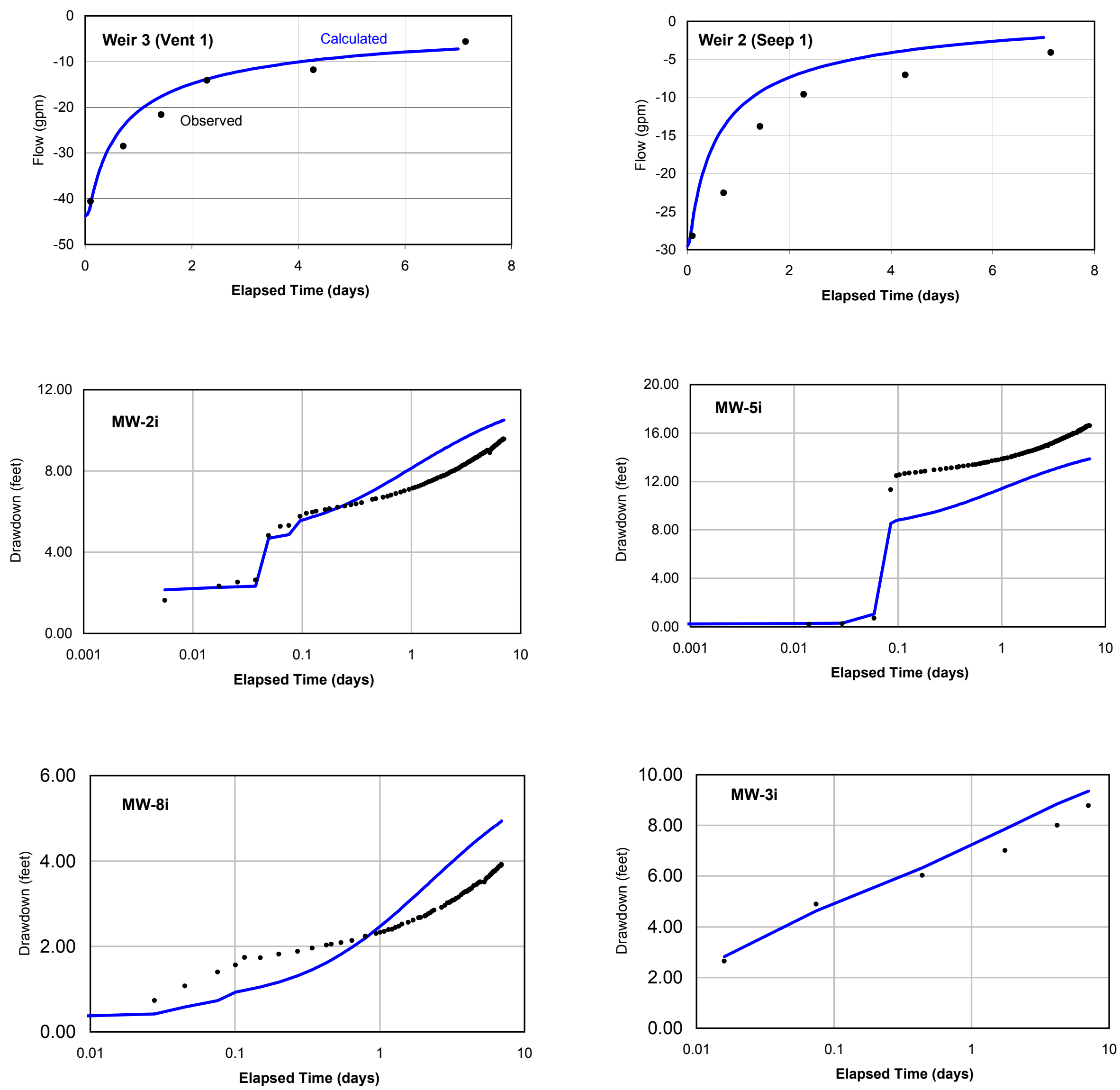


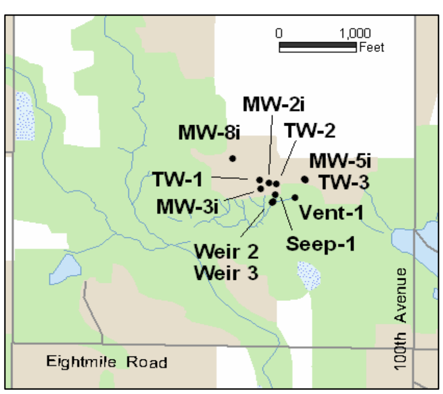
Figure 15 Calculated Steady-State Regional Groundwater Levels



Note: PW-101 pumped for eight days at a rate of 400 gpm.

Figure 16 Comparison of Calculated and Observed Drawdowns During Aquifer Test of PW-101





Notes:

TW-1 started first at rate of 200 gpm, followed one hour later by TW-2 at a rate of 227 gpm, followed one hour later by TW-3 at rate of 296 gpm. Pumping continued for seven days.

Figure 17 Comparison of Calculated and Observed Drawdowns During Aquifer Test of TW-1, TW-2 and TW-3

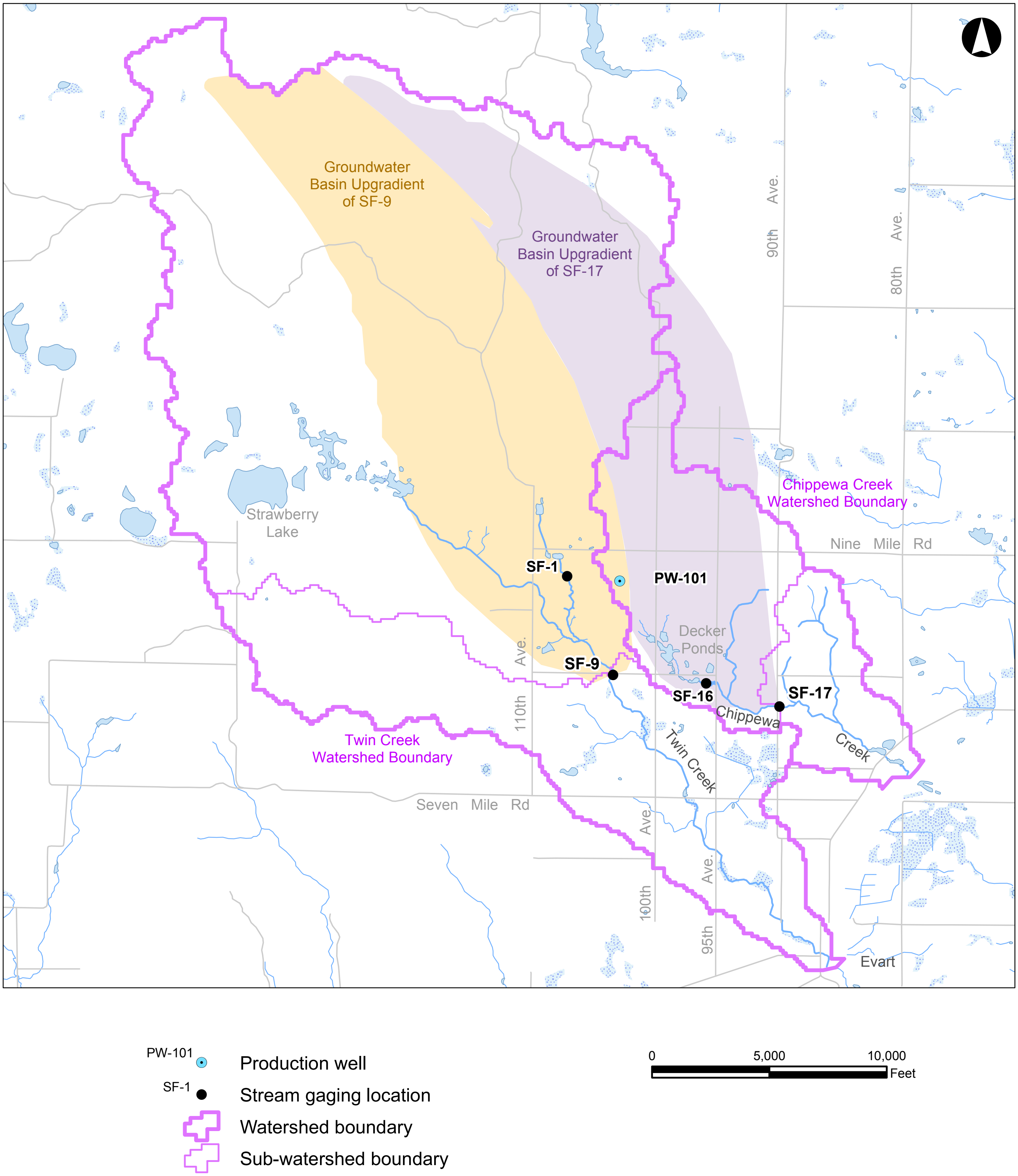
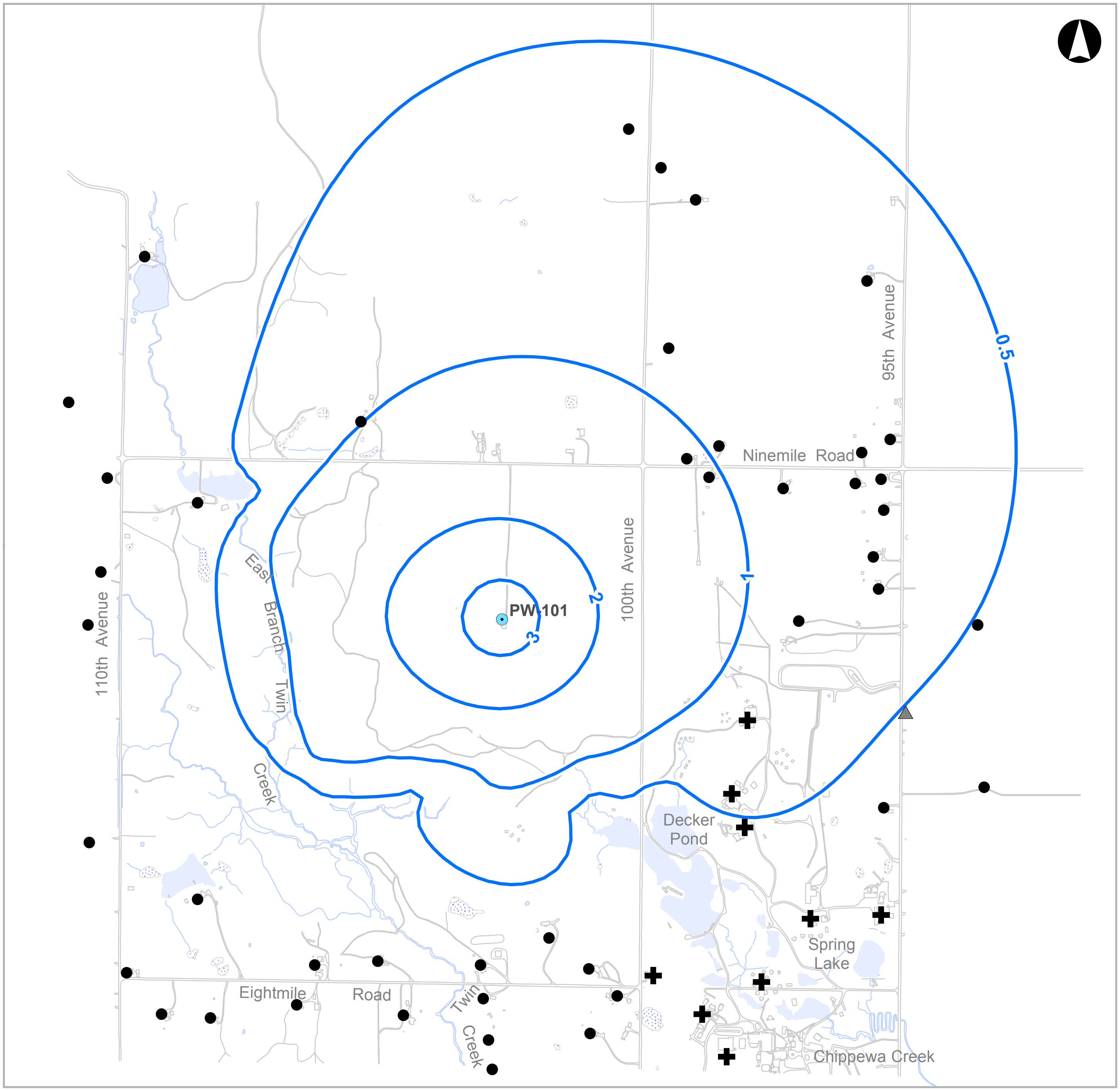


Figure 18 Twin Creek and Chippewa Creek Watersheds and Groundwater Basins



Note: Private wells only shown within one-mile of PW-101.

PW-101	Production well
	Residential well
	Irrigation well
	Spring Hill Camp well
3	Drawdown (feet)

0 1,250 2,500 Feet

Figure 19 Calculated Drawdown after 10 Years from an Increase in Withdrawal Rate from PW-101 from 150 to 400 gpm

TABLES

Table 1

Steady-State Calibration Targets and Residuals

Water Level Targets (feet)			
Well	**Measured**	**Calculated**	**Residual**
MW-1d	1098.25	1098.35	-0.1
MW-1i	1096.6	1096.81	-0.2
MW-1u	1094.09	1096.60	-2.5
MW-2i	1096.12	1097.74	-1.6
MW-3i	1095.05	1097.35	-2.3
MW 4i	1095.13	1097.35	-2.2
MW-5d	1099.11	1098.61	0.5
MW-5i	1098.02	1099.61	-1.6
MW-6i	1100.75	1102.23	-1.5
MW-7i	1098.29	1101.21	-2.9
MW-8i	1097.3	1100.56	-3.3
MW-9i	1098.89	1098.18	0.7
MW-10s	1102.69	1102.42	0.3
MW-11s	1117.79	1116.71	1.1
MW-12i	1119.22	1117.44	1.8
MW-12s	1119.38	1117.26	2.1
MW-13i	1095.64	1097.81	-2.2
MW-101s	1114.25	1113.50	0.7
MW-101d	1122.31	1123.66	-1.4
MW-101L	1106.6	1108.74	-2.1
MW-102i	1118.91	1115.47	3.4
MW-102d	1118.8	1117.89	0.9
MW-103i	1115.72	1113.03	2.7
MW-103d	1116.12	1115.59	0.5
MW-104i	1110.47	1110.59	-0.1
MW-104d	1110.47	1111.80	-1.3
MW-105s	1114.61	1114.24	0.4
MW-105d	1114.01	1113.90	0.1
MW105L	1114.46	1113.48	1.0
MW-106d	1120.32	1121.02	-0.7
MW-107i	1127.07	1124.56	2.5
MW-107d	1126.9	1126.09	0.8
MW-108i	1112.59	1111.83	0.8
MW-109d	1128.82	1129.11	-0.3
MW-110d	1113.7	1112.71	1.0
MW-111d	1098.19	1095.95	2.2
MW-113d	1092.05	1097.80	-5.7
MW-114i	1133.59	1131.59	2.0
PW-101	1114.34	1113.90	0.4
TW-1	1096.42	1097.80	-1.4
TW-2	1097.56	1097.86	-0.3
TW-3	1098.04	1099.46	-1.4

Stream Flow Targets (gpm)				
Stream	**Monitoring Location**	**Measured**	**Calculated**	**Residual**
East Branch	SF-1	671	715	-43
	SF-2	737	738	-1
Twin Creek	SF-11	650	673	-23
	SF-9	2693	2705	-12
	mouth (SF-13)	3065	3050	15
Chippewa Creek	SF-16	956	1001	-45
	SF-18	646	598	48
	SF-19	186	240	-54
	mouth (SF-20)	2758	2750	8
Northern Ridge Spring	Weir 6	7	-6	1
White Pine Springs	Weir 2	28	31	-3
	Weir 3	42	44	-2
	Weir 4	37	41	-4
Chippewa Springs	Weir 5 and SF-8	165	173	-8

Table 2

Calculated Changes in Stream and Spring Flows from an Increase in Withdrawal Rate from PW-101 from 150 gpm to 400 gpm

Spring	Monitoring Location	Average Base Flow (gpm)	Calculated Change in Flow (gpm)	Calculated Percent Change in Base Flow
Calculated Changes in Annual Flows				
East Branch	SF-1	715	-32	-4
Twin Creek	SF-11	701	-25	-4
	SF-9	3029	-118	-4
	SF-13	3819	-127	-3
Chippewa Creek	SF-16	1038	-58	-6
	SF-17	2058	-90	-4
White Pine Springs	SF-6	300	-27	-9
Northern Ridge Spring	Weir 6	8	-1	-13
Chippewa Springs	Weir 5 and SF-8	185	-20	-11
Calculated Changes in August Median (Q50) Flows				
East Branch	SF-1	625	-32	-5
Twin Creek	SF-11	548	-25	-5
	SF-9	2239	-118	-5
	SF-13	3326	-127	-4
Chippewa Creek	SF-16	949	-58	-6
	SF-17	1892	-90	-5
White Pine Springs	SF-6	300	-27	-9
Northern Ridge Spring	Weir 6	8	-1	-13
Chippewa Springs	Weir 5 and SF-8	146	-20	-14