Seminary Fen Phase 2 Hydrologic Study

and

Hydrologic Assessment of Alternative Corridors

TH 41 Tier 1 DEIS Study

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1.0 Introduction

1.1 Project Scope and Objectives

This report summarizes the hydrogeologic evaluation of six proposed alternative TH-41 crossings of the Minnesota River, near Chaska, Minnesota. The locations of these six proposed alternatives are shown on Figure 1-1. The primary purpose of the evaluation is to predict the potential hydrogeologic effects of construction and post-construction of the six alternatives in support of a Tier 1 Draft Environmental Impact Statement (DEIS) that addresses an evaluation of impacts for alternative highway routes that will inform the process of highway corridor preservation.

This analysis focuses on the hydrogeologic effects that may result because of highway construction and the longer-term effects that may occur following construction. The hydrogeologic effects that are analyzed include:

1. A lowering or raising of the water table or the pressure head of groundwater-transmitting geologic units;

2. A reduction or increase in the groundwater contribution to surface-water features, such as streams and wetlands;

3. A change in groundwater flow patterns (direction and rate); and

4. The identification of groundwater flow patterns from potential sources of contamination to potential receptors (e.g., pathways for road salt and runoff to seep into the ground and migrate via groundwater).

The above hydrogeologic effects were evaluated for all six alternatives. However, greater emphasis was placed on analyzing the effects from Alternatives E-1, E-1A, and E-2, which are in close proximity to the Seminary Fen Wetland Complex, as shown on Figure1-1. The Seminary Fen Wetland Complex is located approximately in T 116N R 23W Sec. 34 and 35 and T115N R23W Sec. 2 and 3. Portions of the Seminary Fen Wetland Complex contain calcareous fens. Calcareous fens can form where calcium-rich groundwater flows to the surface – they contain rare plant species and are afforded special protection under Minn. Rule Pt. 8420.1040. The calcareous fen portions of the Seminary Fen Wetland Complex are considered to be much more vulnerable to changes in groundwater flow because its special character is dependent on upwelling groundwater.

The Seminary Fen Wetland Complex area also includes Assumption Creek (Figure 1-2). Assumption Creek currently originates along the south side of a former railroad embankment at the foot of the bluff and northeast of the majority of the Seminary Fen Wetland Complex. It flows as an ephemeral stream to the south and makes an abrupt easterly turn, flowing between fen areas and Highway 212. It passes underneath Highway 212 and flows toward the Minnesota River. A hydrogeologic investigation conducted by Peterson Environmental, Inc. in 2005 and 2006 indicates that Assumption Creek gains flow from groundwater in the northern and eastern portions of the Seminary Fen Wetland Complex.

1.2 Overview of Approach

The evaluation of hydrogeologic effects from the various Highway 41 corridor alternatives requires quantitative predictions in order to compare the relative potential effects of the various alternatives. Because groundwater flow is inherently complex, the only reliable method of making quantitative predictions is through the use of a computer groundwater flow model, specifically developed and calibrated for this area and for these evaluations. Groundwater models were developed and employed in this study in the following general manner:

1. Existing regional geology and hydrogeology data were compiled.

2. A three-dimensional regional groundwater flow model was developed that included southern Carver County, southeastern Hennepin County, and northern Scott County. The model was calibrated to groundwater elevation data from wells.

3. The regional model was used as a basis for developing a more detailed model of the Seminary Fen Wetland Complex and surrounding area. Data and information collected in the Phase 1 hydrogeologic study (Peterson Environmental, 2006) was incorporated into this detailed model. Additional data were also used to recalibrate this model.

4. The calibrated local model of the Seminary Fen Wetland Complex was used to evaluate the effects of construction and post construction of Alternatives E-1, E-1A, and E-2. Assumptions were used concerning construction methodologies and post-construction conditions in order to make predictions of effects.

5. Another local model was developed from the regional model to examine the effects of Alternatives C-2, C-2A, and W-2. The focus for these alternatives was water resources near the Minnesota River.

2.0 Hydrogeology of Study Area

This section describes the major regional hydrogeologic features in the study area and the conceptual model that forms the basis for the computer simulations. A detailed description of the hydrogeology of the Seminary Fen Wetland Complex is presented in Section 2.4.

2.1 Geologic Setting

Geologic units underneath southern Carver County and throughout the metropolitan area fall into three broad categories: (1) Precambrian volcanic and crystalline rocks; (2) late-Precambrian through Ordovician sedimentary rocks; and (3) Quaternary unconsolidated deposits. The Precambrian volcanic and crystalline rocks generally are not considered major water-bearing units and are at a considerable depth below ground surface in southern Carver County. The late-Precambrian through Ordovician[1] sedimentary rocks make up the major regional aquifers and aquitards[2] in the metropolitan area, and include units such as the Hinckley Sandstone, the Prairie du Chien Group, and the Platteville Limestone. The Quaternary unconsolidated deposits include glacial outwash, glacial till, and alluvial deposits. A hydrostratigraphic column in Figure 2-1 shows the relationship between geologic units and major aquifers and aquitards in southern Carver County.

2.1.1 Geologic History

Describing how the various geologic units were deposited can be more instructive in placing southern Carver County in a regional hydrogeologic context than simply describing the characteristics of the units. The large-scale hydrogeologic system is far larger than southern Carver County or the seven-county metropolitan area. The extent of the bedrock geologic units is described here in the historical perspective of their depositional origin and subsequent tectonic activity.

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[1] Precambrian and Ordovician are geologic time periods. Precambrian refers to a time about 570 million years ago and older. Ordovician refers to a time about 500 to 440 million years ago.

[2] An aquifer is a portion or combination of geologic units that can transmit usable quantities of water. An aquitard is a portion or combination of geologic units that are of low permeability and generally cannot transmit much water. The term “confining unit” is sometimes used interchangeably with aquitard.

Portions of Iowa, Minnesota, Wisconsin, Illinois, and Missouri were in a depression (called the Ancestral Forest City Basin) covered by a shallow eperic sea in the late-Precambrian (about 570 million years ago). A northern bay of this sea extended over a syncline in the Precambrian Lake Superior Volcanic rocks into southern Minnesota and western Wisconsin. This bay is called the Hollandale Embayment. The Hollandale Embayment extended from north of Hinckley to the Iowa border, deepening to the south. The study area is in an area believed to have been along the western edge of the Hollandale Embayment. From the late-Precambrian (about 570 million years ago) through the Devonian (about 355 million years ago) the water level in the eperic sea fluctuated causing transgressions (a rising of sea level) and regressions (a dropping of sea level). Depending on the sea level, different sediments were deposited. For example, as the sea level rose, beach sands were deposited (e.g. the Jordan Sandstone), followed by a deeper water environment were carbonate deposits formed from shell-bearing sea animals (e.g. Prairie du Chien Group).

During this depositional process, additional tectonic activity took place, forming a small basin in the Hollandale Embayment, known as the Twin Cities Basin. Faulting of the existing sedimentary rocks took place during the formation of the Twin Cities Basin.

An extended period without evidence of significant deposition took place after the Devonian (about 355 million years ago), as the seas retreated for the last time. If additional deposition did take place, these rocks have been subsequently eroded away. At the beginning of the Quaternary (about 1.5 million years ago), the great continental ice sheets formed and glaciers moved into the area. The glaciers eroded away all or portions of the upper sedimentary units in many locations and their meltwaters carvied deep river channels into the bedrock in some locations. Glacial meltwaters deposited sand and gravel (outwash) in other locations. Ice blocks were left in place to melt as the glaciers retreated. Several glacial advances and retreats took place during the Quaternary. Glacial till deposits were deposited underneath and adjacent to the glaciers.

The ancestral Mississippi River and the River Warren (ancestral Minnesota River) incised back into the glacial deposits, forming wide river valleys with alluvial terrace deposits and backwater areas. The River Warren, in particular, shaped the Quaternary landscape in the vicinity of the Seminary Fen Wetland Complex by deeply incising into the Paleozoic bedrock and leaving behind coarse-grained valley fill and terrace deposits.

2.1.2 Bedrock Stratigraphy

A very general way of looking at the bedrock units in southern Carver County is to imagine a number of layers that are dipping slightly eastward, towards Minneapolis and the center of the Twin Cities Basin. The thickness and textural characteristics of these units can vary from place to place but, in a gross sense, are relatively uniform. A hydrostratigraphic column of the bedrock deposits is shown on Figure 2-1. The general characteristics of these units are described below.

1. Mt. Simon Sandstone

The Cambrian Mt. Simon Sandstone is chiefly a coarse, quarztzose sandstone, with the upper one-third containing many thin beds of well-sorted siltstone and very fine sandstone. The lower two-thirds of this unit has few layers of fine-grained sandstone and consists primarily of medium- to coarse-grained sandstone. The basal contact with the Precambrian Solor Church Formation is erosional. The Hinckley Sandstone is also present in southern portions of Carver County but may be difficult to differentiate from the Mt. Simon Sandstone. The upper contact with the Eau Claire Formation is sharp.

2. Eau Claire Formation

The Cambrian Eau Claire Formation is a siltstone, very fine sandstone, and greenish-gray shale. Some sandstone beds are glauconitic. Minor dolomitic cement is present at the top of the formation. The contact with the overlying Galesville Sandstone is gradational.

3. Ironton and Galesville Sandstones

The Cambrian Ironton Sandstone and Galesville Sandstone are silty, fine- to coarse-grained, poorly sorted, quartzose sandstone underlain by better sorted, fossiliferous, fine- to medium-grained sandstone. The two units are typically difficult to differentiate. The upper contact between the Galesville Sandstone and the overlying Franconia Formation is sharp.

4. Franconia Formation

The Cambrian Franconia Formation is composed of thin-bedded, very fine-grained glauconitic sandstone with shale.

5. St. Lawrence Formation

The Cambrian St. Lawrence Formation consists of dolomitic shale and siltstone that is generally thin bedded. The contact with the underlying Franconia Formation is gradational. The contact with the overlying Jordan Sandstone is also gradational.

6. Jordan Sandstone

The upper part of the Cambrian Jordan Sandstone is medium- to coarse-grained, friable, quartzose sandstone that is trough cross-bedded. The lower part of this unit is primarily massively bedded and bioturbated. The upper contact with the overlying Prairie du Chien Group is relatively sharp. The Jordan Sandstone is approximately 60 to 90 feet thick in southern Carver County.

7. Prairie du Chien Group

The Ordovician Prairie du Chien Group contains the Shakopee Formation (upper) and the Oneota Dolomite (lower). The Shakopee Formation is a dolostone that forms approximately one-half to two-thirds of the Prairie du Chien Group and is commonly thin-bedded and sandy or oolitic. The Shakopee Formation contains thin beds of sandstone and chert. The Oneota Dolomite forms approximately one-third to one-half of the Prairie du Chien Group and is commonly massive- to thick-bedded. Both formations are karsted and the upper contact may be rubbly (from pre-aerial exposure). The Prairie du Chien Group is approximately 145-feet thick where it is in complete section.

8. St. Peter Sandstone

The upper one-half to two-thirds of the Ordovician St. Peter Sandstone is fine- to medium-grained quartzose sandstone that generally is massive- to very thick-bedded. The lower part of the St. Peter Sandstone contains multicolored beds of sandstone, siltstone, and shale with interbeds of very coarse sandstone. The base is a major erosional contact. The full section of the St. Peter Sandstone is approximately160 feet thick. In the eastern part of the study area (Eden Prairie, for example), the St. Peter Sandstone is present as isolated outcrops, typically capped by the Platteville and Glenwood Formations, which are more resistant to erosion. It is not present in the immediate vicinity of the alignments or the Seminary Fen Wetland Complex.

9. Platteville and Glenwood Formations

The Ordovician Glenwood Formation is a green, sandy shale that overlies the St. Peter Sandstone, where present. The Glenwood Formation ranges in thickness up to 15 feet. The Ordovician

Platteville Formation is a fine-grained dolostone and limestone. Both units are present as isolated "mesas" of limited extent and are not present in the area of the alignments or the Seminary Fen Wetland Complex.

2.1.3 Structural Geology and Erosional Limits

The regional dip of the Paleozoic units is toward the northeast, reflecting the position of southern Carver County on the western margin of the Twin Cities Basin. The Twin Cities Basin developed in the Middle Ordovician. The Twin Cities Basin is the result of many small folds and faults in step-wise fashion. The individual folds have a displacement of approximately 100 feet and individual faults have a displacement of 50 to 150 feet.

Quaternary erosion by glaciers has removed much of the St. Peter Sandstone and younger Paleozoic rocks from southwestern Hennepin County. Moving west into Carver County, the bedrock is generally at a higher elevation due to proximity along the western edge of the depositional basin (Hollandale Embayment) and the western edge of the Twin Cities structural basin. As a result, erosion of bedrock above and into the St. Lawrence Formation is more prevalent and there are deep channels in the buried bedrock surface. For example, the extent of the Jordan sandstone is shown on Figure 2-2; clearly indicating those areas were Quaternary fluvial erosion incised into the bedrock and subsequently filled the valley with unconsolidated deposits. The uppermost bedrock units are shown on Figure 2-3 and the elevation of the uppermost bedrock is shown on Figure 2-4 (data from Minnesota Geological Survey).

2.1.4 Quaternary History

Continental ice sheets covered the study area several times over the past 2 million years from two sources in northern Canada, located northwest (Keewatin) and northeast (Labradorean). Keewatin tills were deposited first and covered the entire county at one time. After a long period of weathering and erosion, the Labradorean Superior lobe advance during the Illinoian, depositing reddish till and meltwater sediments. Much of these tills has been subsequently eroded.

The dominating glacial activity took place during the Late Wisconsinan, beginning with the advancement of the Superior Lobe. Early advance of the Superior Lobe resulted in till deposition and formation of the St. Croix Moraine. During formation of the moraine, a subglacial meltwater stream system developed, followed by retreat that left stagnant blocks of ice. A second advance (Des Moines lobe) overrode the moraine and reworked early deposits. The retreat of this final glacial advance

resulted in outwash deposition over stagnant ice in areas now occupied by Lake Minnetonka. The Eden Prairie outwash plain was also laid down at this time (Meyer and Hobbs, 1989).

With the retreat of the Des Moines lobe, glacial Lake Agassiz formed in northern Minnesota, North Dakota, and Canada. Its southern outlet followed the path of the Glacial River Minnesota, but is referred to as the River Warren. The River Warren cut its valley in stages, creating more terraces and alluvial deposition. The valley was subsequently filled by thick alluvial deposits and has been filling to current time (Meyer and Hobbs, 1989). Postglacial lake and bog deposits formed in depressions created by melting of buried ice blocks.

2.2 Hydrostratigraphic Units

Hydrostratigraphic units are either aquifers (one or more geologic units capable of transmitting usable quantities of water, dominated by horizontal groundwater flow) or aquitards (one or more geologic units of low permeability, dominated by vertical groundwater flow). Hydrostratigraphic units comprise geologic formations of similar hydrogeologic properties. Several geologic units might be combined into a single hydrostratigraphic unit or a geologic formation may be subdivided into a number of aquifers and aquitards. The "lumping" and "splitting" of geologic units into hydrostratigraphic units is the single most important function of the Conceptual Model, prior to creation of the computer model. The goal is to simplify the vertical discretization of the aquifer system as much as practical without sacrificing the ability of the computer model to meet the stated purpose and use.

The geologic units that have been selected for the aquifers and aquitards are shown on Figure 1-1. The Mt. Simon-Hinckley Aquifer is not considered in this evaluation because it is relatively isolated hydraulically from overlying units by the low permeability Eau Claire Formation. The following discussion presents the rationale for the selection of hydrostratigraphic units to be included in the model in this evaluation.

2.2.1 Franconia-Ironton-Galesville Aquifer

The deepest aquifer considered in this evaluation is the Franconia-Ironton-Galesville (a.k.a FIG) aquifer, which consists of the Ironton Sandstone, the Galesville Sandstone, and the Franconia Formation. The Franconia-Ironton-Galesville aquifer is not a major water supply for the Twin Cities metropolitan area because sufficient water supplies can usually be obtained from shallower units, such as the Prairie du Chien-Jordan aquifer. Use of the FIG is encouraged where use of shallower

aquifers would tend to cause impacts to other water resources. Recently, the Franconia-Ironton-Galesville aquifer has undergone greater evaluation by the Minnesota Geological Survey, particularly in western Hennepin County, where the Prairie du Chien-Jordan aquifer is not present.

In deep bedrock conditions, hydraulic conductivity values typically range from 1.5 to 28 feet per day and average about 10 feet/day (based on specific capacity tests). In shallow bedrock conditions, interconnected fracture systems seem to develop, resulting in average hydraulic conductivity values of about 28 feet/day (Runkel et al., 2003). Anecdotal information from well drillers suggest that the Franconia-Ironton-Galesville aquifer is less productive in the southwestern metropolitan area than it is in northern parts of the area, but these observations have not been widely verified.

2.2.2 St. Lawrence Confining Layer

The St. Lawrence Formation is a regional leaky confining layer (aquitard) that separates the Franconia aquifer from the overlying Prairie du Chien-Jordan aquifer. Runkel et al. (2003) describe the St. Lawrence Formation as having low bulk hydraulic conductivity in the vertical direction and can provide confinement. These confining characteristics are present where the St. Lawrence Formation is relatively deep and overlain by the Jordan Sandstone. However, where the St. Lawrence Formation is at shallow depth, interconnecting fractures render the St. Lawrence Formation a relatively high yielding aquifer.

2.2.3 Prairie du Chien-Jordan Aquifer

The Prairie du Chien Group and the Jordan Sandstone are typically treated as a single aquifer system in the Twin Cities area; the Prairie du Chien-Jordan Aquifer. The Prairie du Chien-Jordan Aquifer supplies 80 percent of the groundwater pumped in the Twin Cities area, with yields from 85 to 2,765 gpm (Schoenberg, 1990). Groundwater flow in the Jordan Sandstone is primarily intergranular but secondary permeabilities undoubtedly develop due to jointing and differential cementation (Schoenberg, 1990). Groundwater flow in the Prairie du Chien Group is through fractures, joints, and solution features. A small number (perhaps 3 to 5) horizontal fracture zones are responsible for the majority of flow in the Prairie du Chien Group (Runkel et al., 2003).

A tacit modeling assumption made when two geologic units are combined into a single aquifer is that there is not a significant head difference between the two units. On a regional basis, this is likely a good assumption; head differences (where available) are relatively insignificant between the Prairie du Chien Group and the Jordan Sandstone. However, there is evidence that local differences in head

between the two units can develop, especially where pumping is only from the Jordan Sandstone. An example of this phenomenon is in the vicinity of St. Paul Park Well No. 1 and the Marathon Ashland Petroleum Company (formerly Ashland Petroleum) refinery. A pumping and recovery test was performed in the Jordan Sandstone using St. Paul Park Well No. 1 while monitoring at multiple levels in the Prairie du Chien Group and the Jordan Sandstone. A substantial cone of depression developed in the Jordan Sandstone but very little drawdown was observed in the Prairie du Chien Group piezometers (Barr Engineering, 1990). High capacity production wells are also operated in the Jordan Sandstone at the Marathon Ashland refinery with little response in the Prairie du Chien Group. In this area, the two units are distinctly different aquifer systems under hydraulic stresses.

An artificial recharge study on the Prairie du Chien-Jordan Aquifer was conducted by the U.S. Geological Survey in West St. Paul (Reeder, 1976). Reeder (1976) notes that "[a]lthough the Prairie du Chien and the underlying Jordan Sandstone are hydraulically connected, the water levels in the Prairie du Chien wells are at an altitude of 724 feet (221 m) and in the Jordan well at an altitude of 722 feet (220 m)", thus indicating some differences in hydraulic head. During a pumping test in the Prairie du Chien Group, drawdown in the Prairie du Chien Group was noted to be greater than in the Jordan Sandstone, indicating that the two units behave differently even though they are hydraulically connected.

Tipping (1992, unpublished MS Thesis) conducted an isotopic and chemical study of groundwater flow in the Prairie du Chien Group and Jordan Sandstone in northern Scott and Dakota Counties. Tipping (1992, unpublished MS Thesis) found that recharge from the Prairie du Chien Group to the Jordan Sandstone was induced, in part, by high capacity pumping in the Jordan (e.g. Apple Valley). In Apple Valley, a sustained vertical gradient between the two units develops. Different isotopic signatures for the two units also manifest themselves in some locations. Tipping (1992, unpublished MS Thesis) notes that the upper member of the Jordan Sandstone (Coon Valley Member) is typically fine-grained, well-cemented, has a lower conductivity than beds above and below it, and may serve locally as an aquitard.

A recent study by Runkel et al. (2003) has demonstrated that the lower portion of the Oneota Dolomite is massive, of low permeability, relatively unfractured, and acts as a regional aquitard that separates the permeable portions of the Prairie du Chien Group (the upper part of the Oneota Dolomite and the Shakopee Formation) from the Jordan Sandstone.

2.2.3.1 Jordan Sandstone

Many high-capacity wells are completed solely within this unit. The unit is approximately 100 feet thick but may thicken to the south (Bruce Olson, personal communication). The degree of cementation of the Jordan Sandstone varies (Tipping, 1992, unpublished MS thesis). Hydraulic conductivity can vary, depending upon the degree of cementation. Schoenberg (1990) reports a range of horizontal hydraulic conductivity values from 19 to 107 feet/day from field tests.

The Jordan Sandstone subcrops beneath glacial drift and alluvium in major river valleys, which are the primary discharge zones. In these areas, hydraulic head can be expected to be at or slightly above the elevation of the river. As a result, wells drilled into the Jordan Sandstone on the lower river terraces can become flowing wells. Discharge via pumping of high-capacity wells is also a significant discharge route. Recharge is primarily through leakage from the overlying Prairie du Chien Group. Flow in the Jordan Sandstone is toward the Minnesota River, which is the major discharge zone.

2.2.3.2 Basal Oneota Dolomite

The basal Oneota Dolomite is a regional confining layer (aquitard) in the study area and throughout southeastern Minnesota (Runkel et al., 2003). The confining unit is about 40 feet thick and consists of massive, relatively unfractured dolomite. Packer tests performed by the Minnesota Geological Survey suggested that the unfractured portions of the basal Oneota Dolomite may have hydraulic conductivity values as low as 10^{-4} feet/day (Robert Tipping, personal communication). There is some fracturing that cuts through the basal Oneota Dolomite – this fracturing provides the means for leakage between the Jordan Sandstone, below, and the Shakopee Formation of the Prairie du Chien Group, above.

The level of hydraulic communication between the Jordan Sandstone and the Shakopee Formation can only be tested with pumping tests using wells completed only within the Jordan Sandstone. A small number of such tests have been performed (e.g., at St. Paul Park, Burnsville, Savage, and Woodbury (Bonestroo Rosene Anderlik and Assoc., 2004)). The results of these tests indicate a relatively uniform leakage resistance – typically 2,000 to 6,000 days.

2.2.3.3 Shakopee Formation

Along with the Oneota Dolomite, the Shakopee Formation makes up the Prairie du Chien Group. The areal extent of the Prairie du Chien Group is similar to that of the underlying Jordan Sandstone. Horizontal hydraulic conductivity values are in the same range as those of the Jordan Sandstone.

Flow in the Prairie du Chien Group is dominated by 3 to 5 relatively thin (5 to 10 feet) zones of highly connected horizontal fractures in the Shakopee Formation and the upper part of the Oneota Dolomite (Runkel et al, 2003). Horizontal hydraulic conductivity values within these thin zones can exceed 1,000 feet/day. Between these fracture zones, the hydraulic conductivity is much lower. At a very local scale, these horizontal zones of high flow may not be well connected but regional fractures and joints provide good connection on a more regional basis. This allows the upper part of the Prairie du Chien Group to be treated as a single aquifer system.

Unlike deeper hydrostratigraphic units, the Prairie du Chien Group can be unconfined. Where the drift is thin or absent, the water table resides in the Prairie du Chien Group. Recharge is primarily through leakage from the overlying glacial drift and the St. Peter Sandstone, where it is present. Additional recharge enters the aquifer in at the western edges of this unit's areal extent and in buried bedrock valleys as underflow from the unconsolidated sediments that abut the subcrop area of the aquifer. Discharge is to the glacial drift in the Minnesota River valley.

2.2.4 St. Peter-Basal Till Aquitard and St. Peter Sandstone Aquifer

The upper part of the St. Peter Sandstone is poorly cemented, granular, and may be used to supply domestic wells. The lower portion of the St. Peter Sandstone is shaley and functions as an aquitard over the Prairie du Chien Group (Palen, 1990). The St. Peter Sandstone has been eroded away over much of the study area, except in portions of Hennepin County and is present in complete thickness only where overlain by the Glenwood and Platteville Formations.

In those areas where the St. Peter Sandstone is not present, glacial drift overlies the Prairie du Chien Group. In these areas, the St. Peter-Basal Till Aquitard is composed of glacial till or other glacial drift of varying degrees of leakage resistance.

2.2.5 Glacial Drift Aquifers

Glacially deposited sediment can be very complex and its characteristics unpredictable. The modeling of discrete zones of saturation is typically not possible, given the limited amount of reliable data on stratigraphy, hydraulic characteristics, and hydraulic head. In many areas, the existing data will likely be sparse or so complex that the entire thickness of glacial deposits can only be treated as a single aquifer.

At a given location, the glacial drift aquifers may contain several interfingering sand-gravel layers with till; however, these discrete zones may not be correlatable over an extended area. The

transmissive sediments are therefore considered part of the same aquifer system and are assumed to be hydraulically connected. In some locations where the upper St. Peter Sandstone is present, it may be included as part of the glacial drift aquifer.

In the study area, the glacial drift aquifer can generally be divided into a lower unit and an upper unit. The lower unit consists of heterogeneous, stratified glacial drift, including both till and more permeable sand deposits. It is recharge by an upper glacial drift aquifer that is typically either perched above the lower drift aquifer and/or is of low permeability so that saturated flow in this unit is mostly vertically downward. The upper glacial drift aquifer is in direct hydraulic connection with most streams and lakes and receives direct recharge from infiltrating precipitation. Discharge is to streams, lakes, and leakage to underlying aquifers.

2.3 Regional Hydrogeologic Conceptual Model

The *hydrogeologic conceptual model* is a schematic description of how water enters, flows, and leaves the groundwater system. Its purpose is to define the major sources and sinks of water, the division or lumping of hydrostratigraphic units into aquifers and aquitards, the direction of groundwater flow, the interflow of groundwater between aquifers, and the interflow of water between surface waters and groundwater. The hydrogeologic conceptual model is both scale-dependent (i.e. local conditions may not be identical to regional conditions) and dependent upon the questions being asked. In the case of this evaluation, the conceptual hydrogeologic model encompasses a regional view (a portion of southern Carver, southwestern Hennepin and northern Scott Counties) and considers questions being asked deal with the hydrogeologic effects of construction and post construction of six alternative corridors for Highway 41, with emphasis on the effects on the Seminary Fen Wetland Complex.

The regional conceptual hydrogeologic model is depicted on Figure 2-5, showing the general groundwater flow directions and regional contributions.

The bedrock aquifers are present over a very large area (the Hollandale Embayment) and flow in these aquifers is affected by large-scale, regional features. The Mt. Simon-Hinckley aquifer does not outcrop or subcrop beneath in the area. Consequently, this unit is not in direct hydraulic connection with rivers, lakes, or streams that control the piezometric surface (Delin and Woodward, 1984). Furthermore, the hydraulic connection between the Mt. Simon-Hinckley aquifer and the overlying Ironton-Galesville aquifer is poor in the metro area (Palen, 1990). Its poor connection with

overlying aquifers indicates that the Mt. Simon-Hinckley aquifer can be excluded from this evaluation without compromising model results.

2.3.1 Groundwater Flow Directions

Groundwater flows from zones of high piezometric head to low piezometric head. A description of flow directions in the hydrostratigraphic units in the region around the Seminary Fen Wetland Complex is presented below.

2.3.1.1 Franconia-Ironton-Galesville Aquifer

Groundwater flow in the Franconia-Ironton-Galesville aquifer is toward the Minnesota River. Unlike the Mt. Simon-Hinckley aquifer, flow in the Franconia-Ironton-Galesville aquifer does appear to be significantly influenced by the Mississippi, Minnesota, and St. Croix Rivers in the metro area. The hydraulic head distribution suggests that the Minnesota River is a regional discharge zones for the aquifer. Upward leakage to the Minnesota River takes place in response to a lowering of hydraulic head in the overlying aquifers, which discharge to the Minnesota River.

2.3.1.2 Prairie du Chien-Jordan Aquifer

The Prairie du Chien-Jordan aquifer system is heavily influenced by the Minnesota River, which is the major discharge zone. Groundwater flow is toward the Minnesota River (to the south in Carver County).

Near the Seminary Fen, Quaternary and pre-Quaternary erosion has removed the Prairie du Chien Group and the Jordan Sandstone. Elsewhere, the Prairie du Chien-Jordan aquifer is recharged by downward leakage from overlying units (e.g., the upper St. Peter Sandstone and the unconsolidated surficial aquifer) through the intervening confining units (e.g., the lower St. Peter Sandstone and till layers in the unconsolidated surficial aquifer).

2.3.2 Infiltration

The predominant source of water for the aquifer units is infiltrating precipitation. Infiltration of direct precipitation is dependent upon the rate and duration of precipitation, the soil type and soil cover, land use, evapotranspiration, and topography. In a steady-state model, the resulting infiltration rate is typically estimated on an annual basis - although seasonal estimates are sometimes utilized.

Traditionally, average values of infiltration have been estimated through the relationship between the transmissivity of an aquifer and the resulting piezometric head distribution. Transmissivity can be estimated from a number of sources, including results of aquifer tests. Head distribution is estimated from the many water-level measurements obtained from wells in the County - these data are listed in the County Well Index. Both data sets are incorporated into a groundwater flow model in order to estimate the rate of infiltration. This process of "backing into" infiltration values by fixing the values of transmissivity and matching the simulated heads is called the "inverse method".

Various numbers have been used for average infiltration in the Twin Cities area. Norvich et al. (1974) estimated that this rate is between 4 and 10 inches per year. Precipitation in the metro area averages between 26 and 32 inches per year, of which 7 to 9 inches per year are available after evaporation and transpiration for recharge and overland runoff (Schoenberg, 1990). Schoenberg (1990) estimated that the annual groundwater flow to streams is 1.60 to 4.30 inches of precipitation per year, with an average of 4.07 inches per year. Assuming that long-term groundwater recharge is approximately equal to long-term groundwater discharge to streams (Schoenberg, 1990), annual recharge from precipitation is approximately 1.5 to 4.5 inches per year.

Increased urban development generally results in increased impervious areas, due to buildings and pavement. Initial impression would suggest that increases in impervious area would result in decreases in the infiltration rate to groundwater. However, increased impervious area due to development does not equate to decreases in infiltration. The reason for this appears to be that precipitation, after falling on roofs and pavement, is routed to stormwater retention and detention basins where focused infiltration takes place. The infiltration rates in detention basins tend to be higher than in upland areas because stormwater accumulates, increasing the moisture content in the vadose zone (which increases the unsaturated hydraulic conductivity) and provides a driving head for rapid downward percolation. Also, with increased impervious area, evapotranspiration rates decrease (because of less broad-leaf plants) and soil moisture is used up at slower rates by plant transpiration.

A final factor to consider is irrigation – particularly lawn irrigation. During the summer, lawn irrigation is high, which greatly augments the natural recharge rates with water that would otherwise not be available. In many cases, pumped groundwater is the source of the lawn irrigation – the resulting man-made recharge is from the cycling of water from the aquifer system to the ground surface (i.e. there is not a net gain in the water balance). Evaporation and transpiration losses during this period are high, but excessive lawn watering, beyond the needs of grass, is a widely known practice.

Lake Minnetonka is also major source of recharge to the aquifer system. Lake Minnetonka is likely in direct hydraulic connection with the upper drift aquifer. Leakage, driven by the head control imparted by Lake Minnetonka, in turn recharges deeper aquifer units that underlie the lake. Smaller lakes in the region perform a similar recharge function, although they do not contribute as much water as Lake Minnetonka, by virtue of their smaller size.

2.3.3 Regional Discharge

The regional water balance can be estimated, in part, on the basis of groundwater inflows to streams (regional discharge zones). The source of this water enters the aquifer system through infiltrating precipitation for an entire groundwater basin. Groundwater inflows into smaller streams can be estimated from stream-flow gauging records using hydrograph separation. Base-flow conditions (i.e. the groundwater component of stream flow) typically accounts for most of the flow during the winter months, when runoff is small. On an annual average, approximately 15 to 25 percent of total flow in streams results from groundwater discharge into the streams (Schoenberg, 1990).

Various attempts have been made to estimate groundwater inflows into the large rivers in the Twin Cities by detailed gauging of river flows. The most recent efforts were performed by the U.S. Geological Survey, which used sophisticated Doppler measurement techniques to calculate flows in the rivers at several cross sections. In principle, by subtracting the stream flows measured at an upstream section from the stream flows measured at a downstream section (and assuming no tributary inflows), the difference in stream flow should be attributable to base flow from groundwater. In smaller streams, this technique works reasonably well but in large streams, such as the Minnesota and Mississippi Rivers, the error in the measurement, under even the best conditions, is nearly equal to the calculated groundwater inflows – rendering the calculated base flows highly suspect.

The other major source of groundwater discharge is from wells. Most of the communities in the area obtain their water supply from high capacity wells. High capacity wells are shown on Figure 2-6.

2.4 Hydrogeology of the Seminary Fen Wetland Complex

Peterson Environmental Inc. (2006) performed a Phase 1 hydrogeologic study of the Seminary Fen Wetland Complex and Assumption Creek in 2004 and 2005. The primary focus was to characterize the hydrologic regime of the Seminary Fen Wetland Complex for the purpose of identifying those unique features that create habitat for calcareous fen plant communities. The hydrology of the

Seminary Fen Wetland Complex was assessed through identification and location (i.e., mapping) of surface water features characteristic of groundwater discharge, combined with an assessment of hydrologic gradients in nested water table wells and piezometers established in representative areas of the Seminary Fen Wetland Complex. Locations of wells and piezometers are shown on Figure 2-7. Two additional well nests of two wells each (Well nests 7 and 9) were installed in late-fall 2005 by the Lower Minnesota Watershed District at locations shown on Figure 2-8.

2.4.1 Geomorphology

The northern bluff the Minnesota River Valley is composed of calcareous Des Moines lobe till. The steep slope of the bluff face is evidence that it may have originated as a cut bank of Glacial River Warren. There are no bedrock outcrops along the bluff, suggesting that bedrock eroded by Glacial River Warren is till covered and deeper than the elevation of the Minnesota River Valley floor. The toe of the bluff consists of relatively thick deposits of local alluvium and colluvium derived by mass wasting and erosion of the bluffs themselves. Steep coulees are present that dissect the bluffs and lead runoff water through intermittent streams to the valley floor (see Figure 2-9). Alluvial fans associated with upland soils extend from the mouth of the coulees into the Seminary Fen Wetland Complex in several areas. Blanket-type peatland is located downslope of the alluvial material and slopes gently down to the terrace feature that intervenes between the north and south units of the Seminary Fen Wetland Complex. The location of the terrace deposit is shown on Figure 2-9. The peatland is generally at an elevation of 750 feet above mean sea level (MSL) to the north, and 740 feet MSL at the south boundary near a terrace feature, providing for surface drainage and diffuse surface flow to the south. This drainage condition is, in general, compatible with calcareous fen plan communities, which do not tolerate ponded conditions, yet thrive where groundwater discharges beneath and flows through the peat. The peat is underlain by coarse textured sediments deposited by Glacial River Warren and by fine-textured Holocene sediments likely deposited in a shallow lake environment (Peterson Environmental Inc., 2006).

The Seminary Fen Wetland Complex is divided by Peterson Environmental Inc. (2006) into two units that are separated by a terrace feature that forms the southern boundary of the northern unit. The southern unit extends from the terrace to current floodplain of the Minnesota River. Seminary Fen Wetland Complex Areas 1 and 2 (Figure 2-7) are associated with the northern unit and are elevated 15-to-20 feet above Areas 3, 4, and 5 that are located to the south of the terrace unit (Peterson Environmental Inc., 2006).

2.4.2 Vertical Hydraulic Gradients

Peterson Environmental Inc. (2006) found that virtually all of the Seminary Fen Wetland Complex would meet the hydrology criterion for calcareous fens that requires evidence of stable, upward groundwater flow and the presence of peat soils (Histosols) or mineral soils with peat surfaces. Therefore, from a hydrologic perspective, most of the Seminary Fen Wetland Complex is suitable for the development of calcareous fen communities – other non-hydrologic factors, however, must also be considered. Small to substantial upward groundwater flow was observed in all areas examined. The highest upward gradients (approximately four feet of difference between the water table well and the nested piezometer) were observed associated with a component of high quality calcareous fen in the northern part of Area 1 (well nest 1A in Figure 2-7). Other well nests exhibited upward gradients to lesser degrees. Well nests 7 and 9, located along the slope of the bluff (Figure 2-8), showed virtually no vertical gradients when measured in June 2006.

2.4.3 Assumption Creek

Assumption Creek originates in the Seminary Fen Wetland Complex as upwelling groundwater discharges to the ground surface and the current course of Assumption Creek has its headwaters as spring heads and spring runs originating near the bluff toe-slope in the northern unit of the Seminary Fen Wetland Complex. Tributaries of Assumption Creek that lie north of the railroad embankment are perennial streams originating as spring head/spring run systems that have been diverted from their natural course across the north unit of the Seminary Fen Wetland Complex by the railroad embankment. These tributaries join to become Assumption Creek and pass under the railroad embankment through a culvert just south of Area 2. Assumption Creek then flows southeast, takes a right angle turn and then flows east across the mid-line of the terrace deposit. Peterson Environmental Inc. (2006) hypothesize that the course of Assumption Creek across the terrace midline may not be natural. It may represent a diversion that is contemporaneous with the construction of the railroad grade that resulted in extensive hydrologic alteration to surface flows within the entire Seminary Fen Wetland Complex.

The Assumption Creek tributaries north of the railroad embankment were found by Peterson Environmental Inc. (2006) to be perennial, whereas the reach flowing along the western portion of the terrace was intermittent. Assumption Creek again becomes a perennial gaining stream where it breaks out of the eastern portion of the terrace and remains a perennial stream to its confluence with the Minnesota River. Assumption Creek is a perennial, gaining stream in its upper reaches, becomes an intermittent, losing stream in the middle reach that includes the western portion of the terrace, and

then becomes a gaining, perennial stream in the eastern reach upstream of TH 212. A well nest installed by Peterson Environmental Inc. (2006) in the terrace portion of Assumption Creek exhibited strong downward gradient, indicating Assumption Creek is a losing stream where it flows through the terrace deposits. Water lost from Assumption Creek along this reach suggests that the terrace feature is a source of water discharging to Seminary Fen Wetland Complex Areas 3, 4, and 5 that are south of the terrace and TH 212 (Peterson Environmental Inc., 2006).

2.4.4 Ditching and Peat Mining

Portions of the Seminary Fen Weland Complex and associated wetlands (specifically, Areas 1 and 2) have been significantly impacted by ditch and tile drainage in the past. Locations of probable ditching are shown on Figure 2-10. Surface drainage and subsurface tiling of a significant peat mound that was historically a high quality calcareous fen took place prior to the 1950s. The reason for the tiling effort is unknown, but it may have been performed to facilitate peat mining of the area or to provide a water source to the sanatorium that predated the seminary. Tile discharge outlets were observed by Peterson Environmental Inc. (2006) on the eastern flank of the peat mound during fieldwork. Pieces of broken tile were also observed in the spring run to the west of the extensively tiled area. Close inspection of historical aerial photos by Peterson Environmental Inc. (2006) showed the tile scars in the same location from 1951 to 2003. The persistence of the tiling scars is likely the result of localized drainage affecting the adjacent plant community that would favor invasive and native plants that are adapted to drier conditions near the tile. The tile system is currently abandoned and is likely broken in several places. However, the peat mound that was drained was historic calcareous fen that is now experiencing invasion by dogwoods, glossy buckthorn, reed canary and common reed grass.

3.0 Groundwater Flow Model Development and Calibration

3.1 Introduction

A series of groundwater flow models were develop to assess the potential impacts of the proposed alternatives. Details on the modeling codes, modeling methods, and assumptions are described in this section.

The groundwater modeling process included the following steps:

1. A regional-scale, multi-aquifer groundwater flow model was developed using available data and information on geology, groundwater elevations, and hydrology. The scale of this model was chosen to be sufficiently large as to include major potential sources of recharge and discharge, such as Lake Minnetonka and the Minnesota River.

2. The regional model underwent an automated calibration process in which the values of certain parameters were varied within expected ranges in order to obtain a good match between observed conditions and simulated conditions. Observed conditions included groundwater elevation data from wells and estimates of flows into certain streams.

3. A model of smaller scale was constructed from the regional model to encompass the area around Seminary Fen and the three river crossing alignments closest to the Seminary Fen Wetland Complex (Alignments E-1, E-1A, and E-2). The purpose of this smaller scale model was to provide for greater detail and computation accuracy during the evaluations of these alternatives. This smaller scale model also underwent additional automated calibration in order to improve the confidence in the model's predictions.

4. An even smaller scale model was extracted from the Seminary Fen Wetland Complex model for the purpose of closely evaluating the hydrologic effects of dewatering around a single bridge pier. The purpose of this highly detailed model was to evaluate drawdown effects in the immediate vicinity of a bridge pier.

5. For Alignments C-2, C-2A, and W-2, a second smaller scale model was constructed from the regional model to evaluate, in detail, the hydrogeologic effects of these three alignments.

The models were used to make predictions on the hydrogeologic effects of the six alignments during construction and after construction. Methodologies and results of these predictive simulations are described in Section 4.0.

3.2 Groundwater Modeling Codes

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

- MODFLOW is widely used, extensively benchmarked, and widely accepted by scientific and regulatory entities;
- MODFLOW is capable of simulating non-uniform, unsteady flow in multi-aquifer systems and can simulate the interactions between surface water and groundwater in several ways;
- MODFLOW is amenable to both regional groundwater flow simulations and detailed simulation of local areas through the method of telescoping mesh refinement (TMR);
- MODFLOW is highly amenable to use with particle tracking codes, such as MODPATH (Pollock, 1989);
- MODFLOW is highly amenable to automated calibration procedures using companion programs, such as PEST (Watermark Numerical Computing, 2005).

A regional groundwater flow model was calibrated manually and automatically using PEST (Watermark Numerical Computing, 2005). Groundwater flow pathlines were evaluating using the U.S. Geological Survey's particle tracking code MODPATH (Pollock, 1989). The graphical user interface Groundwater Vistas (Environmental Simulations, Inc., 2004) was used to prepare input files and evaluate results for groundwater flow, particle tracking, and parameter estimation.

3.3 Regional Groundwater Flow Model

3.3.1 Vertical Discretization (Layering)

The regional groundwater flow model consists of six layers that represent the following hydrostratigraphic units:

Layer 1: Upper glacial drift

Layer 2: Lower glacial drift and St. Peter Sandstone (where it is present)

Layer 3: Shakopee Formation of the Prairie du Chien Group

Layer 4: Jordan Sandstone

Layer 5: St. Lawrence Formation

Layer 6: Franconia-Ironton-Galesville aquifer

The layering of the model is illustrated in Figures 3-1 and 2-5. There are locations within the modeled area in which the one or more of the above hydrostratigraphic units is missing, having eroded away and been replaced by Quaternary unconsolidated deposits. MODFLOW requires continuity of layers (i.e. a layer cannot “pinch out”). In areas where the above hydrostratigraphic units have been eroded away, hydraulic conductivity zones are used to represent the unconsolidated materials that have filled in the erosional surfaces.

3.3.2 Model Domain and Horizontal Discretization

The regional groundwater flow model domain is shown on Figure 3-1, along with the finite-difference grid. The finite-difference grid divides the modeled system into rectangular cells for the purpose of implementing the finite-difference approximation to the differential equations that govern groundwater flow. Smaller grid cells are utilized where greater computational accuracy is desired. The finite-difference grid consists of 110 columns and 96 rows, over six layers. The maximum cell dimension is 400 m x 400 m and the minimum cell dimension is 50 m x 100 m.

The model domain was selected to encompass large portions of Lake Minnetonka and areas south of the Minnesota River. This domain was deemed sufficiently large to capture the major hydraulic sources and sinks that affect the Seminary Fen Wetland Complex area and the river crossings of the six alignments.

The model employs the UTM NAD83 coordinate system. All units are in meters and all time values are in days.

3.3.3 Layer Base Elevations

The base elevations of the layers were assigned on the basis of digital grid information from the Minnesota Geological Survey in meters above mean sea level (MSL). An example of the model's incorporation of these data is shown on Figure 3-2 for Layer 3 (Shakopee Formation). The top of one layer is equal to the bottom elevation of the overlying layer. Ground surface elevation is used to assign the top of Layer 1.

3.3.4 Hydraulic Conductivity Zones

Hydraulic conductivity (or "permeability") is a property of geologic materials (aquifers and aquitards) that controls the direction and rate of groundwater flow. Ranges for values of hydraulic conductivity for major hydrostratigraphic units the Twin Cities area have been developed in a number of studies (e.g., Reeder, 1976; Schoenberg, 1990; Barr Engineering, 1998; Hansen and Seaberg, 2000; Runkel et al., 2003). However, each setting is unique and parameter values generally are estimated in modeling studies on a case-by-case basis through the calibration process.

There are two approaches to assigning hydraulic conductivity values: (1) in zones with uniform values for each zone and (2) continuously varying values, interpolated from one location to the next. Both approaches are equally valid. In this study, the zone approach was employed because zones could be assigned most readily using information on geologic units in the area. For example, a single zone could be used to assign hydraulic conductivity values for the Shakopee Formation where it is directly overlain by glacial drift.

An example of hydraulic conductivity zonation is shown on Figure 3-3 for Layer 3. The values of hydraulic conductivity shown on Figure 3-3 are in meters per day and reflect values arrived at through the automated calibration process (discussed in a subsequent section). The red areas on Figure 3-3 are where the Shakopee Formation is present. Other zones represent areas of differing conditions of glacial drift that has been deposited where the Shakopee Formation had been eroded away.

Hydraulic conductivity is a tensor – that is, values can differ from one another in the three principal directions. In this study, hydraulic conductivity was assumed to be laterally isotropic (i.e. the same in both the north-south and east-west directions). This is a very common and typically valid assumption. Vertical hydraulic conductivity is typically lower than horizontal hydraulic conductivity for a variety of reasons. Vertical hydraulic conductivity is the primary controlling factor that limits

leakage and flow between aquifers and aquitards. An example of the zonation for vertical hydraulic conductivity is shown on Figure 3-4 for Layer 3.

3.3.5 Boundary Conditions

Boundary conditions control how much water enters or leaves the modeled system. A no-flow boundary prevents groundwater from flowing at all. By default, the edges and bottom of the MODFLOW model domain are no-flow boundaries. Other no-flow boundaries in Layer 1 are shown on Figure 3-5 where bedrock is near ground surface and Layer 1 is unsaturated.

Rivers, lakes, and wetlands are simulated using one of three boundary condition elements: (1) constant head boundaries; (2) River Package boundaries; and (3) Drain Package boundaries. Constant head boundaries are used for large, deep lakes that fully (or nearly fully) penetrate a layer. An example of a constant head boundary is the Minnesota River (Figures 3-5 and 3-6). Constant head boundaries fix the head (groundwater elevation) in the cells they occupy at a value equal to the elevation stage of the water feature it is representing (thus, changes in storage are ignored in the water body).

Lake Minnetonka and other lakes and large wetlands in the model domain are simulated using the River Package in MODFLOW. In addition to river (or lake) stage elevation, a conductance value is assigned for the bottom sediments in the lake or river. Conductance is a function of the bottom sediment's vertical hydraulic conductivity divided by its thickness. Thus, lakes with lower permeability bottoms would tend to have lower conductance values. In practice, neither the bottom sediment thickness nor the bottom sediment hydraulic conductivity can be reliably known without core data or possibly geophysical studies. They are typically calibration parameters in the model. The major functional difference between River Package cells and constant head cells is that the head in the layer in which the River Package cell is assigned does not necessarily have to equal the stage elevation of the lake or river.

The Drain Package is used to simulate Assumption Creek in the regional model. The Drain Package is very similar to the River Package except that the Drain package is "shut off" in cells where the simulated groundwater level drops below the stage elevation. This is different from the River Package, which can have reversals of flow (i.e. the River Package cells can put water into the aquifer as well as take it out, depending upon whether or not the aquifer heads are above or below the assigned stage elevation). Drain Package cells were used for Assumption Creek in the regional model to help determine if flows into Assumption Creek were being adequately approximated by the model.

3.3.6 Wells

The model domain contains 155 pumping wells. These are all higher capacity wells for which there are water appropriations permits. Pumping rates were assigned to the wells on a steady-stage, annually average basis for values reported to the DNR for 2003 (a year of approximately average water usage). These wells pump mostly from Layer 4 (Jordan Sandstone) and Layer 3 (Shakopee Formation). Some wells pump from Layer 6 (Franconia-Ironton-Galesville aquifer). Locations of these wells and their relative pumping rates are shown on Figure 2-6. The combined pumping in the regional model is 29,787 gallons per minute (42.9 million gallons per day).

3.3.7 Recharge

Recharge from infiltrating precipitation accounts for approximately 43 percent of the total inflows into the modeled system. Recharge rates in the Twin Cities metropolitan area are typically estimated to be in the 1.5 to 12 inch per year range (Reader, 1976; Schoenberg, 1990; Barr Engineering 1998). Total annual average rainfall is about 28.5 inches per year.

Recharge is not the same as infiltration. Infiltration refers to water that enters the soil, whereas recharge is that portion of the infiltrated water that moves downward below the root zone and eventually reaches the water table. Much of the water that infiltrates is intercepted by the root system of plants and is evapotranspired back into the atmosphere.

Estimation of recharge is a complicated process that involves consideration for land cover, vegetation, topography, soil type, depth to the water table and climate. Very few studies have actually attempted to simulate these processes; one example is the Barr Engineering Co. (2005) surface-water – groundwater model of southern Washington County. In this study, the program MIKE SHE (Danish Hydrologic Institute, 2004) was used in conjunction with MODFLOW to quantify the spatial and temporal variability of recharge by considering vegetation type, soil type, topography, precipitation, and climate. The result of this study was a map of average annual infiltration that correlated reasonably well with the hydrologic grouping (A, B, C, and D) of soils – i.e., the hydrologic properties of the surficial soil was a good indicator of the relative amount of recharge. This correlation was used in this study to assign estimates of recharge, based on the soil type. Digital soil survey maps (Figure 3-7) for Carver, Hennepin, and Scott Counties were complies and ranked according to hydrologic grouping. Average annual recharge values for the various hydrologic groupings from the Washington County model were used to distribute values of recharge over the model domain, as shown on Figure 3-8.

3.4 Groundwater Modeling Calibration Process

Calibration is the process in which selected hydrologic parameters in the model are adjusted within expected ranges in order to achieve a satisfactory match between simulated model results and measured conditions. Model calibration is a crucial step, for without it, the model has little relationship to real-world conditions. The predictions made using a well-calibrated model are much more reliable.

Calibration is necessary because hydrologic parameters either are not known with great certainty or, in many instances, cannot be directly measured (e.g., infiltration). It is not desirable for all of the many parameters in a model to be varied during the calibration process because no unique solution can be attained. Therefore, care must be taken to determine which parameters to adjust and which to keep constant.

3.4.1 Calibration Targets

In the calibration for this study, the regional model's simulated piezometric head (i.e. water levels) where compared to "measured" water levels for 1,157 wells in several aquifers in the model domain (Figure 3-9). Water-level targets located in the upper drift aquifer (Layer 1) were obtained from data provided by Emmons and Olivier Resources (EOR) as part of their evaluation of the Highway 212 wetlands studies and consisted primarily of water levels from soil borings and shallow wetlands (Figure 3-10). Calibration targets for Layers 2 through 4 were obtained from the calibration data set developed by the MPCA as part of the Metro Model (Hansen and Seaberg, 2000). Calibration targets for Layer 6 (Franconia-Ironton-Galesville aquifer) were estimated from County Well Index data, maintained by the Minnesota Geological Survey. All targets were weighted equally.

3.4.2 Automated Calibration Procedure

An automated calibration procedure was employed that is commonly referred to as "automated inverse optimization" because it solves for the "inverse problem", which simply means that it finds the values of parameters that allow for the best match between simulated conditions and the calibration targets. The primary purpose of automated inverse optimization is to minimize the differences between simulated conditions and observed conditions. For the steady-state optimizations, this means minimizing the difference or residual between the simulated hydraulic head and the measured head (i.e. observed condition) at the calibration target locations. The sum of the

squared weighted residuals for all targets is the objective function that is to be minimized. In this case, all targets were given an equal weight of one. The square of the residual is used because some residuals are negative and some are positive.

Only those parameters selected to vary in the optimization process are allowed to affect the resulting calibration. Some parameters are more correlated than others, which means that different combinations of some parameter values can produce nearly identical results. This is particularly true of horizontal hydraulic conductivity and recharge parameters. Thus, an optimized model may be very non-unique – which is not a desirable outcome. The more (and more varied) types of head targets improve the optimization by reducing this non-uniqueness. Also, placing constraints on the range a parameter can vary (i.e. upper and lower limits) can sometimes assist in reducing non-uniqueness but often this is not a good method because the optimization procedures need to vary the parameter values over large ranges in order to assess the numerical derivative. Fixing one parameter (i.e. not allowing it to vary), adding prior knowledge, and tying parameter values to one another are procedures that are used to improve optimization.

The program PEST (Watermark Computing, Inc, 2001: 2005) was used to perform the optimization procedure. Recharge, horizontal hydraulic conductivity, bottom-sediment conductance of major lake, and vertical hydraulic conductivity were allowed to vary in the optimization – a total of 51 parameters. The model was found to be most sensitive to the value of bottom sediment conductance of Lake Minnetonka (which is not surprising because of the size of the lake and its relative contribution to the water balance – 11% of total model inflows). The model was also relatively sensitive to vertical hydraulic conductivity values, which are responsible for controlling leakage between aquifers.

3.4.3 Calibration Results

A plot showing the comparative values of simulated and observed hydraulic head (in meters) is on Figure 3-11. If the calibration were perfect, all simulated values would be equal to their corresponding observations (targets), which would result in all data plotting exactly on the diagonal line on Figure 3-11. A perfect calibration is virtually impossible because the natural system cannot be perfectly simulated or even understood completely. The best that can be achieved is to balance out the relative differences between observed and simulated. The absolute residual mean value is 5.25 m. The Residual standard deviation divided by the range in head values is 0.057.

The resulting calibrated piezometric surfaces for Layers 1 and 2 are shown on Figure 3-12 and for Layers 3 and 4 on Figure 3-13. A north-south cross section through the model and the Seminary Fen Wetland Complex area is shown on Figure 3-14. As can be seen on Figure 3-14, vertical head gradients are predominantly downward in the upper layers and horizontal in the lower layers. Near the river and fen area, upward flow gradients dominate. The regional model predicts a total base flow increase into Assumption Creek along its entire reach of approximately 2.3 cubic feet per second (cfs).

3.5 Groundwater Flow Model of the Seminary Fen Wetland Complex

3.5.1 Model Domain

The regional model (described above) formed the basis for a more detailed groundwater flow model of the region in and around the Seminary Fen Wetland Complex and the eastern three TH 41 river crossing alignments with a smaller areal domain. A smaller model was desired because it would afford for a higher level of discretization in the fen and alignment areas to improve numerical accuracy and to provide for the incorporation of more detailed hydrologic features.

The process used to extract a smaller model from the regional model is called “telescoping mesh refinement”, or “TMR.” The TMR model, once extracted, contains layering and parameter distribution that is identical to the regional model. The boundaries of the TMR model are head-specified cells, with head elevations equal to the computed head values along the TMR model edges from the regional model. This new TMR model is then rediscretized to reduce the cell sizes in the area of interest – the Seminary Fen Wetland Complex and Assumption Creek.

The location of the TMR model within the regional model domain is shown on Figure 3-15. The grid mesh for the TMR model is shown on Figure 3-16. Grid cells dimensions range from 98 meters on a side along the model periphery to 9 meters on a side in the fen area itself.

3.5.2 Boundary Conditions

As discussed above, the boundaries of the TMR model are constant head cells with values equal to the computed heads in the Regional model along those boundaries. River Package cells, representing creeks, wetlands, and lakes, were refined to better fit actual areas and conform to the finer discretization, as shown on Figure 3-17.

A major difference in boundary conditions between the regional model and the TMR model is the inclusion of a substantial number of Drain Package cells in the fen and Assumption Creek area. Drains were placed in all cells in this area, with stage elevations equal to ground-surface elevation, as defined by a 10-meter Digital Elevation Model (DEM). This is a particularly advantageous approach to modeling the fen area because it allows for quantification of the model's predicted discharge of groundwater to the surface, based on the relationship between hydraulic head and ground-surface elevation. In this same manner, Assumption Creek is also modeled. The drains function in the model only where the piezometric elevation exceeds the ground-surface elevation.

3.5.3 Calibration of TMR Model

The TMR model's calibration was good initially because it was derived from a calibrated regional model. However, an even better calibration was desired in order to have a better predictive tool for this evaluation. Groundwater level data from piezometers installed as part of the Phase 1 investigation (Peterson Environmental Inc., 2006) were included as additional calibration targets. A total of 201 head targets were in the TMR model. The head targets observed versus simulated results are plotted on Figure 3-18.

3.5.4 Discussion of TMR Model Results

The simulated piezometric head in Layer 1 (upper drift unit) is shown on Figure 3-19. Groundwater flow is perpendicular to contours – south-southeast toward the Minnesota River. Hydraulic gradients flatten noticeably south of the bluff line. This flattening is likely in response to discharge of groundwater flow to the surface as springs, seeps, and base flow to Assumption Creek, which reduces the pressure head in the uppermost unit. This reduction in pressure head, in turn, causes the development of upward vertical gradients from the lower glacial/alluvial deposits, as the model simulation shows on Figure 3-20. These upward vertical gradients, which were observed from piezometer nests installed by Peterson Environmental Inc. (2006) at various locations in the Seminary Fen Wetland Complex, is the likely mechanism that allows for the discharge of groundwater to the Seminary Fen Wetland Complex.

It is interesting to note on Figure 3-20 that the largest upward vertical hydraulic gradients are predicted to be in the areas south of Highway 212, where vertical gradients may be as high as 25 feet. Again, this is consistent with the findings of Peterson Environmental Inc. (2006). The model results indicate that the entire area south of the bluff is an area of substantial groundwater upwelling.

The upward vertical head differences between upper drift and the deep valley fill alluvium that is represented by Layer 3 in the model (alluvial deposits corresponding stratigraphically to the Shakopee Formation where the Shakopee Formation is eroded away) are shown on Figure 3-21. These results, as depicted on Figure 3-21, suggest that upwelling of deeper groundwater does not take place in fen areas north of Highway 212 – only in those areas south of Highway 212, with greatest upward vertical gradients corresponding to the spring heads at the headwaters of the tributaries of Assumption Creek.

The uppermost bedrock in the vicinity of the Seminary Fen Wetland Complex is St. Lawrence Formation and/or the Franconia-Ironton-Galesville units. The upward vertical head differences between the upper drift and the bedrock are shown on Figure 3-22. The pattern of upward vertical head differences is similar to the pattern between the upper drift unit and the deeper alluvium, although there appears to be steeper gradients directly underneath the Minnesota River channel. Upward vertical gradients are predicted to be south of Highway 212, but generally not north of Highway 212.

The modeling results indicate that the groundwater that is discharging to areas north of Highway 212 (areas where the best examples of calcareous fen were found) is originating not mostly from the deep aquifer system or the bedrock but mostly from shallow groundwater flow. However, the upward vertical gradients in the deep aquifer system play an important role in preventing downward vertical gradients within the shallow aquifer systems. Areas south of Highway 212 also receive most of their water from the shallow aquifer system, even though upwelling from deeper units is taking place.

The model's prediction (using reverse particle tracking from major discharge areas in the Seminary Fen Wetland Complex) of the area of recharge for the Seminary Fen Wetland Complex is shown on Figure 3-23. The area where shallow groundwater discharges to the Seminary Fen Wetland Complex (i.e. water that does not move deeper than approximately 5 feet below the water table) is about 500 acres and is shown in red cross-hatching on Figure 3-23. A much larger recharge area, shown in yellow cross-hatching on Figure 3-23, contributes flow to the groundwater discharging to the Seminary Fen Wetland Complex from the deeper unconsolidated deposits. This area includes Hazeltine Lake, which the model predicts as contributor of groundwater to the Seminary Fen Wetland Complex. The model predicts an aerially averaged discharge of groundwater to the Seminary Fen Wetland Complex equal to approximately 21 inches per year. The model predicts that approximately 7 cfs discharge to the Seminary Fen Wetland Complex, of which approximately 1.7 cfs becomes base flow in Assumption Creek. This results in a predicted annual discharge to the

remainder of the Seminary Fen Wetland Complex of 5.3 cfs, which contributes to evapotranspiration, springhead discharge, and reinfiltration/groundwater flow to the Minnesota River.

3.6 Groundwater Flow Model for Western Alignments

The regional model was used as the basis for a refined inset model of the three western TH 41 alternative alignments (Alignments C-2, C-2A, and W-2). The telescoping mesh refinement (TMR) approach, described above, was used to construct this local model. The location of the western detailed model is shown on Figure 3-24. The relative location of the grid with respect to the western alignment alternatives and the level of discretization is shown on Figure 3-25. The minimum grid size is 11 meters on a side and the maximum grid size (away from the areas of prime interest) is 60 meters on a side.

This model, unlike the TMR model of the Seminary Fen area, did not undergo a second calibration process, primarily because detailed calibration targets are not available for this area. In addition, while there are important water-resource features in the vicinity of the western alignment alternative, there are not believed to be as critical and sensitive as the calcareous fens of the Seminary Fen Wetland Complex.

3.7 Detailed Model of Bridge Piers

In addition to the two TMR models, described above, a very detailed, local model was developed to examine construction dewatering effects immediately adjacent to alternative bridge piers. The purpose for this very detailed model was to improve numerical accuracy near the bridge piers that could not be practically examined even with the TMR models. An example of one of the bridge pier models is shown on Figure 3-26. This grid has a uniform cell size of 2.5 meters on a side. It was extracted from the TMR Seminary Fen Wetland Complex model through a further TMR process. General head boundary conditions were used around the perimeter of this model to minimize boundary effect. The TMR extraction process was performed after the simulation of the bridge piers in the larger model so that the stress field at the boundary would be correct. This modeling is discussed in detail in Section 4.

4.0 Simulation of Hydrogeologic Effects of Alternative Alignments

4.1 Introduction

Local models of the two groups of proposed alignments and a local model used to compare two alternative dewatering methods during construction of the bridge piers are described in this section. Model results were compared on the basis of the following criteria.

- Drawdown caused by dewatering during construction. For the eastern alignments, drawdown beneath the fen can be compared directly. For the western alignments, no measurable drawdown beneath the Seminary Fen Wetland Complex is likely to occur, but drawdown can be compared between the scenarios and the potential for impact to other water resources can be evaluated.

- Reduction in seepage in the Seminary Fen Wetland Complex caused by dewatering during construction. Figure 4-1 shows the locations of the zones considered in the modeling. Results are summarized in Table 4-1.

- Changes to the modeled rates of seepage for the zones shown in Figure 4-1 are summarized for the post-construction scenarios in Table 4-2.

- Flowpaths for water impacted by salt spray from the proposed roadways after construction.

Greatest emphasis was placed on evaluating hydrogeologic effects in the vicinity of the Seminary Fen Wetland Complex, north of the Minnesota River. Simulation results of drawdown for areas north of the Minnesota River were applied to areas south of the Minnesota River for the purpose of assessing likely effects in northern Scott County.

4.2 Assumptions and modeling methods

MnDOT identified the sections of the proposed alignments that would be bridges. A spacing of 250 feet was assumed between bridge piers, based upon discussions with MnDOT staff. One pier was modeled for each direction of traffic on the 250-foot spacing. Schematics for two methods of construction of the bridge piers are shown on Figures 4-2 and 4-3.

4.2.1 Construction Assumptions

These construction assumptions were developed in consultation with MnDOT staff. The typical bridge pier construction and dewatering assumption (Figure 4-2) is used where high organic, marly, or peaty soils are not expected. The use of a sheet-piling coffer dam with a concrete bottom seal (Figure 4-3) is the method used by MnDOT where organic, marly, or peaty soils are expected. The coffer dam/sheet piling approach is expected to be used for all bridge pilings within the Seminary Fen Wetland Complex. In modeling the effects of dewatering during construction, it was assumed that the pilings would have no effect on the hydraulic conductivity of the deeper materials.

The telescoped local models have irregular grid spacing. Model cells in the bridged sections of the roadways have approximately the same dimensions as the bridge piers (approximately 40 ft by 40 ft). A drain cell was added to each model cell that would contain a bridge pier. Drain cells only remove water if the water level in the aquifer rises above the stage of the drain. The stage of the drain was set at 5 feet below ground surface and the conductance was set high enough to guarantee that the stage would be maintained if it was necessary to simulate the removal of water due to the water table being within 5 feet of the ground surface. In this way, the influence of topography and the depth to the water table could be compared between the scenarios based on the criteria described above.

The use of the drain cells generally simulates the effect of the coffer dam by limiting the area over which dewatering must take place to the footprint of the coffer dam interior – a larger area with somewhat deeper dewatering would be necessary using conventional construction methods without a coffer dam and the likely result would be more widespread drawdown. *In the modeling of construction effects, the effect of the bottom seal in reducing dewatering was not included – this results in predictions of drawdown which are likely overestimates (i.e. worse-case situations in which the bottom seal is completely ineffective at reducing upward flow into the coffer dam).* In the model, the conductance of the drain cells that represent the dewatering of the piers were set sufficiently high that they did not affect the rate of drawdown – the upward flow into the drain cell was controlled primarily by the vertical hydraulic conductivity of the aquifer material in the model. The effects of the bottom seal were evaluated in a detailed model, which is described in Section 4.6

The modeling assumed that steady-state conditions would be quickly attained – therefore, no transient simulations were performed.

4.2.2 Post-Construction Assumptions

Post-construction conditions were evaluated as follows. It was assumed that the shallow soils would undergo compaction during construction. The influence of this compaction was evaluated by reducing the hydraulic conductivity of the cells in the footprint of the bridged sections by a factor of 10. In addition, the hydraulic conductivity of the cells containing the bridge piers was reduced by a factor of 100.[3] Recharge was set to zero over the entire footprint of the proposed alignment west and north of the Minnesota River. The purpose of this modeling was to determine the influence of the construction and operation of the highway. In particular, road spray containing de-icing agents and other contaminants would infiltrate along the right of way of the highway. This does not include salt spray that might be carried airborne some distance from the roadway and then deposited. Particle tracing with results from the groundwater flow modeling was used to predict where these infiltrating contaminants would flow and where they may impact surface water.

Detail topographic information was added to both local models that were used to evaluate the impacts of the proposed alternatives. Seepage of groundwater to surface water in the local model that encompasses the Seminary Fen Wetland Complex was evaluated by assigning each model cell a drain boundary condition with the drain elevation specified at land surface and the conductance representing a vertical hydraulic conductivity of 0.1 times the horizontal hydraulic conductivity. This allows the simulation of seepage without pinning the water level at the land surface. Similar detailed boundary conditions were not added to the local model used to evaluate Alternatives C-2, C-2A, and W-2 because the Seminary Fen Wetland Complex does not extend into this area.

4.3 Alternatives E-1, E-1A, and E-2

Predicted impacts from the three alternatives closest to the Seminary Fen Wetland Complex are compared in this section. Modeled drawdown during construction due to dewatering for the bridge

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[3] Cohesive soils (such as clays) that are compacted for dam construction have ranges in permeability reductions of “one log cycle” (factor of 10) to “a one-hundred fold increase” (factor of 100) (Bell, 1987, p. 44/16). Less cohesive soils and cohesionles soils (such as silts and sands) have less permeability reduction under compacted conditions. Assuming that the soils in the area that might undergo compaction are cohesive, permeability reductions for clays were used in this analysis. A reduction of a factor of 10 was applied for areas that would undego construction traffic and the extreme reduction value of 100 was applied where the footings for the bridge piers would be installed.

piers is shown on Figures 4-4 through 4-6. The minimum contour on these figures is 0.1 ft. A contour interval of 0.5 ft was used on these figures. Groundwater flow directions before and after construction are shown on Figures 4-7 through 4-9.

4.3.1 Effects During Construction

All three scenarios are predicted to cause a reduction in seepage in the Seminary Fen Wetland Complex during construction. Figure 4-1 shows the locations of the zones considered in the modeling. These areas were identified as zones of strong groundwater discharge by Peterson Environmental Inc. (2006). Seepage reduction results are summarized in Table 4-1.

Alternative E-2 is predicted to require the greatest dewatering during construction of the bridge piers; a combined total of 0.49 cubic feet per second (cfs) (see Table 4-1). This withdrawal is predicted to cause a reduction in seepage in the fen of -0.056 cfs. Due to its proximity to the Seminary Fen Wetland Complex, Alternative E-2 also causes drawdown of water levels over the greatest area of the Seminary Fen Wetland Complex (see Figure 4-6).

Alternative E-1A produces the greatest reduction of seepage in the Seminary Fen Wetland Complex primarily because this corridor passes through the zone labeled “667” on Figure 4-1. This zone includes the toe of the bluff and the upstream reach of Assumption Creek. Alternative E-1A also produces drawdown over a greater portion of the Seminary Fen Wetland Complex than Alternative E-1. Alternative E-1 has the least predicted impact because it is the furthest of the three alternatives from the Seminary Fen Wetland Complex and because this alternative has the shortest length located over areas with the water table within 5 feet of the surface.

4.3.2 Post-Construction Effects

Predicted changes to the rates of seepage in the zones identified in Figure 4-1 caused by soil compaction and construction of the bridge piers are summarized on Table 4-2. No active dewatering is simulated in the post-construction scenarios. Alternatives E-1 and E-2 are predicted to cause small net decreases in the rate of seepage in the Seminary Fen Wetland Complex, due to decreases in recharge that would result from increases in impervious area within the footprint of the alignments. Alternative E-1A is predicted to cause a small net increase in seepage in the Seminary Fen Wetland Complex of less than 0.1 cfs. The increase is attributed to changes in permeability of soils that have undergone compaction during construction, which slightly alter groundwater flow paths.

Predicted groundwater flow paths around the alternatives are shown on Figures 4-7 through 4-9. These flow paths indicate where de-icing salt or other contaminants contained in road spray might infiltrate and where this potentially degraded groundwater would discharge to surface waters. The alternatives are compared in the following list.

- In Alternative E-1, many of the flow paths originating toward the west discharge to the unnamed drainage west of the alternative corridor or to the Minnesota River. Many of the flow paths originating toward the east in Alternative E-1 discharge in the vicinity of Areas 4 and 5 in the western portion of the Seminary Fen Wetland Complex, south of Highway 212.

- In Alternative E-1A, only those flow paths originating toward the western extreme of the corridor discharge to the Minnesota River. The majority of the flow paths in Alternative E-1A discharge to Areas 3, 4, and 5 of the Seminary Fen Wetland Complex, south of Highway 212.

- In Alternative E-2, only a few flow paths originating toward the western extreme of the corridor discharge to the Minnesota River. The vast majority of the flow paths in Alternative E-1A discharge to Areas 3, 4, and 5 of the Seminary Fen Wetland Complex.

4.4 Alternatives C-2, C-2A, and W-2

Predicted impacts from the three alternatives furthest from the Seminary Fen Wetland Complex are compared in this section. Modeled drawdown during construction due to dewatering for the bridge piers is shown on Figures 4-10 and 4-11. The minimum contour on these figures is 0.1 ft. A contour interval of 0.2 ft was used on these figures. Groundwater flow directions before and after construction are shown on Figures 4-12 through 4-14. Less drawdown is predicted in these scenarios than for those located closer to the Seminary Fen Wetland Complex because, on average, the modeled water table is further below land surface in this area than near the Seminary Fen Wetland Complex.

4.4.1 Effects During Construction

Alternatives C-2, C-2A, and W-2 are far enough from the Seminary Fen Wetland Complex that any dewatering performed during construction is not predicted to cause measurable drawdown in the Seminary Fen Wetland Complex area or measurable reduction of groundwater discharge to the Seminary Fen Wetland Complex. Potential impacts of these alternatives are compared in terms of

drawdown in the vicinity of these corridors. As discussed in Section 4.3.1, the amount of drawdown is a function of the number of bridge piers that must be constructed in areas where the water table is within 5 feet of the ground surface. Alternative W-2 has the least amount of drawdown. Alternative C-2 is predicted to cause more than 0.1 foot of drawdown over an area of approximately 300 acres (Figure 4-10). Alternative C-2A is predicted to cause more than 0.1 foot of drawdown over an area of approximately 860 acres (Figure 4-11).

4.4.2 Post-Construction Effects

After construction, Alternatives C-2, C-2A, and W-2 are predicted to have no measurable effect on the rates of seepage in the Seminary Fen Wetland Complex. Predicted groundwater flow paths around the alternatives are shown on Figures 4-12 through 4-14. These flow paths indicate where de-icing salt or other contaminants contained in road spray might infiltrate and where this potentially degraded groundwater would discharge to surface waters. These analyses are not as detailed in terms of simulating seepage to wetlands or surface water features other than the Minnesota River and other perennial streams in the area because the water resources in these areas, while important, are assumed for this study to not be as unique or sensitive as portions of the Seminary Fen Wetland Complex. The alternatives are compared in the following list.

- In Alternative C-2, all of the flow paths discharge to the Minnesota River (Figure 4-12).
- In Alternative C-2A, several of the flow paths originating toward the east discharge to the model cells representing Chaska Creek and the rest discharge to the Minnesota River (Figure 4-13).

In Alternative W-2, a few flow paths originating toward the western extreme of the corridor are captured by the specified head cells at the perimeter of the model. The vast majority of the flow paths in Alternative W-2 discharge to the Minnesota River (Figure 4-14).

These conclusions of effects relate only to the hydraulic responses to construction and post construction and to groundwater flow paths. It is beyond the scope of this modeling analysis to interpret these effects in terms of significance to biota or other parameters related to the health of wetland or other water resource features.

4.5 Comparison of Alternatives East of the Minnesota River

The groundwater flow model used to compare alternatives based on the impacts of construction dewatering for piers north of the Mississippi River (Carver and Hennepin Counties) was designed to address questions centered on the Seminary Fen Wetland Complex. The Minnesota River is a major discharge zone for all of the aquifer layers north of the river. Consequently, detailed topographic and hydrologic information was not included south of the Minnesota River (Scott County). The alternatives were therefore compared based on the length of bridged sections south of the Minnesota River (Scott County).

This comparison consisted of estimating the number of bridge piers that would be required south of the river assuming a 250-foot spacing with separate piers for each direction of traffic. The maximum drawdown caused by dewatering during construction of piers south of the river was estimated by multiplying the alternative with the greatest drawdown per bridge pier north of the river (Alternative E-1 with 0.12 ft/pier) by the number of piers south of the river. This result is summarized in Table 4-4. An additional comparison was made in which the greatest distance to the 0.1 ft drawdown contour for the alternatives north of the river was divided by the total number of bridge piers. The greatest value (41.6 ft/pier for Alternative E-1A) was multiplied by the number of piers south of the river.

Alternative W-2 has the greatest estimated maximum drawdown (7.1 ft) and maximum distance to the 0.1 ft drawdown contour for the piers south of the river (2,420 ft) in Scott County. By comparison, Alternative E-1A had the greatest maximum drawdown north of the river (6.1 ft) in Carver County and the greatest distance to the 0.1 ft drawdown contour north of the river (2500 ft) in Carver County.

4.6 Bridge Pier Construction Options Analysis

Two alternatives for constructing the bridge piers were compared using a very-finely discretized local model of a single bridge pier. A plan view and a cross-section view through the model in the vicinity of the excavation are shown on Figure 4-15. The two alternatives are shown in Figures 4-2 and 4-3. The first alternative is a standard side-sloped excavation with no measures taken to reduce the rate of groundwater discharge into the excavation. This was modeled in a similar manner as that described in Section 4.2. Drain cells were added across the footprint of the excavation and side-slopes. This baseline model indicated a pumping rate of approximately 0.022 cfs to dewater the excavation to a depth of 5 feet (Table 4-3). This model indicated that less than 1 percent of the water

would come through the base of the excavation due to the extremely low vertical hydraulic conductivity (Kz) of Layer 2.

This low vertical hydraulic conductivity value was the result of the model calibration and is a primary factor allowing the model to simulate the large upward gradients in head between Layers 1 and 2. In other words, this is a reasonable value at the scale of the model. In order to evaluate the sensitivity of the estimated dewatering rate to this model input, a local zone of vertical hydraulic conductivity was established that was limited to the footprint of the excavation (see Zone 3 on Figure 4-15). The sensitivity of modeled discharge to a range of Kz values for Zone 3 is summarized on Table 3. If the value is set to one-tenth of the horizontal hydraulic conductivity of Layer 2 (3.94 ft/day), the discharge required to dewater the excavation doubles. Note that the sensitivity of this estimate to other hydraulic conductivity values was not performed because the purpose of this study was a comparison of the two dewatering methods, not a quantitative estimate of the required rate of discharge.

The effects of limiting discharge into the excavation by driving sheet piling as shown in Figure 4-3 was evaluated by establishing another zone for hydraulic conductivity labeled Zone 2 on Figure 4-15. The sensitivity of the modeled discharge into the excavation and the modeled drawdown caused by the dewatering in the model cell just beyond the limits of the side-slope is summarized in Table 4-3.

The effect of limiting discharge into the excavation by placing a grout seal in the base of the excavation as shown on Figure 4-3 was evaluated by sensitivity analysis described above for the vertical hydraulic conductivity value of Zone 3. It is important to note that this discharge-limiting effect of the grout seal was not included in the predictions of drawdown and seepage for Alternatives E-1, E-1A, and E-2, as shown on Figure 4-4 through 4-6 (i.e. grout seal was assumed to *not limit* flow into the coffer dam).

4.7 Summary and Comparison of Alternatives

Based on the results of the modeling analyses described in this report, the following are concluded:

1. <u>Dewatering with the use of a coffer dam results in localized draw down of the water table and reductions in seepage.</u> The modeling results indicate that the drawdown effects and seepage reduction in some areas of the Seminary Fen Wetland Complex with this construction method employed will not be widespread and will not cover the entire Seminary Fen Wetland Complex. The predicted drawdowns and seepage rates likely represent a worse-case situation

because the simulated drawdown did not assume that a bottom seal (which would be implemented in the bridge pier construction) would limit dewatering.

2. Of the three alternatives closest to the Seminary Fen Wetland Complex (eastern alignments), Alternative E-1 is predicted to have the least impact on the Seminary fen Wetland Complex in terms of the drawdown during construction, reduced discharge of groundwater to the Seminary Fen Wetland Complex during construction, and in terms of discharge of degraded groundwater to the fen after construction. Alternative E-1 is also predicted to have the lowest total dewatering rate of the three alternatives located nearest the fen. This conclusion assumes that the coffer dam approach to bridge construction will be used in areas near the Seminary Fen Wetland Complex.

3. Alternative E-1A is predicted to have the greatest effect on seepage to areas in the Seminary Fen Wetland Complex during construction, followed by Alternative E-2. However, Alterative E-1A is predicted to have result in a slight net increase in seepage to areas of the Seminary Fen Wetland Complex – this seems to primarily be due to some rerouting of seepage paths through compaction of soils, forming shallow barriers to flow.

4. Alternatives E-1A and E-2 have a greater likelihood of transmitting salt spray to areas in the Seminary Fen Wetland Complex via groundwater transport than Alternative E-1. Alternative E-1 primarily affects the westernmost portion of the fen complex and does not appear to generate flow paths that would be directed to the higher quality wetlands in the Seminary Fen Wetland Complex in the eastern portion of the wetland complex. Changes in recharge, resulting from increased impervious areas upgradient (north) of the Seminary Fen Wetland Complex were predicted to be very small.

5. Of the three alternatives furthest from the Seminary Fen Wetland Complex, Alternative W-2 is predicted to have the least impact on local water resources in terms of drawdown. None of the scenarios will generate excessive drawdown if the depth of dewatering is limited to within 5 feet of ground surface as assumed in this modeling.

In summary, of the three eastern alignments, Alternative E-1 has the potential for the least impact to the Seminary Fen Wetland Complex from seepage and salt spray-transport aspects. The three western alternative alignments have very little drawdown impact and would not affect the Seminary Fen Wetland Complex.

5.0 Potential Mitigation Measures

The modeling results presented in this report indicate the benefits of using sheet piling around the excavations for the bridge piers as illustrated in Figure 41. These benefits include reduced drawdown beyond the limits of the excavation and reduced impact to the rate of seepage of groundwater into the Seminary Fen Wetland Complex. The addition of a planned grout seal at the base of the excavation should further reduce the drawdown effects, although the seepage-limiting effects of the grout seal were not included in the modeling of the drawdown effects.

Construction dewatering during the non-growing season has the potential to cause less impact to plants that depend on upwelling groundwater conditions. Utility dewatering in the vicinity of the Savage Fen Wetland Complex on the south side of the Minnesota River has been performed during non-growing season to minimize impacts. Drawdown in that case was predicted in the surficial sands, but not within the layer that Savage Fen depends on for upwelling through the peat.

Soil compaction during construction may lead to longer term disturbances of groundwater flow paths (and in some case actually increase flows to some areas in the Seminary Fen Wetland Complex). Methodologies to minimize the footprint and extent of compaction could be evaluated. For example, construction and haul roads could be confined to well-defined routes, over which temporary weight-distributing platforms could be placed. In areas where cohesive and/or peaty soils are present, temporary bridged platforms might be an alternative to minimizing areas of compacted soils. Additional mitigation measures could include: requirements for wide-track (balloon) tires or tracks on construction vehicles; removable construction platforms, and construction during frozen ground conditions.

It is important to recognize that soil compaction that takes place due to increased loads on soils during construction is different from the soil compaction that results from consolidation in response to dewatering. Dewatering has the potential to lower the effective stress in soils, which can result in compaction of cohesive soils. Peaty soils, in particular, are vulnerable to this type of consolidation from dewatering because of their fibrous structure and high void ratio. The high void ratio results in a substantial portion of the bearing load of these soils to be carried by the water in the soil pores (i.e., effective stress) – when hydraulic head is reduced, these pore structures can collapse irreversibly, resulting in permanently reduced permeability. This is believed to be the circumstances that took place several years past during construction activities at the Nicols Fen near Eagan. The analyses in this study indicate that the proposed pier construction technique (sheet piling with a concrete base)

results in dewatering that is limited to the immediate footprint of the pier itself with minimal lowering of hydraulic head beyond the immediate pier areas.

There are potential opportunities for restoring the hydrologic regime of the Seminary Fen Wetland Complex. The substantial network of abandoned drain tile in portions of the Seminary Fen Wetland Complex appears to be actively removing water and is likely lowering the hydraulic head in portions of the wetland complex. Portions of this drain tile network could be removed or plugged (e.g., grouted in place). This activity has the potential for enhancing groundwater upwelling. Methodologies for tile removal or plugging would require careful evaluation in order to minimize disturbances. Improving drainage through and underneath the railroad embankment represents a similar mitigation opportunity. For example, some culverts through the embankment appear to be plugged and may need reconstruction to return surface hydrology to something more akin to predevelopment conditions.

The upwelling conditions in the Seminary Fen Wetland Complex are the result of both local and regional groundwater flow conditions, including groundwater flow in bedrock aquifers. Increased regional development in Carver and southwestern Hennepin County has the potential to reduce groundwater recharge, which could result in reduced groundwater upwelling at the Seminary Fen Complex. There are methods that can be employed to promote or even enhance infiltration in conjunction with development; however these methods would likely need to be employed as part of a regional watershed management program.

Of somewhat more significant importance is future increased demand for groundwater supplies in the Carver-southwestern Hennepin County area and immediately south of the Minnesota River in Scott County. Increased pumping of the bedrock aquifers (in particular, the Prairie du Chien-Jordan aquifer system) has the likely potential of causing reduced upwelling of groundwater in the Seminary Fen Wetland Complex. Similar concerns in the area around the Savage Fen Wetland Complex in Scott County has resulted in the MDNR limiting well location and pumping in the Prairie du Chien-Jordan aquifer system in portions of Scott County.

6.0 References

Barr Engineering Company, 1990. Remedial Investigation, St. Paul Park Refinery, prepared for Ashland Petroleum Company.

Barr Engineering Co., 1998. Source-Water Protection Model for Scott and Dakota Counties.

Barr Engineering Co., 2000. Source-Water Protection Model for Scott and Dakota Counties – modifications and inclusion of Ramsey-Washington Counties into model.

Barr Engineering Co., 2003. Cottage Grove Nitrate Study, prepared for Washington County Dept. of Public Health & Environment, 33 p.

Bell, F.G., 1987. Ground Engineer's Reference Book, Butterworth and Co.

Bonestroo Rosene Anderlik and Assoc., 2004., City of Woodbury Well 15 aquifer test report, prepared for the City of Woodbury, Proj. No. 31-02-175, 27 p.

Danish Hydrologic Institute, 2004. MIKE SHE, An integrated hydrological modeling system.

Delin, G.N. and D.G. Woodward, 1984. Hydrogeologic setting and the potentiometric surfaces of regional aquifers in the Hollandale Embayment, southeastern Minnesota, 1970-1980: U.S. Geol. Surv. Water-Supply Paper 2219, 56 p.

Environmental Simulations, Inc., 2004. Guide to using Groundwater Vistas, Version 4, Environmental Simulations Inc.

Hansen, D.D., and J.K. Seaberg, 2000. Metropolitan Area Groundwater Model Project Summary-Lower Aquifers Model Layers 4 and 5; Ver. 1.00.

Harbaugh, A.W., and McDonald, M.G., 1996. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Hill, M.C., 1990. Pre-conditioned conjugate gradient 2 (PCG2); a computer program for solving groundwater flow equations: U.S. Geological Survey Water Resources Investigations Report 90-4048, 48 p.

Meyer, G.N. and H.C. Hobbs, 1989. Surficial Geology, Plate 3, in Geologic Atlas of Hennepin County: N.H Balaban and H.C. Hobbs (eds.): Minn Geol. Survey County Atlas Series, Atlas C-4, 9 plts.

Kanivetsky, R. and J.M. Cleland, 1990. Hydrogeology, Plate 5, in Geologic Atlas of Washington County, L. Swanson and G.N. Meyer (eds.): Minn Geol. Survey County Atlas Series, Atlas C-5, 7 plts.

McDonald, M.G., and A.W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Groundwater Flow Model, U.S. Geological Survey Techniques of Water Resource Investigations, TWRI 6-A1, 575 p.

Meyer, G.N., R.W. Baker and C.J. Patterson, 1990. Surficial Geology, Plate 3 in Geologic Atlas of Washington County, L. Swanson and G.N. Meyer (eds.): Minn Geol. Survey County Atlas Series, Atlas C-5, 7 plts.

Mossler, J.H. and B.A. Bloomgren, 1990. Bedrock Geology, Plate 2, in Geologic Atlas of Washington County, L. Swanson and G.N. Meyer (eds.): Minn Geol. Survey County Atlas Series, Atlas C-5, 7 plts.

Mossler, J.H., and R.G. Tipping, 2000. Bedrock geology and structure of the seven-county Twin Cities metropolitan area, Minnesota, Miscellaneous Map series M-104, Minnesota Geological Survey.

Mossler, J., 2003. Structural contours of the top of the Jordan Sandstone, southern Washington County, Minnesota Geological Survey, unpublished map.

Norvitch, R.F., T.G. Ross, and A. Brietkrietz, 1974. Water resources outlook for the Minneapolis-St. Paul metropolitan area; Metropolitan Council of the Twin Cities area, 219 p.

Palen, B.M., 1990. Bedrock Hydrogeology, Plate 5, in Geologic Atlas of Dakota County: N.H Balaban and H.C. Hobbs (eds.): Minn Geol. Survey County Atlas Series, Atlas C-6, 9 plts.

Peterson Environmental, Inc., 2006. Phase 1 Characterization, Seminary Fen Wetland Complex, TH 41 Over the Minnesota Highway Project, Carver County, Minnesota, 78 p.

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model, USGS Open File Report 89-391, 188 pp.

Reeder, H.O., 1976. Artificial recharge through a well in fissured carbonate rock, West St. Paul, Minnesota: U.S. Geol. Surv. Water-Supply Paper 2004, 80 p.

Runkel, A.C., R.G. Tipping, E.C. Alexander, J.A. Green, J.H. Mossler, and S.C. Alexander, 2003. Hydrogeology of the Paleozoic bedrock in southeastern Minnesota, Rept. of Investigation 61, ISSN 0076-9177, 105 p.

Schoenberg, M.E., 1990. Effects of present and projected ground-water withdrawals on the Twin Cities aquifer system, Minnesota: U.S. Geol. Survey Water-Resources Investigation Report 90-4001, 165 p.

van Genuchten, M. Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44(5): 892-898.

Watermark Numerical Computing . 2001, PEST ASP Upgrade Notes.

Watermark Numerical Computing, 2005. PEST: Model-Independent Parameter Estimation. User Manual. 5th edition.

Tables

Summary of Construction Dewatering Scenarios

Zone #	Change in modeled seepage (cfs) E-1	E-1A	E-2
667	**-0.0023**	**-0.089**	**-0.0073**
668	**-1.4E-05**	**-1.7E-05**	**-0.00055**
669	**-2.6E-06**	**-4.1E-06**	**-0.00022**
670	**-3.3E-07**	**-3.9E-07**	**-1.1E-05**
671	**-2.6E-07**	**-2.5E-07**	**-2.7E-06**
672	**-4E-07**	**-7.7E-07**	**-3.3E-06**
673	0	0	0
674	**-3.9E-07**	**-6.7E-06**	**-9.3E-06**
675	**-1.2E-05**	**-0.0059**	**-0.048**
Total change (cfs)	**-0.0023**	**-0.094**	**-0.056**
Dewatering rate (cfs)	0.12	0.43	0.49

Table 4-2

Summary of Post-construction Scenarios

Zone #	Change in modeled seepage (cfs) E-1	E-1A	E-2
667	**-0.011**	0.085	**-0.0017**
668	**-5.8E-05**	**-0.00012**	**-0.0012**
669	**-8.6E-06**	**-1.9E-05**	**-0.00029**
670	**-3.8E-07**	**-1E-06**	**-1E-05**
671	**-1.4E-07**	**-4.9E-07**	**-1.5E-06**
672	**-2.6E-06**	**-8.8E-06**	**-7.1E-06**
673	0	0	0
674	**-3.9E-05**	**-0.00013**	**-0.0001**
675	**-0.00091**	**-0.0077**	**-0.036**
Total	**-0.012**	**0.076**	**-0.0025**

Table 4-3

Summary of Bridge Pier Excavation Dewatering Study

Scenario	Hydraulic Conductivity (ft/day) Kx – horizontal Kz - vertical Kx Zone 2	Kz Zone 2	Kx Zone 3	Kz Zone 3	Discharge (cfs) Total	Sides	Bottom	Maximum Drawdown (ft)
1	11.9	1.57	39.4	0.000321	2.15E-02	2.15E-02	6.13E-06	4.46
2	11.9	1.57	39.4	3.94	4.10E-02	2.05E-02	2.06E-02	
3	11.9	1.57	39.4	0.394	2.70E-02	2.12E-02	5.84E-03	
4	11.9	1.57	39.4	0.0394	2.22E-02	2.15E-02	7.35E-04	
5	11.9	1.57	39.4	0.00394	2.16E-02	2.15E-02	7.76E-05	
6	1.19	1.57	39.4	0.000321	1.28E-02			2.46
7	0.119	1.57	39.4	0.000321	2.56E-03			0.558
8	0.0119	1.57	39.4	0.000321	3.68E-04			0.177
9	0.00119	1.57	39.4	0.000321	1.59E-04			0.0131

Table 4-4

Summary of Construction Dewatering Scenarios

Alternative	Number of piers east of the river	Estimated maximum drawdown (ft)	Estimated distance to 0.1 ft drawdown (ft)
E-1/E-1A	48	5.9	2000
E-2	42	5.1	1750
C-2	40	4.9	1670
C-2A	24	2.9	1000
W-2	58	7.1	2420

Figures

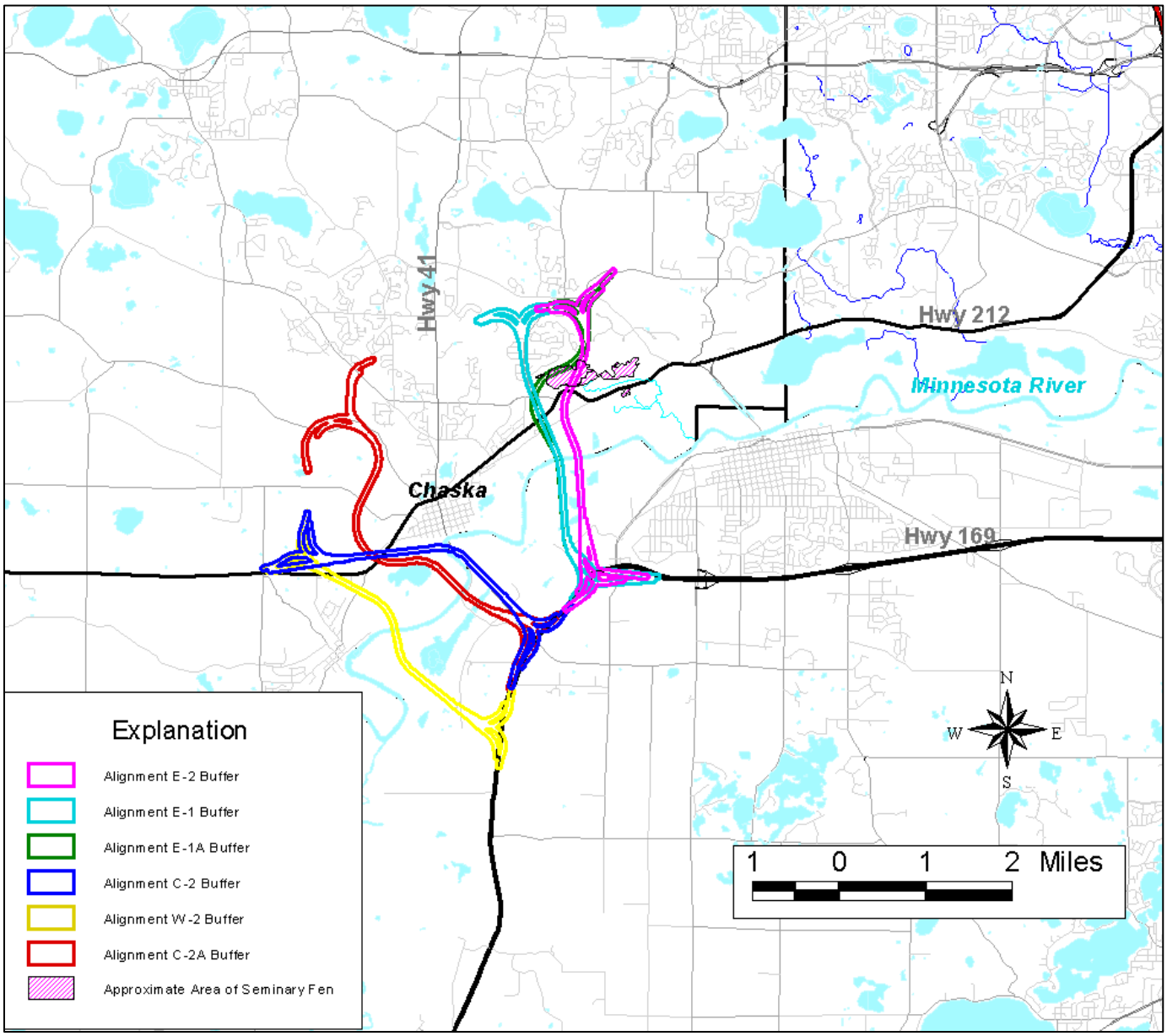

Figure 1-1

Location of Alignments and Seminary Fen Area

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Figure 1-2

Approximate Location of Assumption Creek in Seminary Fen Area

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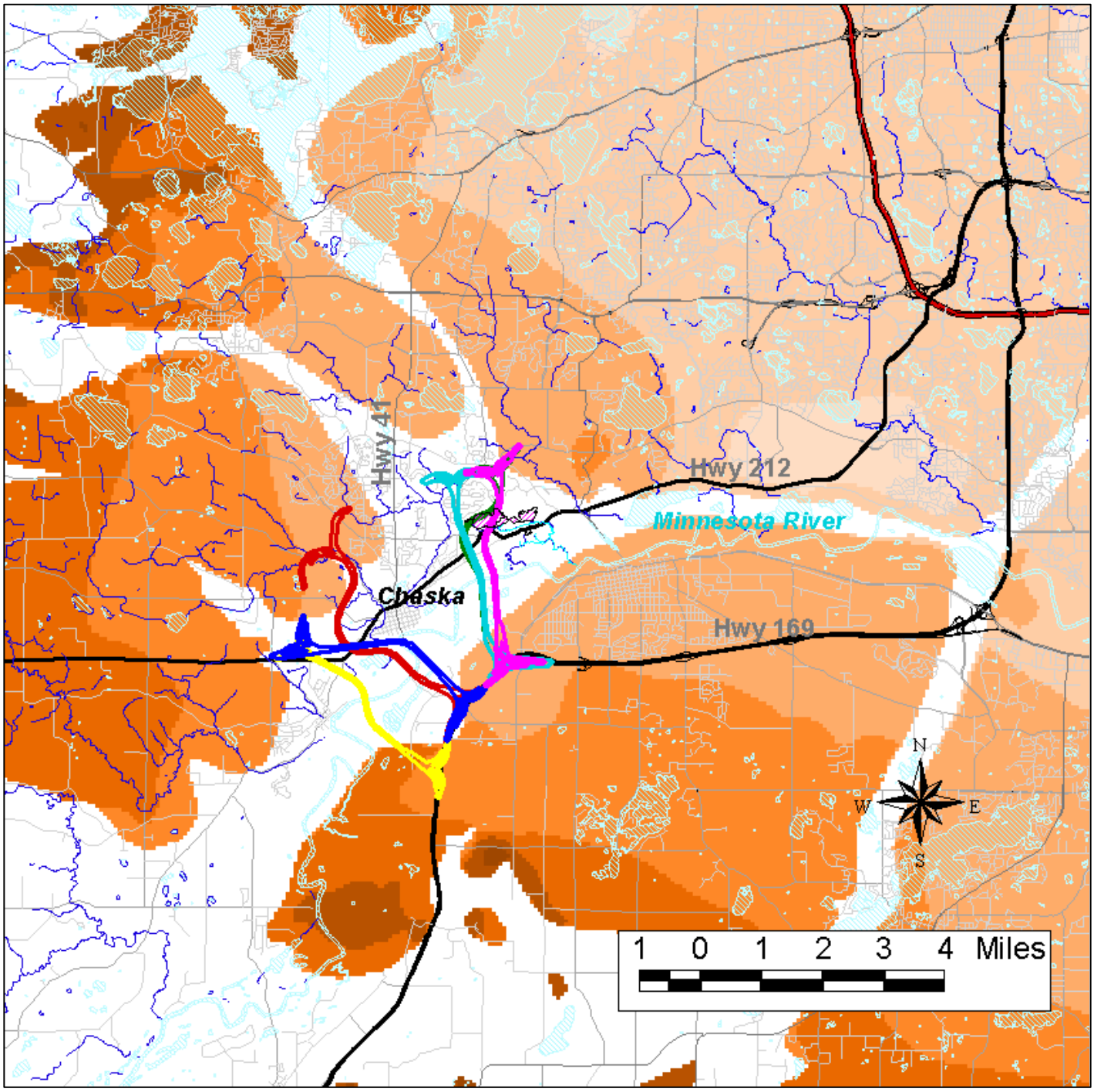
GEOLOGIC UNITS	DESCRIPTION	HYDROSTRATIGRAPHIC UNIT	MODFLOW Model Layer
Glacial Drift/Recent Alluvium	mostly silt, sand, and gravel with till lenses and lake deposits	Aquifer with some local aquitard units	Typically Layers 1 & 2
Decorah Shale	glauconitic shale	Aquitard	Not in model
Platteville Formation and Glenwood Shale	massive to thinly bedded, fractured dolomite & shale	poorly transmissive aquifer to aquitard	Not in model
St. Peter Sandstone	upper 100 feet is uniform fine sandstone; lower 50 feet is shale	Aquifer	Typically Layer 2
		Aquitard	Leakance on Layer 2
Prairie du Chien Group	Shakopee Fm (upper unit) contains zones of highly fractured rock; Oneota Dol. (lower) is massive	Aquifer (Shakopee)	Layer 3
		Aquitard (Oneota)	Leakance on Layer 3
Jordan Sandstone	medium sandstone with fractures and some cementation	Aquifer	Layer 4
St. Lawrence Formation	dolomitic shale	Aquitard	Layer 5
Franconia Formation	calcareous sandstone to shaley sandstone	Aquifer (upper Franconia)	Layer 6
		Aquitard (lower Franconia)	
Ironton-Galesville Sandstones	fine to medium sandstone	Aquifer	
Eau Claire Formation	dolomitic shale	Aquitard	Not in model
Mt. Simon and Hinckley Sandstones	sandstone	Aquifer	Not in model
Precambrian Crystaline Rocks	undifferentiated crystalline and volcanic rocks	Aquitard	Not in model

Figure 2-1

Hydrostratigraphic Column for Study Area, Showing Corresponding Groundwater Model layers



White areas are locations where glacial activity eroded away bedrock above the St. Lawrence Formation

Figure 2-2

Extent of Jordan Sandstone

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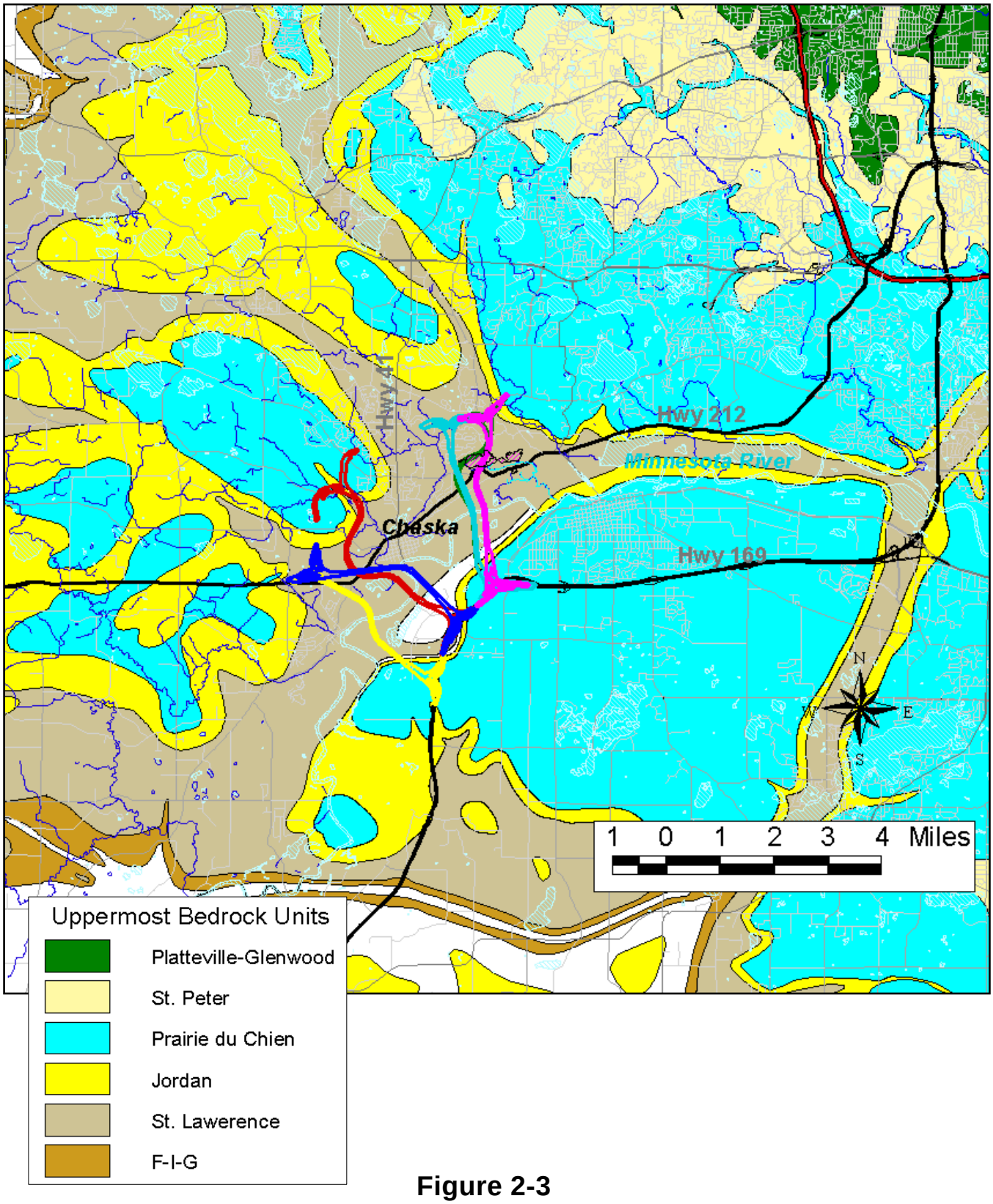

Figure 2-3

Uppermost Bedrock in Study Area

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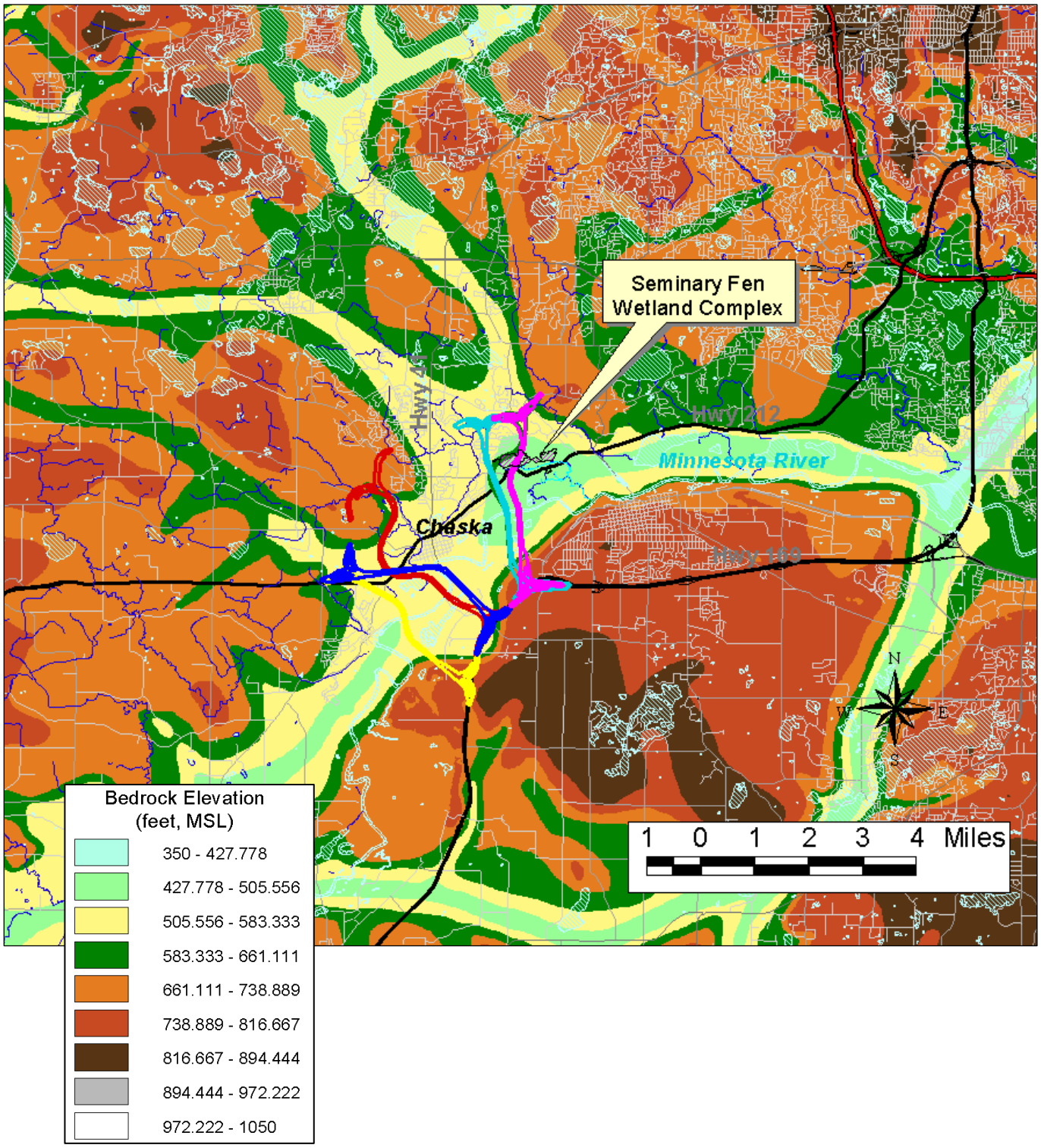

Figure 2-4

Elevation of Uppermost Bedrock in Study Area

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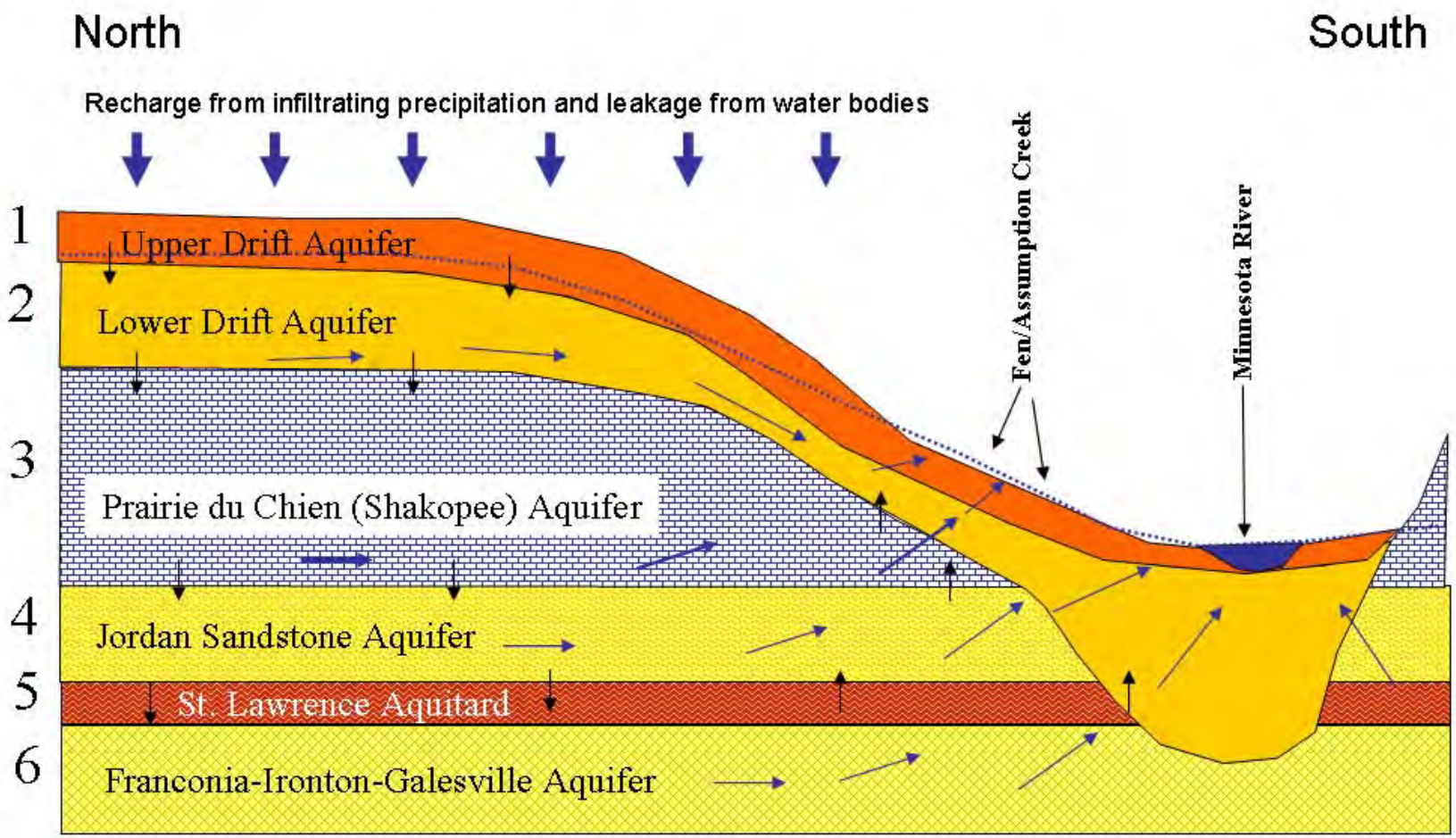
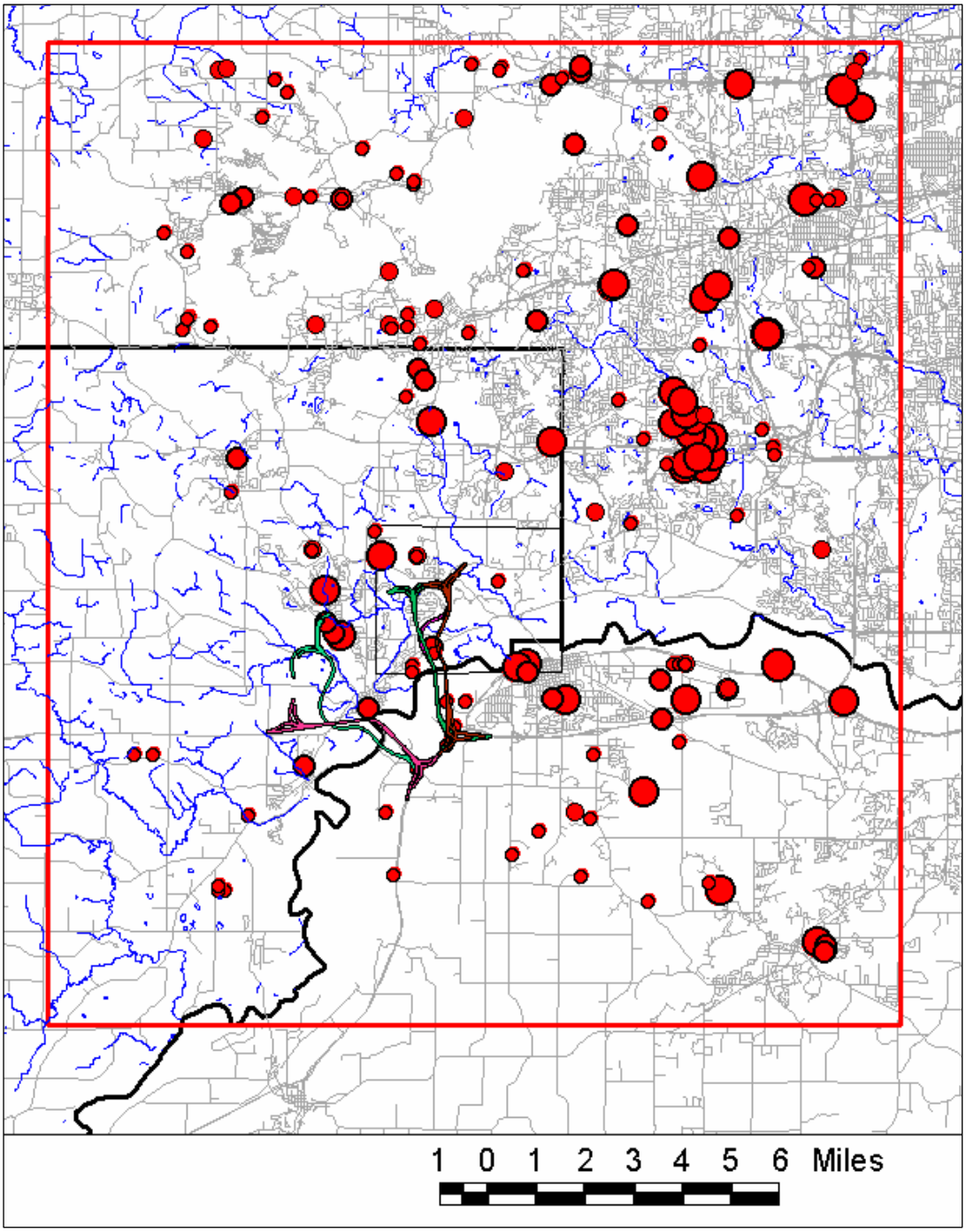


Not to scale

Figure 2-5

Schematic Cross Section Depicting Conceptual Hydrogeologic Model (Regional Scale)



Relative size of circle indicates relative pumping rate for 2003 (streams in Scott County not shown)

Figure 2-6

Location of High-Capacity Wells in Study Area

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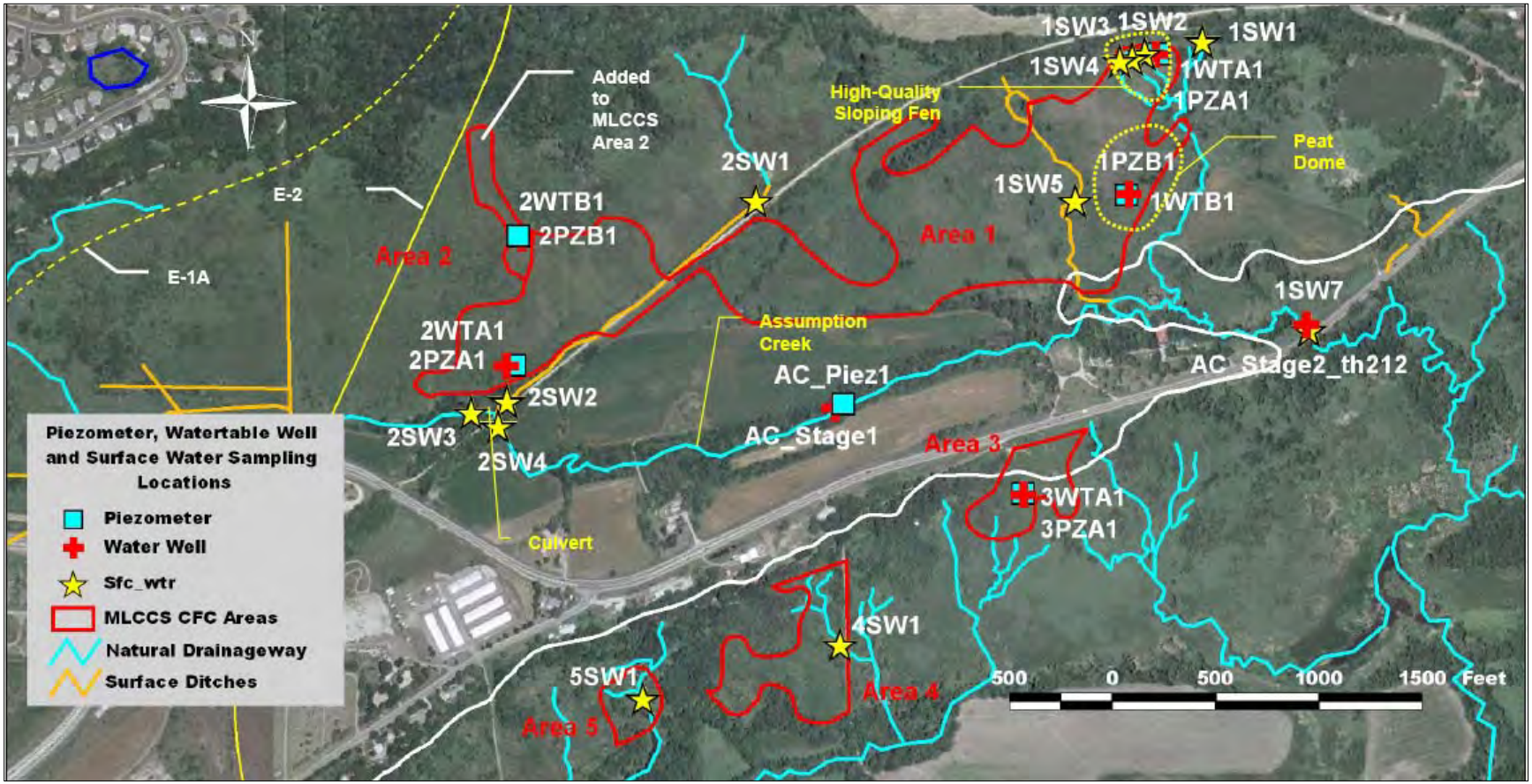

(from Figure 5-1 in Peterson Environmental Inc. (2006))

Figure 2-7

Locations of Piezometers and Wetland Areas

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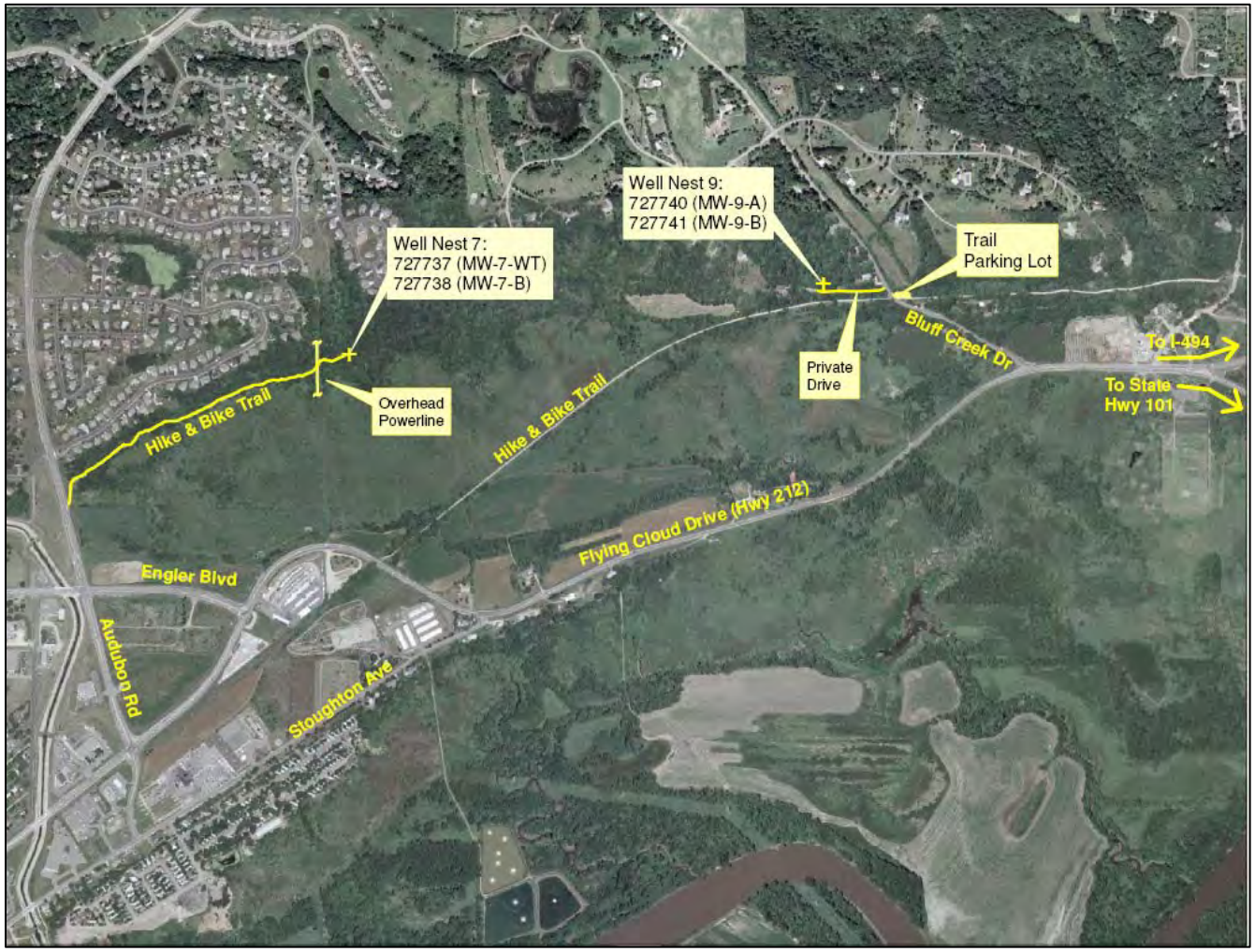

Figure 2-8

Location of Well Nests 7 and 9 Along Bluff, North of Wetland Complex Areas

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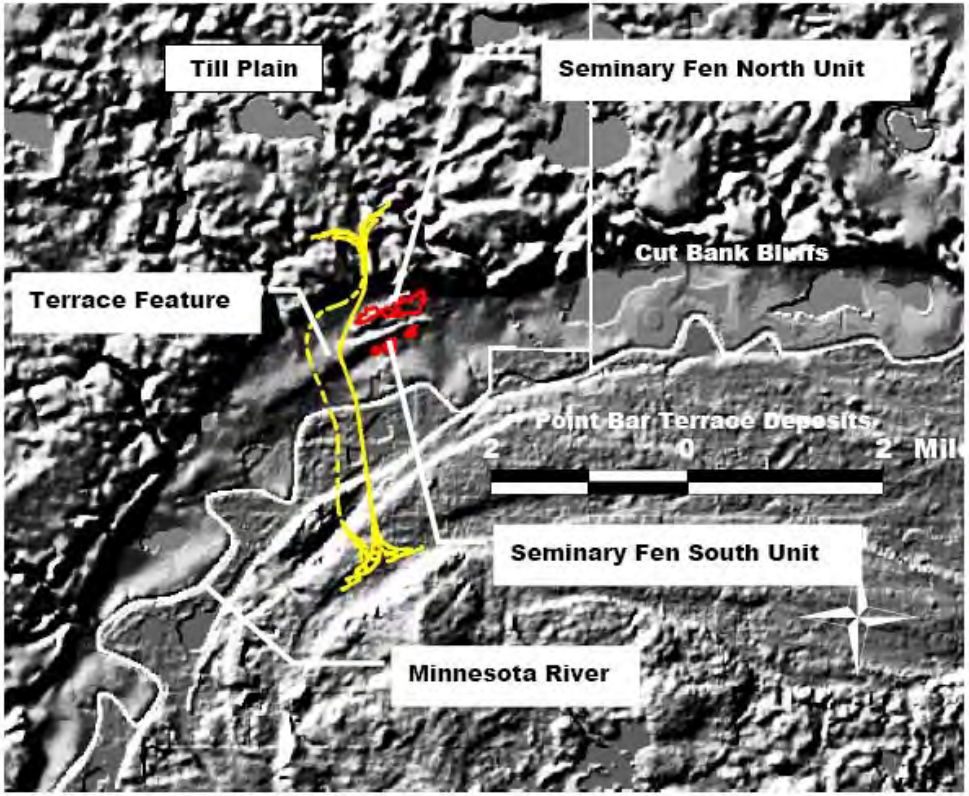
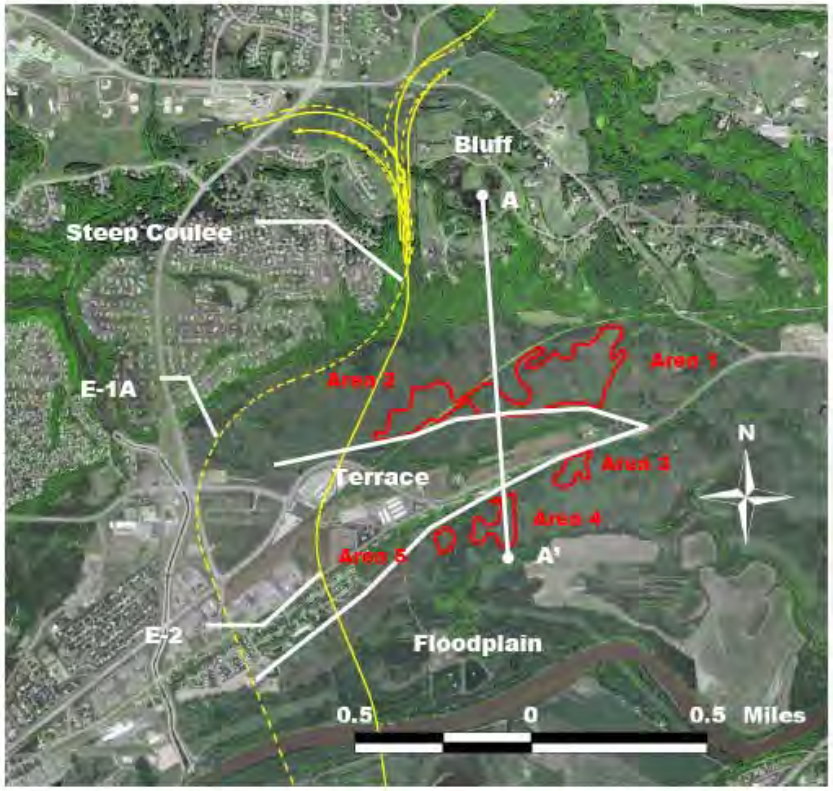


Shaded Relief Map: Seminary Fen Area



Topography and Relief: Seminary Fen Area

(from Figure 3.4 in Peterson Environmental Inc., 2006)

Figure 2-9

Location of Terrace Deposit and other Geomorphological Features in the Seminary Fen Wetland Complex Area

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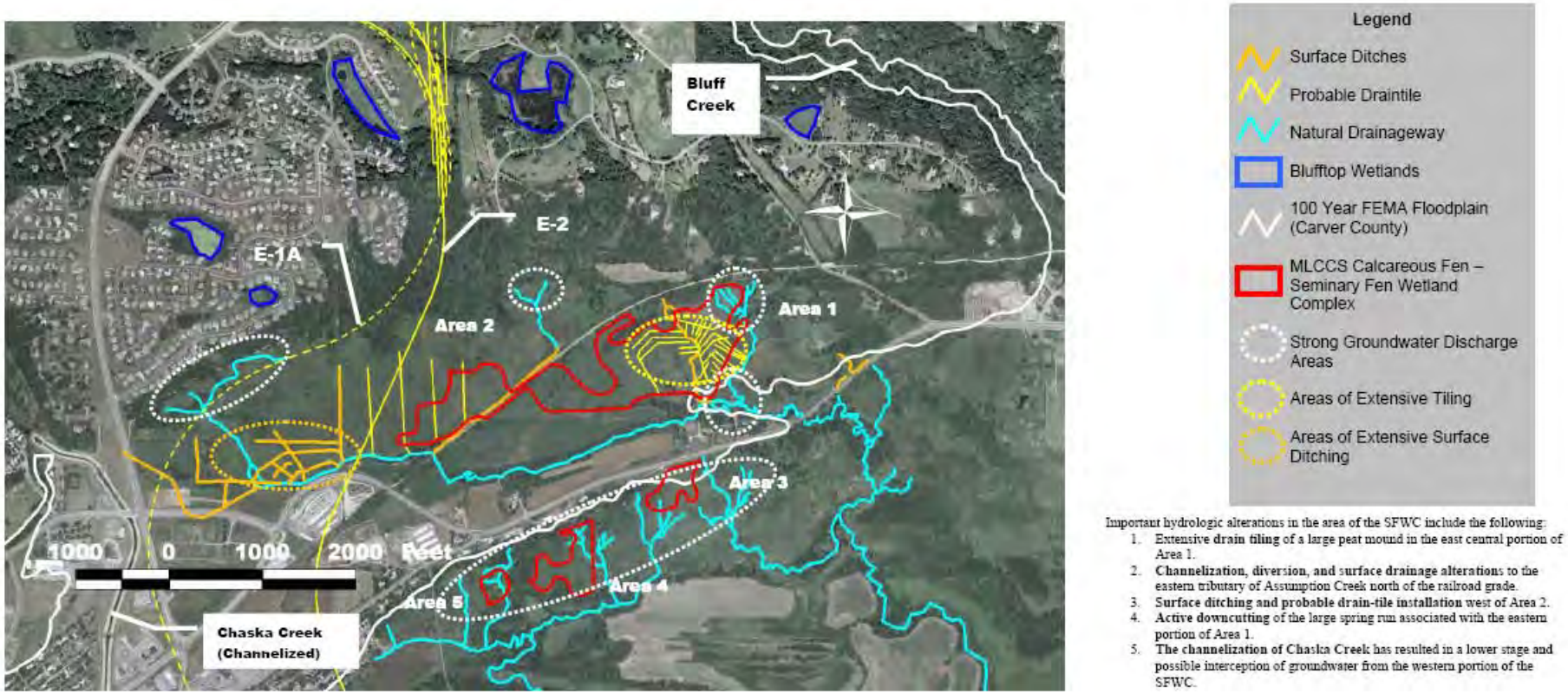

Important hydrologic alterations in the area of the SFWC include the following:

1. Extensive **drain tiling** of a large peat mound in the east central portion of Area 1.
2. **Channelization, diversion, and surface drainage alterations** to the eastern tributary of Assumption Creek north of the railroad grade.
3. **Surface ditching and probable drain-tile installation** west of Area 2.
4. **Active downcutting** of the large spring run associated with the eastern portion of Area 1.
5. **The channelization of Chaska Creek** has resulted in a lower stage and possible interception of groundwater from the western portion of the SFWC.

(from Figure 3.10 in Peterson Environmental Inc., 2006)

Figure 2-10

Locations of Man-Made Drainage Features in the Seminary Fen Wetland Complex

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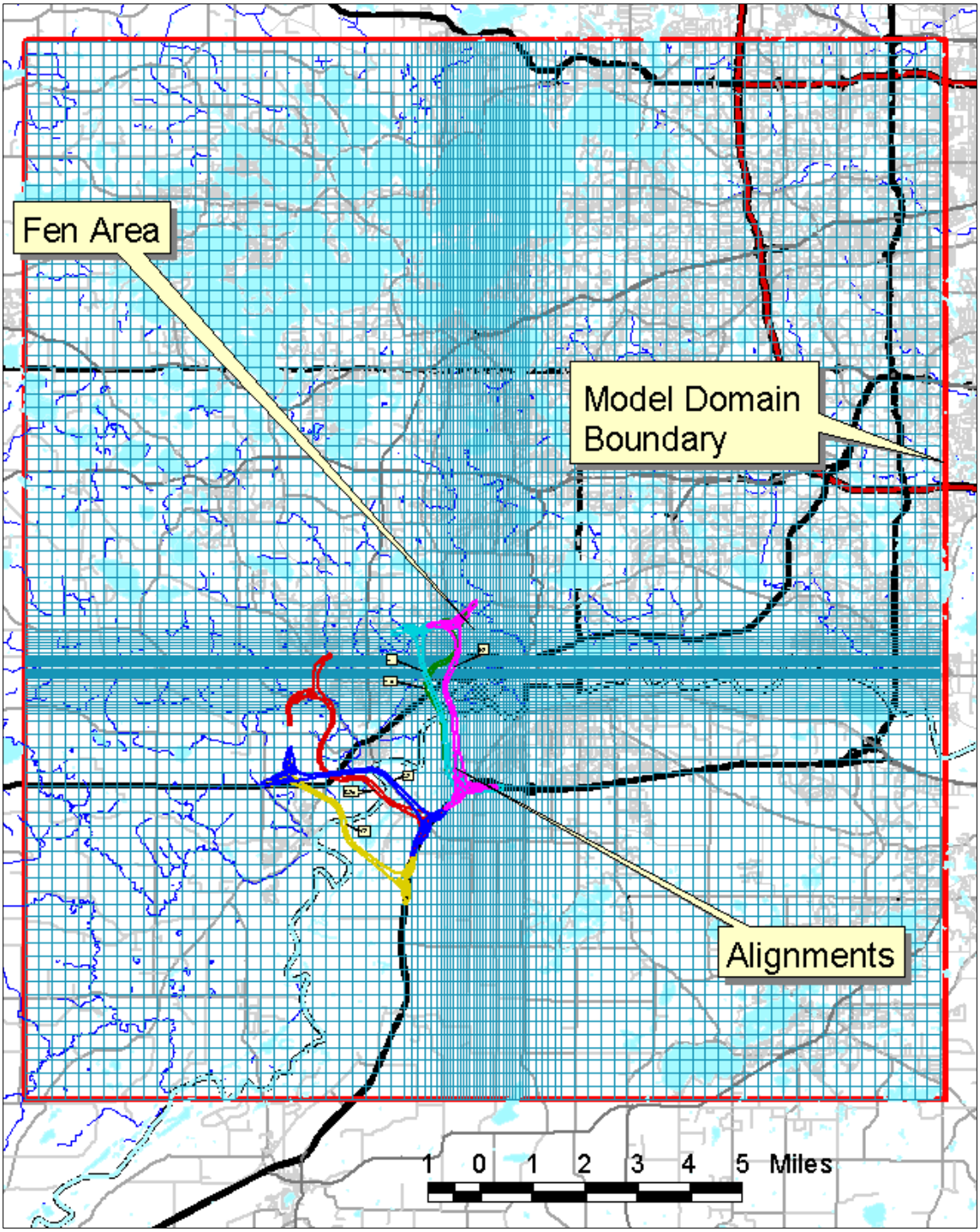
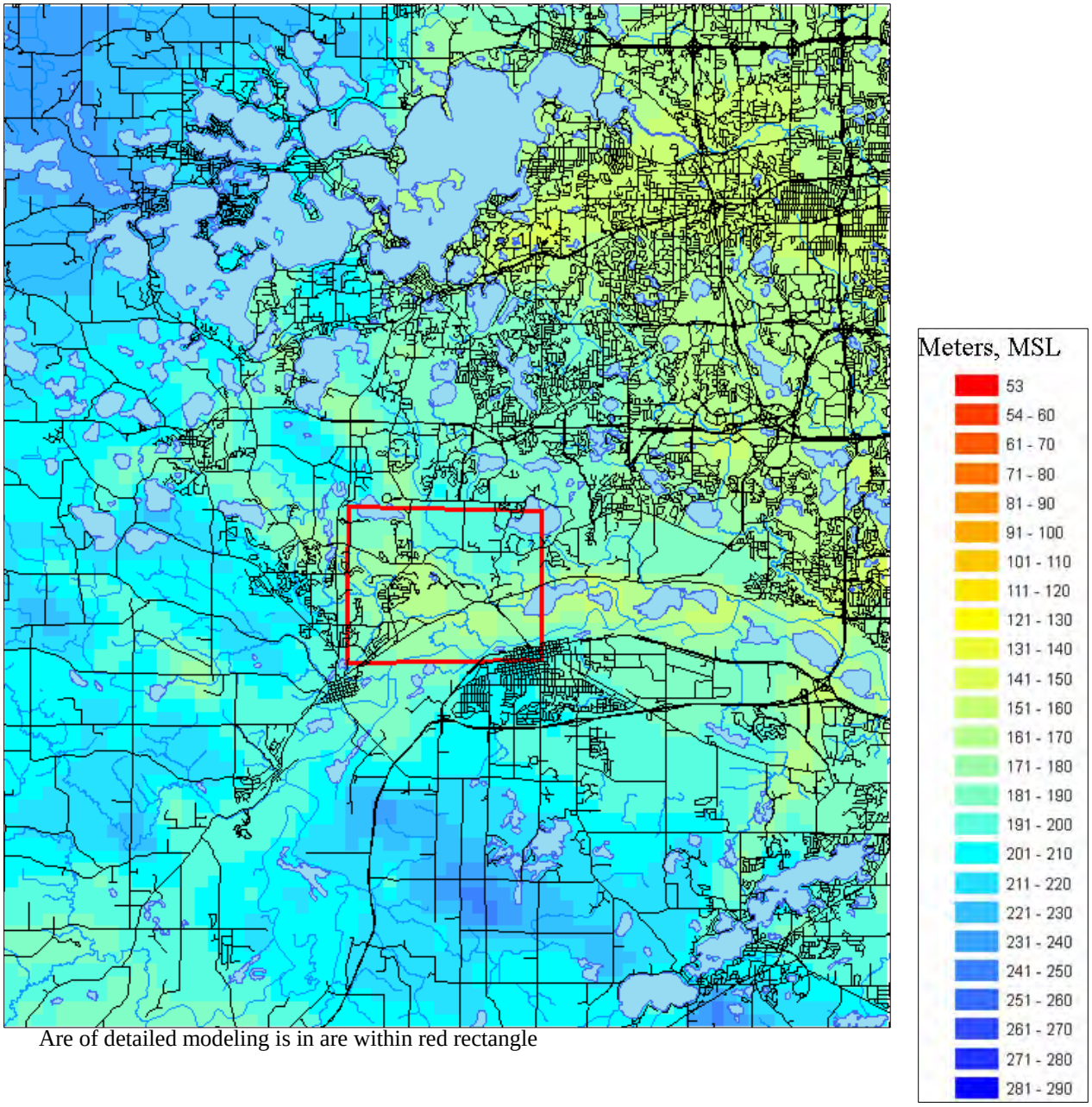


Figure 3-1

Extent of Regional Groundwater Model Domain and Finite-Difference Grid



Are of detailed modeling is in are within red rectangle

Figure 3-2

Example of Base Elevations in Model : Base Elevation for Layer 3 (Shakopee Formation)

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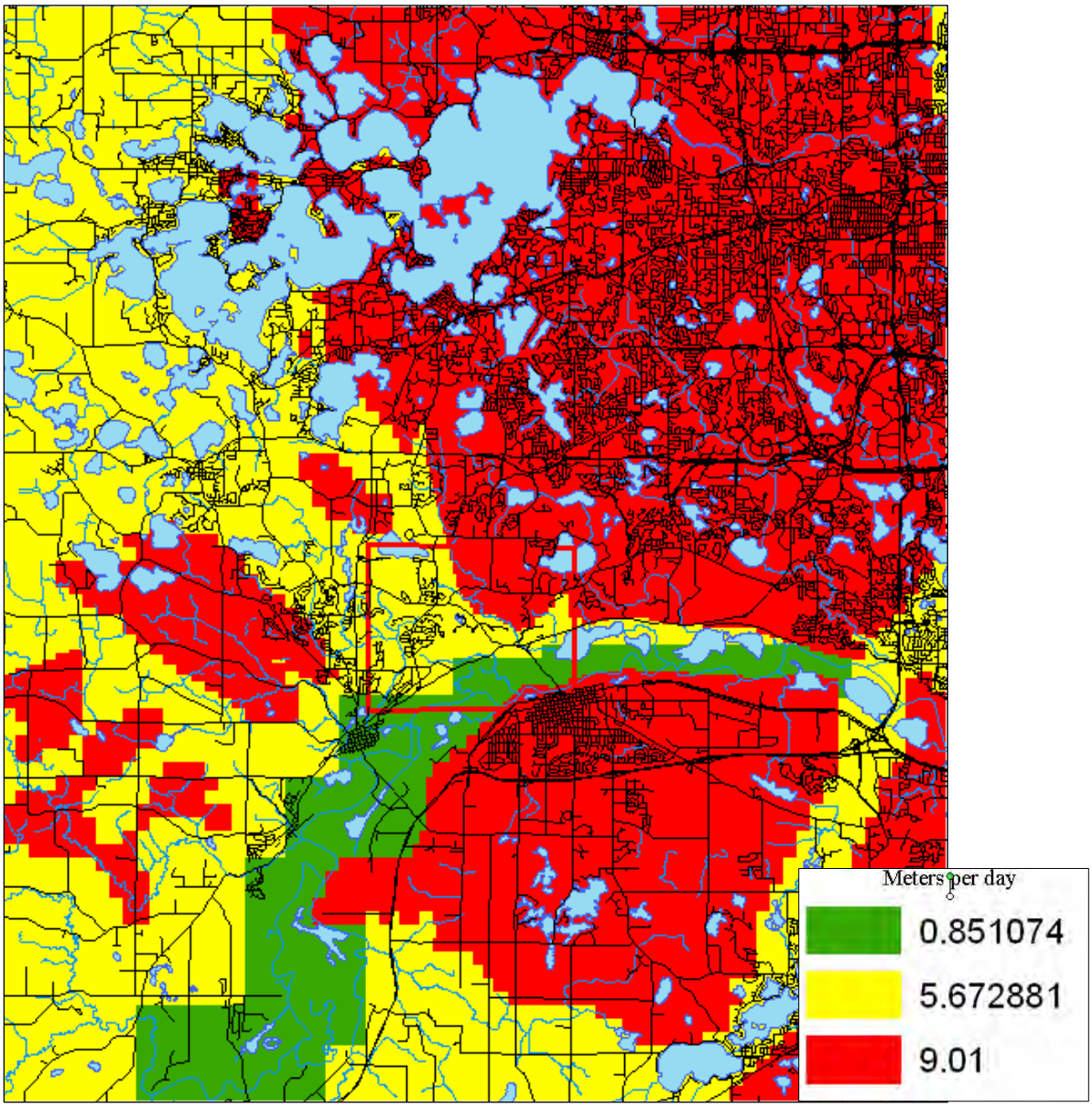

Figure 3-3

Example of Hydraulic Conductivity Zonation in Model: Layer 3

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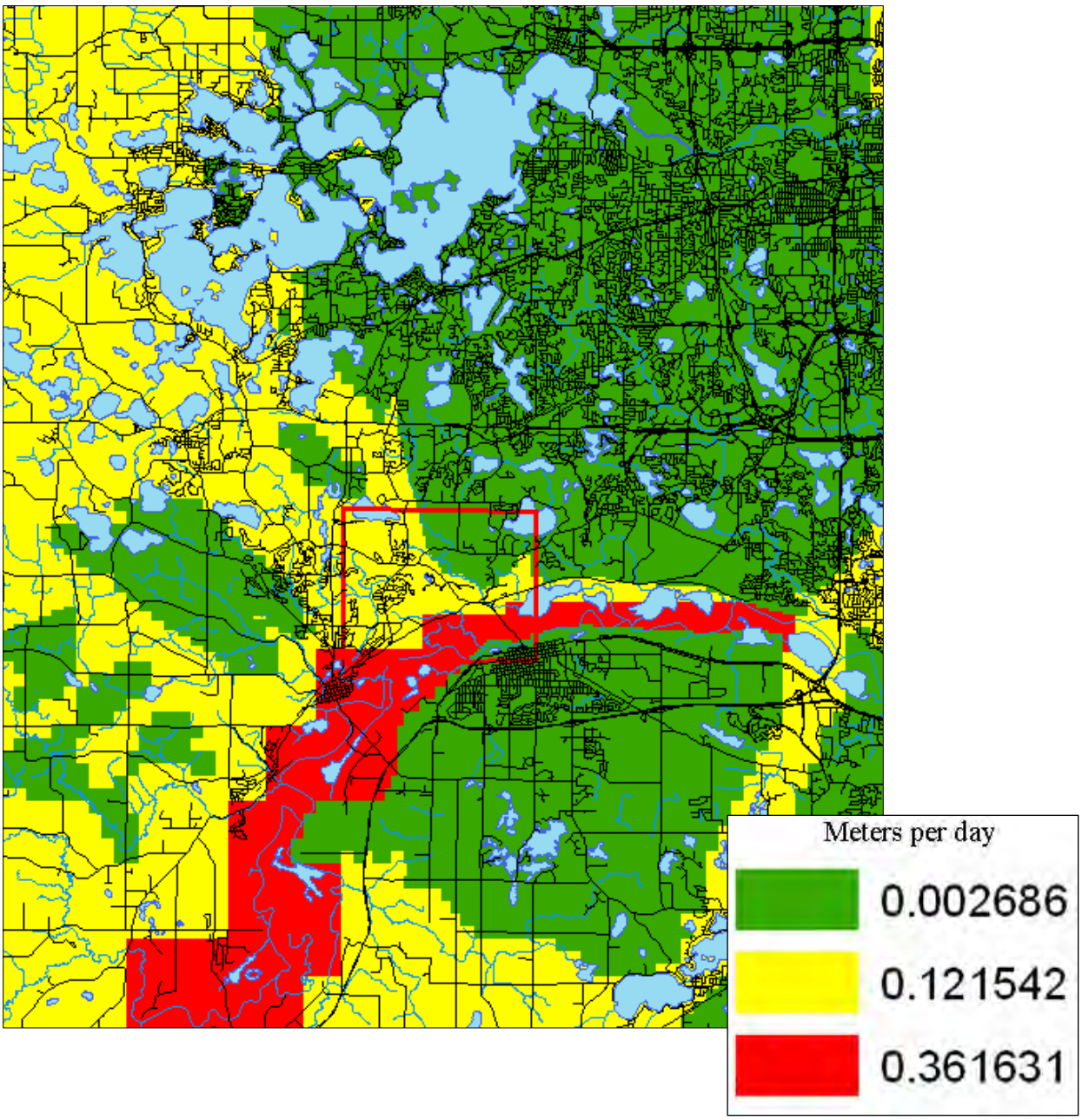

Figure 3-4

Example of Vertical Hydraulic Conductivity Zonation in Model: Layer 3

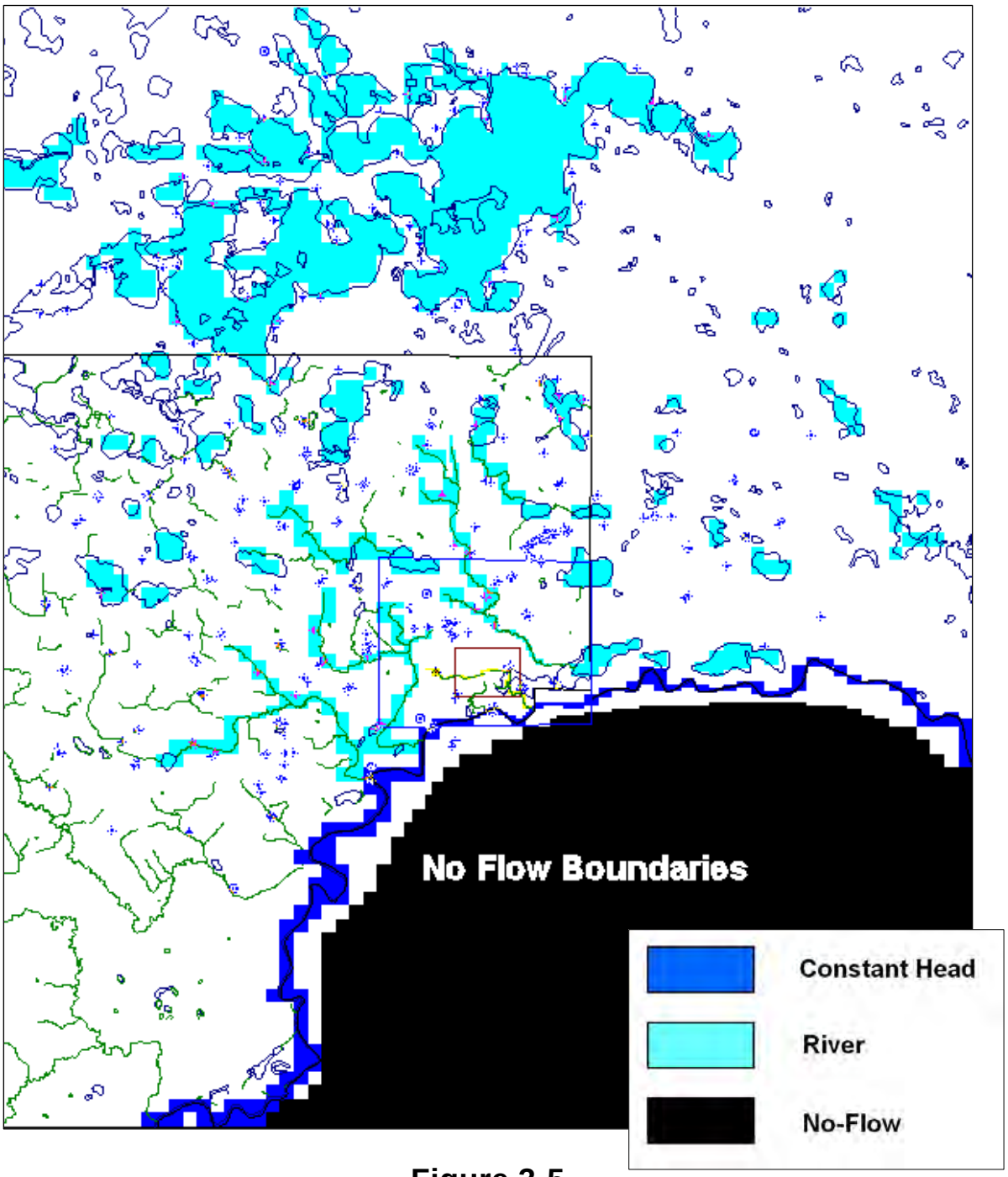

Figure 3-5

No-Flow Boundaries in Layer 1

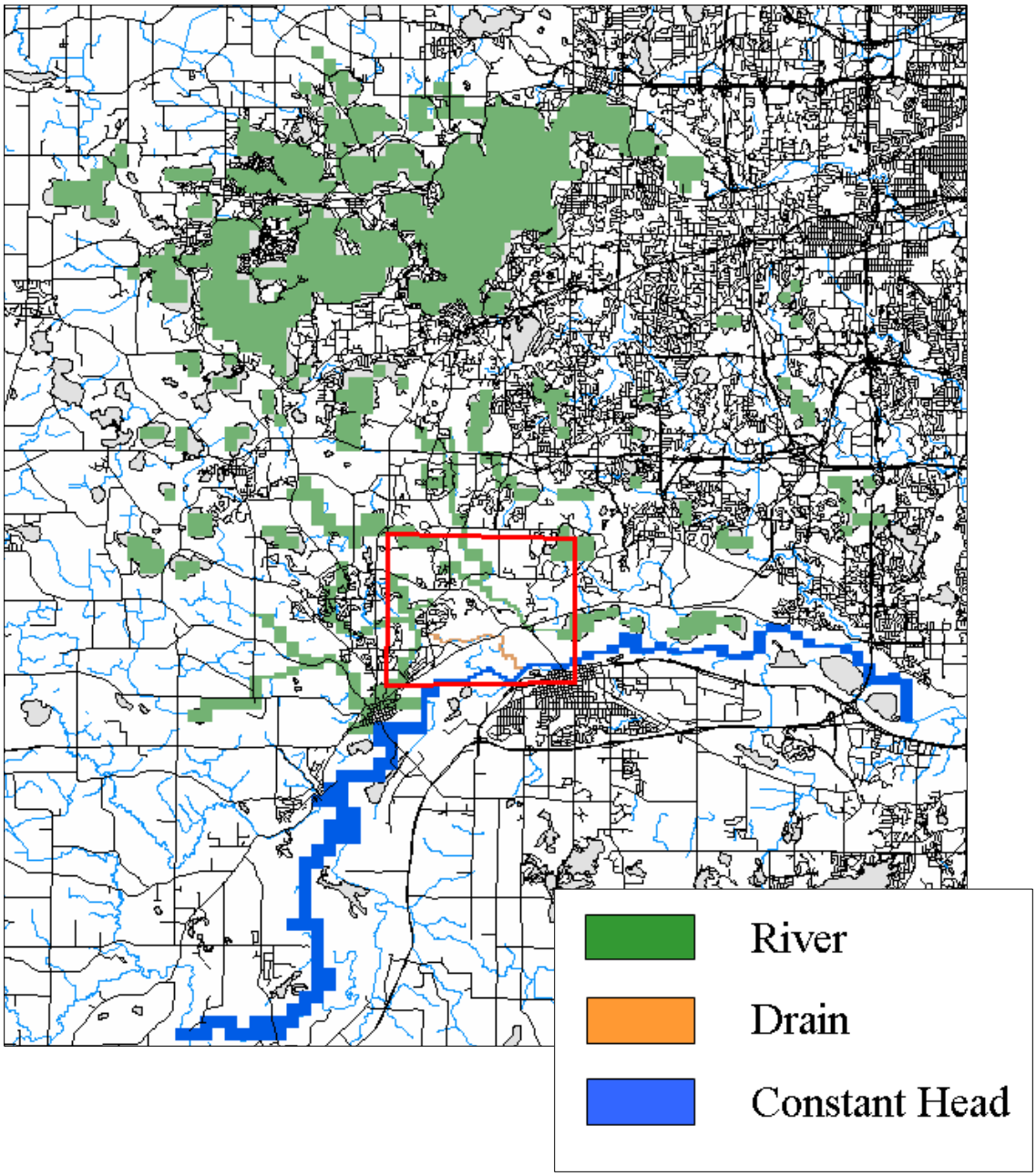

Figure 3-6

Boundary Conditions in Layer 1 (exclusive of No-Flow Boundaries)

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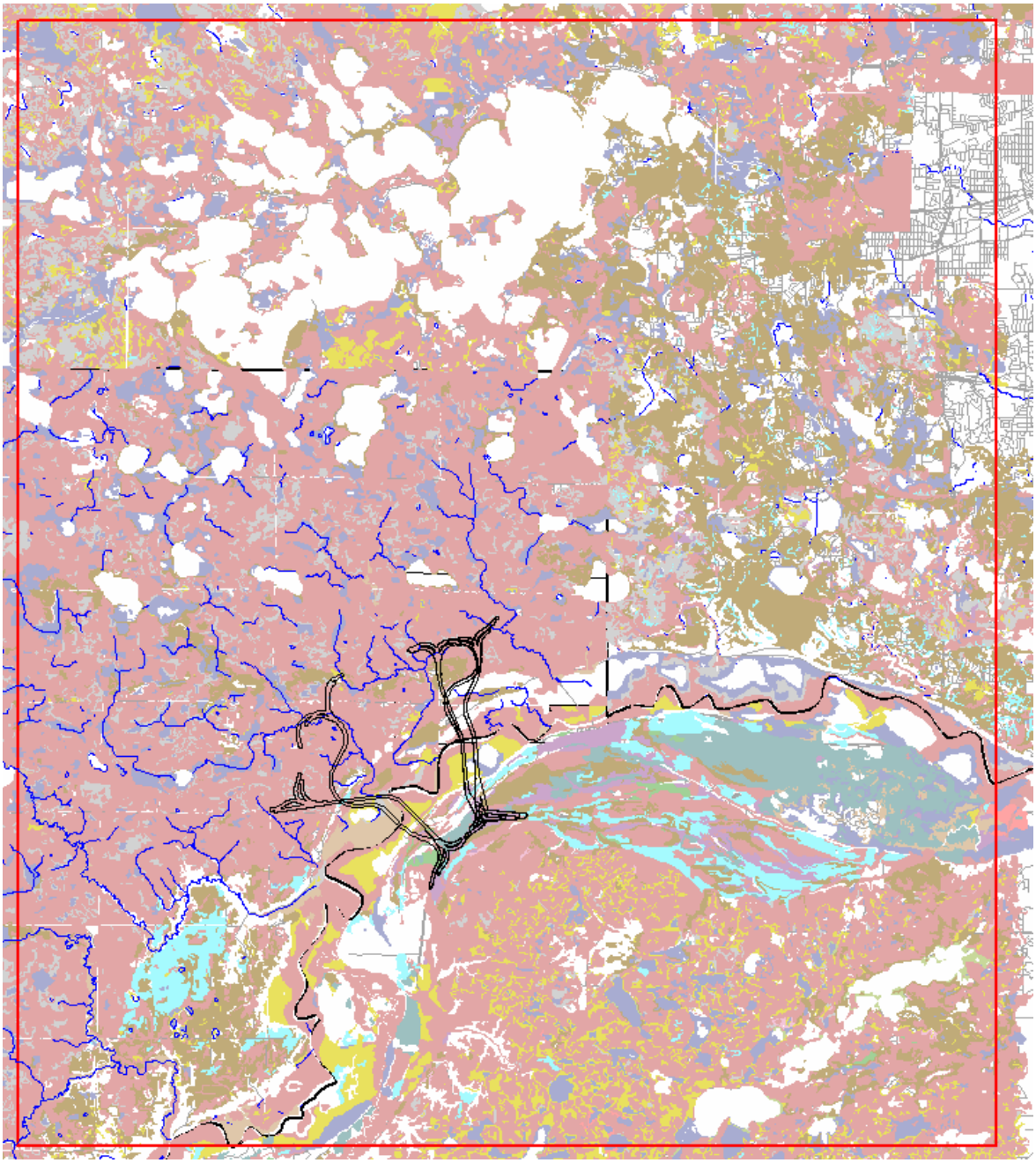


Figure 3-7

Compiled Digital Soil Survey Map within Model Domain

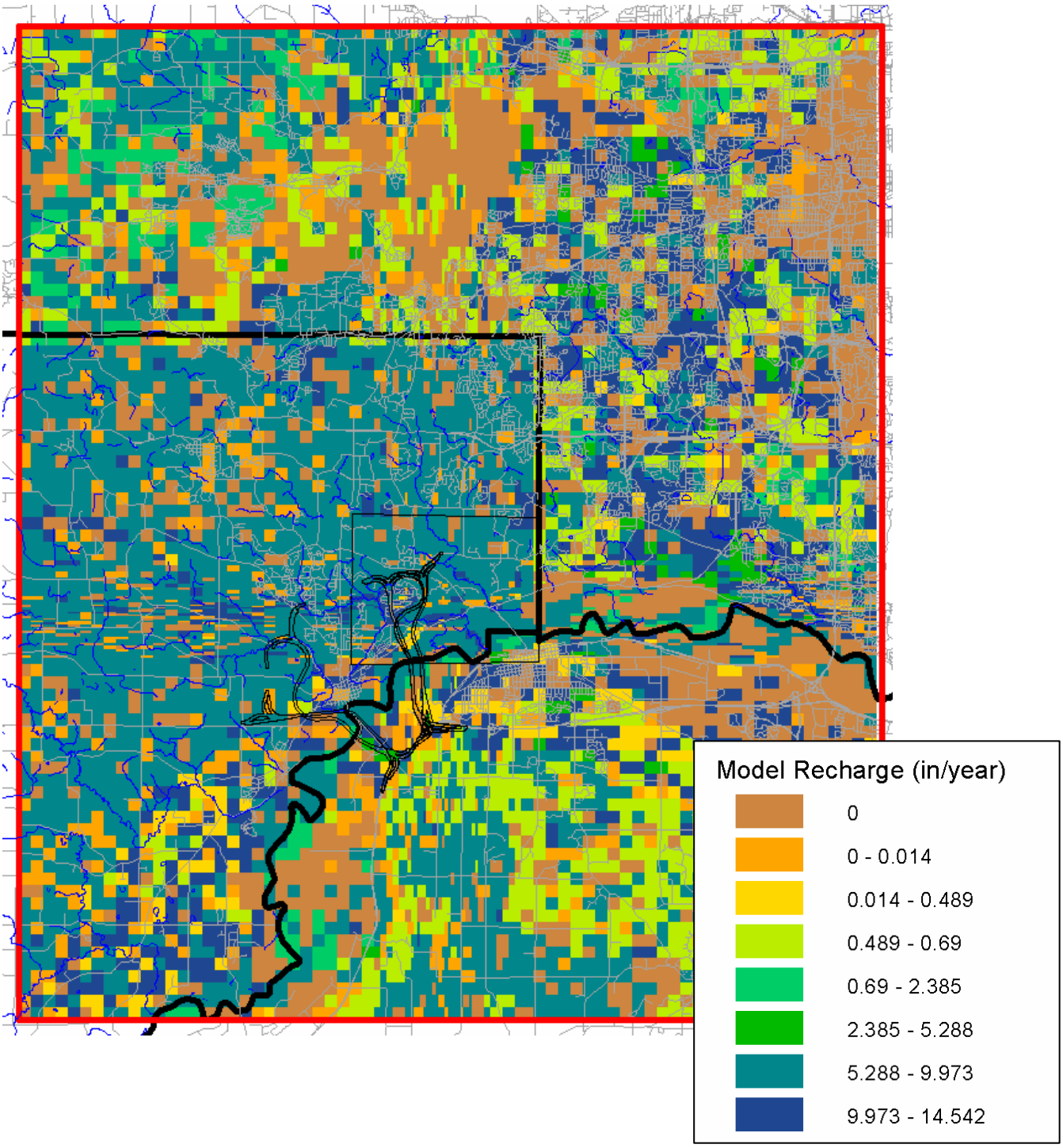


Figure 3-8

Model Distributed Recharge

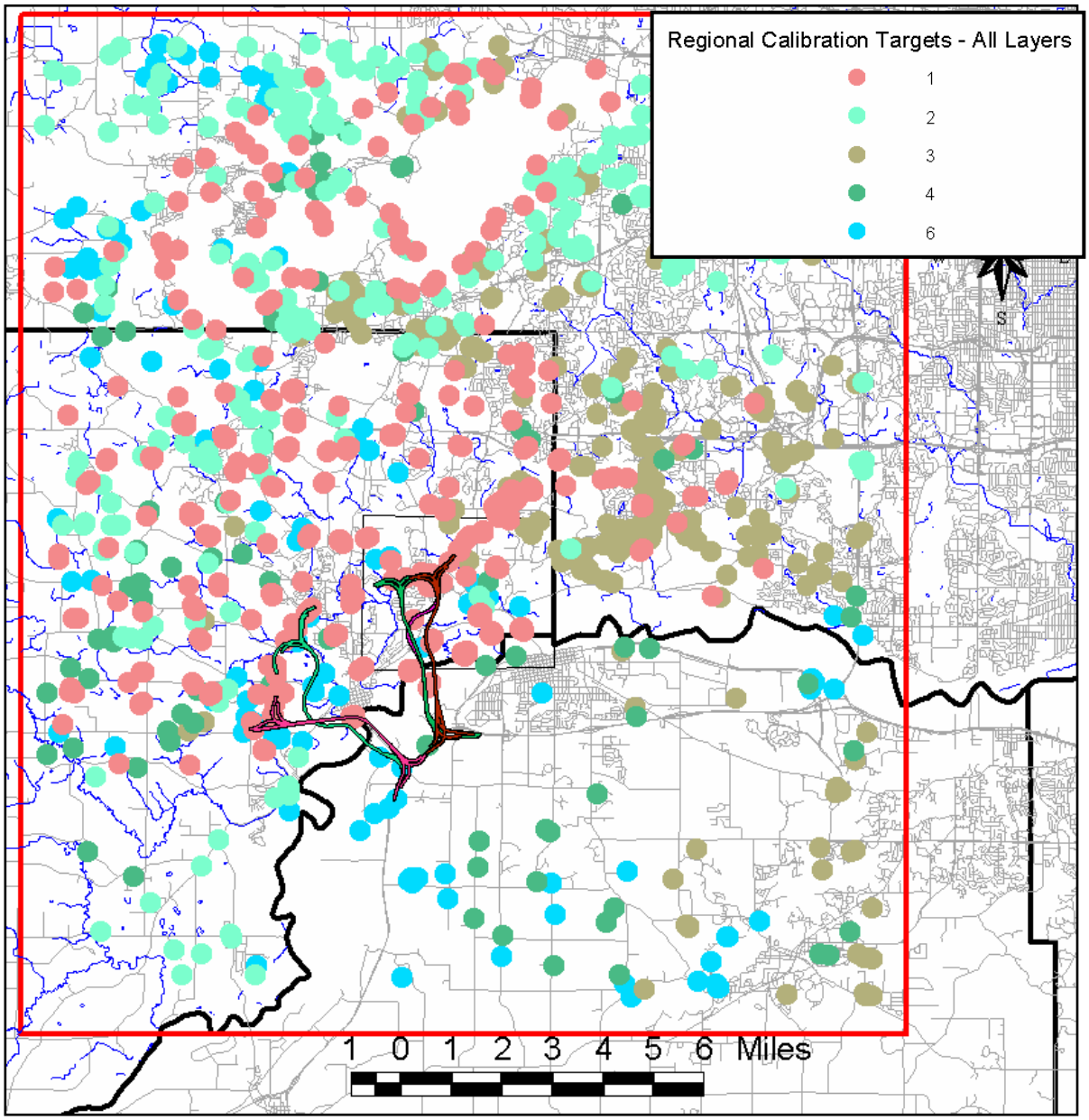


Figure 3-9

Location of Regional Model Calibration Targets

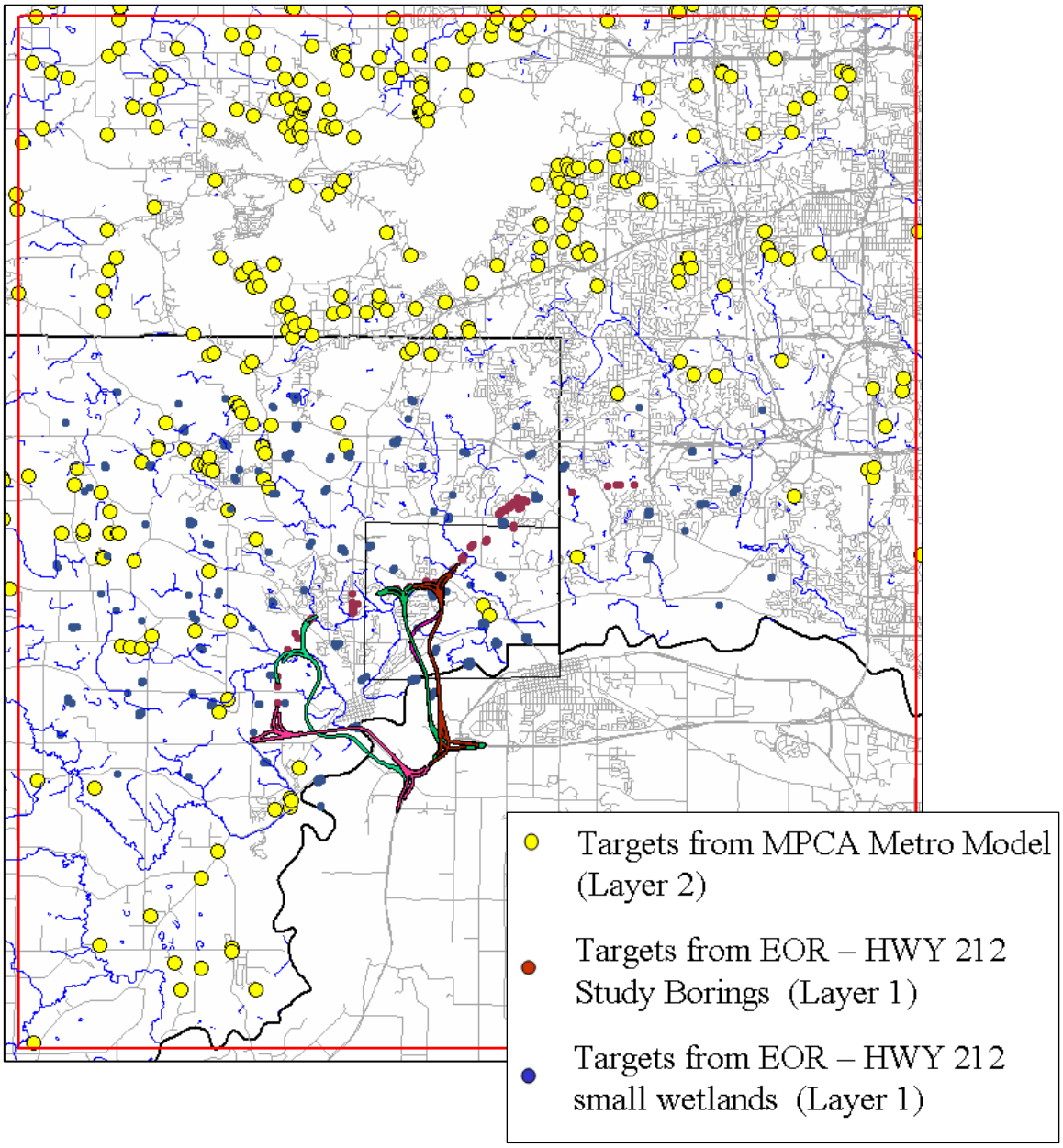


Figure 3-10

Calibration Targets in Layers 1 and 2

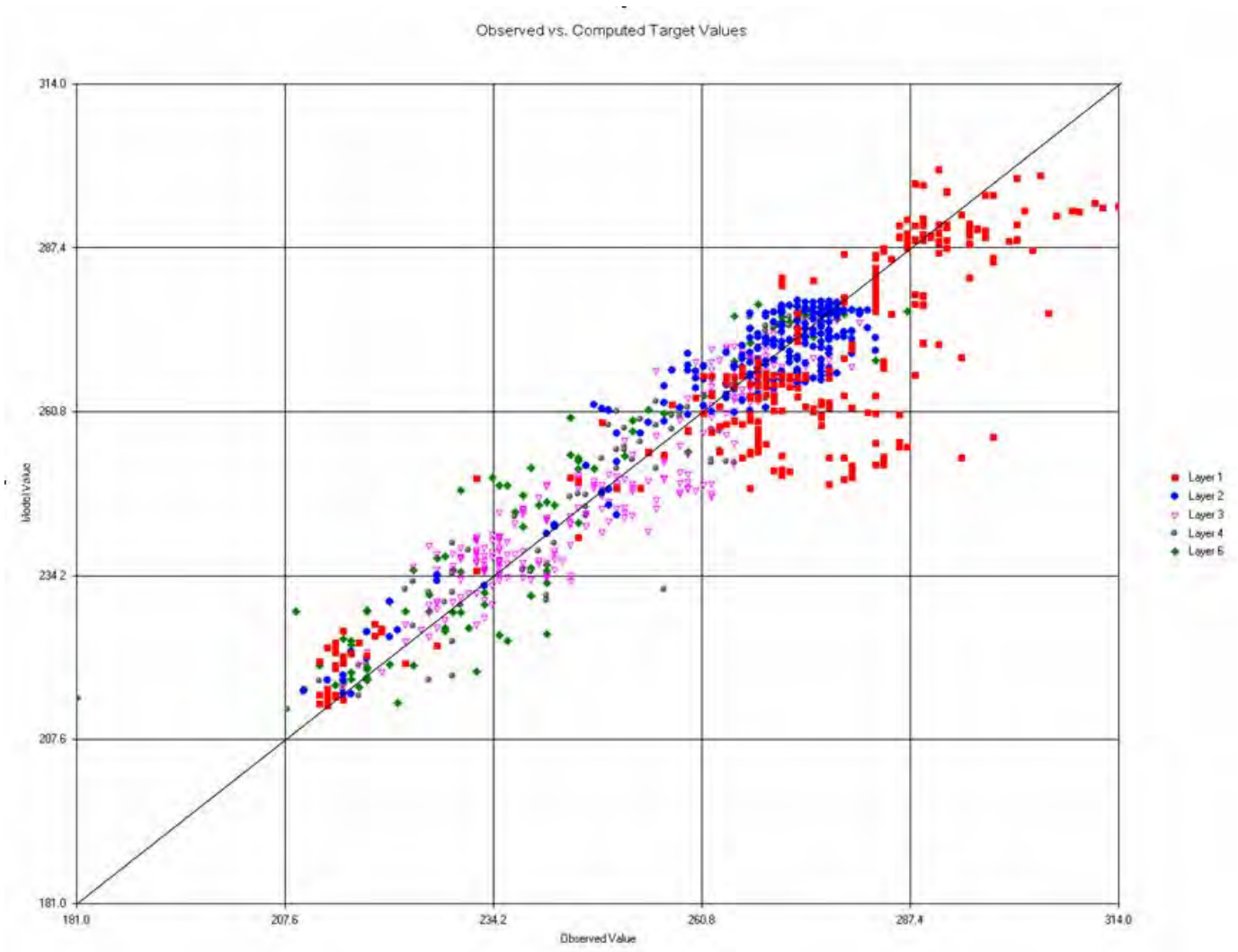
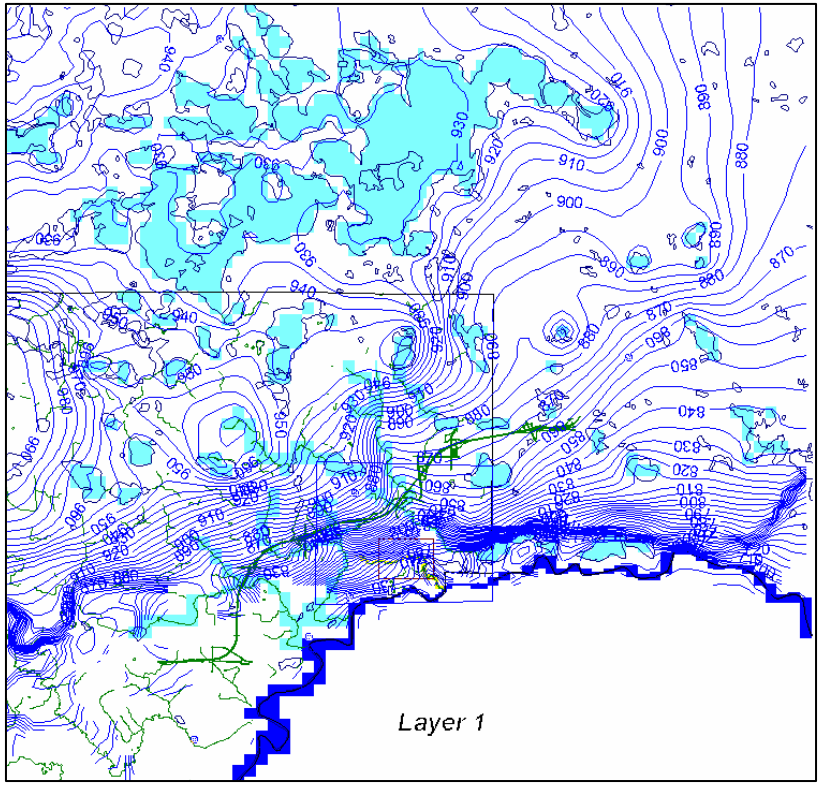
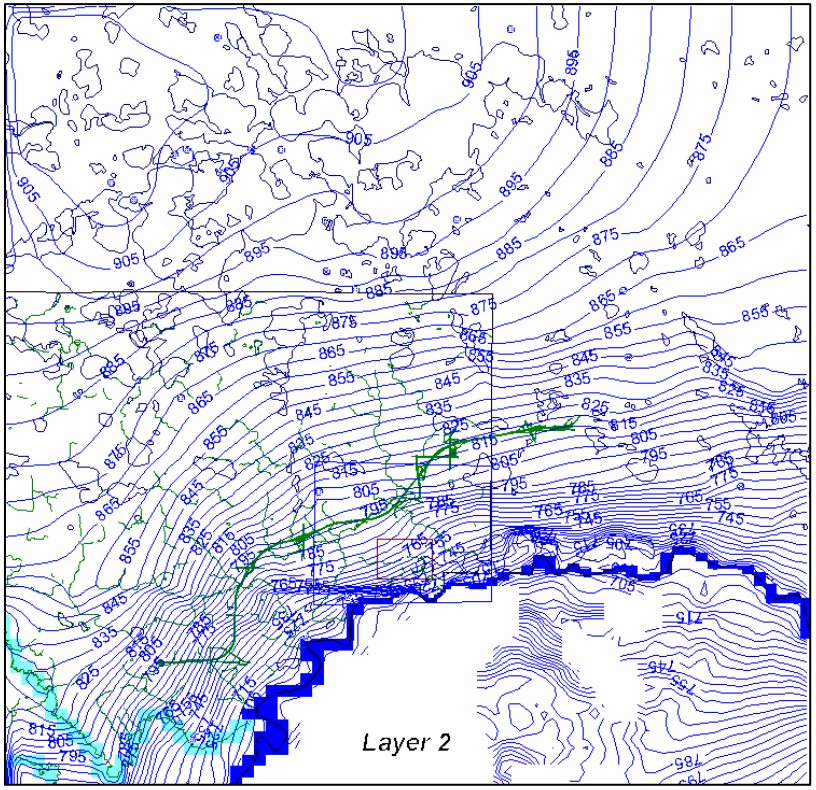


Figure 3-11

Plot of Regional Calibration: Observed vs. Simulated Heads

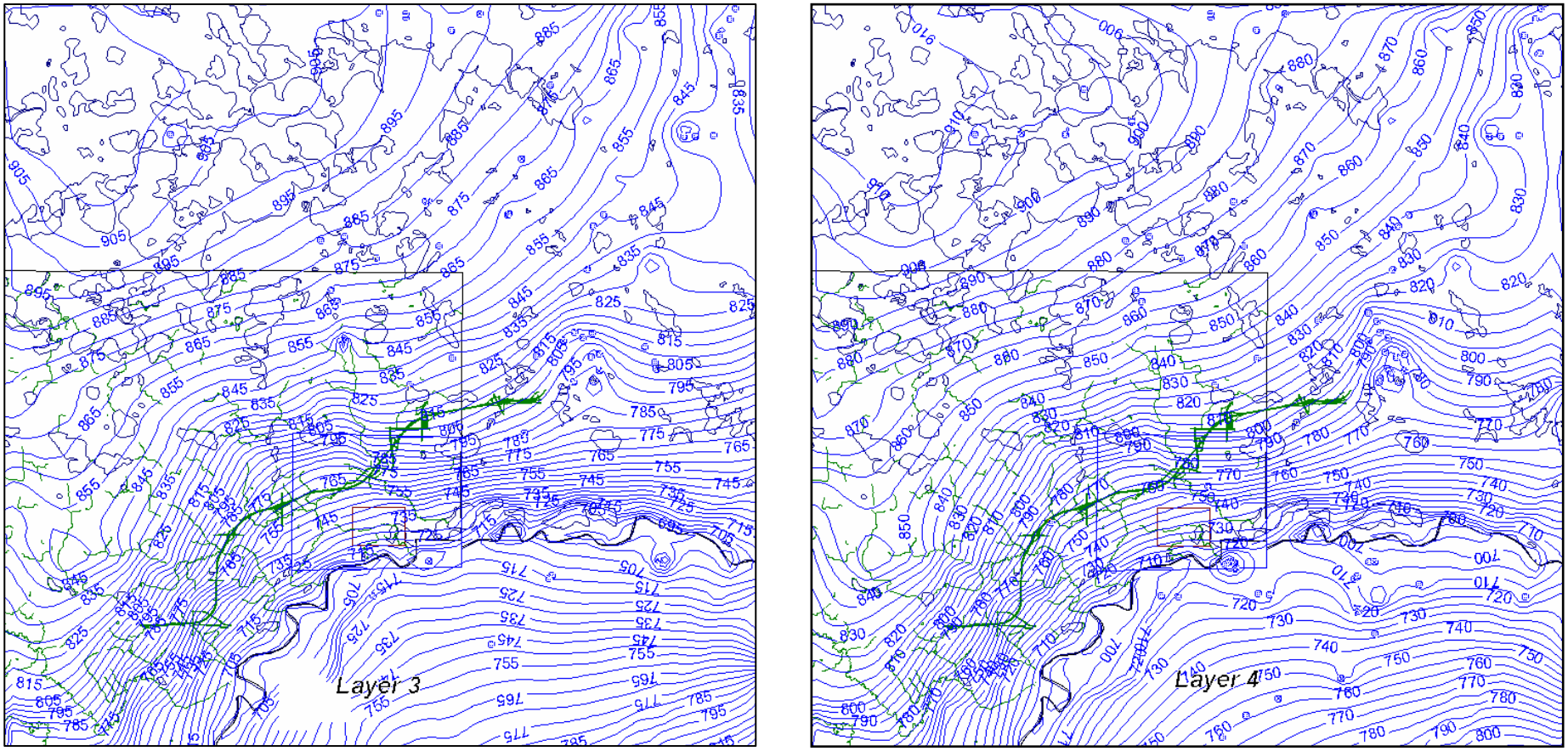




Contour Interval = 5 feet

Figure 3-12

Calibrated Piezometric Surfaces (feet, MSL) for Layers 1 and 2 of Regional Model



Contour Interval = 5 feet

Figure 3-13

Calibrated Piezometric Surfaces (feet, MSL) for Layers 3 and 4 of Regional Model

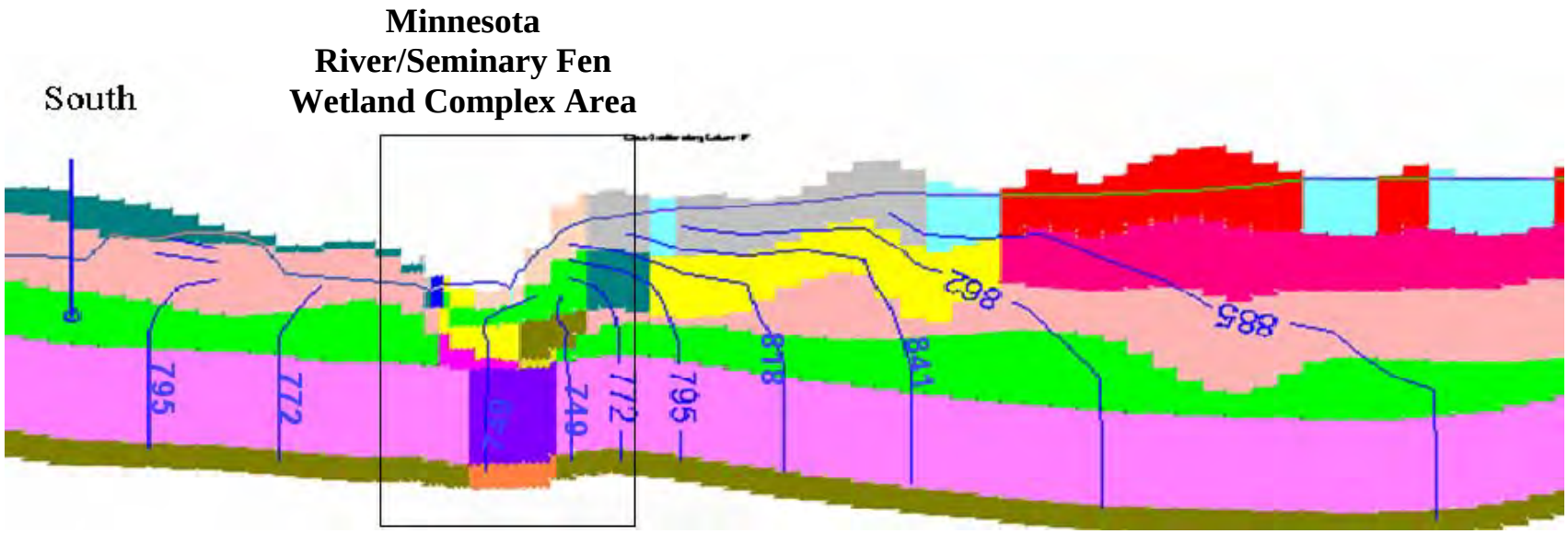


Figure 3-14

North-South Cross Section Through Regional Model Showing Vertical Distribution of Head

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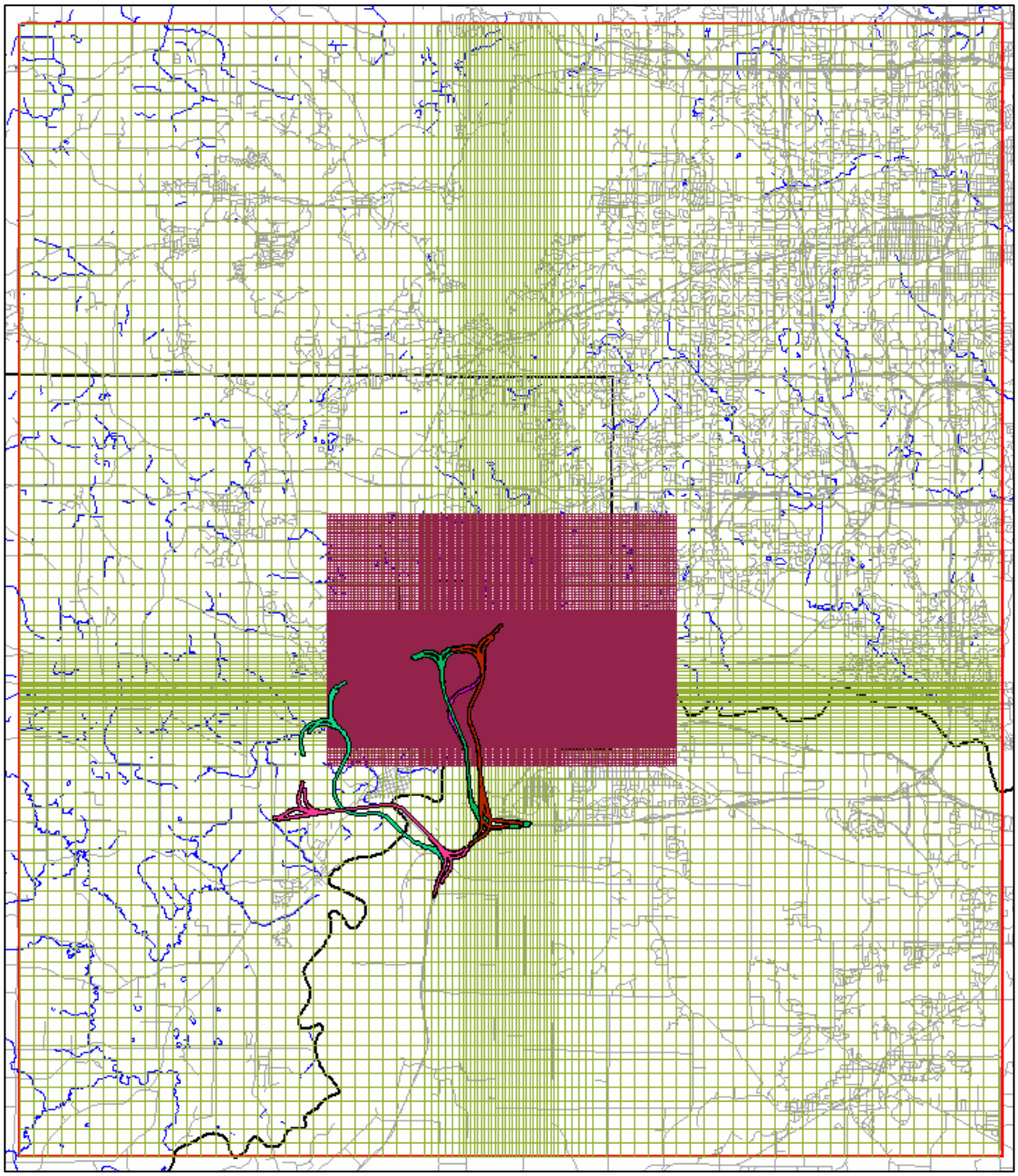


TRM model grid of Seminary Fen Wetland Complex area shown in red

Figure 3-15

Location of TMR Local Model of Seminary Fen Wetland Complex Area

DRAFT

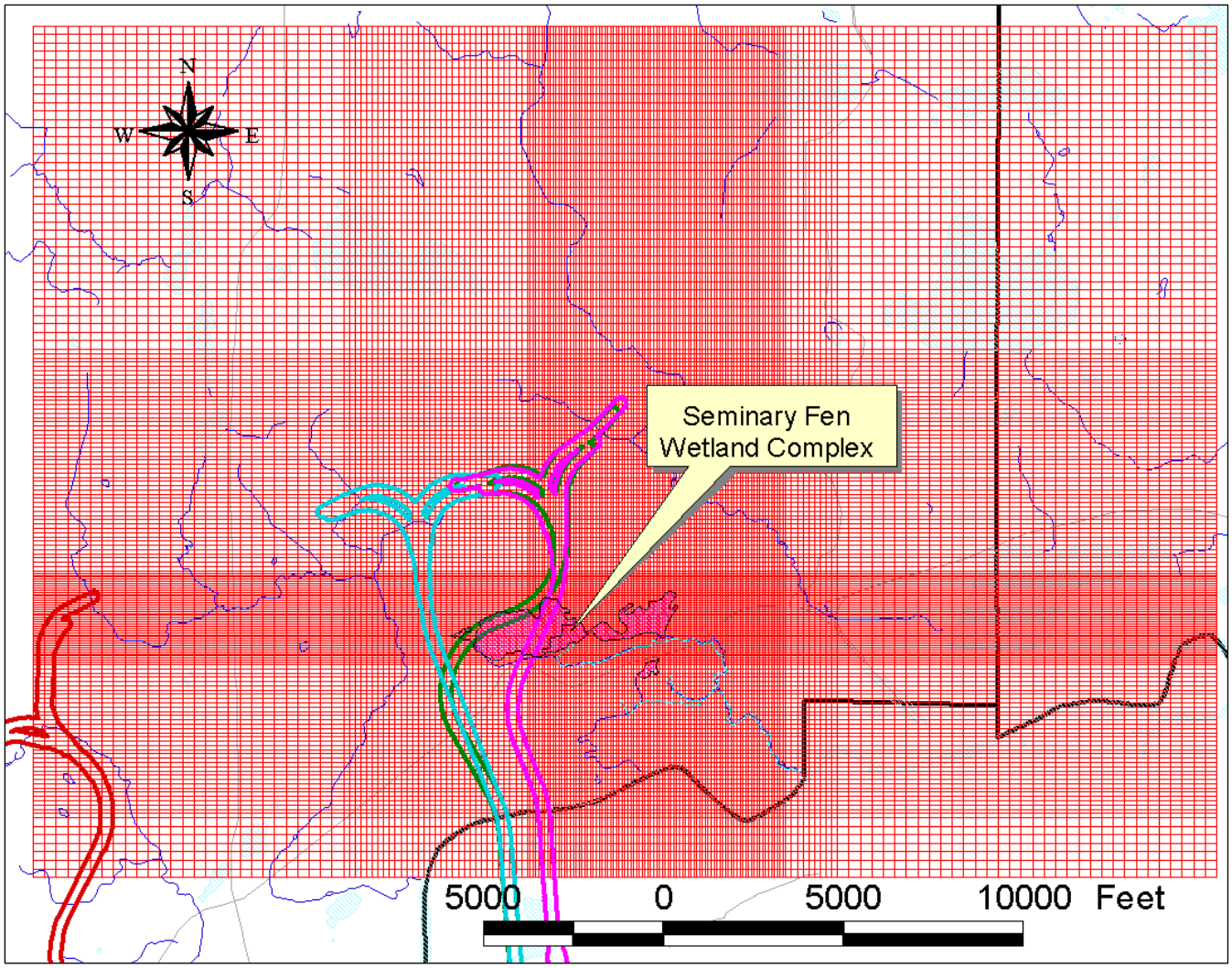


Figure 3-16

Grid Mesh of TMR Model of Seminary Fen Wetland Complex Area

DRAFT

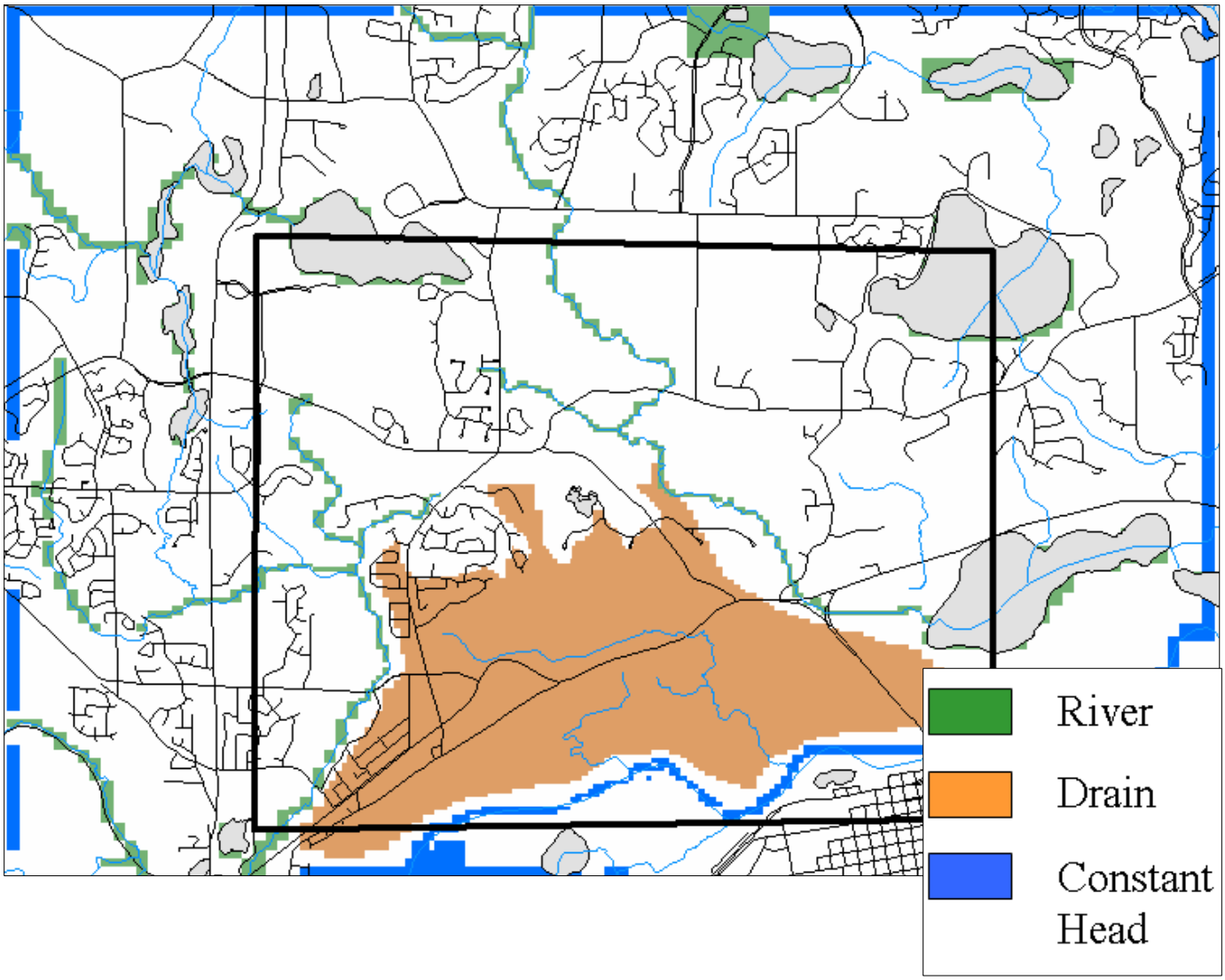


Figure 3-17

Boundary Conditions in TMR Model of Seminary Fen Wetland Complex Area

DRAFT

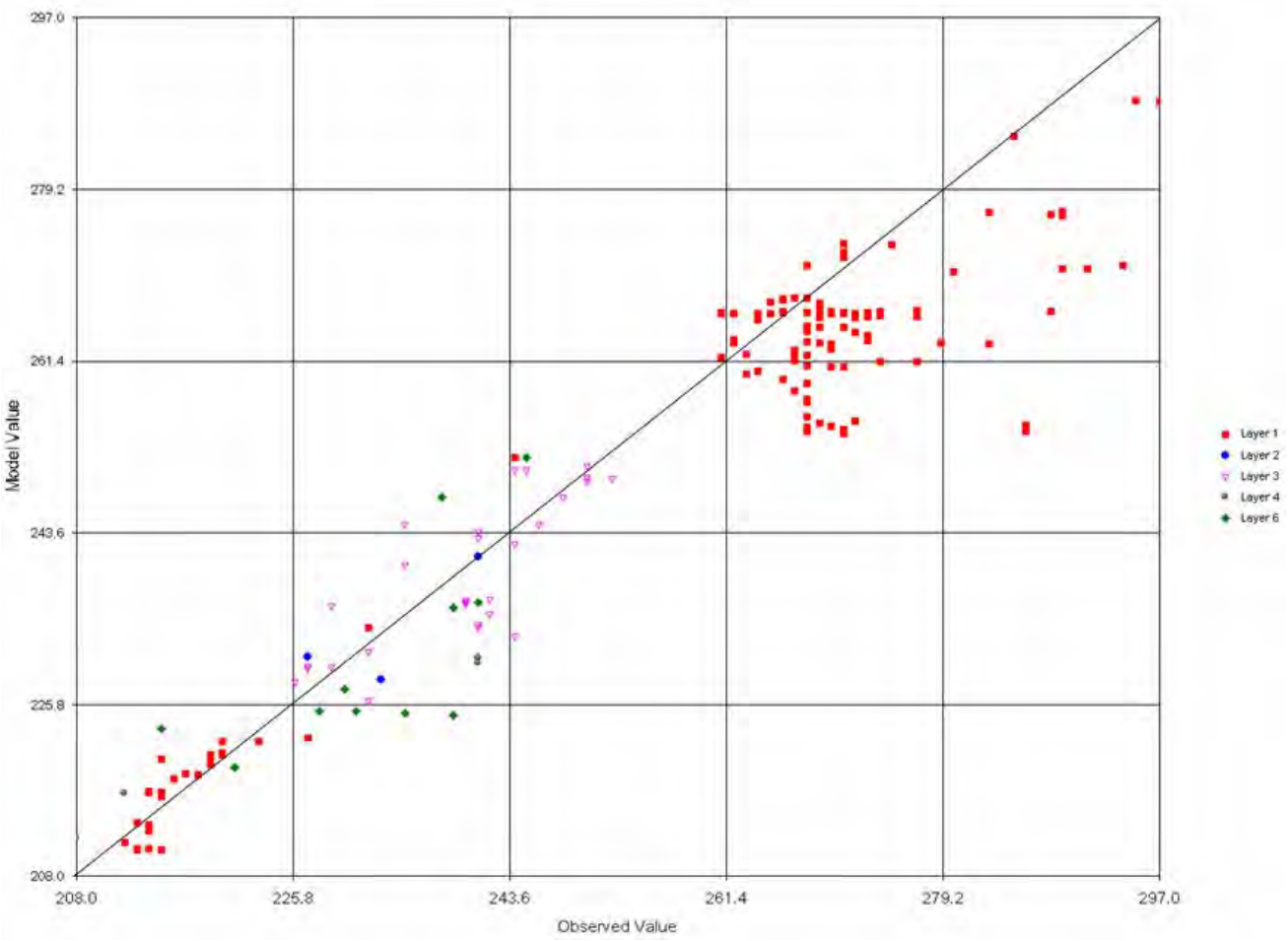
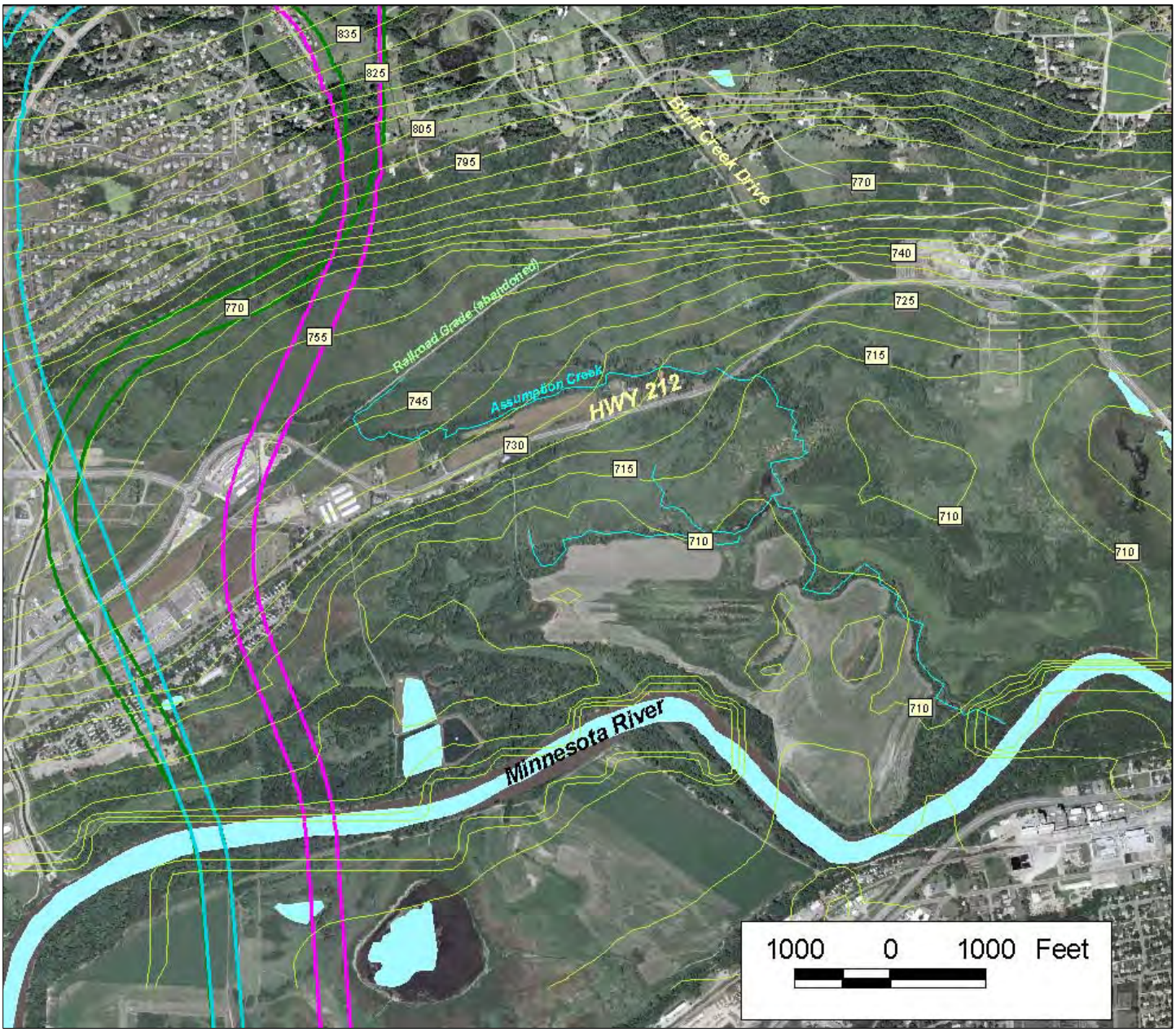


Figure 3-18

Observed vs. Simulated Head (meters, MSL) for TMR Model of Seminary Fen Wetland Complex

DRAFT

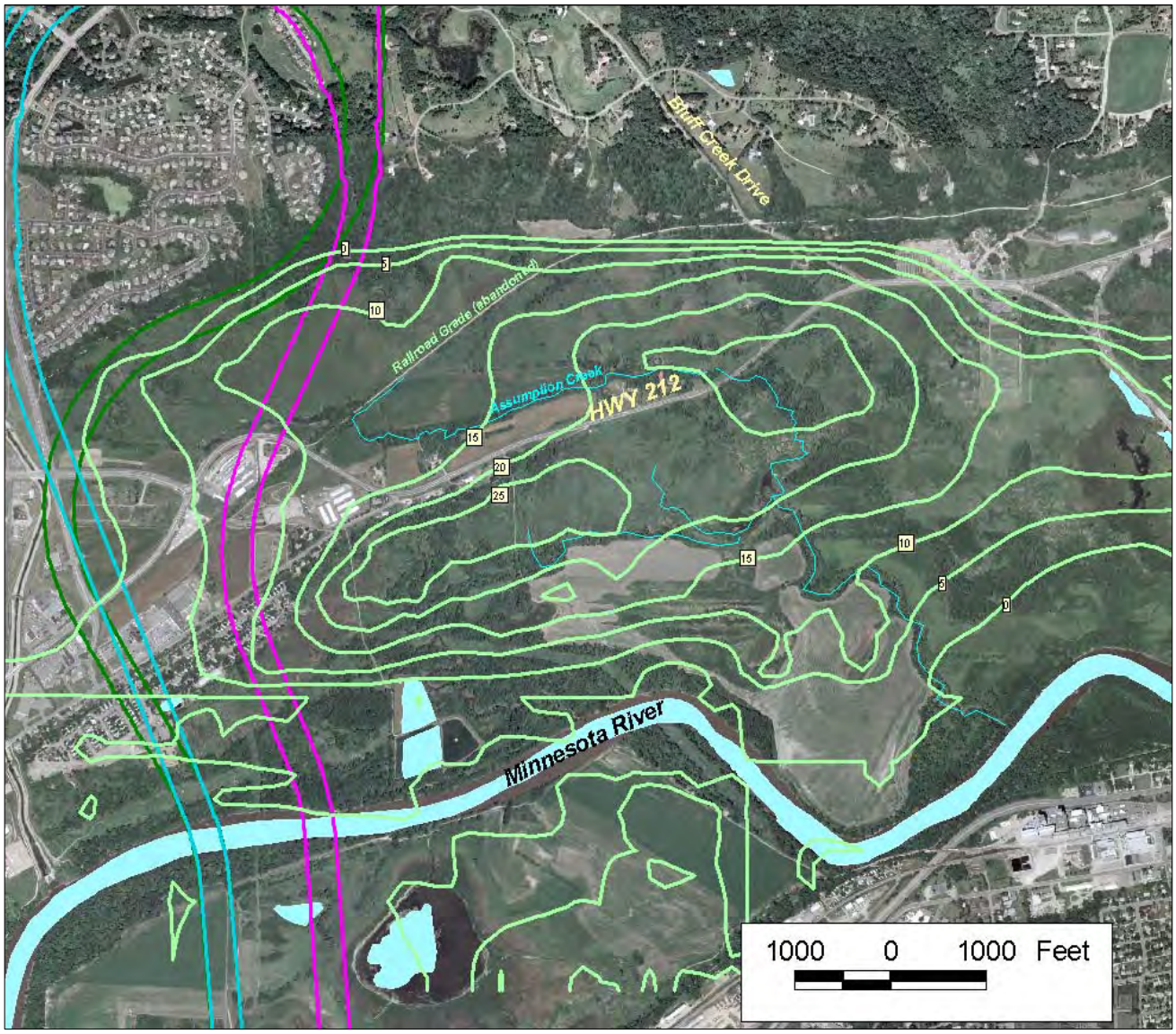


Contour Interval = 5 feet Piezometric Head in feet above mean sea level

Figure 3-19

Simulated Piezometric Head for Layer 1 (water table in upper drift) from TMR Model of Seminary Fen Wetland Complex

DRAFT

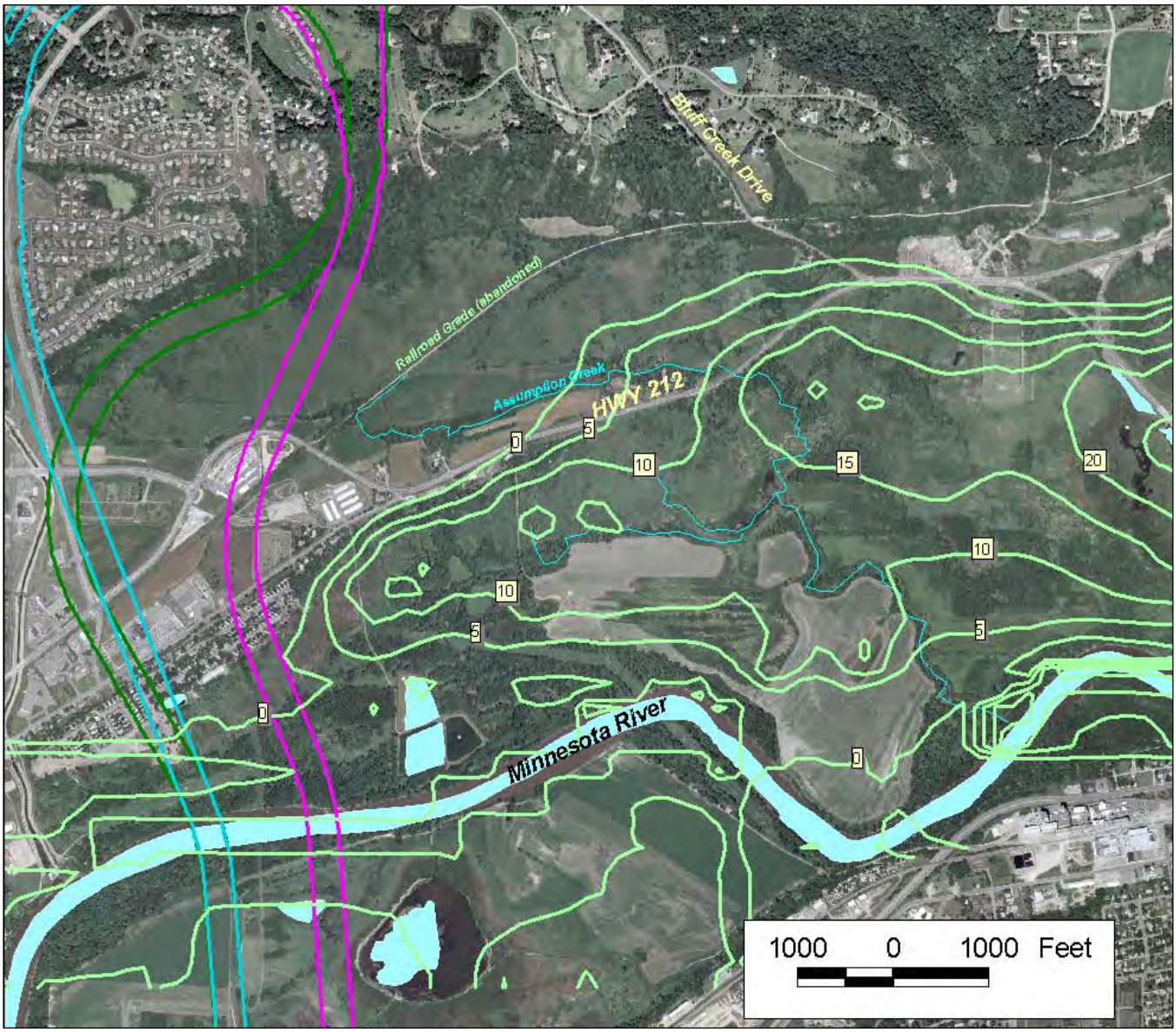


Contour Interval = 5 feet positive values indicate upward gradients in feet

Figure 3-20

Simulated Upward Vertical Gradients Between Upper and Lower Drift Units (Layers 1 and 2) in Vicinity of Seminary Fen Wetland Complex

DRAFT

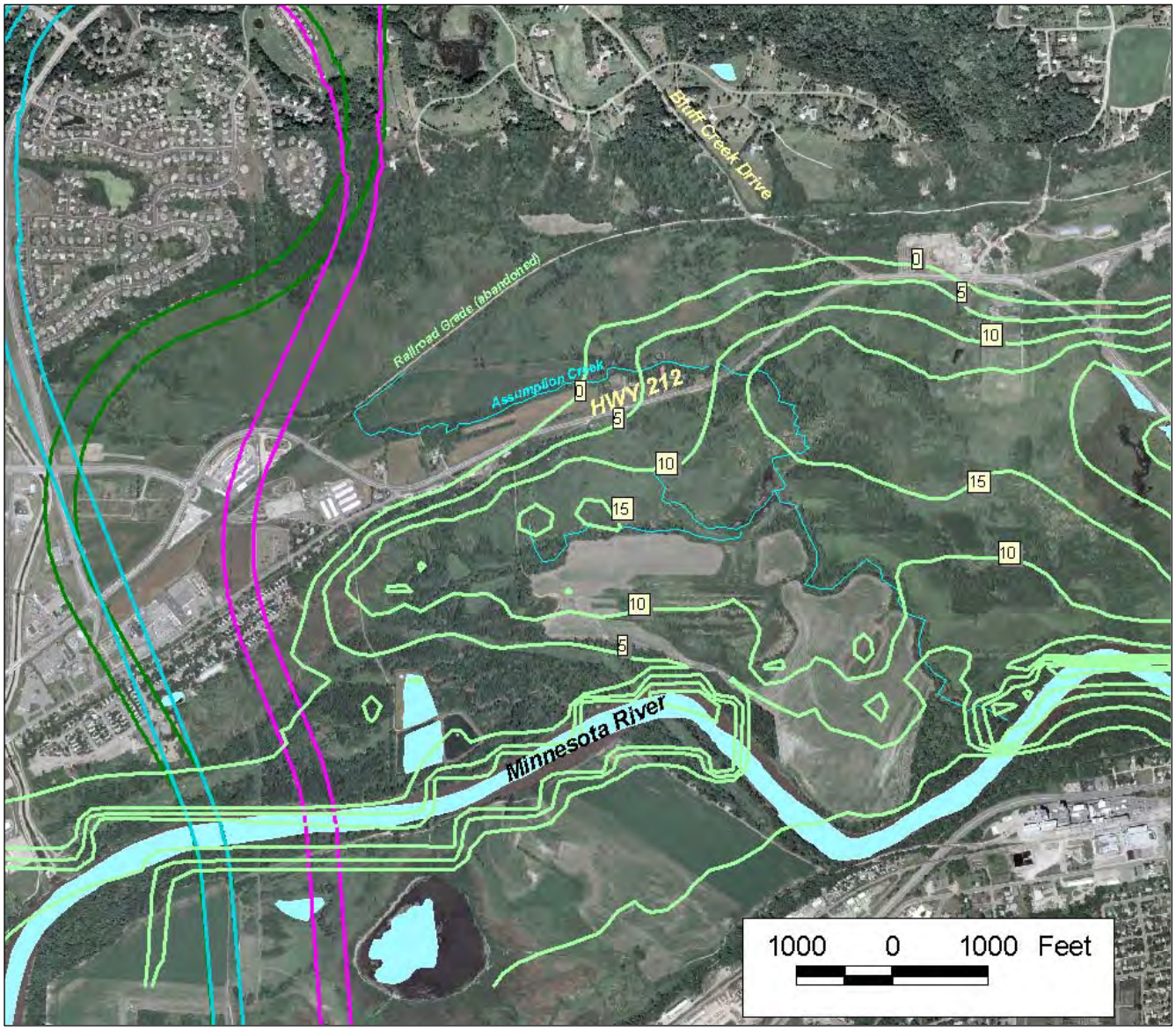


Contour Interval = 5 feet positive values indicate upward gradients in feet

Figure 3-21

Simulated Upward Vertical Gradients Between Upper Drift and Deep Valley-Fill Alluvium (Layers 1 and 3) in Vicinity of Seminary Fen Wetland Complex

DRAFT

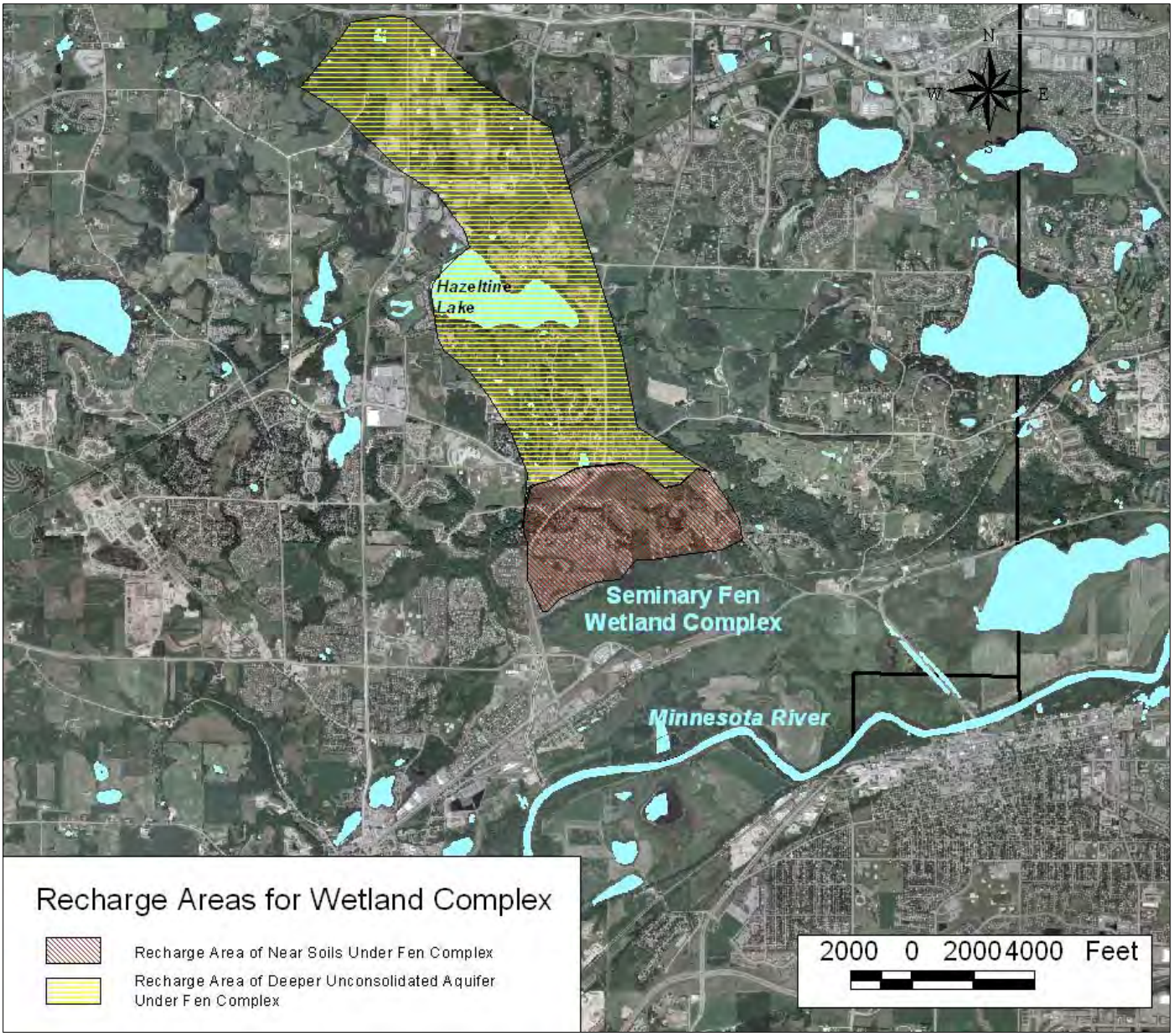


Contour Interval = 5 feet positive values indicate upward gradients in feet

Figure 3-22

Simulated Upward Vertical Gradients Between Upper Drift and Franconia-Ironton-Galesville (Layers 1 and 6) in Vicinity of Seminary Fen Wetland Complex

DRAFT



Cross-hatched area is regions where groundwater in fen discharge is predicted to originate

Figure 3-23

Model's Prediction of Where Seminary Fen Wetland Complex Discharges Originate as Recharge

DRAFT

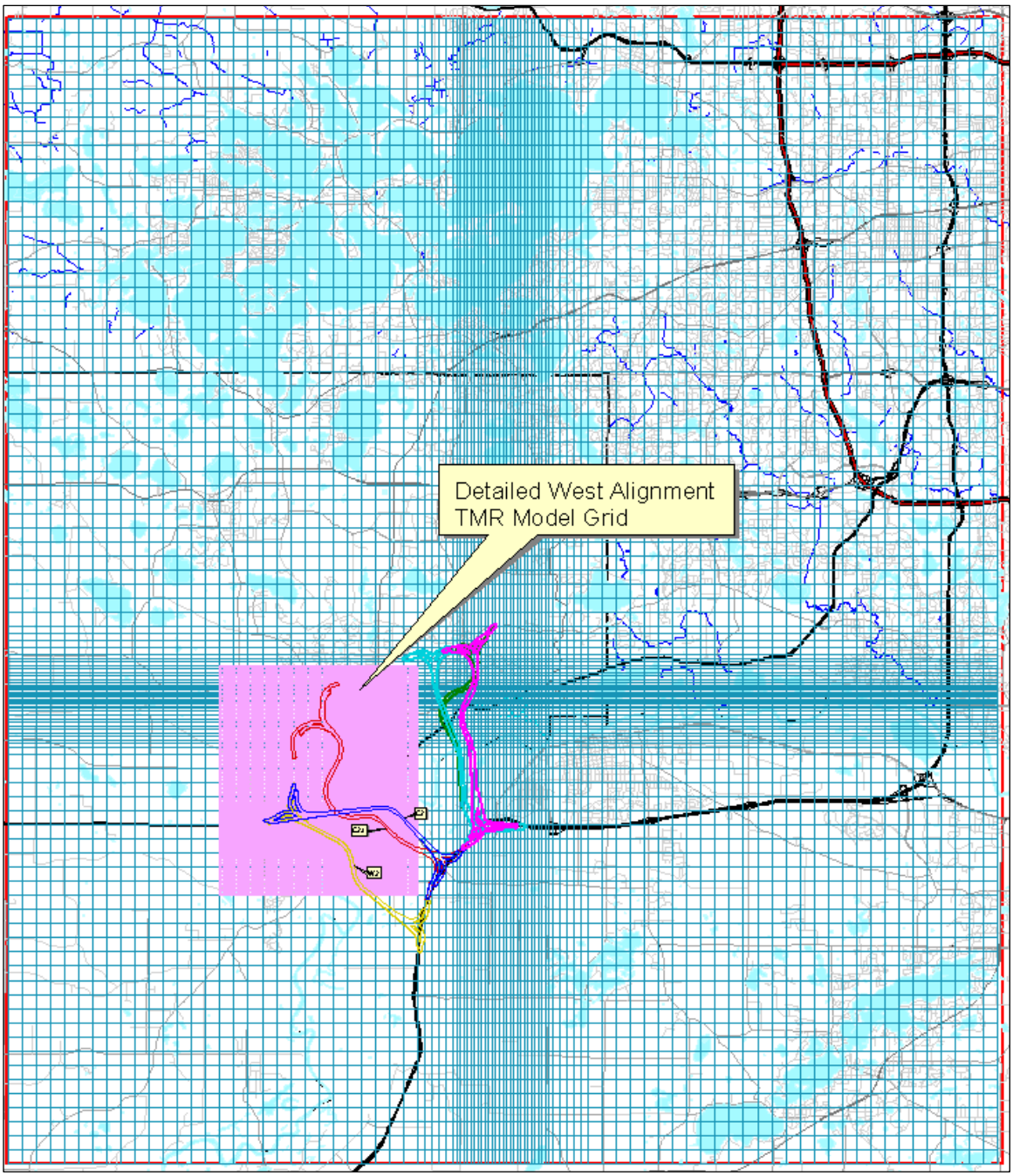


Figure 3-24

Location of Detailed Model for the Evaluation of the Three Western Alternative Alignments

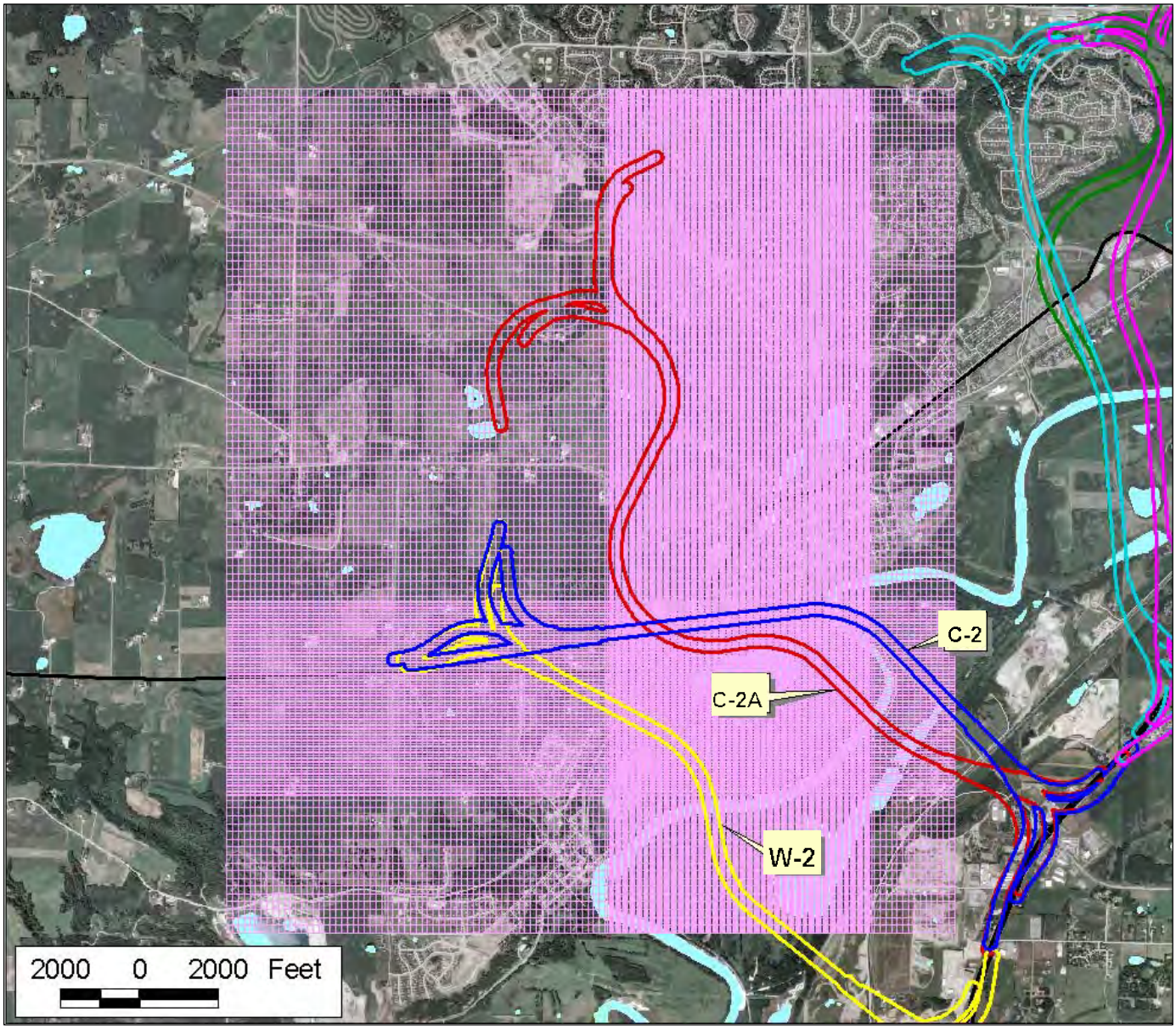


Figure 3-25

Western Model Grid and Western TH 41 Crossing

Alternative Alignments

DRAFT

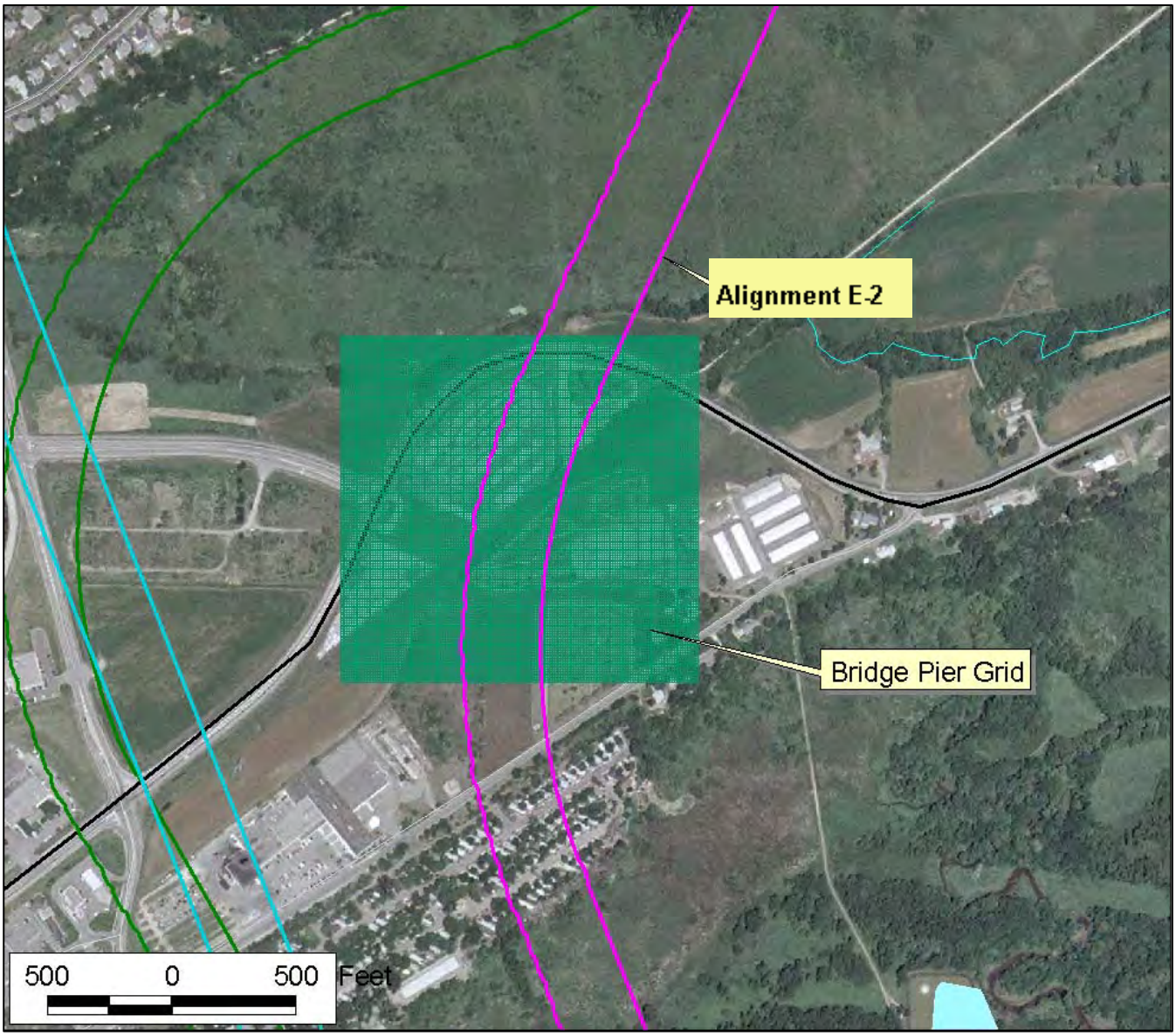
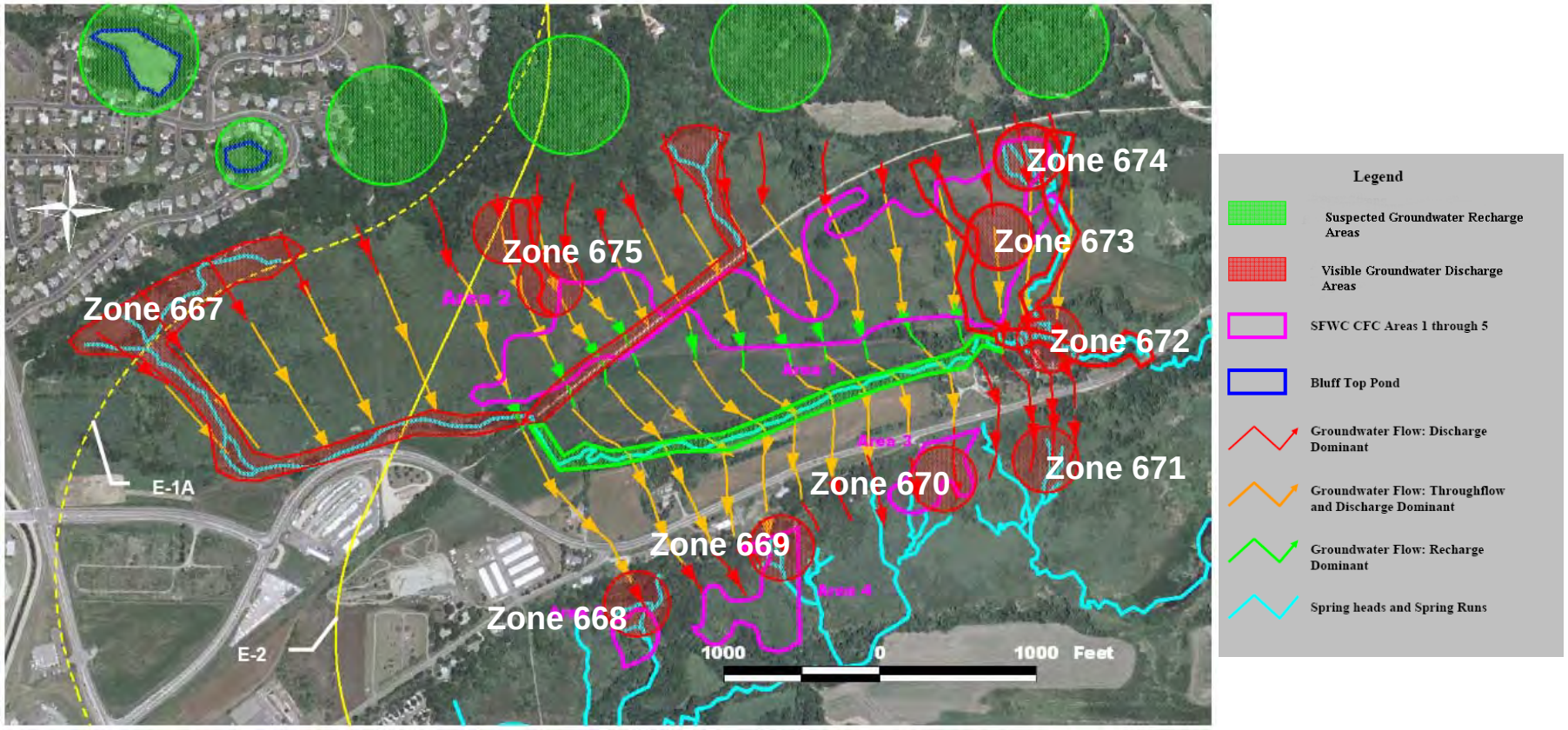


Figure 3-26

Example of Detailed Bridge Pier Model Grid



(from Figure 5.16 in Peterson Environmental Inc. (2006))

Figure 4-1

Seepage Zones Used in Comparing Alternatives

DRAFT

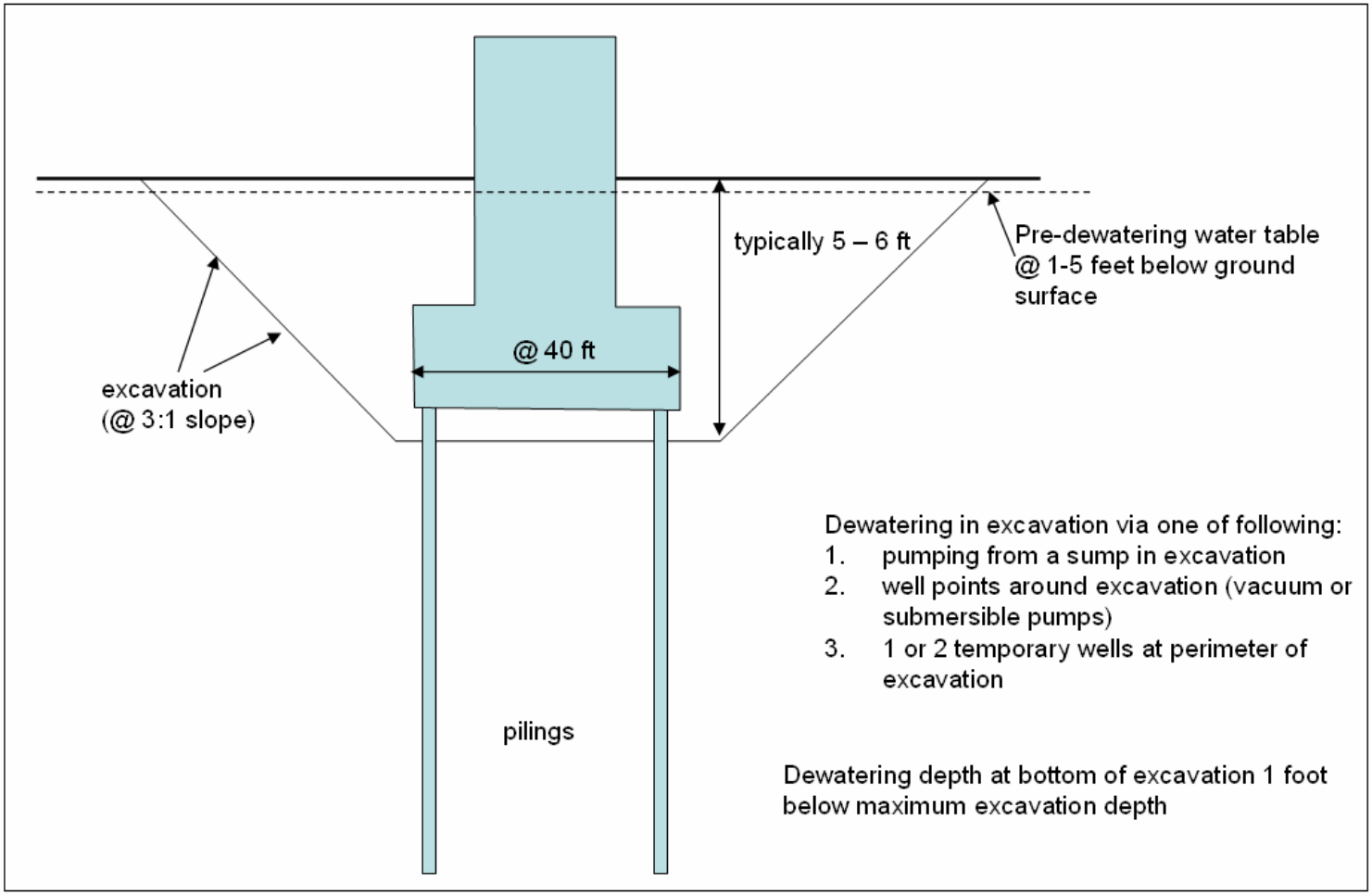


Figure 4-2

Bridge Pier Construction Schematic for Typical Conditions

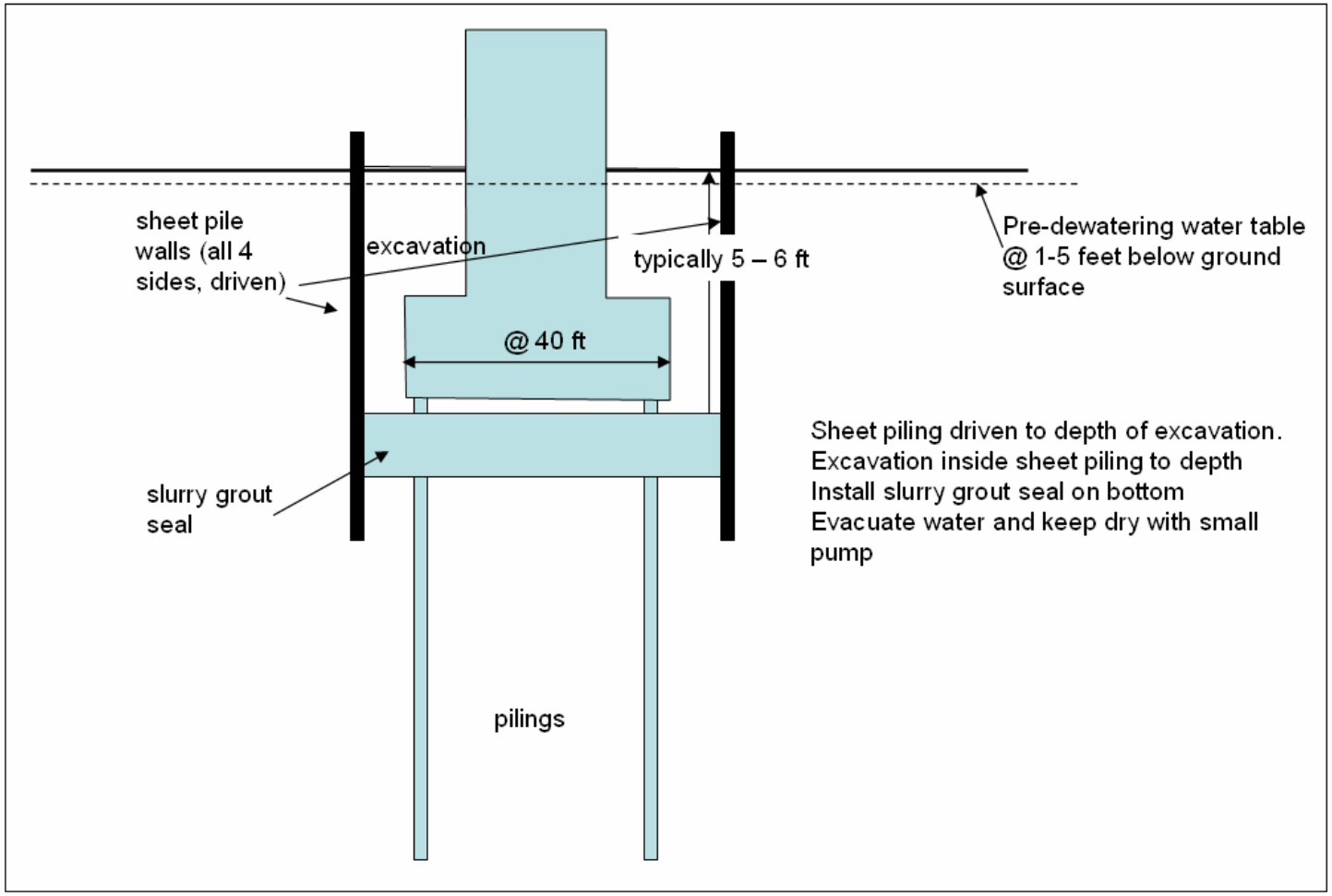


Figure 4-3

Bridge Pier Construction Schematic for Peat or Organic Soils

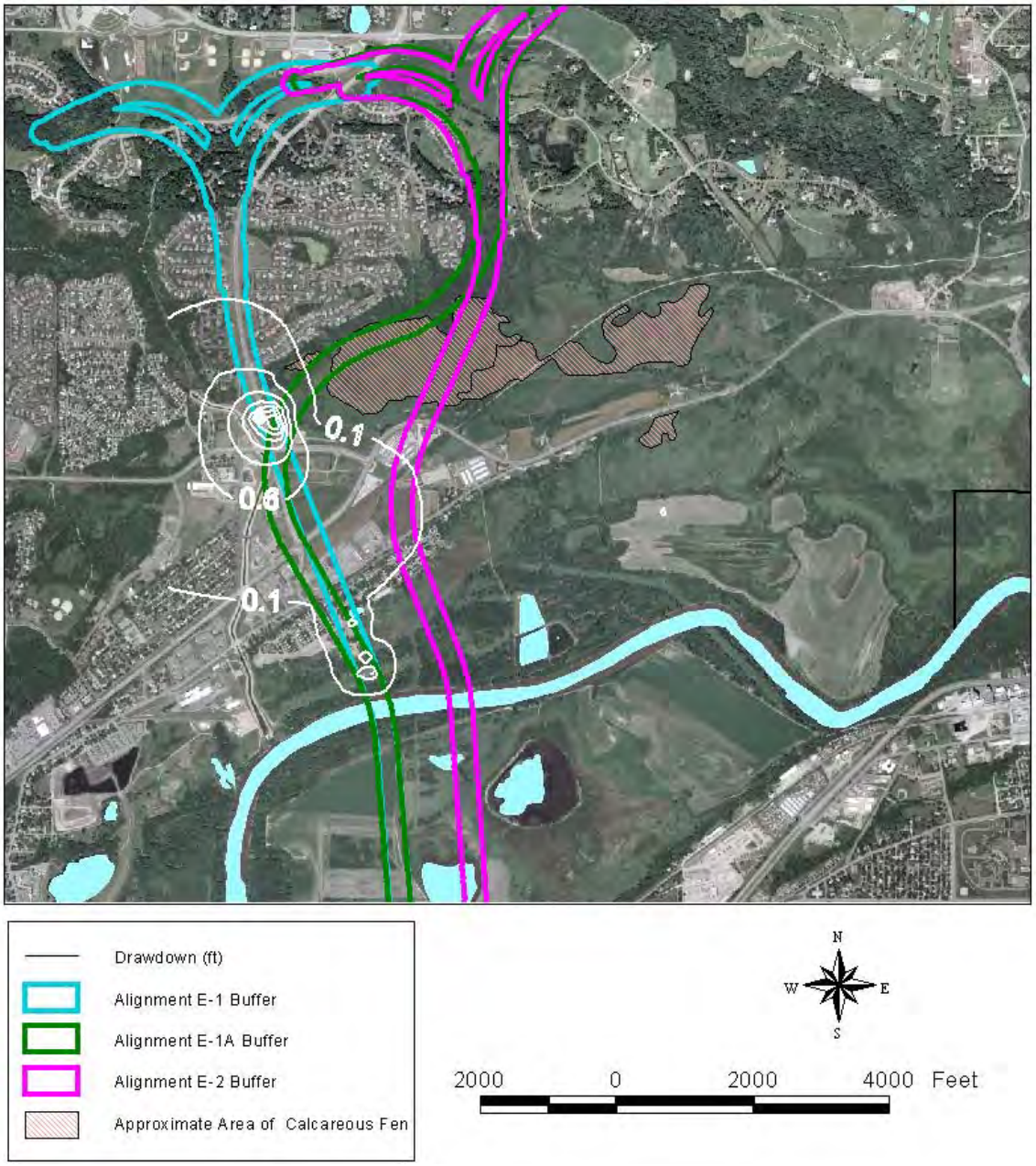


Figure 4-4

Modeled Drawdown During Construction of the E-1 Bridge Piers

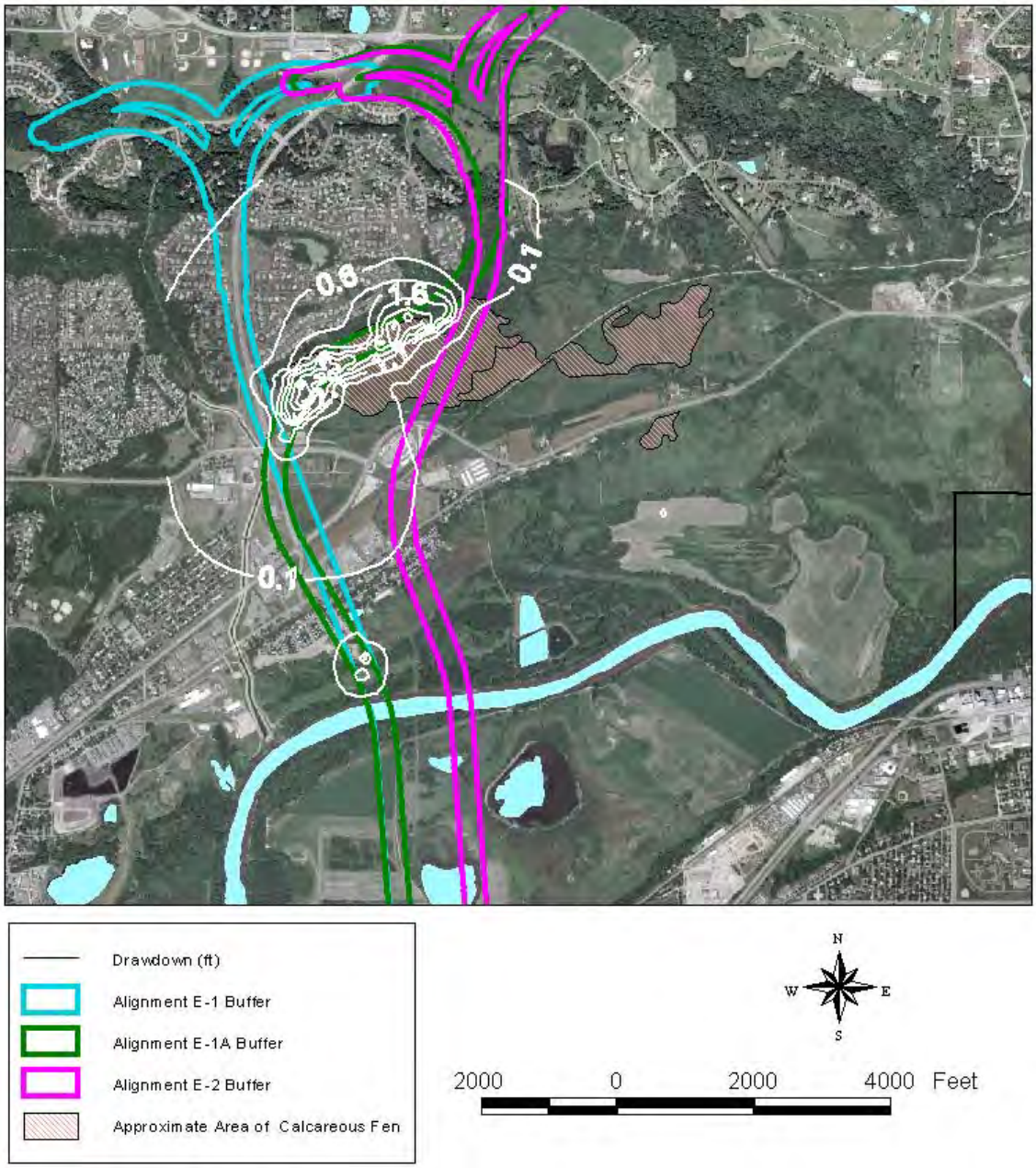


Figure 4-5

Modeled Drawdown During Construction of the E-1A Bridge Piers

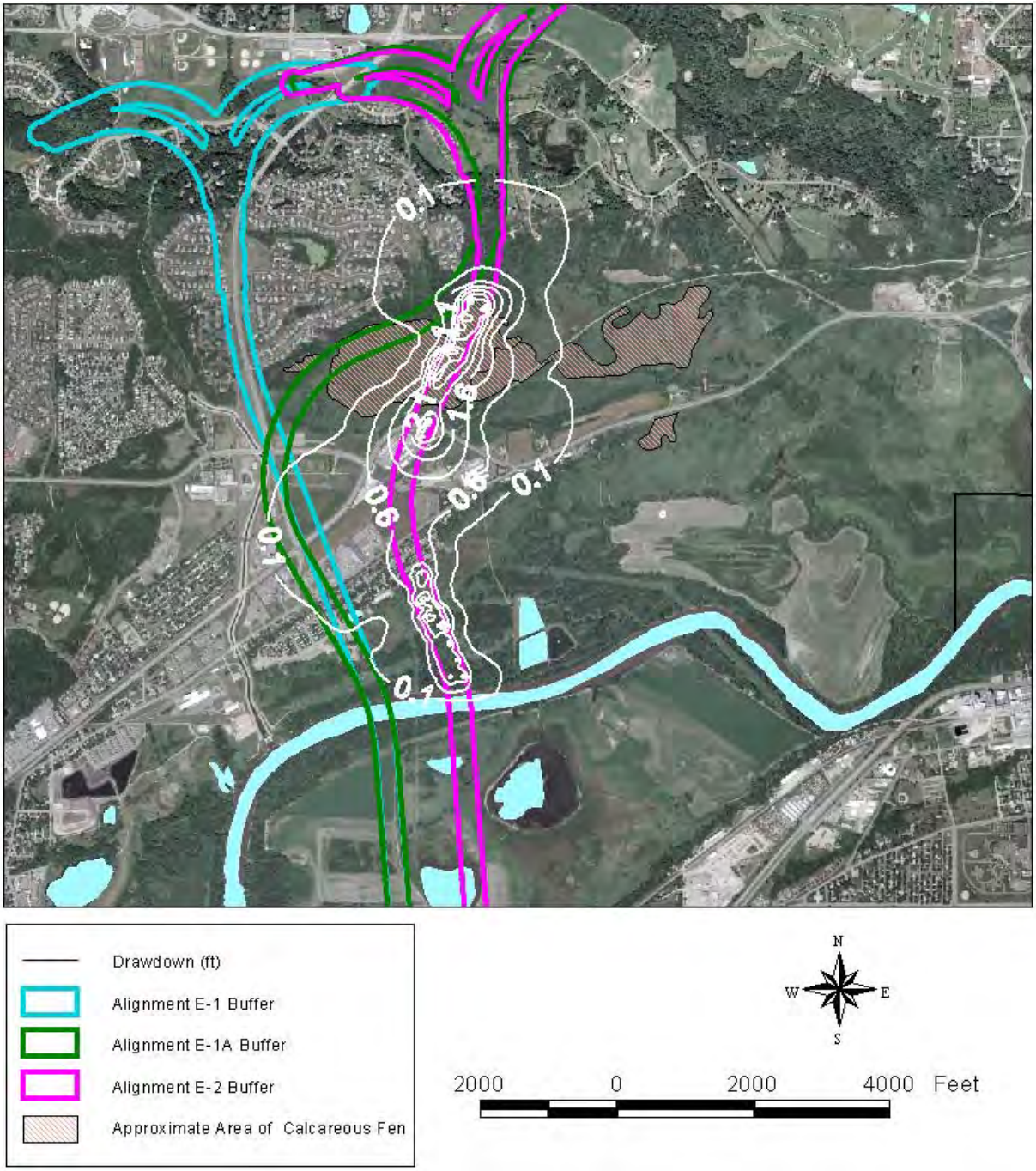


Figure 4-6

Modeled Drawdown During Construction of the E-2 Bridge Piers

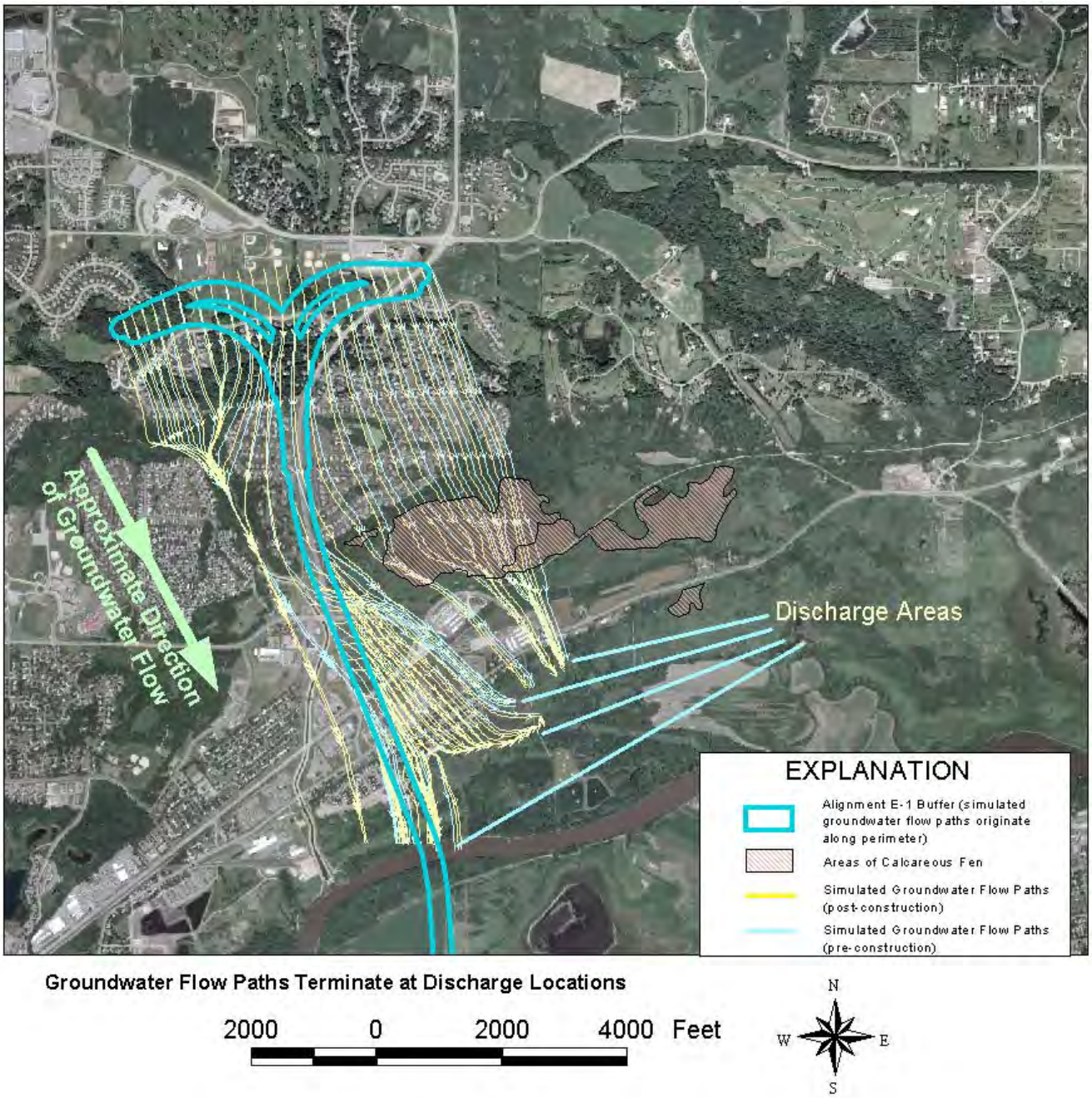


Figure 4-7

Modeled Flowpaths Before and After Construction for Alternative E-1

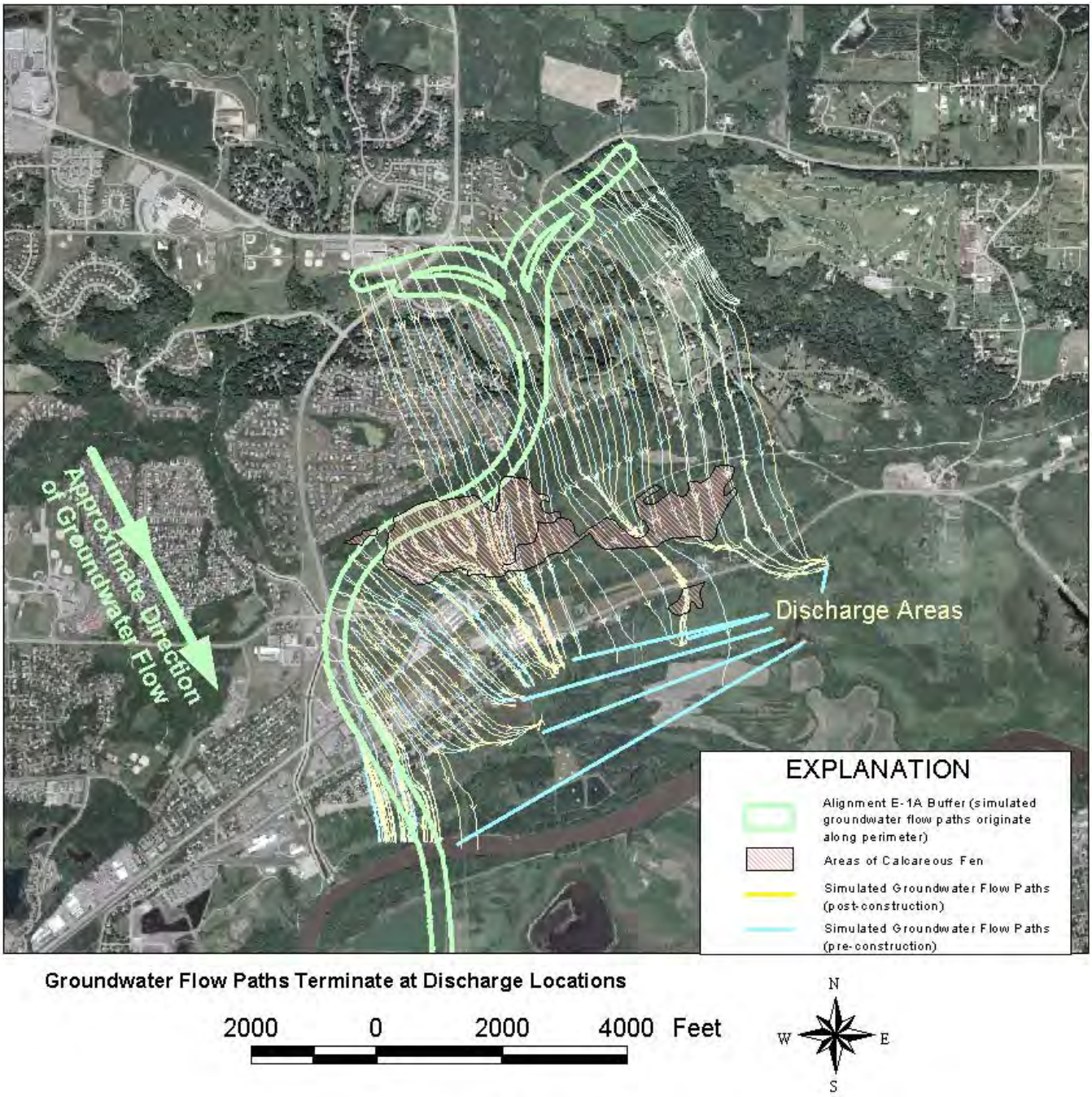


Figure 4-8

Modeled Flowpaths Before and After Construction for Alternative E-1A

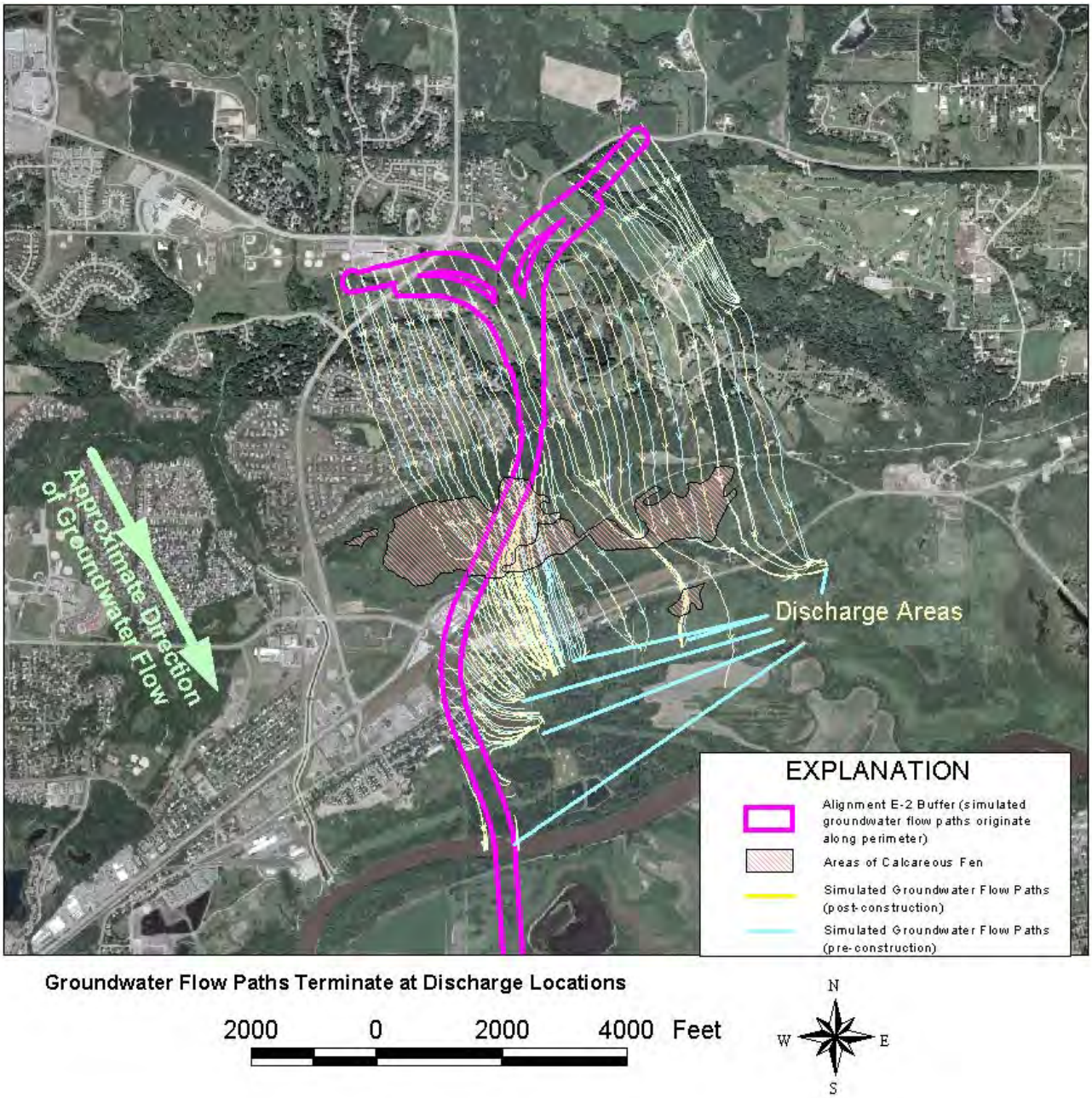


Figure 4-9

Modeled Flowpaths After Construction for Alternative E-2

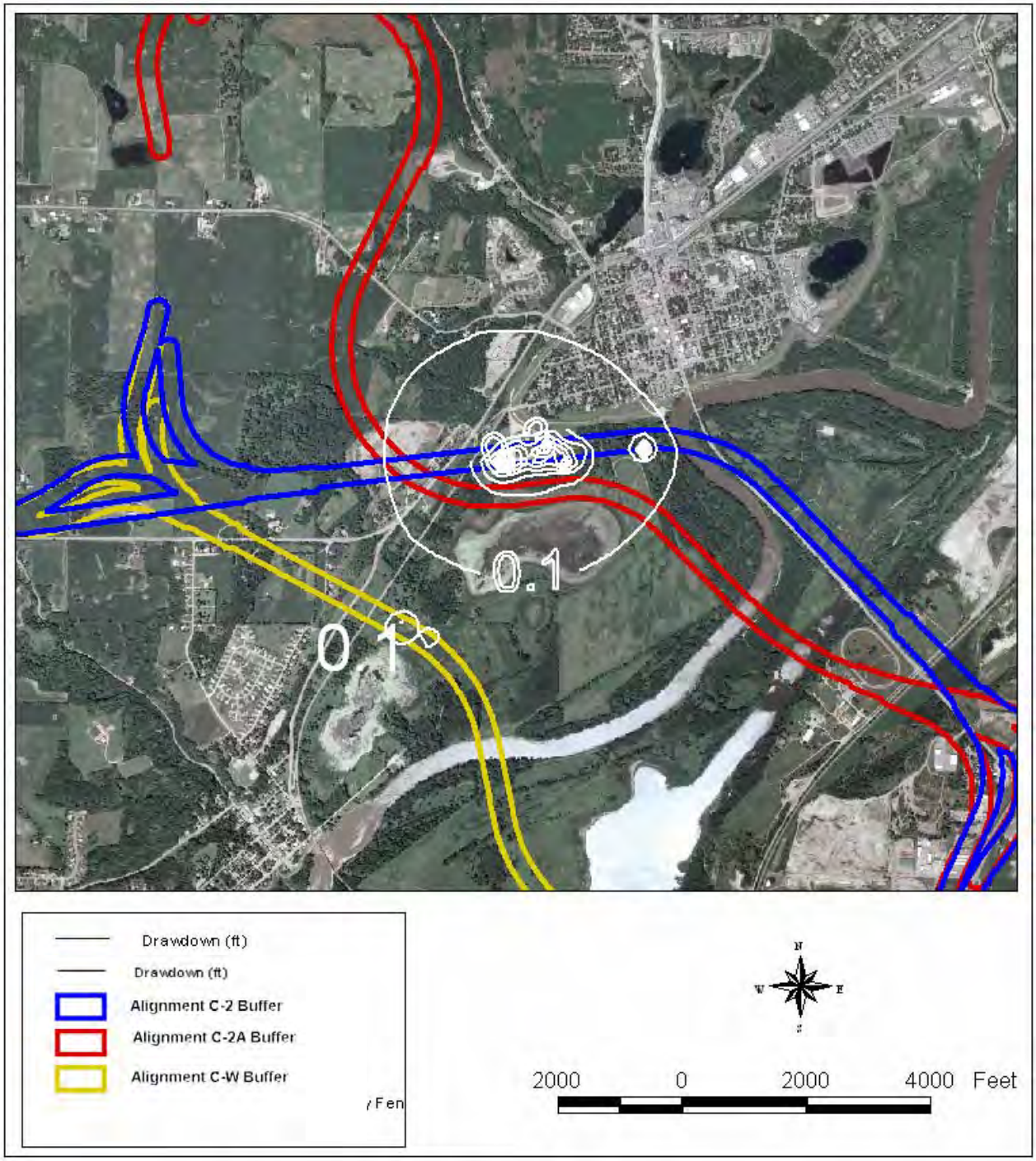


Figure 4-10

Modeled Drawdown During Construction of the C-2 and W-2 Bridge Piers

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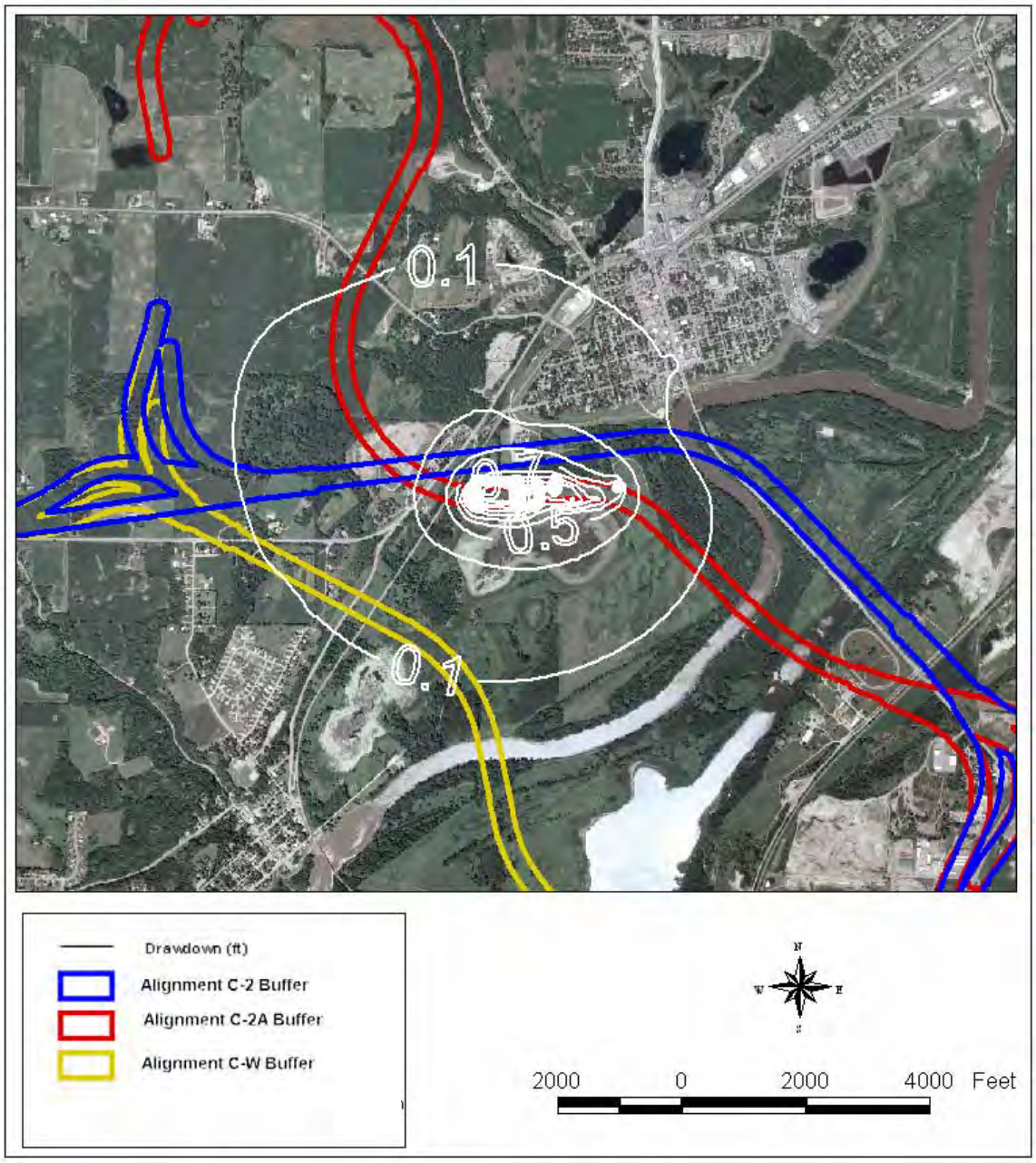

Figure 4-11

Modeled Drawdown During Construction of the C-2A Bridge Piers

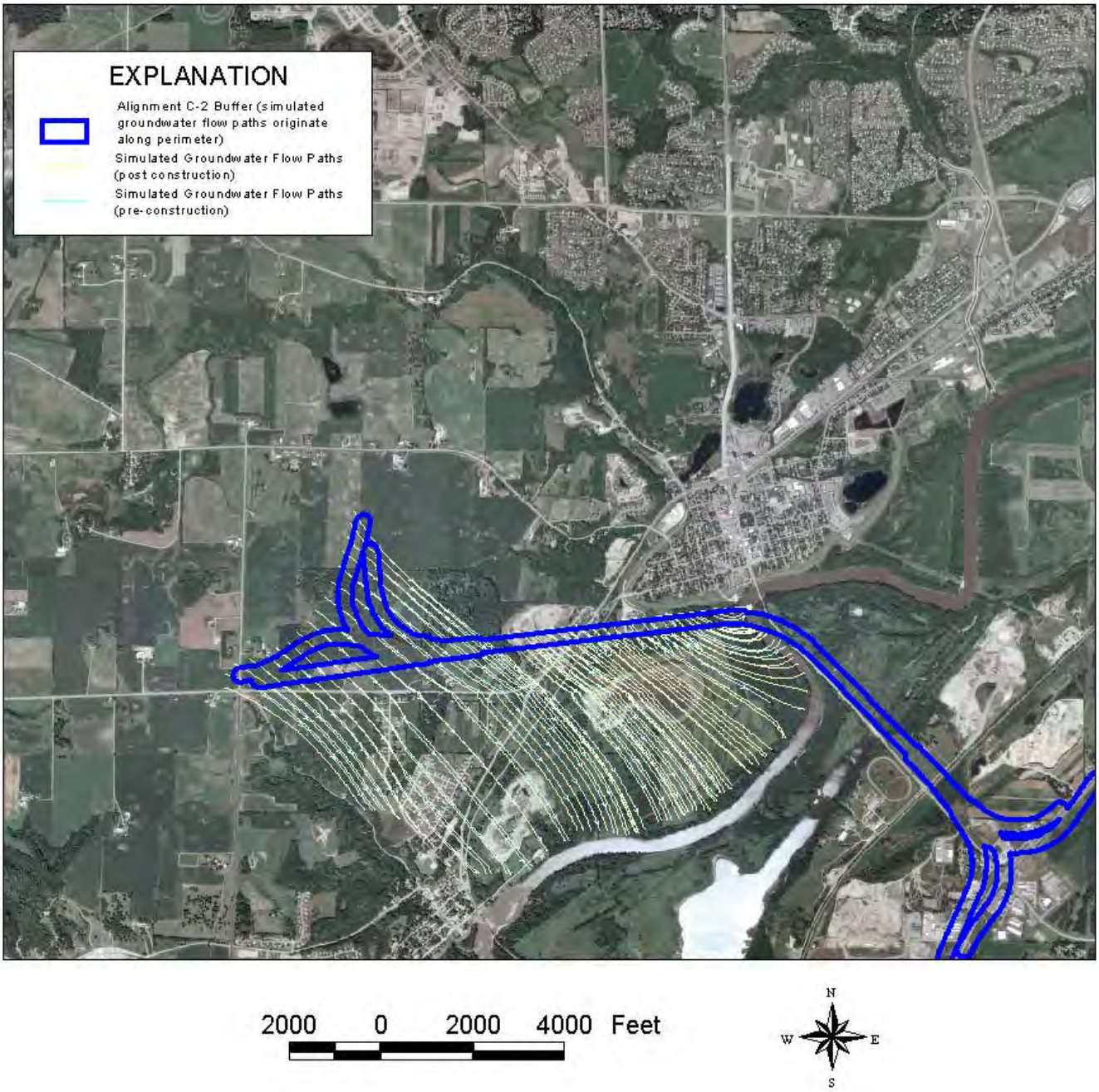

Figure 4-12

Modeled Flowpaths Before and After Construction for Alternative C-2

DRAFT

Figure 4-13

Modeled Flowpaths Before and After Construction for Alternative C-2A

DRAFT

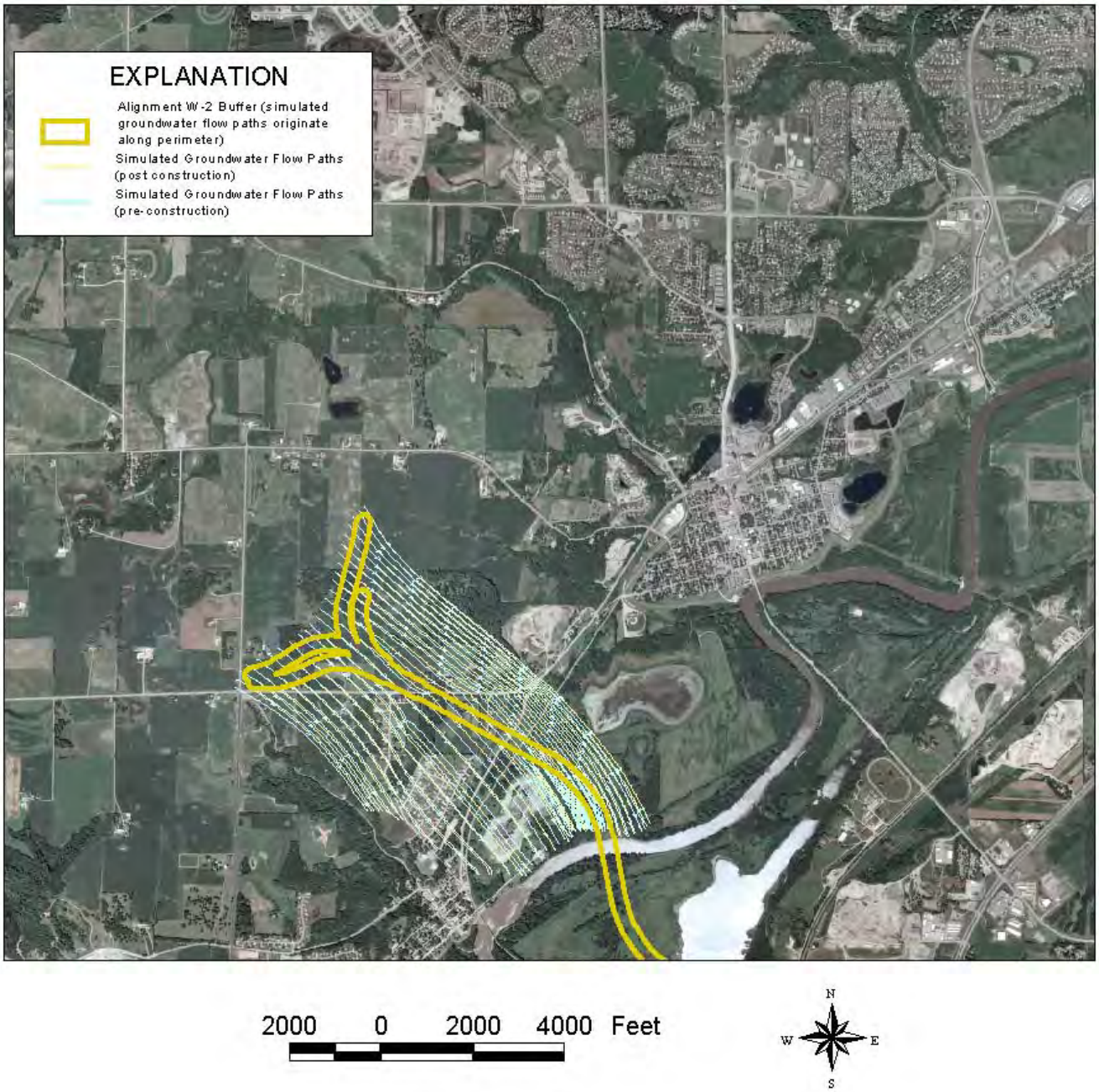

Figure 4-14

Modeled Flowpaths Before and After Construction for Alternative W-2

DRAFT

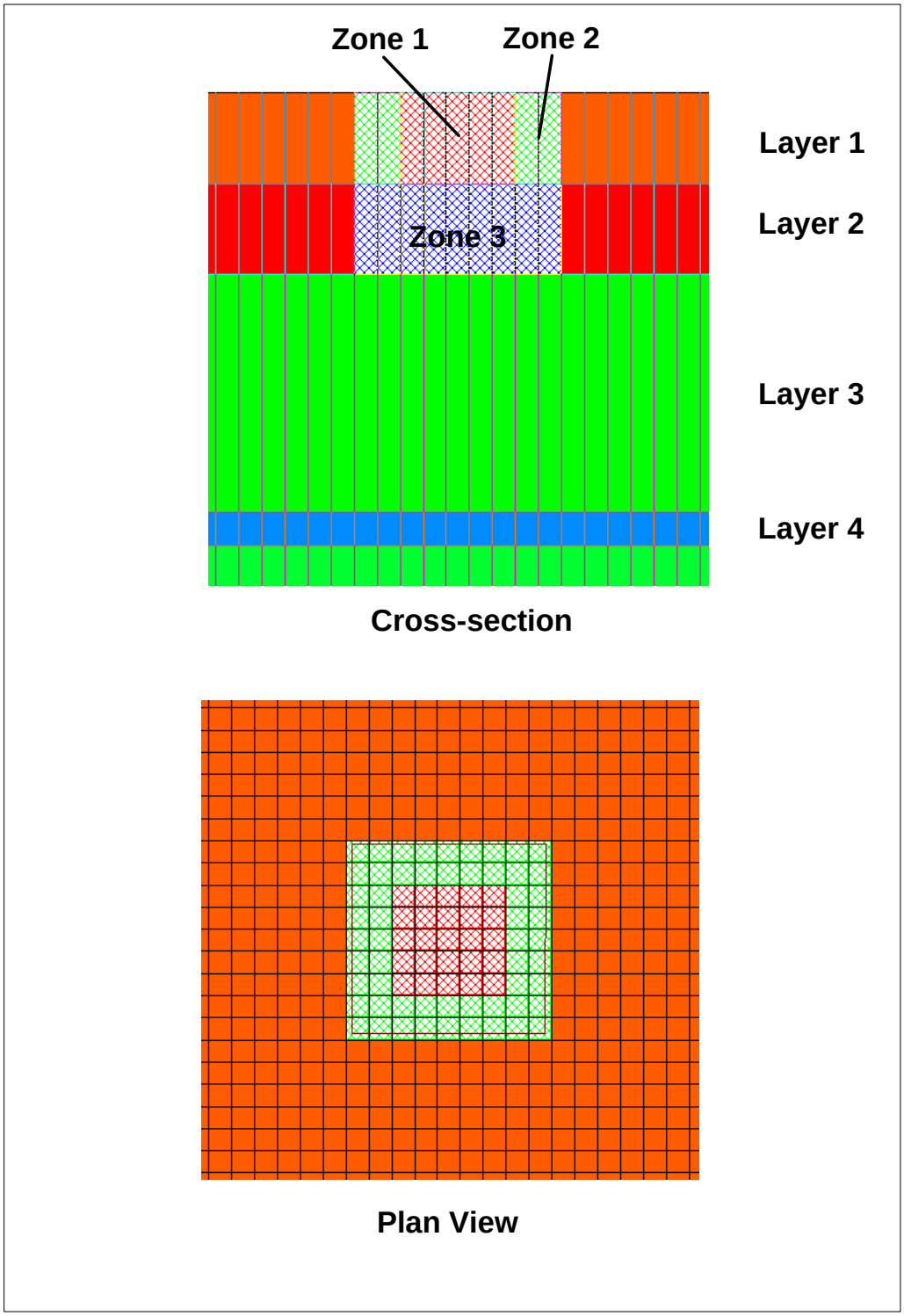

Figure 4-15

Hydraulic Conductivity Zones in the Vicinity of the Excavation