Geologic controls on groundwater and surface water flow in southeastern Minnesota and its impact on nitrate concentrations in streams

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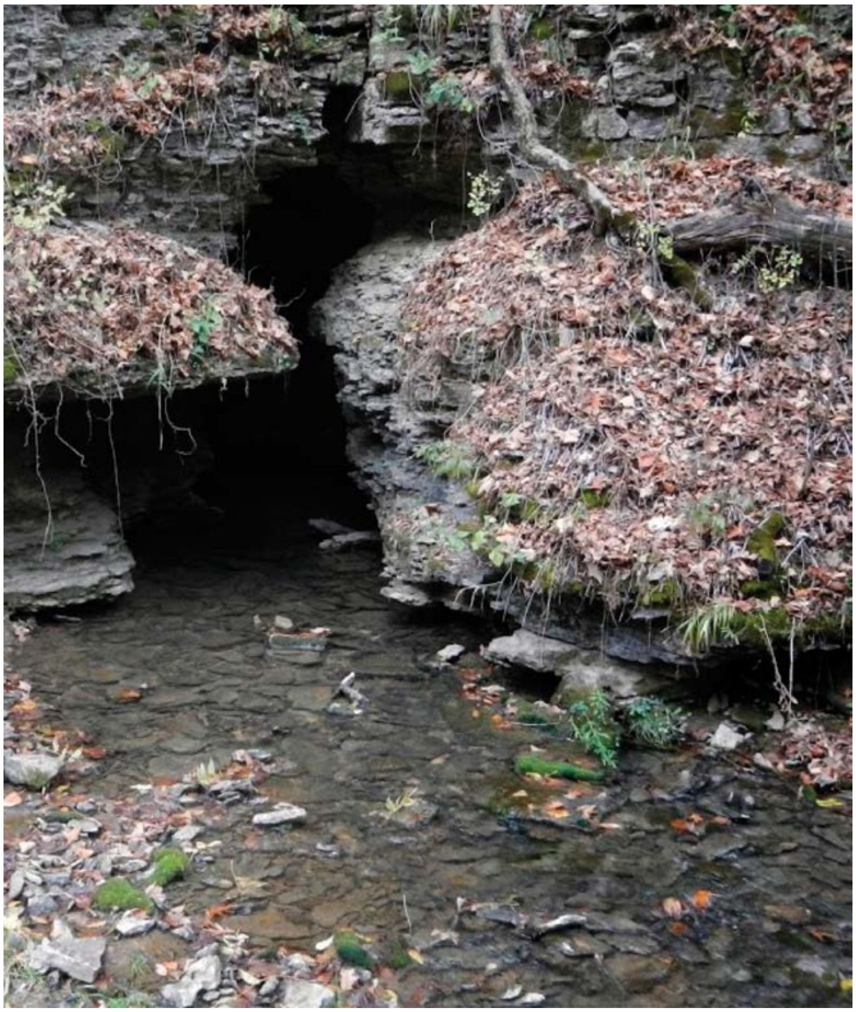

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CLEAN WATER LAND & LEGACY AMENDMENT

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Cover photo shows Fountain Big Spring, which discharges from the Cummingsville Formation near the City of Fountain, Fillmore County Minnesota. Springs provide baseflow to cold water streams in the bedrock dominated landscape of southeastern Minnesota.

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EXECUTIVE SUMMARY

This report summarizes the results of a Minnesota Geological Survey (MGS) investigation conducted for the Minnesota Pollution Control Agency (MPCA) designed to support watershed planning efforts in southeast Minnesota. Specifically it provides better understanding of the geologic controls on nitrate transport in the region, including nitrate in groundwater that is the source of baseflow to streams. Nitrate contamination of surface water and groundwater is a long-standing issue in southeastern Minnesota.

We focused much of our investigation on an evaluation of nitrate (NO_3 ion) transport in the Root River watershed because of the relatively advanced understanding of the karstic conditions in that area. However, the overall scope of the project includes the entire bedrock-dominated landscape of southeast Minnesota. Our results therefore support a broader MPCA watershed planning effort that directly pertains to the Root River, as well as to other watersheds within the Lower Mississippi River Basin in Minnesota.

Our tasks included two approaches defined by scale. One is at regional scale and included a compilation of geologic maps and databases relevant to the characterization of nitrate transport for the southeastern Minnesota study area. A database of nitrate concentrations compiled from analyses of both surface water (stream baseflow) and groundwater (springs and water wells) samples were evaluated in the context of the hydrogeologic attributes of the bedrock and surficial deposits depicted on the maps. The evaluation focused on hydrogeologic controls that can account for variability in nitrate concentrations that do not appear to be adequately explained by land use practices alone (Watkins et al., 2011). Specific areas that best exemplify geologic controls on nitrate transport are portrayed in a large number of cross sectional views to support interpretations of how geologic setting impacts nitrate concentration in streams and groundwater.

The second approach, at a local scale, focused on a relatively small part of the Root River watershed where we conducted new mapping that provides a more detailed depiction of the geologic conditions in a three dimensional electronic format suitable for groundwater-surface water modeling. In addition, we used existing maps and reports along with new field data collected during the course of this project to improve the hydrostratigraphic characterization of the bedrock. Cross sections within and near the local project area are used to demonstrate how nitrate transport occurs in the ground and surface water system.

Our evaluation of the hydrogeologic system and geologic controls on the transport of nitrate in the bedrock dominated landscape of southeastern Minnesota concludes that:

- Nitrate is transported in a groundwater- surface water system that is fracture dominated, with the largest volumes of water travelling rapidly through a complex system of conduit networks.
- Aquitards between the major aquifers result in an anisotropic groundwater system, limiting the volume and velocity of vertical flow and promoting rapid lateral flow that discharges as baseflow to streams
- Groundwater in uppermost bedrock units, especially on the karstic plateaus that dominate the landscape of southeastern Minnesota, is typically nitrate-enriched, with concentrations commonly between 5-15 ppm.
- Nitrate concentration diminishes across aquitards, typically in a stratified manner that correlates with groundwater age, reflecting the anisotropy caused by aquitards.
- The most important factor we have identified that impacts both the magnitude and variability of nitrate concentration in spring water and stream baseflow is the proportion of regionally sourced, nitrate-poor water contributed from deep aquifers relative to more locally sourced, nitrate-enriched water from shallower aquifers.
- The relative proportion of these contributions to stream baseflow can commonly be correlated with the hydrogeologic setting.

Our results have relevance for both surface and groundwater management efforts to mitigate nitrate loading. One implication is that the response time of nitrate concentrations to changes in land use practices will likely vary in different hydrogeologic settings. The most significantly lagged response in southeastern Minnesota should be expected in the deep valleys incised into the Prairie du Chien Plateau, where significant baseflow is derived from deep, siliciclastic-dominated bedrock sources with one or more overlying aquitards. The quantity and chemical composition of baseflow in these settings is buffered from changes in anthropogenic and natural conditions at the land surface. In contrast, quicker changes in baseflow nitrate concentrations can be expected in areas where the geologic setting allows only a relatively minimal contribution of regional flow. Instead, baseflow is dominated by locally derived water with fast-flow pathways that are well connected to the land surface.

The distribution of nitrate in ground and surface water we depict in this report represents the advance of nitrate from the land surface into the ground and aquifer systems over about 60 years. The accuracy of predictions of future water quality will in part be dependent on an appreciation of the dynamic nature of the transport system. Particularly important is recognition that contaminants will be transported to progressively deeper aquifers and are likely to increase in concentration with time due to a number of natural and anthropogenic factors. Assuming nitrate input from the land surface does not decrease in the future, increased levels of contamination in progressively deeper parts of the groundwater system should be expected.

While our results provide an improved understanding of geologic controls on nitrate transport in the bedrock dominated landscape of southeastern Minnesota, they also highlight the need for additional work beyond the scope of this project. Predicting the impact of changing land use practices on baseflow nitrate concentrations would be facilitated by quantitative estimates of the proportion of contributions to baseflow of shallow, nitrate-enriched water relative to deeper, nitrate-poor water in variable hydrogeologic settings. Strategies to protect deep aquifers that are currently nitrate-poor would be improved by a better understanding of the manner in which nitrate is transported beneath aquitards. The rate at which processes such as denitrification occur in variable hydrogeologic settings is also uncertain, and could be an important factor in controlling the rate at which deeper aquifers may become enriched in nitrate.

A better understanding of geologic controls on transport and concentration of nitrate in groundwater, and evaluating their importance relative to other controls such as land use practices and climate, will require datasets that appear to be scarce in southeastern Minnesota. For example, a more comprehensive sampling of nitrate concentration from uppermost groundwater across southeastern Minnesota is needed to better characterize the degree to which this water is impacted, and to monitor trends in concentration through time. We also recognize a scarcity of data collected at highly resolved spatial and temporal scales, especially from sites where groundwater discharge contributes to stream baseflow.

More complete knowledge of the surface and groundwater systems will allow for better understanding of potential pollutant source areas and transport, which is critical for developing reduction scenarios aimed at reducing pollutant loads in pursuit of water quality standard attainment. Addressing these (and related) questions will facilitate informed recommendations pertaining to nutrient management in the bedrock-dominated landscape of southeast Minnesota at a higher spatial resolution than previously.

INTRODUCTION

This report summarizes the results of a Minnesota Geological Survey (MGS) investigation conducted for the Minnesota Pollution Control Agency (MPCA) designed to support watershed planning efforts in southeast Minnesota. It provides a better understanding of the geologic controls on nitrate transport in the region, including nitrate in groundwater. An improved understanding of nitrate in groundwater is important, because surface water is well-known to be intimately linked to shallow groundwater across much of southeast Minnesota (e.g. Alexander and Lively, 1995; Tipping et al., 2001; Green et al., 2002; Luhmann et al., 2011; Green et al., 2012). Nitrate contamination of surface water and groundwater is a long-standing issue in the region. Impacts to municipal and private drinking water supplies by nitrate are widespread and well-documented. High nitrate concentrations in drinking water have been linked to the occurrence of methemoglobinemia in infants, and may increase cancer risks in adults (Weyer et al., 2001). Also, nitrate can reach toxic levels that impair the ability of aquatic animals to survive, grow and reproduce (Camargo and Alonso, 2006). Further, loading of excess nutrients (including nitrate) to still-water systems (lakes, reservoirs, and the Gulf of Mexico) and large rivers can accelerate eutrophication, a problem that can lead to nuisance algae blooms and low levels of dissolved oxygen, as in the northern Gulf of Mexico. Variability in geologic conditions, particularly in the hydrostratigraphic (water-bearing) attributes of bedrock, can cause variability in groundwater chemistry (e.g. Zhang, 1995), and therefore of stream water chemistry in the region. For example, geologic controls may account for why some streams are demonstrating impairment and others consistently show low nitrate concentrations, even though land use practices may be generally similar (Fig. 1).

Pollutants can move rapidly from the land surface through unconsolidated sediment and bedrock as part of the groundwater system that provides base flow to streams in southeastern

Minnesota. Flow through fractures and other relatively large voids plays a particularly important hydrologic role (e.g. Alexander and Lively, 1995; Runkel et al., 2003). Fracture-dominated flow is especially pronounced in karst settings, exemplified by the intensively studied Root River watershed in Fillmore County (e.g. Alexander et al., 1996; Witthuhn and Alexander, 1995; Alexander and Lively, 1995; Luhmann et al., 2011). We focused much of our investigation on an evaluation of nitrate (NO_3 ion) transport in the Root River watershed because of the relatively advanced understanding of the karstic conditions in that area. However, the overall scope of the project includes the entire bedrock-dominated landscape of southeast Minnesota. Our results therefore support the broader MPCA watershed approach as it pertains to the Root River, as well as other watersheds within the Lower Mississippi River Basin in Minnesota.

Our tasks included two approaches defined by scale. One approach is at regional scale and included a compilation of geologic maps and databases relevant to the characterization of nitrate transport for the southeastern Minnesota study area. The maps depict bedrock geology and topography, and thickness and lithology of the unconsolidated sedimentary deposits that overlie bedrock. Other published map coverages used in our evaluation depict groundwater potentiometric levels, locations of springs, sinkholes, and other features provided in the University of Minnesota/Minnesota Department of Natural Resources Karst Features Database (KFDB), as well as maps that show the results of dye traces, which are a direct measure of flow paths. A database of nitrate concentrations compiled from analyses of both surface water (streams) and groundwater (springs and water wells) samples were evaluated in the context of the hydrogeologic attributes of the bedrock and surficial deposits depicted on the maps. Specific areas that best exemplify geologic controls on nitrate transport are portrayed in a large number of cross sectional views to support interpretations of how geologic setting impacts nitrate concentration in groundwater and streams.

The second approach, at a local scale, focused on a relatively small part of the Root River watershed (Fig. 1). This area was chosen for the abundance of karst features, relatively good subsurface geologic information from water well records, and comprehensive previous and ongoing study of the groundwater and surface water system, such as dye trace and water chemistry investigations (e.g. Alexander et al., 1996; Witthuhn and Alexander, 1995; Zhang and Kanivetsky, 1996). We conducted new mapping that provides a more detailed depiction of the geologic conditions in a three dimensional electronic format suitable for groundwater-surface water modeling. In addition, we used existing maps and reports along with new field data collected during the course of this project to improve the hydrostratigraphic characterization of the bedrock. Cross sections within and near the local project area are used to demonstrate how nitrate transport occurs in the ground and surface water system.

These analytical tasks support work already underway [Minnesota Departments of Natural Resources (DNR) and Agriculture (MDA), and the University of Minnesota] to describe in detail the geologic and hydrologic characteristics of small, coldwater stream springsheds. More complete knowledge of the surface and groundwater systems will allow for better understanding of potential pollutant source areas and transport, which is critical for developing reduction scenarios aimed at reducing pollutant loads in pursuit of water quality standard attainment. Addressing these (and related) questions will facilitate informed recommendations pertaining to nutrient management in the bedrock-dominated landscape of southeast Minnesota at a higher spatial resolution than previously. Nutrient management will be a critical component of all comprehensive watershed management strategies completed in the basin. Thus, this work will provide support for multiple watershed projects over time.

REGIONAL GEOLOGIC MAPPING

MAP COMPILATION

We compiled a large number of existing maps that depict in a number of ways the bedrock and overlying unconsolidated sediment across the regional study area. GIS files used to create these maps are provided as feature classes and associated layer files in ArcGIS geodatabase format, with examples provided as illustrations in this report. Both the thickness and material properties of the unconsolidated sediment were mapped regionally as part of our compilation (Fig. 2). The surficial map depicts the distribution of unconsolidated sediment immediately below topsoil across the land surface. For example, Figure 2 shows the surficial distribution of till (diamicton), a relatively fine-grained sediment, in the regional study area as well as where unconsolidated sediment is greater than 50 ft thick. The surficial map is linked to a database of texture attributes where available, and an assigned range of hydraulic conductivities based on estimates from a previous investigation (Tipping et al., 2010). The relative permeability of unconsolidated deposits raster is an interpolated surface representing relative vertical permeability of unconsolidated material on top of bedrock. It is presented later in this report.

A bedrock map (Fig. 3), shows the distribution of consolidated geologic material. It is a depiction of the bedrock formations that are exposed at the land surface or lie immediately below the unconsolidated sedimentary cover. Regional compilations of bedrock topography, depth to bedrock, and relative permeability of unconsolidated deposits are also provided as grid (raster) datasets as part of this investigation. The Karst Features Database (KFDB) is a compilation of karst features data maintained by the University of Minnesota Department of Earth Sciences and the Minnesota Department of Natural Resources (MNDNR). Springs, sinkholes, and losing streams from the KFDB are plotted on the bedrock geologic map in Figure 3.

All of the maps and associated raster products are based on a compilation of maps and other data that were produced over a span of three decades. The compilation is current as of the publication date of each of its components; with the exception of our work in the local springshed project area, no additional new mapping was undertaken. Additional information about these maps and associated products, including metadata and ancillary information on rock properties is provided in Appendix B.

REGIONAL GEOLOGY OVERVIEW

The regional geologic setting for southeastern Minnesota is characterized by Paleozoic sedimentary bedrock overlain by a greatly variable thickness of unconsolidated sediment related mostly to glacial processes (Fig. 4). The bedrock in southeastern Minnesota, described in detail by Mossler (2008) is Cambrian to Devonian in age, about 505 to 350 million years old (Fig. 5). Most individual formations are subhorizontal layers of sedimentary rock from 50 to 200 feet thick that are dominated by either fine- to coarse-grained, quartz-rich sandstone; very fine-grained sandstone, siltstone and shale; or carbonate rock (limestone and dolostone) (Figs. 5, 6). The lower part of this stack of layers, Cambrian in age, is dominated by siliciclastic material (sandstone, siltstone and shale) whereas the upper part of the stack, Ordovician and Devonian in age, is dominated by carbonate rock and shale. The bedrock formations across most of the regional project area dip shallowly (typically less than two degrees) to the southwest (Fig. 6) as part of the eastern margin of a subtle structural depression called the Hollandale embayment. Rice and Steele Counties are on the western limb of the embayment, where the bedrock dips shallowly to the east. As a result of the overall subtle southwestward dip of the formations across most of the region, and of relatively deep erosion along the Mississippi River and its tributaries, the Cambrian formations are exposed or occur as subcrop mostly within those river valleys, with progressively younger, overlying formations present as uppermost bedrock to the south and west (Figs. 3,6).

Across much of southeastern Minnesota unconsolidated sediment on top of bedrock is less than 50 ft thick (Fig. 4), referred herein as a “bedrock dominated landscape”. The landscape in this broad area of thin cover largely reflects the topography of the bedrock (Fig. 7) (Mossler and Hobbs, 1995). It is characterized by relatively flat plateaus and mesas separated by escarpments and cut by narrow valleys. Plateaus and smaller mesas are mostly underlain by resistant limestone and dolostone, which are exposed as the highest cliffs and bluffs along streams crossing plateaus. The lower parts of escarpments between plateaus, the sides of mesas, and the floors and lower parts of valley walls along deeply entrenched streams are composed of weaker sandstone and shale.

The carbonate rock layers forming the plateaus and mesas across southeastern Minnesota contain large, solution-enhanced fractures and other cavities that are expressed at the surface as a karst landscape (Fig. 7) (Alexander and Lively, 1995; Alexander et al., 1996; Green et al., 1997, 2002). Karst landscapes are characterized by features such as sinkholes, caves, closed drainages, and sinking streams. These features are an integral part of the hydrogeologic system of southeastern Minnesota, described in greater detail in subsequent sections of this report.

Two thick bedrock layers composed mostly of karstic carbonate rock form two regionally extensive plateaus across the bedrock dominated landscape (Figs. 4, 6, 7). The Upper Carbonate Plateau (also called the Galena-Cedar Valley plateau) is composed of resistant carbonate rock of the upper part of the Galena Group (Prosser, Stewartville and Dubuque Formations), the Maquoketa Formation, and the Wapsipinicon and Cedar Valley Groups (Fig. 7A). The outer, eroded edge of the Upper Carbonate Plateau is an escarpment composed of, from bottom to top, the St Peter Sandstone, Glenwood and Platteville Formations, Decorah Shale, and

Cummingsville Formation (Fig. 7B). This escarpment steps down to the Prairie du Chien Plateau, which extends generally eastward to the edge of the Mississippi River, where it forms the resistant cap on top of the bluffs. Relatively smaller mesas (flat-topped hills) of St Peter Sandstone capped by remnants of the Platteville Formation are scattered across the Prairie du Chien Plateau (Fig. 7C).

The unconsolidated sediment that overlies bedrock in southeastern Minnesota is Quaternary in age (less than 2 million years old) and was deposited by processes related to glaciers present in the area at that time, and by more recent post-glacial deposition in the past 10,000 years. Quaternary sediment can be generally divided into coarse-grained sand- and gravel-dominated material deposited mostly in rivers, and finer-grained material that includes significant silt and clay, which was deposited in lakes, on floodplains, and as till that accumulated from melting glaciers. Many glacial deposits are heterolithic, containing a wide range of material of different composition and grain size, such as colluvium that formed along valley walls.

The western part of the regional study area is characterized by an extensive and thick (greater than 50 ft) layer of Quaternary unconsolidated sediment overlying bedrock (Figs. 2, 4). In most places the maximum thickness is less than 200 ft, with the exception of within buried bedrock valleys. This drift-dominated landscape, in most places, is characterized by a more subdued surface topography compared to the bedrock dominated landscape. The unconsolidated sediments are highly variable in properties from place to place, and have not been comprehensively mapped in three dimensions. However, subsurface cross sections produced for individual County Geologic Atlases (Hobbs, 1988, 1998; Hobbs et al., 1995; Meyer and Mossler, 1998) and water well drilling records across the region indicate that till and other relatively fine-grained material with significant clay and silt are volumetrically dominant. Till associated with the Des Moines Lobe is especially prevalent, composing the uppermost “surficial” mapped material across much of the drift dominated landscape (Fig. 2). Sand and gravel is present as more widely scattered and isolated bodies within the finer- grained layers. To the east, on the bedrock dominated landscape, Quaternary sediment on top of bedrock plateaus is a complex mix of relatively thin, patchy remnants of till, wind-blown silt (loess), sand and gravel, and the weathered residuum of bedrock. Thicker deposits partly filling bedrock valleys are mostly sand-dominated.

LOCAL PROJECT AREA GEOLOGIC MAPPING

We conducted detailed geologic mapping at a more local scale within the Root River watershed (Fig. 8) to facilitate a better understanding of groundwater flow paths in a karstic landscape characteristic of much of this watershed, and to provide a geological framework for the modeling of groundwater-surface water flow that may be part of subsequent investigations. The local scale study area covers about 75 square miles of southwestern Fillmore County, and was chosen for the abundance of karst features, and good quality subsurface information, such as drilling records for basic geologic mapping and dye trace data that distinguish groundwater flow paths (Alexander et al., 1996, and unpublished subsequent dye tracing results provided in 2013 by Jeff Green of the MNDNR). An abundance of bedrock exposures also provided important controls for the mapping, and insights into hydrostratigraphic characteristics. Selection of this area also facilitates collaboration with an ongoing nitrate transport investigation by the Minnesota Department of Agriculture within the local study area.

Mapping tasks included compiling existing maps and associated databases (Mossler, 1995; Mossler and Hobbs, 1995; University of Minnesota/MNDNR KFDB), as well as collecting new data. An outcrop inventory was created using existing bedrock maps and outcrop databases that were field checked for veracity, and supplemented with previously unmapped exposures.

Existing natural gamma logs of water wells were interpreted to improve accuracy and consistency in identification of stratigraphic contacts, and to better characterize hydrostratigraphic components. Locations of relatively recently drilled water wells were established, and the drilling records merged with records of previously located wells. New and revised interpretations were made for some drilling records, using the natural gamma logs and outcrops as control points. All wells in the study area have a land surface elevation based on LiDar coverage that has an accuracy of +/- 5 ft. Information from the MGS Quaternary Database Index (QDI) provided additional information on depth to bedrock and the characteristics of the unconsolidated glacial deposits in outcrops and shallow auger holes.

The geologic map for the local project area was made in the form of a 3-dimensional model with 10 m grid cell size, produced in ESRI software. Figure 9 shows a representative illustration of the three-dimensional model. Digital Elevation Models (DEMs) were created that depict the bedrock topography and all bedrock unit surfaces. All DEMs can be viewed 2-dimensionally in ArcMap or 3-dimensionally in ArcScene. Two cross sections were created in the local study area to add conventional perspective on the dimension of depth, and illustrate the stratigraphic, structural and topographic relationships of the bedrock units; as well as the variable thickness of the overlying Quaternary sediments (e.g. Fig. 10).

The local study area lies entirely within the bedrock dominated landscape of southeastern Minnesota. The formations present as uppermost bedrock in the local study area are, from uppermost to lowermost, the Spillville, Maquoketa, Dubuque, Stewartville, Prosser, Cummingsville, Decorah, Platteville, Glenwood, St. Peter, and Shakopee. The formations generally dip less than one degree to the southwest, as part of the regional structural trend along the eastern margin of the Hollandale embayment. Local scale, relatively subtle folds extending a few miles are superimposed on the regional dip. The regional southwestern dip of bedrock formations and deeper erosion to the northeast results in a transition from the outer part of the Upper Carbonate Plateau to the inner margin of the Prairie du Chien Plateau along a southwest to northeast traverse across the study area (Figs. 8, 9, 10). The two plateaus are separated by the Cummingsville-St Peter escarpment along sinuous valley walls.

Unconsolidated sediment on top of the bedrock is less than 50 ft thick in most places (e.g. Fig. 10). On the plateaus this includes small patches of sandy Windrow Formation of Cretaceous age, large areas of wind-blown silty loess, and till in the southwestern part of the study area. These materials were not mapped separately as part of this project, but their distribution is shown on a 1:100,000 scale map by Mossler (1995). Unconsolidated sediment greater than 50 ft. thick is mostly restricted to the bottom of present valleys that dissect the plateaus, and are likely dominated by sand.

In addition to our detailed mapping, we also improved our understanding of the hydrostratigraphic attributes of the bedrock within the local project area, described in the next section of this report. This effort included assimilating information from a large number of reports on a contamination site located approximately four miles northwest of the local study area (Fig. 4) known as the British Petroleum (formerly Amoco) Spring Valley Terminal (Delta Environmental consultants, 1996, 2002). Water chemistry databases and borehole videos for this site were also provided to us by AnteaGroup in 2012 and 2013. A wealth of hydrostratigraphic information is available from ongoing groundwater monitoring at the site which includes dozens of traditionally constructed monitoring wells, and at least 13 multi-level system wells. We also examined large outcrops and quarries in the local study area, which provided insights into the stratigraphic positions at which vertical fractures preferentially terminate. The locations of karst features (springs, seeps, sinkholes and sinking streams) were plotted on the DEMs to determine their precise stratigraphic position.

HYDROSTRATIGRAPHY

BEDROCK

Understanding of contaminant transport in the bedrock of southeastern Minnesota has been improved since implementation of a hydrostratigraphic approach to hydrogeologic characterization, as opposed to reliance on lithostratigraphic approaches (Runkel et al., 2003). A hydrostratigraphic approach is one in which hydraulic data are interpreted within the context of the three dimensional distribution of porosity and permeability. This more rigorous process, which includes insights gained from relatively new techniques such as borehole flowmeter logging and mechanical stratigraphy (e.g. Tipping et al., 2006; Runkel et al., 2006a; Anderson et al., 2011), results in improved delineation of individual aquifers and aquitards, and leads to greater predictability in flow paths and speeds.

The matrix in Paleozoic bedrock of southeastern Minnesota can be broadly divided into three distinct hydrostratigraphic components (Runkel et al., 2003, 2006a): 1) fine clastic; 2) coarse clastic; and 3) carbonate rock (Fig. 11). Fine clastic strata consist of very fine grained sandstone, siltstone, and shale, and have a bulk porosity that typically ranges from 5-30 %. Permeability is low to very low, with a vertical hydraulic conductivity that typically ranges from 10^{-6} to 10^{-10} ft/day. Horizontal permeability is commonly about two orders of magnitude greater than vertical. The coarse clastic component consists mostly of fine- to coarse-grained, quartzose sandstone with a bulk porosity of about 15 to 30 % and a high vertical hydraulic conductivity of 10^{-1} to as much as a few hundred ft/day. Horizontal permeability typically is roughly equal to, or as much as an order of magnitude greater than vertical permeability. The carbonate rock component consists of very fine to coarse-grained dolostone and limestone with variable amounts of silt, sand and shale as interbeds or admixed in the carbonate matrix. Rock matrix bulk porosity and vertical permeability values are typically less than 20 % and 10^{-5} ft/day respectively. Limited tests of horizontal permeability indicate that it is commonly about two orders of magnitude greater than vertical permeability where the carbonate rock is horizontally laminated.

Matrix characteristics of bedrock are of particular importance because the greatest volume of water stored is within the small pore spaces of matrix blocks. The largest volumes of flow, however, travel more rapidly through larger pore spaces (Fig. 12), collectively referred to herein as fractures. Figure 13 shows in cross-sectional view a representative example of the distribution of fractures in the bedrock of the Upper Carbonate Plateau in the local project area, and Figure 14 is a more generalized regional-scale cross section displaying where fractures are most prominently developed. The illustrations highlight two fundamental kinds of fracture networks based on orientation relative to bedding. Openings that preferentially align congruent to bedding (e.g. Figs. 12A,B,F) are referred to as bedding-parallel fractures in this report. Outcrop and large diameter borehole observations indicate that bedding-parallel fractures in three dimensions are part of an anastamosing network of such elongate apertures developed along discrete stratigraphic intervals (Runkel et al., 2006a). Other fractures intersect bedding at a relatively high angle (e.g. Figs. 12C,D) and include vertical to subvertical fractures such as systematic joints that commonly penetrate several feet to tens of feet, as well as nonsystematic, irregular fractures that are less linearly extensive. Systematic joints occur in sets with a preferred orientation that intersect one another to create an orthogonal network in plan view.

Both bedding parallel and vertical fractures are now known to be common in all Paleozoic bedrock formations across southeastern Minnesota, and to play a major role in the groundwater flow system (e.g. Runkel et al, 2003; Tipping et al, 2006; Runkel et al, 2006a, 2006b). The greatest volume of water flowing at relatively rapid speeds, and thus a source of significant baseflow to streams, preferentially occurs through fracture networks. Averaged across thick (tens of feet) intervals, bulk hydraulic conductivities of Paleozoic bedrock commonly range from several tens to hundreds of feet per day, significantly greater than intergranular permeability alone would accommodate. Individual fractures intersected by boreholes have conductivities measured as high as tens of thousands of feet per day. Dye traces demonstrate that fracture networks commonly accommodate flow speeds measured in tens of yards to miles per day (e.g. Alexander and Lively, 1995; Runkel et al., 2003; Green et al., 2012).

The pathways for groundwater flow in the Paleozoic bedrock of southeastern Minnesota are consistent with the concept of “triple porosity” systems. Worthington (2003) describes a triple porosity system as one in which there are three porosity elements. The rock matrix is a three-dimensional element of relatively low permeability through intergranular pore spaces. Planar elements are two-dimensional fractures such as vertical joints. Linear elements, referred to as channels, are the third type of porosity. Channels serve as a very high permeability network of conduits accommodating large volumes of water travelling with rapid speeds. Large cavities dissolved in carbonate rock along discrete parts of bedding planes and vertical fractures are examples of channel porosity. The elongate, bedding parallel pores with inch-scale apertures in siliciclastic bedrock of southeastern Minnesota also are likely part of a network of channels, but they are significantly more limited in aperture width than in karstic carbonate rock, and their origin is unlikely to be primarily the result of solution (Stewart et al., 2012).

An important outcome of research on Paleozoic bedrock hydrostratigraphy over the past 15 years is documentation of stratigraphic distribution of fractures (Figs. 11, 14) (e.g. Tipping et al., 2006; Runkel et al., 2006a). This provides a degree of predictability to identifying preferential flow paths through high conductivity fracture networks. For example, bedding parallel fracture networks are densely clustered along specific stratigraphic intervals.

Conversely, specific stratigraphic intervals have been shown to be resistant to the through-going development of vertical fractures (e.g. Anderson et al., 2011) (Fig. 15), and these intervals hinder groundwater flow in a vertical direction. Such intervals serve as the aquitards in the Paleozoic bedrock hydrogeologic system depicted in Figures 11 and 14.

The degree to which fractures are developed in bedrock varies in a predictable fashion whereby density and connectivity decrease with increasing depth below the bedrock surface (Figs. 13, 14). In conditions of relatively deep burial by younger bedrock (50 feet or greater), fractures are typically limited to discrete intervals with abundant, bedding-plane parallel openings and subvertical fractures, such as systematic joints, and have relatively narrow apertures compared to shallow conditions of burial. In conditions of shallow burial by younger bedrock (less than 50 ft), fractures are more abundant, better-connected, and have larger apertures compared to conditions of deeper burial. The term “shallow bedrock conditions” in this report refers to the upper 50 ft of Paleozoic bedrock regardless of the thickness and composition of overlying unconsolidated materials. This 50 ft boundary is somewhat arbitrary in the sense that the change from shallow bedrock conditions to deep bedrock conditions is in reality transitional, and will vary in depth from place to place.

In addition to depth of burial beneath younger bedrock, the composition of the bedrock also has an impact on the development of fracture networks (Fig. 12). Fractures in siliciclastic-dominated units (coarse clastic and fine clastic strata) (Fig12 F-G) generally have relatively small apertures, and limited trace lengths of vertical fractures, based on outcrop observations. Apertures of individual bedding parallel fractures in siliciclastic bedrock are very rarely greater than a few inches (Runkel et al., 2006a, 2006b). In contrast, apertures in carbonate rock (Fig. 12 A-E) range upward to markedly larger sizes, including cave networks, and commonly have vertical fractures with large apertures that extend continuously for over 100 ft. Much of the enhanced aperture development in the carbonate bedrock is the result of solution, and as such this kind of bedrock is consistent with the traditional definition of a karst system: an integrated mass-transfer system in soluble rocks with a permeability structure dominated by conduits dissolved from the rock and organized to facilitate the circulation of fluid (Klimchouk and Ford, 2000). Our hydrogeologic framework therefore also delineates three major karst systems (Runkel et al., 2003) (Figs. 11, 14), based largely on the work of Alexander and Lively (1995), Alexander et al. (1996), and Green et al. (1997, 2002). Southeastern Minnesota karst systems are composed of strata dominated by carbonate rock that extend upward to the land surface, and in ascending stratigraphic order include the Prairie du Chien, Galena-Spillville, and Cedar Valley karst systems. Each karst system is characterized by relatively abundant, solution enlarged bedding parallel and vertical fractures. These features may be expressed at the land surface by caves, numerous springs and many sinkholes in areas with only a thin cover of unconsolidated material, but the same aquifer properties often exist in areas with greater cover and with few, if any, obvious surface karst features.

The carbonate-dominated Platteville Formation is also known to contain solution-enlarged fractures, including caves (Spong, 1980), where it is at or near the land surface in southeastern Minnesota. It is therefore a fourth karst system in southeastern Minnesota, although with a more limited aerial extent near the land surface than the major karst systems described above. It is also well-known to have properties that in a vertical direction are consistent with aquitards (Runkel et al., 2003; Anderson et al, 2011). For the purposes of this report we have included the Platteville Formation as part of the Cummingsville-Glenwood aquitard in our regional-scale framework, with the understanding that at least in local conditions of shallow burial it has hydrogeologic properties of a karstic aquifer. In such areas, the properties of the Platteville are such that they are consistent with the traditional definitions of both aquifer and aquitard. We have therefore informally used the term “aquitardifer” (Anderson et al., 2011) to refer to bedrock units with such properties in any single location. The St Lawrence Formation is another example of an aquitardifer.

As part of this investigation we devoted considerable effort towards improving our understanding of the hydrogeologic attributes of the bedrock that forms the Upper Carbonate Plateau, which dominates the landscape across much of the upper reaches of the Root River watershed, including the local scale project area. Our local scale work therefore included an evaluation of driller’s logs, geophysical logs and video logs of the monitoring wells installed at the British Petroleum Spring Valley contamination site in western Fillmore County (Fig. 4) to further characterize the hydrostratigraphic conditions of the bedrock. This led to an improved understanding of preferential development of bedding parallel fractures along specific stratigraphic positions in the Galena Group (Figs. 16, 17). Video logs were used to identify bedding parallel fractures, and compared against natural gamma logs, which indicated that they are most commonly located in the Spillville Formation and along the Dubuque/Stewartville and Prosser/Cummingsville contact strata. To improve our understanding of vertical fractures, we examined large outcrops and quarries in the local study area. This provided insights into the stratigraphic positions at which vertical fractures preferentially terminate (Fig. 15), which includes the uppermost part of the Cummingsville Formation and the top and bottom of the Dubuque Formation. These insights are depicted schematically on the cross sections in this report (e.g. Figs. 13 and 14).

We also plotted the locations of karst features (springs, seeps, sinkholes and sinking streams) on the DEMs from our 3-dimenional map of the local project area to determine their precise stratigraphic position. Some of these features (mostly springs) were field checked for location and were moved slightly to portray a more accurate stratigraphic position. The top of the

Decorah was used as our datum and each karst feature was intersected with the Decorah DEM and assigned an elevation in feet above or below the top of the Decorah depending on its stratigraphic position. Using five foot bins, the frequency of a karst feature intersecting a particular five foot interval in the stratigraphic package was plotted in a vertical histogram to further characterize the hydrostratigraphy of the local study area (Fig. 18). The results show springs primarily occur in the lower Prosser and Cummingsville formations, corresponding to where our observations indicate that bedding parallel fracture networks are preferentially located and vertical fractures commonly terminate. Seeps primarily occur within the lower Cummingsville and Decorah formations where through-going vertical fractures and bedding parallel fractures are less common. Sinking streams and sinkholes primarily occur in the lower Maquoketa, Dubuque and Stewartville formations. Other observations in the local project area are that prominent vertical fractures are typically through-going across the Stewartville Formation, and well-developed cave systems appear to be most common in the Dubuque and Stewartville formations (Alexander et al., 1996). Although this analysis was limited to a relatively small area of southeastern Minnesota, this kind of stratigraphic control on karst features applies to similar geologic settings elsewhere (e.g. Runkel et al., 2003). As an example, Figure 18B shows that the stratigraphic position of springs in Olmsted County corresponds closely to those in the local project area of southwestern Fillmore County.

The formal classification of Paleozoic bedrock into aquifers and aquitards (Figs. 11B, 13B, 14B) used in this report is based on hydraulic data interpreted within the context of hydrostratigraphic attributes, summarized in Runkel et al. (2003, 2006a), and includes the insights gained from our new evaluation of the bedrock on the Upper Carbonate Plateau. Because all parts of the Paleozoic bedrock section, even those with very low matrix permeability, are known to yield water in economic quantities in a horizontal direction through high conductivity fractures, our hydrogeologic classification is based on first identifying aquitards that limit flow in a vertical direction. Intervals of strata between these aquitards are by default classified as aquifers. Local variability in both matrix and fracture characteristics necessarily results in conditions which are not entirely consistent with our regional scale classification. For example, some of the aquitards we recognize, such as the lower Jordan-St Lawrence aquitard, internally contain discrete intervals with bedding parallel fracture networks or coarse clastic interbeds that have moderate to even high horizontal conductivity even in deep bedrock conditions (Runkel et al., 2006b). In shallow bedrock conditions, many springs emanate through fractures in the units we classify herein as aquitards, and therefore they accommodate baseflow to streams through fast-flow conduit networks (Green et al., 2008, 2012) just as the aquifers do. As with the Platteville Formation, we have used the term “aquitardifer” to convey our understanding that the St Lawrence Formation can have properties of both aquifers and aquitards, even at a single location. Conversely, some aquifers we have defined at a regional scale are known to contain aquitards, such as carbonate rock with few fractures in the Prosser Formation. Classification of aquifers and aquitards in shallow bedrock conditions is especially difficult because of the ubiquitous presence of fractures and the limited number of comprehensive groundwater studies conducted in such settings in Minnesota. Particularly noteworthy is that aquitards are locally breached by interconnected fractures where they occur close to the bedrock surface. Therefore even though each of the aquitards in our framework has the *potential* to provide hydraulic separation, the relative effectiveness and scale at which they can do so is poorly understood and can be expected to be extremely variable even at local scale. The characterizations we provide at site specific scale later in this report, via hydrogeologic cross sections (e.g. Fig. 13), attempt to depict some of these complexities.

UNCONSOLIDATED SEDIMENT

The heterolithic unconsolidated sediment on top of bedrock in southeastern Minnesota can, from a hydrostratigraphic perspective, be divided into units that are dominated by sand versus units that have a significant component of silt and clay. Relatively fine-grained units with significant percentages of clay and silt, such as diamictons (tills) range in conductivity from about 10^{-1} ft/day to 10^{-6} ft/day. These values take into consideration enhanced bulk conductivity provided by fractures known to be common in clay-rich deposits such as tills (Tipping et al., 2010). Coarser grained units with significant sand, such as glacial outwash deposits, range from 10^{-1} ft/day to a few thousand ft/day. Using this two-fold subdivision of the unconsolidated deposits based on permeability, the sand-dominated material is traditionally classified as an aquifer, and the finer grained material with significant silt and clay as an aquitard.

Figure 2 shows the distribution of relatively low permeability tills where they are the surficial map unit across the regional study area. To characterize permeability of the entire vertical glacial sediment sequence we constructed a raster grid representing relative vertical permeability of unconsolidated material on top of bedrock (Fig. 19). Raster input data were created from well logs by reclassifying well log driller's descriptions of unconsolidated material into classes ranging from 1 (least permeable) to 3 (most permeable). Logs reporting intervals as "drift" were excluded from the calculation. Values were weighted by reported thickness, and then averaged for each well location. Average values were then interpolated (ordinary kriging) to produce the final raster.

FLOW

BEDROCK DOMINATED LANDSCAPE

The focus of this investigation is on the bedrock dominated landscape, where the vast majority of the cold water streams in southeastern Minnesota, including most designated trout streams, are located. Flow in this setting is characterized by a large volume of rapidly moving water through bedrock fractures that intimately connect groundwater to surface water. Fracture-dominated flow has been documented with a number of techniques, including dye traces (e.g. Alexander et al., 1996; Green et al., 2012), flowmeter logging of boreholes (e.g. Runkel et al., 2003; Tipping et al., 2006; Runkel et al., 2006a, 2006b) and in land surface and cave observations of stream and spring behavior (e.g. Alexander and Lively, 1995; Luhmann et al., 2011). Much of our understanding of the interaction between the ground and surface water systems in southeastern Minnesota is derived from decades of research specifically targeting the well-known karst terrains that have abundant large conduits expressed at or near the land surface by relatively high discharge springs, subterranean streams, and locally high volume stream losses (Alexander and Lively, 1995; Alexander et al., 1996, 2011; Green et al., 1997, 2002; Campion and Green, 2002; Tipping et al., 2001; Tipping, 2002). The very low hydraulic conductivity of the rock matrix and exceedingly high conductivity of the conduit networks can lead to pulsed, rapid recharge events and lateral flow speeds measured in tens of feet to miles per day. Springs that provide baseflow to cold water streams commonly respond quickly to changes in land surface conditions such as major precipitation events and seasonal temperature fluctuations (Luhmann et al., 2011).

More recently it has become clear that fracture-dominated flow, including turbulent flow through conduits, is not limited to the well-known karstic carbonate rock, it also is characteristic of siliciclastic bedrock of southeastern Minnesota (e.g. Runkel et al., 2003, 2006a; Swanson et al., 2006; Green et al., 2012). Dye trace investigations by Green et al. (2008, 2012) have recently demonstrated flow speeds as fast as hundreds of feet per day through siliciclastic bedrock (lower Jordan Sandstone, St Lawrence Formation, and Tunnel City Group) along fracture paths that provide a fast-flow connection between losing streams at the land surface and springs that discharge at lower elevations. However, the relatively limited size of fracture apertures and higher matrix porosity and permeability of siliciclastic bedrock compared to that of karstic carbonate rock is reflected by differences in flow between the two settings. Luhmann et al. (2011) used temperature logging to show that springs emanating from siliciclastic-dominated bedrock typically have a more buffered or lagged response to climatic conditions than those discharging from carbonate bedrock. Some dye traces by Green et al. (2008, 2012) through siliciclastic rock had temporally extended recovery tails of years duration that likely reflect a larger component of storage and travel though intergranular matrix blocks and fracture networks with limited aperture size compared to some carbonate-dominated bedrock such as the Galena-Spillville karst system. Given the apparent limitation on fracture aperture size and the relatively high matrix porosity and permeability in the siliciclastic bedrock, the proportional volume of flow through individual conduits versus matrix blocks is likely to be lower than in karstic carbonate rock.

While interconnected fractures accommodate much of the groundwater flow in the bedrock-dominated groundwater system of southeastern Minnesota, aquitards retard flow, thereby also influencing flow paths, rates of recharge, and water chemistry. Groundwater age dating conducted as part of County Geologic Atlas projects in five counties (Fillmore, Rice, Mower, Goodhue, and Wabasha) within the regional study area has been especially useful in characterizing the impacts of aquitards on the flow system (Zhang and Kanivetsky, 1996; Campion, 1997, 2002; Berg, 2003; Petersen, 2005). In any given area, the uppermost bedrock aquitard that is relatively deeply buried (>50 ft) beneath younger bedrock sufficiently limits vertical recharge to produce groundwater bodies that are stratified in age across extensive, mappable areas. Representative examples from Mower, Fillmore and Wabasha Counties are shown in cross section view in Figures 20, 21, and 22. Uppermost bedrock groundwater is dominantly recent in age, and commonly contains anthropogenically-derived constituents such as chloride and nitrate (discussed later in this report) because it is dominated by locally sourced recharge from the past few decades that moves rapidly through shallow, well-connected bedrock fractures. Underlying deeply buried aquitards that are not significantly breached by interconnected vertical fractures or cut out by erosional windows separate this shallow bedrock water from water of measurably older age. In most places, the water beneath the uppermost deeply buried aquitard is of mixed or vintage age and part of a flow system that is of more regional extent, containing a mixture of locally and regionally sourced water. Successively lower aquitards can produce additional age-stratified water bodies, commonly culminating with water that is at least several thousands of years old (e.g. Figure 21).

Figures 23-30 are a series of cross sections illustrating how water travels through this layered succession of fractured bedrock aquifers and aquitards in a variety of settings in the bedrock-dominated landscape of southeastern Minnesota. A regional-scale cross section (Figure 31) compiles these local conditions to show flow in a more schematic fashion across most of the bedrock dominated landscape in a west to east, generally downgradient direction. The depictions of flow are based on the assimilation of results from a large number of investigations in southeastern Minnesota summarized earlier in this report, interpreted within the context of hydrostratigraphic attributes. Across the Upper Carbonate and Prairie du Chien Plateaus the combination of a thin, patchy cover of fine grained unconsolidated sediment, a well-developed uppermost bedrock fracture network, and relatively large (feet to tens of feet) downward head gradients leads to rapid recharge from the land surface to an upper bedrock groundwater. In any given area, downward flow is retarded by the uppermost bedrock aquitard that is relatively deeply buried (>50 ft) by younger bedrock. This leads to the largest volumes of recharged water travelling rapidly in a horizontal direction. In essence, water flows mostly across the top of the aquitard, rather than vertically through it.

Relatively rapid recharge of recent water to deeper aquifers locally occurs where aquitards lose their vertical integrity. This includes where they are cut by buried erosional windows such as in buried bedrock valleys, and anywhere they are breached by well-connected vertical fractures. This is especially common where the aquitards become less deeply buried by younger bedrock, in shallow bedrock conditions. For example, Figure 21 shows a step-down of recent water via vertical fractures across the lower Maquoketa/Dubuque aquitard in western Fillmore County where the aquitard reaches shallow bedrock conditions (within 50 ft of the bedrock surface).

Much of the uppermost bedrock groundwater travelling laterally across the top of aquitards commonly discharges along erosional escarpments and in incised valleys (Figs. 23-30). This discharge is a significant component of baseflow to streams, and can occur directly at the land surface as seeps and springs, or in the shallow subsurface through unconsolidated sediment that partly fills a valley. If valley incision is sufficiently deep, multiple aquifers and aquitards may be breached, and the baseflow supplied in any one area can be a mix of both discharge from uppermost bedrock aquifers lacking an overlying aquitard, and more deeply sourced water travelling beneath aquitards in upgradient directions. The presence of local upward head gradients in deeper, confined aquifers along many of these incised valleys can lead to a component of upward flow of older, more regionally sourced water that mixes with the discharge sourced from shallower conditions. This is particularly common in the deeply incised valleys on the Prairie du Chien Plateau where the Jordan aquifer has a potentiometric level that exceeds the elevation in the valleys (e.g. Fig. 22).

The surface and ground water pathways described above occur along somewhat consistent stratigraphic positions, governed by position of aquitards and of preferentially developed bedding parallel fracture networks. The best documented and most visibly pronounced example at the land surface is the preferential discharge in the form of springs and seeps from the Cummingsville Formation along the upper part of the escarpment that separates the Upper Carbonate from the Prairie du Chien Plateau (Figs. 18, 23, 24, 25). The enhanced development of bedding parallel conduits as well as the propensity for vertical fracture termination in the upper to mid Cummingsville together result in strongly anisotropic conditions that lead to preferential discharge of groundwater at this stratigraphically controlled position in the landscape. Water discharged out of the upper to middle Cummingsville Formation travels downward across the Cummingsville-Glenwood escarpment, through shallow subsurface fractures and at the land surface, where it recharges the inward edge of Prairie du Chien Plateau (Figs. 26, 27). This step-down to a zone of focused recharge is known as the “Decorah Edge” phenomenon (Delin, 1991).

Particularly large and well integrated fracture networks accommodating significant horizontal flow are also present along the lower Spillville/upper Maquoketa formations, the lower part of the St Lawrence and upper Tunnel City Group, and the middle part of the Prairie du Chien Group (uppermost Oneota Dolomite) (Runkel et al., 2003, 2006A, 2006B; Tipping et al., 2001, 2006; Tipping, 2002; Luhmann et al., 2011; Green et al., 2012). The surface water - groundwater interactions associated with these intervals are not as well documented as those in the “Decorah edge” setting, but these intervals are known to be locally marked at the land surface by higher densities of springs, and to provide increased baseflow to streams across relatively short distances. For example, Groten and Alexander (2013) showed a pronounced increase in baseflow to Trout Brook, Dakota County, where the valley intersects the middle Prairie du Chien conduit system (Fig. 29). Ruhl (1995) also recognized a marked increase in baseflow along a reach of the South Branch of the Root River in Fillmore County near the town of Preston that we now know (Mossler, 1995) similarly corresponds to where the valley intersects the middle Prairie du Chien conduit system. Conversely, under different landscape and hydrologic settings, stratigraphic intervals with preferentially developed fractures such as lower Dubuque and upper Stewartville formation strata can be associated with preferential loss of surface water, e.g. as sinking streams (Figs. 8, 18, 24). The middle Prairie du Chien high conductivity conduit system that accommodates enhanced baseflow in some areas is also known to be associated with preferential loss of surface water in others (Tipping et al., 2001; Tipping, 2002). Catastrophic losses of water are documented along this same stratigraphic position at the land surface, including the abrupt draining of wastewater treatment ponds described by Alexander and Book (1984), Alexander et al. (1993) and Jannik et al. (1992).

In this type of anisotropic, fracture dominated system, there are potentially multiple surface to ground to surface water paths across the bedrock dominated landscape (Fig. 31). For example, water that recharges the Upper Carbonate Plateau in eastern Mower County may emerge at springs or as distributed baseflow to streams to the east near Spring Valley (Figs. 23, 31). Water lost into the underlying Galena aquifer ultimately can emerge as discharge along the Cummingsville-Glenwood escarpment farther to the east, where it recharges uppermost bedrock along the inner part of the Prairie du Chien Plateau (Figs. 26, 31). Laterally flowing water within the Prairie du Chien Group can re-emerge along deeply incised valleys closer to the Mississippi River (Figs. 28, 30). The Cambrian siliciclastic-dominated uppermost bedrock in these valleys is also now known to have fracture dominated system of alternating aquifers and fractured aquitards in which sinking and re-emergence of water is common. Green et al, (2008, 2012) showed that water preferentially sinks where valleys intersect uppermost St Lawrence Formation, and emerges in the lower St Lawrence and underlying Tunnel City Group (Green et al., 2008, 2012) (Fig. 30). Surface-to-ground-to-surface pathways can in this manner be repeated through progressively lower parts of the stratigraphic section in a generally west to east direction towards the Mississippi River.

The cross sections in Figures 23-30 depict a generalized approximation of bulk flow directions in 2 dimensions, but adding a third, plan view dimension and ascertaining greater detail is a longstanding difficulty in hydrogeology. It is especially difficult in fracture-dominated systems. Potentiometric maps, based primarily on water levels in wells, can provide insight into generalized, bulk flow directions. Across most of the regional study area they show a dominantly northeastward flow towards the Mississippi River (Fig. 32A) (Delin and Woodward, 1984). A regional groundwater divide extending from approximately the southwestern corner of Fillmore County northwestward to central Rice County separates this generally northeastward directed flow from flow that is dominantly to the southwest. At a more local scale, flow directions can differ significantly from those inferred from regional potentiometric data (Fig. 32B). In erosionally dissected bedrock settings local flow directions in the water table system can, to some extent, be predicted on the basis of topography. Uppermost bedrock aquifer water is generally directed towards bedrock valleys, with groundwater divides beneath the plateaus approximately midway between valleys (Fig. 32B). Water table aquifers can have groundwatershed boundaries that generally approximate surface watershed boundaries in this setting, but many other factors besides topography impact flow directions. Dye tracing in the karst terrains of southeastern Minnesota has shown that groundwatershed boundaries commonly differ from surface watershed boundaries, and local flow paths can differ considerably from what one would predict based on potentiometric levels measured from water wells and from topographic characteristics (e.g. Alexander et al., 1996).

Lateral flow directions in karst terrains of southeastern Minnesota have been most extensively delineated in western Fillmore County where dye trace investigations have delineated springshed boundaries and local flow directions in uppermost bedrock aquifers across a significant part of the Upper Carbonate Plateau (Fig. 33) (Alexander et al., 1996). So many factors impact flow directions in complex, karst-dominated settings that even with the results of these many traces in hand, predictability in flow directions for areas that have not been traced remains problematic. Recent research initiated by Alexander et al. (2008) and subsequently expanded in scope as part of an ongoing University of Minnesota/MNDNR springshed mapping project, has indicated that geologic structure, specifically the dip of beds in the Paleozoic bedrock, can have a significant impact on flow directions in certain settings. In these settings, springshed flow is preferentially directed down structural dip, springshed divides correspond to anticlinal crests, and water emerges as springs preferentially along synclinal axes (Figs. 33, 34A). Several of these springsheds are in settings toward the outer margins of the Upper Carbonate Plateau, where the Galena aquifer is high on ridges separated by deeply entrenched bedrock valleys forming karst interfluves. This creates water-table dominated aquifers with thin saturated thickness near the lower part of the Galena aquifer (Alexander et al., 2008). Flow direction in such a setting can be controlled largely by gravity, with water flowing down dip across the underlying Cummingsville-Glenwood aquitard (Fig. 34A). Other springsheds do not appear to be strongly controlled by geologic structure. In these, flow is commonly up structural dip, springshed boundaries do not correspond closely to anticlinal axes, nor do spring locations appear to be preferentially located in synclines (Figs. 33, 34B). Many of these springsheds are in settings farther to the southwest in Fillmore County, where the Upper Carbonate Plateau is less deeply incised, and a thicker saturated section of bedrock with multiple aquitards supplying water to the springs. This leads to conditions where factors such as the configuration of the water table and hydrostatic heads of individual aquifers have a greater impact on flow direction than dip of the aquitards. Research on controls of flow directions in this area is ongoing, and we will continue to sort out these and other factors that likely play a role on the sensitivity of flow directions to structural control.

Given the large number of factors that control flow in the fracture-dominated bedrock of southeastern Minnesota the groundwater sources of baseflow to streams across this region can be markedly variable from place to place. Hydrogeologic conditions in some settings dictate that baseflow will be heavily dominated by recently recharged water within a relatively localized area, whereas other settings are more likely to have a significant baseflow component of older water sourced from more regionally extensive flow systems. For example, in western Fillmore County baseflow to upper reaches of tributary valleys to the Root River system along the outer margins of the Upper Carbonate Plateau is likely heavily dominated by locally sourced water recharged relatively recently into the Galena aquifer (Fig. 35). The springsheds near the town of Fountain are two such examples (Figure 34A, 35). Farther west on the plateau, near the eroded edge of the Maquoketa Dubuque aquitard, baseflow to the tributary valleys in the Root River watershed will also have a component of locally derived water. However, the hydrogeologic setting dictates that there is also contribution from deeper, more regionally sourced aquifers that are capped by aquitards in upgradient directions (southwest) (Figs. 23,35). Similarly the Prairie du Chien Plateau will have stream reaches in which the source of baseflow is dominated by locally derived, relatively recent recharge, and other stream reaches that include a significant component of more deeply derived, older water. The latter will likely be particularly common where valleys are deeply incised below the Oneota aquitard, and the Jordan and lower aquifer systems discharge into streams (e.g. Fig. 28).

DRIFT DOMINATED LANDSCAPE

The interaction between surface and groundwater within unconsolidated sediment was not a substantial part of our investigation, which was focused on the bedrock-dominated landscape. The pathways from surface to groundwater, and thence to discharge as baseflow to streams are believed to generally occur in a more diffuse manner than in fracture dominated bedrock, largely through the sand and gravel bodies in intergranular fashion. Fine grained units such as tills can serve as aquitards that retard flow. However, preferential flow through fractures in till and other fine-grained units is well documented in this part of the continent, especially where such units are at or within about 50 ft of the land surface (Tipping et al., 2010 and references within).

Across the drift dominated landscape, flow of water from the land surface, into the ground, and back to the land surface fundamentally differs in some respects from the bedrock-dominated landscape. The rate at which water infiltrates from the land surface into uppermost bedrock across the regional study area is one such difference. Groundwater age-dating in Fillmore, Mower, Rice, Goodhue and Wabasha Counties (Zhang and Kanivetsky, 1996; Campion 1997, 2002; Berg, 2003; Petersen, 2005) collectively best shows the impact of the thickness and extent of unconsolidated sediment on recharge rate to bedrock. Water in uppermost bedrock across the bedrock dominated landscape where unconsolidated sediment is relatively thin and contains aquitards of only limited extent most commonly contains recent water, dominated by recharge that has occurred over the past few decades (e.g. Figs. 20-22). In contrast upper bedrock water in the drift dominated landscape contains older water of mixed or vintage age, as a result of slower recharge rates from the land surface to bedrock (e.g. Campion, 1997, 2002). This reflects the presence of relatively thick and extensive fine-grained unconsolidated aquitards that retard recharge.

ANTHROPOGENICALLY INFLUENCED FLOW

Cultural activities also play an important role in how the groundwater-surface water system functions. Conditions associated with development of the landscape such as impervious surfaces, storm water systems, agricultural drainage, and water extraction for consumption, irrigation and industrial purposes are among many activities that can significantly alter the natural flow system, and therefore impact transport paths and rates. Drain tiles can have a particularly large impact in the shallowest part of the hydrogeologic system across areas dominated by agricultural activity, as is much of southeastern Minnesota. Tiles provide a network of fast-flow conduits in the shallow subsurface that alter the natural patterns of recharge and discharge, including the delivery of nutrients (e.g. Schilling and Helmers, 2008).

Groundwater extraction via water wells has a number of impacts. The uncased (open-hole) part of water wells, and ungrouted or incompletely grouted annular spaces, can serve as fast-flow, vertical pathways across bedrock aquitards that otherwise protect underlying groundwater. Pumping is a culturally induced form of discharge that can cause several kinds of changes to the natural flow system. For example, groundwater drawdown from pumping can change natural flow directions towards the pumping activity, and can diminish natural discharge that provides the baseflow to nearby streams.

Pumping also impacts the natural recharge-discharge cycle by increasing the rate at which relatively old water in deep aquifers is replaced by younger water from shallower aquifers. Over the past few decades, wells have more commonly been constructed to draw water from deeper aquifers than they were in the past. Regulatory codes for drinking water supplies promote the construction of wells in a manner whereby aquitard-protected, mixed or vintage age water is withdrawn. This old water is discharged to the land surface where it is carried away by streams, recharges into the shallow groundwater system, or evaporates. The pumping to extract this water also increases downward vertical gradients, which increases the recharge rate to the deeper aquifers. The net result of pumping is therefore an increase in the rate of discharge of relatively old water from the deeper aquifers, and an increase in rate of recharge of younger water to replace the extracted water. The city of Rochester has by far the greatest withdrawls in our regional study area, and the impacts to the flow system are currently being studied by Tipping (in progress).

NITRATE ANALYSIS

A principal task in this project was to determine how geologic controls may impact nitrate concentrations in the groundwater- surface water system of southeastern Minnesota. Our evaluation uses a database of nitrate concentrations (ppm) from about 19,000 samples of groundwater and surface water from wells, springs, and streams (Fig. 36). Greg Brick, as a graduate student at the University of Minnesota, compiled most of the data, which we then synthesized and placed into a format amenable for use in GIS programs. It consists mostly of a compilation of about 15,000 water well samples, which range in sampling dates from 1988 to 2012 (4.2% have no associated sampling date). All of the numerical values for nitrate, are reported as parts per million (or the equivalent mg/liter) of the nitrogen in the nitrate ion, i.e. as ppm nitrate-nitrogen. Additional information about the database is provided in Appendix B.

There are a large number of factors, both geologic and anthropogenic, that are known to impact nitrate concentrations in ground and surface water, and concentration can vary markedly over relatively short spatial and temporal scales. A MPCA 2013 report provides a comprehensive overview of such factors, especially those regarded as most relevant to Minnesota (e.g.Mulla et al., 2013; Pearson and Wall, 2013; Wall 2013a, 2013b; Wasley, 2013). Land use practices such as application rates of fertilizer, manure management, irrigation, drain tiling, and density and types of sewage systems, are all known to have the potential to impact surface and groundwater nitrate concentrations. Particularly relevant to this project, in a study across the bedrock dominated landscape of southeastern Minnesota, Watkins et al. (2011) noted a strong correlation between nitrate concentrations in stream baseflow and percent of row crop land use in the associated watershed (Fig. 37). They concluded that, in general, land use has over time impacted the condition of the underlying aquifers that are the source of these streams' baseflow.

A number of hydrologic and geologic conditions also affect the concentration of nitrate in ground and surface water. Climate is well documented to cause variability in nitrate concentrations. For example, Mulla et al. (2013) describe the correspondence between precipitation patterns and variable rates of leaching of nitrate through unconsolidated sediment to shallow groundwater in Minnesota. Liu et al. (1997) and Rowden et al. (2001), in a study of a karstic springshed in northeast Iowa, also showed nitrate concentrations were strongly controlled by precipitation, with higher concentrations generally corresponding to wetter years. In the springs they monitored, concentrations varied substantially, even on a daily time scale, in response to individual precipitation events.

Attenuation of nitrate concentrations can occur through chemical and biological processes, such as vegetative uptake, and via denitrification, which is promoted by reduced (low oxygen) conditions with suitable electron donors. These processes are especially common in relatively low permeability rock and sediment where flow is slowed, and are known to occur in southeastern Minnesota in the soil, in underlying unconsolidated sediment, as well as in association with deeper subsurface bedrock aquitards (Trojan et al., 2002; Jones et al., 2010). Aquitards also are a physical barrier to flow that can retard the transport of nitrate-enriched water to greater depths. Nitrate enriched water can be diluted by mixing with less contaminated water sourced from aquifers protected by aquitards in upgradient directions (e.g. Dubrovsky et al., 2010). This less contaminated water is commonly older, and may largely predate land surface activities that are a source of nitrate, or may be younger water in which nitrate has been attenuated by processes such as denitrification.

Monitor well water samples from the British Petroleum Spring Valley Terminal contamination site in western Fillmore County over a 4 year period (Figs. 38, 39) exemplify the variability in groundwater nitrate concentrations that can occur over short intervals of time. Eight stratigraphic zones in unconsolidated sediment and karstic carbonate dominated bedrock to a depth of about 300 ft were sampled from 65 wells at the site, which is located in an area of high row crop agricultural activity. Pulses of water with nitrate concentrations exceeding 4 ppm are characteristic of all but the deepest monitored zones, but they occur infrequently, and are not uniformly distributed across any given discrete stratigraphic interval during an individual sampling event. These pulses of nitrate-enriched water are superimposed on background levels (median and average values) of less than 2 ppm, and the most frequently measured values in all zones were less than 1 ppm (Figs. 38, 39). Additional insights from this data set, including interpretation of potential geologic controls, are discussed later in this report.

With these variables in mind, our evaluation of geologic controls on nitrate transport targeted individual locations in southeastern Minnesota where water chemistry, geologic, and hydrologic data were collectively of the best quality to depict a generalized distribution of relative nitrate concentrations within the context of a hydrogeologic framework. These depictions are presented in map and cross-sectional view in Figures 40-48, and are representative of a number of variable geologic and hydrologic settings across the regional study area. Each cross section shows relatively high, moderate and low nitrate concentrations. Relative concentrations are depicted because of the difficulties in quantifying concentration of a nonconservative contaminant in a groundwater system with spatially and temporally variable flow using a database that includes only a small number of long term monitoring sites sampled in systematic fashion. As a general frame of quantitative reference for the depiction of nitrate in these cross-sections, the relatively high concentrations should be expected to range from between 5ppm and 15 ppm (Table 1). This range is based on concentrations sampled from springs, wells, and baseflow in hydrogeologic conditions most representative of uppermost bedrock groundwater within the available dataset.

Table 1. Summary of measures of nitrate concentration in relatively shallow groundwater of the bedrock dominated landscape. (1) Springs outside of incised valleys on the Upper Carbonate and Prairie du Chien Plateaus. All discharge from stratigraphic levels above the Jordan Sandstone. From database compiled for this project (2) Springs and seeps on Prairie du Chien Plateau, Upper Carbonate Plateau, and escarpment between the plateaus. All discharge from stratigraphic levels above the Jordan Sandstone. (3) Springs along Trout Creek, discharging from Prairie du Chien Group (Groten and Alexander, 2013). (4) Water wells sampled as part of MDA private well monitoring network. All have open hole interval that includes Prairie du Chien Group or higher stratigraphic level, in setting where geologic conditions indicate the absence of aquitard above open-hole interval. (5)Water wells sampled by Dakota County as part of water quality monitoring program. All wells open to Prairie du Chien Group where Prairie du Chien Group is uppermost bedrock. (6) Water wells in database compiled for this report. All wells located where unconsolidated sediment is less than 50 ft thick. Wells open to St Peter Sandstone or Prairie du Chien Group, or Galena Aquifer, where those units are not overlain by known, regionally extensive bedrock aquitards. (7) Stream baseflow samples from Watkins et al. (2011). All samples from stream reaches on top of Prairie du Chien Group of higher stratigraphic levels. See Appendix C for databases with additional information on sources of information and geologic context.

Spring Database

No. of springs	Nitrate range (ppm)	Nitrate mean (ppm)	Sample dates	Counties sampled
13(1)	4.2 to 14.1	8.8	1976 to 2010	Fillmore, Wabasha
251(2)	no detect to 39.6	6.9	1986	Olmsted
12(3)	9.2 to 25.5	15.2	2011 to 2012	Dakota

Well Database

No. of wells	Nitrate range (ppm)	Nitrate mean (ppm)	Sample dates	Counties sampled
13(4)	1.4 to 26.1	8.7	2009 to 2012	Fillmore, Goodhue, Wabasha
9(5)	no detect to 26.4	7.3	2004 to 2006	Dakota
304(6)	no detect to 32.8	5.2	1988 to 2011	Dakota, Goodhue, Rice, Wabasha, Dodge, Olmsted, Winona, Fillmore

Stream Baseflow Database

No. of sample sites	Nitrate range (ppm)	Nitrate mean (ppm)	Sample dates	Counties sampled
40(7)	4.8 to 17.4	9.4	2005 to 2010	Dakota, Goodhue, Rice, Wabasha, Olmsted, Winona, Fillmore, Houston

The most insightful analysis of geological controls on nitrate concentration comes from areas where published County Geologic Atlases are available (e.g. Zhang and Kanivetsky, 1996; Campion 1997, 2002; Berg, 2003; Petersen, 2005), providing a detailed geologic and hydrologic framework, and where groundwater chemistry datasets were collected over relatively short intervals of time (typically within 2-3 years), which mitigates to some extent the impact of temporal changes in groundwater conditions on our analysis. Our depictions of the surface and subsurface distribution of nitrate concentrations in individual areas of southeastern Minnesota were then compared against one another, to identify repeated patterns that are indicative of geologic controls already documented in the literature to have an impact on nitrate transport and loading, and appear to be inconsistent with the effects of land use practices alone. One such pattern for example, is the correspondence between buried bedrock aquitards and stratification of groundwater nitrate concentrations that in turn mimic stratified groundwater ages.

We also analyzed the entire nitrate database compiled for this project to determine if the relationships between hydrogeologic conditions and the concentration of nitrate revealed from our evaluation of individual locations are reflected by variability in groundwater nitrate concentration at regional-scale. For example, we compare nitrate concentrations in groundwater above and below regionally extensive aquitards. The dataset and analyses are presented as frequency percent tables and corresponding histograms. A constant bin or class was used for nitrate concentrations that include: <2 ppm, 2-5 ppm and >5 ppm. Multiple samples from individual wells were averaged. For samples with nitrate concentration less than the detection limit, the detection limit was used as the value for statistical analyses. Water wells without adequate construction or geologic information to confidently interpret the hydrogeologic conditions (e.g. aquifer) from which the sample was collected were excluded from the statistical analyses.

The results of our evaluation of geologic controls on nitrate concentrations are presented below in two parts. The first part is an analysis of nitrate concentrations in groundwater sampled from wells and springs, focused mostly on the subsurface geologic controls that impact nitrate transport and loading. The second part focuses on stream baseflow nitrate concentrations, in an evaluation of the variability in concentrations relative to agricultural practices (Watkins et al., 2011), within the context of our understanding of the subsurface groundwater system.

GEOLOGIC CONTROLS ON GROUNDWATER NITRATE CONCENTRATION

Relatively thick (>50 ft) and low permeability unconsolidated sedimentary cover is well-known to provide a measure of protection from contamination to deeper aquifers in southeastern Minnesota, especially in the extensive drift dominated landscape (e.g., Campion, 1997, 2002; Dakota County Environmental Management Department, 2006). A representative example in cross sectional view is in central Mower County (west side of cross sections in Figs. 21 and 40) where uppermost bedrock groundwater is of mixed age, and nitrate-poor. A correspondence between thicker unconsolidated sedimentary cover and lower nitrate concentrations in underlying aquifers is subtly revealed in our regional database by a comparison of concentrations of relatively shallow bedrock groundwater (<200 ft) sampled from wells located where unconsolidated sediment cover is thicker than 50 feet, to wells where cover is less than 50 ft (Figs. 49, 50A). In this analysis, 11.8% of wells where sedimentary cover is less than 50 feet thick had a nitrate concentration greater than 2 ppm whereas 8.1% of wells where the cover is more than 50 feet had values greater than 2 ppm. This relationship is much more pronounced in a comparison of shallow bedrock groundwater from wells within the *interior* of the drift dominated landscape, to all other areas (Figs. 49, 50B). The results indicate that 12.5% of wells outside of the interior of the drift dominated landscape have nitrate concentrations greater than 2 ppm and only 1.77% wells within the interior of the drift dominated landscape, nearly an order of magnitude less, have nitrate concentrations that exceed 2 ppm. The marked contrast between the two analyses indicates that a relatively continuous cover of unconsolidated sediment greater than 50 ft thick is required to generally protect underlying bedrock aquifers from nitrate contamination. In areas of less continuous cover, individual wells located where unconsolidated sediment is greater than 50 ft thick have nearly the same probability of having nitrate concentrations greater than 2 ppm as do wells elsewhere in the bedrock dominated landscape where the cover is thinner. This reflects the three dimensional character of the flow system in the bedrock dominated landscape: An individual well located on an isolated patch of thick sedimentary cover is drawing water that likely in part includes a source of nitrate-enriched water from nearby areas lacking a thick cover of unconsolidated sediment, and transported laterally to the well site.

A much smaller sample of wells that draw water from unconsolidated sand and gravel aquifers within and along the margins of the drift dominated landscape also appears to reflect limited nitrate-enriched water at depth in this area (Fig. 51). Only 9.5% (4 of 42) of these relatively shallow wells (casing less than 100 ft) exceed 2 ppm nitrate. The relatively low nitrate concentration in the unconsolidated and upper bedrock aquifers across the drift dominated landscape is inconsistent with what would be expected from land use activities alone because the percentage of land utilized for row crop production is generally higher in the drift dominated landscape than it is in the bedrock dominated landscape (Fig. 37A). The widespread, fine grained aquitards characteristic of the drift dominated landscape may physically inhibit vertical flow and divert nitrate enriched water laterally to discharge at streams, limiting the rate of recharge to deeper unconsolidated and upper bedrock aquifers. Near-surface fractures in these aquitards, as well as drain tile networks (Schilling and Helmers, 2008; Dubrovsky et al. 2010) will enhance this lateral movement. Denitrification likely also plays a major role. The process is well documented to occur in unconsolidated sediment of this region, especially in till-dominated landscapes (Rodvang and Simpkins, 2001; Helmke et al., 2005; Wall, 2013b). Within our database, the nitrate concentrations from the British Petroleum Spring Valley Terminal contamination site appear to be characteristic of chemical or biological attenuation of nitrate at relatively shallow depths in the unconsolidated sedimentary cover. Over a four year period samples from 27 individual wells most commonly yielded nitrate values of less than 1 ppm, but those sampling events were punctuated by events when the water was nitrate-enriched, with individual samples commonly exceeding 4 ppm (Figs. 38A, 39). Average and median Eh, and total iron concentrations of water from the same well network are indicative of conditions that promote denitrification (Trojan et al., 2002). In addition to iron, organic carbon in fine grained unconsolidated sediment, as well as in contaminants at the site, would promote denitrification. Average and median dissolved oxygen (DO) concentration are higher than conditions typically conducive to denitrification but sufficiently low DO values were present during some sampling events in nearly all wells.

It is difficult to evaluate at regional scale the effect of variable permeability of unconsolidated sediment on groundwater nitrate concentration, mostly because detailed 3-dimensional subsurface mapping of this material across most of the regional study area is lacking. Locally, Campion (2002) and Campion and Green (2002) showed that small areas of Mower County contained sand and gravel deposits of sufficient abundance and connectivity to provide high permeability avenues for rapid recharge and delivery of recent water to underlying bedrock. Such high permeability "windows" of rapid recharge in an otherwise aquitard-dominated area of thick unconsolidated sediments (>50 ft) are well documented elsewhere in Minnesota outside of our regional study area (e.g. Tipping, 2012; Dakota County Environmental Management Department, 2006). A regional evaluation in which we compared calculated drift permeability to nitrate concentrations from individual wells in upper bedrock aquifers (cased < 200 ft into bedrock) does show a relationship consistent with these local observations (Figs. 52, 53). Wells located where unconsolidated sediment on top of bedrock has a relatively low calculated permeability (<2) have lower nitrates than wells located where drift permeability is higher (>2). Specifically, 16.1% of wells with a high drift permeability (>2) had nitrate concentrations greater than 2 ppm and 7.3% wells with a low drift permeability (<2) had nitrate concentrations greater than 2 ppm (Fig. 53A). This applies even in areas where unconsolidated sediments are greater than 50 ft thick. For example, wells with high drift permeability (>2) and > 50 feet of drift have nitrate concentrations greater than 2 ppm (16.4%) slightly more frequently than wells with high drift permeability and < 50 feet of drift (14.9% have concentrations greater than 2 ppm) (Fig. 53B).

In the bedrock dominated landscape of southeastern Minnesota, bedrock aquitards exert significant control on the concentration of nitrate in groundwater. This is best illustrated by the stratification of concentrations shown on cross sections (Figs. 40-48), which generally mimics groundwater age stratification described earlier in this report. Relatively high nitrate concentrations, commonly exceeding 5-15 ppm (Table 1), are characteristic of water well and spring samples from uppermost bedrock water table aquifers across this landscape, reflecting rapid recharge through the largely thin cover of unconsolidated sediment and fracture dominated flow through bedrock. This nitrate-enriched water typically extends downward to an aquitard that separates it from older water with relatively low nitrate concentration below. Across the regional study area such stratification is known to occur across a number of aquitards, including the Dubuque-Maquoketa (e.g. Fig. 40), Cummingsville-Glenwood (e.g. Figs. 40-42), Oneota (e.g. Figs. 43-47), and lower Jordan/St Lawrence (e.g. Figs. 43, 44). Our cross sections do not include a representative setting where similar stratification is present above and below the Tunnel City aquitard, but such locations can be identified along the lower reaches of the tributaries to the Mississippi River in the GIS project that accompanies this report. In addition to the evidence provided on the individual cross sections, the stratification in groundwater age (presented earlier in this report) and/or in nitrate concentration across each of these aquitards is supported by data in other areas, shown in maps and cross sections for County Atlas projects in Rice (Campion, 1997), Fillmore (Zhang and Kanivetsky, 1996), Mower (Campion, 2002), Goodhue (Berg, 2003), and Wabasha (Petersen, 2005) counties of southeastern Minnesota. As with the aquitards in unconsolidated sediment, attenuation of nitrate concentrations in association with bedrock aquitards to some degree likely reflects retardation of vertical flow and diversion of nitrate enriched water laterally, limiting the rate of recharge to underlying aquifers. Conditions promoting chemical attenuation such as denitrification are also known to be present in association with bedrock aquitards in southeastern Minnesota (Trojan et al., 2002).

In an attempt to determine how nitrate attenuation across bedrock aquitards is reflected in our large database of nitrate values from water wells, we categorized the wells into subsets based on the position of the open hole-interval relative to bedrock aquitards in the borehole (Fig. 54A). Wells with sufficient stratigraphic and construction information were categorized into three groups, those in which the open hole is: 1) entirely above all aquitards 2) within an aquitard (and underlying aquifer), and 3) entirely below an aquitard. Limitations inherent in many well records led to the exclusion of most wells that would address the effects of the Oneota aquitard, and all aquitards above the Decorah Shale (see caption to Fig. 54A for further explanation of this and other limitations to analysis). Despite the limitations of our dataset, the analysis does subtly reflect the ability of an aquitard to attenuate nitrate concentration in underlying groundwater: 12.7% of wells that are cased above all bedrock aquitards have nitrate concentrations greater than 2 ppm, whereas wells cased partly into, and fully below an aquitard have slightly lower percentages, 9.7% and 9.3%, respectively, of wells with nitrate concentrations exceeding 2 ppm. The relationship between the presence or absence of an aquitard above the open-hole interval and nitrate concentration is a bit more pronounced in a comparison of wells yielding samples exceeding 5 ppm (Fig. 54A).

In a second analysis we selected wells located only in the bedrock-dominated landscape, where unconsolidated sediment provides relatively little protection to the bedrock aquifers from nitrate enriched water, and we focused on the Decorah Shale part of the Glenwood-Cummingsville aquitard (Fig. 54B). The Decorah shale is regarded as having the greatest aquitard integrity (lowest bulk vertical permeability) of all Paleozoic aquitards in southeastern Minnesota, and presumably would therefore have the greatest ability to protect underlying aquifers from nitrate contamination. Wells in this analysis are open to the St Peter Sandstone and/or Prairie du Chien Group. The results showed that 24.5% of wells that draw water from an open-hole interval unprotected by the Decorah Shale (Decorah Shale absent or well open across the Decorah) had nitrate concentrations greater than 2 ppm. Only 13.9% of wells (79) drawing water from open hole intervals beneath the Decorah yielded nitrate concentrations greater than 2 ppm (Fig. 54B). The results of this analysis more strongly reflects the ability of an aquitard to attenuate nitrate concentrations than the results of our analysis that tested multiple aquitards, and included wells in the drift dominated landscape.

Although limitations to the well records preclude precise determination of open hole interval relative to the position of the Oneota aquitard, a comparison of wells drawing from any part of the Prairie du Chien Group to wells drawing only from the Jordan Aquifer provides some insight into the ability of the Oneota to limit nitrate concentrations below it (Fig. 54C). Across the Prairie du Chien Plateau of the regional study area, wells open to the Prairie du Chien Group are more than twice as likely to yield water with a nitrate concentration above 2 ppm (30.3%) than are wells open only to the Jordan Sandstone (12.3%), a reflection of the ability of the Oneota aquitard to diminish transport of nitrate-enriched water downward into the Jordan. Locally the impact of the Oneota aquitard is even more pronounced. For example 56% of wells open to the Prairie du Chien Group in northern Olmsted and southern Wabasha Counties yield water with nitrate concentration exceeding 2 ppm, whereas only 8% of wells open only to the Jordan in the same area exceed that value (Figs. 55-56). Other areas with nitrate-poor water in the Jordan Sandstone beneath nitrate enriched, overlying Prairie du Chien Group water are illustrated in the cross sections of Figures 43-46. This marked difference in contamination between Prairie du Chien and Jordan aquifer water has also been documented in previous southeastern Minnesota investigations (Setterholm et al., 1991; Wall and Regan, 1994).

Breached aquitards, both in the subsurface and at erosional edges at the land surface, described earlier in this report, lead to elevated nitrate concentrations in progressively lower aquifers in a generally southwest to northeast direction across the region, shown in greatest detail on individual cross sections in Figures 40-47, and summarized in the regional cross section in Figure 48. Via these kinds of step-downs across successive aquitards, the transport of nitrate in the groundwater-surface water system at regional scale mimics our earlier description of the flow system across the bedrock dominated landscape. Step-down of nitrate-enriched water to progressively lower aquifers occurs as successively lower aquitards are breached in a generally southwest to northeast direction. This can lead to recharge of nitrate enriched water into upper bedrock aquifers that in up-gradient areas are nitrate-poor. Water discharged out of the Cummingsville Formation that recharges the inward edge of Prairie du Chien Plateau at the eroded edge of Glenwood-Cummingsville aquitard (the "Decorah Edge" setting) is perhaps the best documented, near-surface example of this phenomenon (Delin, 1991) (Figs. 41,43,44). Breaching of the Dubuque-Maquoketa aquitard as it transitions to a shallow bedrock setting in western Fillmore County (Fig. 40) is a subsurface example of otherwise generally similar conditions. Low or undetectable nitrate concentrations in the Galena aquifer transition laterally to moderate concentrations where the overlying Maquoketa-Dubuque aquitard reaches a position near the bedrock surface in a west to east direction across the Upper Carbonate Plateau in eastern Mower and western Fillmore Counties (Fig. 40). Dye traces and contaminant transport paths at the British Petroleum Spring Valley Terminal contamination site, which is located in this transitional area, demonstrate that the Maquoketa-Dubuque aquitard is relatively ineffective at protecting the underlying Galena aquifer from pollution (Alexander and Alexander, 1998). Nitrate enriched water appears in "pulses" even near the bottom of the Galena aquifer (Figs. 38, 39). Similarly, nitrate concentrations in the Jordan aquifer commonly increase near bedrock valleys across the Prairie du Chien Plateau, where enhanced development of vertical joints through the Oneota aquitard provide a pathway for nitrate enriched water from the Shakopee aquifer to recharge more rapidly into the Jordan (Fig. 45) (Petersen, 2005; Tipping et al., 2006).

Nitrate-enriched water in bedrock aquifers is not entirely limited to places where immediately overlying aquitards have been removed by erosion or breached by vertical fractures in shallow bedrock settings. It can also be found locally directly beneath fairly extensive cover of deeply buried aquitards that are presumed to have very low bulk vertical conductivity. This appears to be common beneath the Cummingsville-Glenwood aquitard within a few miles of its irregular erosional escarpment, where St Peter and Shakopee aquifer water commonly has relatively high nitrate concentrations locally (e.g. Figs. 43, 44). Although downward flow through vertical fracture networks in the aquitard cannot be entirely discounted, this phenomenon may be best explained by the presence of local flow paths that transport nitrate-enriched water on the Prairie du Chien Plateau laterally into areas beneath the Cummingsville-Glenwood aquitard. This phenomenon likely accounts for many of the nearly 14% of St Peter and Prairie du Chien wells in our analysis with nitrate values exceeding 2 ppm (Fig. 54B) even though they draw water from beneath the Cummingsville-Glenwood aquitard. Generally similar flow conditions may occur near the edges of other aquitards in the bedrock system.

Although erosional edges of aquitards can be a preferential pathway for recharge of contaminated water into underlying aquifers, recent research has shown that nitrate concentrations may be attenuated along the discharge to recharge pathway. The best documented example is along the "Decorah Edge", where the concentration of nitrate in water discharged from the Upper Carbonate Plateau is reduced via chemical and biological processes along wet landscapes (hydric soils) on the Cummingsville-Glenwood escarpment. As a result, the nitrate concentration of the water that ultimately recharges the downgradient St Peter and Shakopee aquifers can be lower than the concentration in the discharged Galena water. Some component of dilution from water with lower nitrate concentration along this pathway may also cause the attenuation (Jones et al., 2010). It is possible that nitrate attenuation may occur through similar processes along the erosional edges of other aquitards. Such a setting within valleys incised below the Prairie du Chien Plateau has been referred to as the "St. Lawrence Edge" (Center for Rural Design, University of Minnesota, 2008) although we believe the name is a misnomer because our field observations indicate the wet land surface areas characteristic of where nitrate attenuation may occur correspond to where the lower part of the Tunnel City Group is uppermost bedrock, not the St. Lawrence Formation.

In addition to chemical and biological processes such as denitrification, dilution of nitrate enriched water by mixing with less contaminated water is also a common phenomenon (e.g.

Dubrovsky et al., 2010). It is common in parts of aquifer systems that have both a local source of nitrate-enriched water from the land surface, and a deeper source of water that in upgradient directions is relatively protected by aquitards. Such conditions are present in many places in the hydrogeologic system across southeastern Minnesota, given the context of bulk flow directions, chemically stratified water bodies, and breached aquitards. The hydrogeologic circumstances dictating the process of dilution are best visualized in cross sectional view in Figures 40, 43, 45, 46, and 48. Each cross section includes an area where locally derived, nitrate-enriched water mixes with more regionally-derived nitrate-poor water. At a broader scale, the regional-scale cross section (Fig. 48) illustrates how groundwater discharge in major stream valleys characteristically will include some component of regionally derived deeper water that mixes with locally sourced water.

Data from individual sites across southeastern Minnesota also provide evidence that variability in nitrate concentrations can be accounted for by mixing of waters with different sources. Groten and Alexander (2013) recently described a systematic decrease in nitrate concentrations and chloride/bromide ratios of spring water in a downstream direction along Trout Brook in southeastern Dakota County. They hypothesized that the springs farther downstream have springsheds that included longer flow paths draining deeper parts of the aquifers. These deeper flow paths would be more buffered from land surface activity in upgradient directions. We show their spring nitrate concentration data in cross section view along with nitrate concentrations from water wells in Figure 46. Groundwater that is relatively nitrate-poor is more likely to contribute to springs in a downstream direction along Trout Brook.

Galena Aquifer water chemistry at the British Petroleum Spring Valley Terminal contamination site may also reflect the impact of dilution (Figs. 38, 39). The maintenance of relatively low average nitrate concentrations in the Galena aquifer (Zones S2 down to S1) can be explained by dilution via lateral flow of nitrate-poor water from more regionally extensive sources to the west where the aquifer is better protected by overlying aquitard(s), as depicted on the cross section in Figure 40. Episodic pulses of nitrate enriched water in the Galena aquifer at the site are likely more locally sourced and reflect local conditions of relatively intensive agricultural activity, a thin cover of unconsolidated sediment, and rapid flow through bedrock via fractures. Relatively high dissolved oxygen and low total iron concentrations measured in Galena Group water over this same period of time are not conducive to the process of denitrification (Trojan et al., 2002), in contrast to the conditions in the unconsolidated sediment at the site.

Spring water nitrate data compiled for this project (Figs. 57-60) also show characteristic patterns that may reflect the degree of dilution from nitrate-poor water sourced from regional flow systems that mixes with more locally derived, nitrate-enriched water. Springs sourced from the karstic bedrock on the Upper Carbonate and Prairie du Chien Plateaus show a high degree of variability in nitrate concentration, reflecting strong connection to variable surface conditions such as changes in precipitation and land use practices. In contrast, springs in incised valleys that are sourced from siliciclastic-dominated bedrock and from the Oneota aquitard discharge water with relatively low variability in nitrate concentrations (Figs. 58, 59). The springs located along deeply incised valleys are likely to have a significant, sustained contribution of nitrate-poor water from upgradient sources protected by one or more aquitards. Rock matrix in these deep settings beneath aquitards can yield older, nitrate-poor water that mixes with younger, nitrate-enriched water carried in fracture networks. The comparatively limited fracture development, and high matrix conductivity in the siliciclastic units in this part of the section compared to karstic carbonate rock would promote more thorough mixing of nitrate-poor regional water with nitrate-enriched, locally derived water, leading to lesser variability in concentrations.

Results from dye trace investigations by Green et al. (2008, 2012) and spring monitoring by Luhmann et al. (2011) are consistent with our interpretation of variable degrees of mixing between regional and locally sourced water. Some dye traces through these formations (Green et al., 2008, 2012) had temporally extended recovery tails of years duration that likely reflect a larger component of storage and travel though intergranular matrix blocks and fracture networks with relatively limited aperture size compared to some carbonate-dominated bedrock such as the Galena-Spillville karst system. Under baseflow conditions, locally derived water for St Lawrence and Tunnel City springs in these settings is apparently a small proportion of discharge compared to many springs in carbonate dominated karstic rock. Luhmann et al. (2011) used temperature logging of springs in southeastern Minnesota to correlate relatively limited fracture flow with spring temperature patterns indicative of thermally effective flow paths. Five springs categorized as thermally effective by Luhmann et al. (2011) are also part of our nitrate database (Fig. 58), and all five show relatively low variability in nitrate concentration over time. Despite these differences between the fully karstic and siliciclastic dominated systems, it is important to recognize that preferential flow paths that facilitate high groundwater flow velocities exist in all parts of the Paleozoic bedrock hydrogeologic system, including the sandstone aquifers (e.g. Runkel et al. 2006; Swanson et al., 2006).

Variability in nitrate concentrations for six Galena Group springs located on the Upper Carbonate Plateau of western Fillmore County may also in part reflect variable degrees of dilution controlled by geologic conditions (Fig. 60). Three of these springs (Fountain, Quarry, and Stagecoach) are located in two springsheds unlikely to have significant contribution from regionally sourced water (Fig. 35). These springs have relatively large variability in concentration over a number of years (Fig. 60). In contrast, the other three springs (Cache, Grabau, and Moth) are located in hydrogeologic settings conducive to significant contribution from regionally sourced flow (Fig. 35). Two of the three have relatively low variability in nitrate concentration (Fig. 60).

The overall lower average nitrate concentration in the springs that also have lower variability in concentration could also be explained by dilution. Indeed, the hydrogeologic setting at these springs indicates that mixing of regionally derived, nitrate-poor water with more locally derived nitrate-enriched water occurs up-gradient of these springs. However, land use practices are very likely an important factor as well. Cropland maps for the past several years (e.g. Fig. 37A) show that the karstic plateau setting in which the springs with high average nitrate concentrations are located generally have had a significantly higher percentage of row crop production than areas characterized by incised valleys where springs from siliciclastic bedrock are mostly located. Similar agricultural data are not available for much of the earlier sampling period of these springs, but it is reasonable to assume that land use was generally similar. In the next section of this report, agricultural practices are taken more fully into consideration as part of our analysis of geologic controls on baseflow to streams.

GEOLOGIC CONTROLS ON STREAM NITRATE CONCENTRATION

The correlation between stream baseflow nitrate concentrations and row crop production for the bedrock dominated landscape documented by Watkins et al. (2011) (Fig. 37) suggests that land use activity has a significant impact on stream water quality. There is, however, variability in the strength of the correlation, indicating that other factors such as geologic conditions play a role as well. In much of the following analysis we evaluate whether the variability in the correlation between land use and stream baseflow nitrate concentration can be accounted for by the geologic conditions that affect groundwater nitrate concentration described in the previous section. We selected areas within the watersheds studied by Watkins et al. (2011) that expressed variability in the correlation between land use and baseflow nitrate concentration, and evaluate these variations within the context of the hydrogeologic setting, using maps and cross sections (Fig. 61) as context. The results of our evaluation indicate that variable degrees of dilution from the introduction of relatively nitrate-poor water from deeper parts of the aquifer system is a significant factor that impacts baseflow nitrate concentrations in streams. We present these results beginning with site-specific examples comparing stream and spring measurements that provide evidence for dilution of stream flow via water from relatively deeply sourced aquifers. This is followed by a larger number of examples documenting the link between particular hydrogeologic settings and stream baseflow values that are higher or lower than expected based on agricultural activity.

The recent research by Groten and Alexander (2013) along Trout Brook in the Cannon River Watershed (CRW) in southeastern Dakota County may be the best documented example of progressive diminishment of baseflow nitrate concentrations along an individual stream reach as deeper sources of water are contributed downstream. They used synoptic measurements of nitrate, springflow, and streamflow to show that a decrease in nitrate concentration of stream water in a downstream direction is coincident with both a downstream systematic decrease in spring water nitrate concentration, and a progressive increase in streamflow rate (Fig. 62). The increase in streamflow appears to be most pronounced where the valley intersects the mid Prairie du Chien high conductivity conduit system, and is contributed mostly by distributed baseflow, with a subordinate component from springs. Groten and Alexander (2013) interpreted these conditions to be indicative of a greater proportional contribution to baseflow via deeper groundwater sources in a downstream direction. Their interpretation is supported by our hydrogeologic characterization of the site, which takes into consideration fracture attributes, head levels, and bulk flow directions in underlying groundwater system (Fig. 46). Deeper, less contaminated water is increasingly more accessible via conduits that intersect the bedrock valley, including contribution from Jordan aquifer water with markedly lower concentrations than that of the Trout Brook stream water and springs.

Other locations across the Prairie du Chien Plateau and its incised valleys show relationships analogous to those described above. One site is along the lower reach of the South Fork of the Whitewater River, Winona County (Fig. 63), within the upper part of the Mississippi-Whitewater (MSW) watershed sampling area. Nitrate concentrations from Crystal Springs State Fish Hatchery #1 spring, which emanates from the St. Lawrence Formation, averaged about 4 ppm measured over a five year period from early 2005 to late 2009. This water drains into the South Fork of the Whitewater, which over the same 5 year period averaged over 7 ppm nitrate at a sampling station (MSW02) only 0.4 miles up the valley from the Hatchery. Water from this spring, and likely most other baseflow (springs as well as distributed flow) sourced from the St. Lawrence and deeper stratigraphic levels in the lower part of the valley would serve to dilute the nitrate enriched stream water of the South Fork as it passes through this area.

A few miles west of the Crystal Springs Hatchery, along the North Fork of the Whitewater River, stream water nitrate concentrations systematically decrease relative to row crop production in a downstream direction as the valley is incised progressively deeper into the stratigraphic section (Fig. 64). The most upstream sampled locations are relatively high on the Prairie du Chien Plateau, on the Shakopee Formation, and the most downstream sample sites are located where the valley is incised below the level of the Jordan Sandstone. Progressively greater contribution from more deeply sourced, nitrate-poor groundwater (e.g. Fig. 44) likely accounts for this trend of downstream-decreasing stream water nitrate concentrations relative to row crop production. The upper reaches of the South Fork of the Whitewater River in this area has only two surface water sampling sites, but is analogous to the North Fork in that stream water in the far upper reaches of the tributary has a high nitrate concentration relative to row crop production, compared to the sampling point in the downstream location (Fig. 64). The upper sampling site is along the Cummingsville-Glenwood escarpment, where stream water may be dominated by nitrate-enriched water discharged from the Galena aquifer on the Upper Carbonate Plateau. The downstream location is on the Shakopee aquifer, which may contribute water with a relatively low nitrate concentration.

A broader-scale evaluation across the upper part of the MSW watershed shows some of the same relationships that can be explained through variable degrees of dilution from deeper sources of water with relatively low nitrate concentrations (Fig. 65). The three sampling locations with lowest nitrate concentrations relative to row crop production (MSW 4, 11, 16) are within relatively deeply incised valleys where the Oneota Dolomite through the St. Lawrence Formation (or Tunnel City Group) are uppermost bedrock. These reaches of tributaries can be expected to have a more significant baseflow contribution from deeper aquifers with nitrate-poor water. The relatively low nitrate concentration of water emanating from springs Crystal Springs Hatchery relative to nearby stream water concentrations (described earlier) is a representative example of such dilution in this area. In contrast to these areas where dilution is likely significant, locations with high baseflow nitrate concentrations relative to row crop production are, with one exception (MSW8), positioned farther upstream along tributaries. Baseflow along these stream reaches is likely dominated by nitrate-enriched water that originated as local recharge into the Galena or Prairie du Chien Groups.

Two other watersheds, the Zumbro River (ZRW) and Mississippi River Pepin (MSP), characterized by deeply incised valleys in the Prairie du Chien Plateau, each have stream water sampling sites that are dominated by low nitrate concentrations relative to row crop production, compared against the correlation for all watersheds combined (Figs. 66, 67). Shallow groundwater in the Prairie du Chien at higher elevations in these areas is known to be nitrate-enriched (e.g. Fig. 45). Dilution via baseflow contribution from the lower bedrock levels that are incised in these deep valleys is likely a major factor accounting for the dominance of relatively low nitrate concentrations relative to row crop production. The cross section in Figure 45 illustrates an example of discharge of relatively nitrate-poor Jordan aquifer water as baseflow in this manner. The ZRW watershed also includes an example of diminishment in nitrate concentration relative to row crop production along an individual stream reach, similar to that described above for Trout Brook and the MSW watershed: Stream water nitrate concentration relative to row crop production along the Long Creek tributary to the Zumbro river decreases in a downstream direction as the valley is incised progressively deeper into the stratigraphic section.

One sample location in each of the ZRW and MSP watershed areas yielded a high stream water nitrate concentration relative to row crop production. The location in the Mississippi Pepin watershed (MSP 09) is the only one in that area positioned relatively high in a tributary valley, where contribution from deeper aquifers would be relatively minor compared to the other sampling sites (Fig. 67). In the Zumbro River watershed, the sampling site with the outlying relatively high nitrate concentration (ZRW5) is positioned on the lower part of a small tributary valley where the Jordan Sandstone is uppermost bedrock (Fig. 66), in all appearances similar in position to others in the area with lower relative nitrate concentrations. The apparent lack of significant dilution at ZRW5 may represent local conditions that lead to minimal discharge of deeper aquifer water, or discharge of deeper water already relatively high in nitrate concentration (Fig. 45, Fig. 66 inset). The nitrate concentration in a nearby spring that contributes to the stream baseflow at this location showed an elevated value compared to other springs in this area emanate from the Jordan and lower stratigraphic positions, lending some support to the latter scenario.

Hydrogeologic conditions that lead to variable degrees of nitrate-poor baseflow contribution from deeper groundwater paths can also account for some of the variability in stream nitrate concentrations relative to row crop production across the Upper Carbonate Plateau, its erosional escarpment, and the inner part of the Prairie du Chien Plateau in the upper part of the Root River Watershed (RRW) (Fig. 68). Sampling locations with low nitrate concentrations relative to row crop productivity are preferentially along stream reaches where locally sourced contributions to baseflow can be expected to be mixed with less contaminated water derived from regional flow systems. Two hydrogeologic settings are conducive to having a significant component of regionally sourced water. One such setting is similar to conditions in other watersheds we have already described, whereby the Oneota Dolomite and especially the units below it provide a source of nitrate-poor water along valleys deeply incised into the Prairie du Chien Plateau. An example of this phenomenon is illustrated in cross sectional view in Figure 43. The second setting is along stream reaches near the eroded edge of the Maquoketa-Dubuque aquitard. This latter hydrogeologic setting is conducive to a significant baseflow contribution of nitrate-poor Galena aquifer water that is protected by the Maquoketa-Dubuque aquitard in upgradient directions (e.g. Figures 40, 41). Elsewhere in the upper RRW, stream water nitrate concentrations that are relatively high compared to row crop activity are dominated by sample locations along the Cummingsville-Glenwood erosional escarpment, and across the Prairie du Chien Plateau above the deepest parts of the incised valleys. Baseflow to streams close to the escarpment may be dominated by nitrate-enriched water that originated as local recharge into nearby areas of the Upper Carbonate Plateau, and then relatively rapidly discharged across the escarpment directly into tributary streams, as well as local, direct recharge from the land surface across the Prairie du Chien Plateau.

At a smaller scale, Willow Creek and its tributaries in the eastern part of the local springshed project area represent one of the few examples of a downstream increase in nitrate concentration relative to row crop production (Fig. 69). This too can be explained by relative degree contribution from regionally sourced water. The most upstream sampling site (RRW 33), lies near the edge of the Maquoketa-Dubuque aquitard in the headwaters of Willow Creek, a setting conducive to significant contribution from nitrate poor water in the Galena aquifer. Farther down the valley, sampling sites (RRW 30, 31, 32) show a marked increase in nitrate concentration relative to row crop production. Enrichment in nitrate concentration relative to row crop production can be accounted for by a progressive downstream contribution from nitrate-enriched Galena aquifer water on the plateaus directly above the valley. The Galena aquifer on these plateaus does not have the protective cover of the Maquoketa- Dubuque aquitard.

The variability in stream water nitrate values along the Cannon River watershed (CRW) (Fig. 70) also can be accounted for to some extent by variable geologic settings. The two sampling sites with the highest nitrate concentrations relative to row crop production (CRW29, 30) are along a reach of Trout Brook where Shakopee Formation is uppermost bedrock. Upgradient areas of southeastern Dakota County are characterized by patchy, irregular distribution of unconsolidated sediment that exceeds 50 ft in thickness. Most of the unconsolidated sediment is dominated by sand and gravel. This area is also heavily irrigated (Minnesota Department of Natural Resources, 2013), which may also play a role in the delivery of nitrate enriched water to the groundwater system (e.g. Muir et al., 1973; Townsend and Young, 1995). Collectively these factors may explain the relatively high stream water nitrate values relative to row crop production. A third sampling location near the downstream end Trout Brook (CRW26) shows lower stream water nitrate concentrations relative to row crop production, which was described earlier in this report and attributed to an increase in contribution from more deeply sourced groundwater with relatively low nitrate concentration.

All but one of the remaining sampling stations for the CRW, with the exception of CRW 28, are located in areas where the unconsolidated sediment cover is more uniformly greater than 50 ft thick, and tills are more abundant (Fig. 70). Most are in relatively narrow valleys in which baseflow is sourced from within, or beneath this thick cover. These locations are dominated by nitrate concentrations that are markedly low relative to row crop production. Baseflow in this area appears to be dominated by contribution from unconsolidated sediment and upper bedrock aquifers that in upgradient areas are overlain by unconsolidated aquitards (e.g. tills and clay and silt-rich lake deposits). As described earlier in this report, very low nitrate concentrations in groundwater are characteristic of the drift dominated landscape. In addition to fine-grained aquitards such as tills physically impeding recharge of nitrate-enriched water, denitrification likely also plays a significant role in the general maintenance of relatively low nitrate concentrations in the groundwater of this region.

SUMMARY AND DISCUSSION

Our evaluation of the hydrogeologic system and geologic controls on the transport of nitrate in the bedrock dominated landscape of southeastern Minnesota concludes that:

- Nitrate is transported in a groundwater- surface water system that is fracture dominated, with the largest volumes of water travelling rapidly through a complex system of conduit networks.
- Aquitards between the major aquifers result in an anisotropic groundwater system, limiting the volume and velocity of vertical flow and promoting rapid lateral flow that discharges as baseflow to streams

- Groundwater in uppermost bedrock units, especially on the karstic plateaus that dominate the landscape of southeastern Minnesota, is typically nitrate-enriched, with concentrations commonly between 5-15 ppm.
- Nitrate concentration diminishes across aquitards, typically in a stratified manner that correlates with groundwater age, reflecting the anisotropy caused by aquitards.
- The most important factor we have identified that impacts both the magnitude and variability of nitrate concentration in spring water and stream baseflow is the proportion of regionally sourced, nitrate-poor water contributed from deep aquifers relative to more locally sourced, nitrate-enriched water from shallower aquifers.
- The relative proportion of these contributions to stream baseflow can often be correlated with the hydrogeologic setting.

Our results have relevance for both surface and groundwater management efforts to mitigate nitrate loading. One implication is that the response time of nitrate concentrations to changes in land use practices will likely vary in different hydrogeologic settings. Studies outside of southeastern Minnesota have concluded that some hydrogeologic systems function in a manner whereby changes in baseflow nitrate concentrations lag changes in land use practices by decades (e.g. Tesoriero et al, 2013). The most significantly lagged response in southeastern Minnesota should be expected in the deep valleys incised into the Prairie du Chien Plateau, where significant baseflow is derived from deep, siliciclastic-dominated bedrock sources with one or more overlying aquitards. The quantity and chemical composition of baseflow in these settings is buffered from changes in anthropogenic and natural conditions at the land surface. In contrast, quicker changes in baseflow nitrate concentrations can be expected in areas where the geologic setting allows only a relatively minimal contribution of regional flow. An example is the upper parts of stream reaches across the Prairie du Chien and Upper carbonate plateau settings where baseflow is dominated by locally derived water with fast-flow pathways that are well connected to the land surface.

The distribution of nitrate in ground and surface water we depict in this report represents the advance of nitrate from the land surface into the ground and aquifer systems over about 60 years, based on groundwater age dating, and the marked increase in fertilizer application that began in the late 1940's (Dubrovsky et al, 2010). The accuracy of predictions of future water quality will in part be dependent on an appreciation of the dynamic nature of the transport system. Particularly important is recognition that contaminant concentrations in progressively deeper aquifers are likely to increase with time, especially if input of nitrate is not reduced. All of the aquitards in the hydrogeologic system are leaky, and vertical gradients in most places are downward. Therefore through time younger more contaminated water is transported into deeper underlying aquifers. Lateral flow also transports contaminated water beneath aquitards. Furthermore, the relatively old water that serves to dilute contaminant concentrations is a finite resource that is diminishing with time, through natural discharge and from extraction by well pumping. Pumping also increases downward vertical gradients, increasing the rate at which older water is replaced with younger, more contaminated water. Attenuation of nitrate via denitrification may also diminish if electron donors become depleted and conditions change from reduced to oxic (Dubrovsky et al., 2010). As a result of these factors, assuming nitrate input from the land surface does not decrease in the future, increased levels of contamination in progressively deeper parts of the groundwater system should be expected.

While our results provide an improved understanding of geologic controls on nitrate transport in the bedrock dominated landscape of southeastern Minnesota, they also highlight the need for additional work beyond the scope of this project. Predicting the impact of changing land use practices on baseflow nitrate concentrations would be facilitated by quantitative estimates of the proportion of contributions to baseflow of shallow, nitrate-enriched water relative to deeper, nitrate-poor water in variable hydrogeologic settings. Strategies to protect deep aquifers that are currently nitrate-poor would be improved by a better understanding of the manner in which nitrate is transported beneath aquitards. The relative importance of anthropogenically caused transport from well construction and pumping versus natural pathways such as through faulted and fractured aquitards, and via lateral flow paths beneath aquitards, remains uncertain. Better measurements of hydraulic gradients across these aquitards in space and time would improve our understanding of vertical transport. The rate at which processes such as denitrification occur in variable hydrogeologic settings is also uncertain, and could be an important factor in controlling the rate at which deeper aquifers may become enriched in nitrate (Wall, 2013b). Denitrification and vegetative uptake of nitrate in riparian settings within incised valleys may be particularly important in diminishing stream concentrations (Puckett, 2004, Puckett and others, 2008, Tesoriero et al., 2000) in addition to the dilution effect that we have documented.

A better understanding of geologic controls on transport and concentration of nitrate in groundwater, and evaluating their importance relative to other controls such as land use practices and climate, will require datasets that appear to be scarce in southeastern Minnesota. The database we have compiled, while containing a large number of nitrate values, is a collection of samples that are spatially and temporally incomplete. For example, samples representative of the shallowest, unconfined groundwater are significantly under-represented. A more comprehensive sampling of nitrate concentration from uppermost groundwater across southeastern Minnesota is needed to better characterize the degree to which this water is impacted, and to monitor trends in concentration through time. Given the scarcity of wells constructed to draw water in such conditions, a broader scale sampling effort measuring spring water nitrate concentrations, especially in upper reaches of tributary valleys in the karstic plateaus, would be one way to collect such data. We also recognize a scarcity of data collected at highly resolved spatial and temporal scales, especially from sites where groundwater discharge contributes to stream baseflow. Synoptic sampling for water chemistry, in conjunction with measures of flow rates in springs and streams at a local scale is especially needed. Groten and Alexander (2013) collected such data for one stream reach in the Prairie du Chien plateau. Ongoing research by the MDA in Fillmore and Houston counties includes generally similar sampling strategies, as well as tracking land use practices and precipitation. Similar studies from other hydrogeologic settings across a larger area of southeastern Minnesota would contribute valuable new insights that could be applied to management of water quality to streams in the region.

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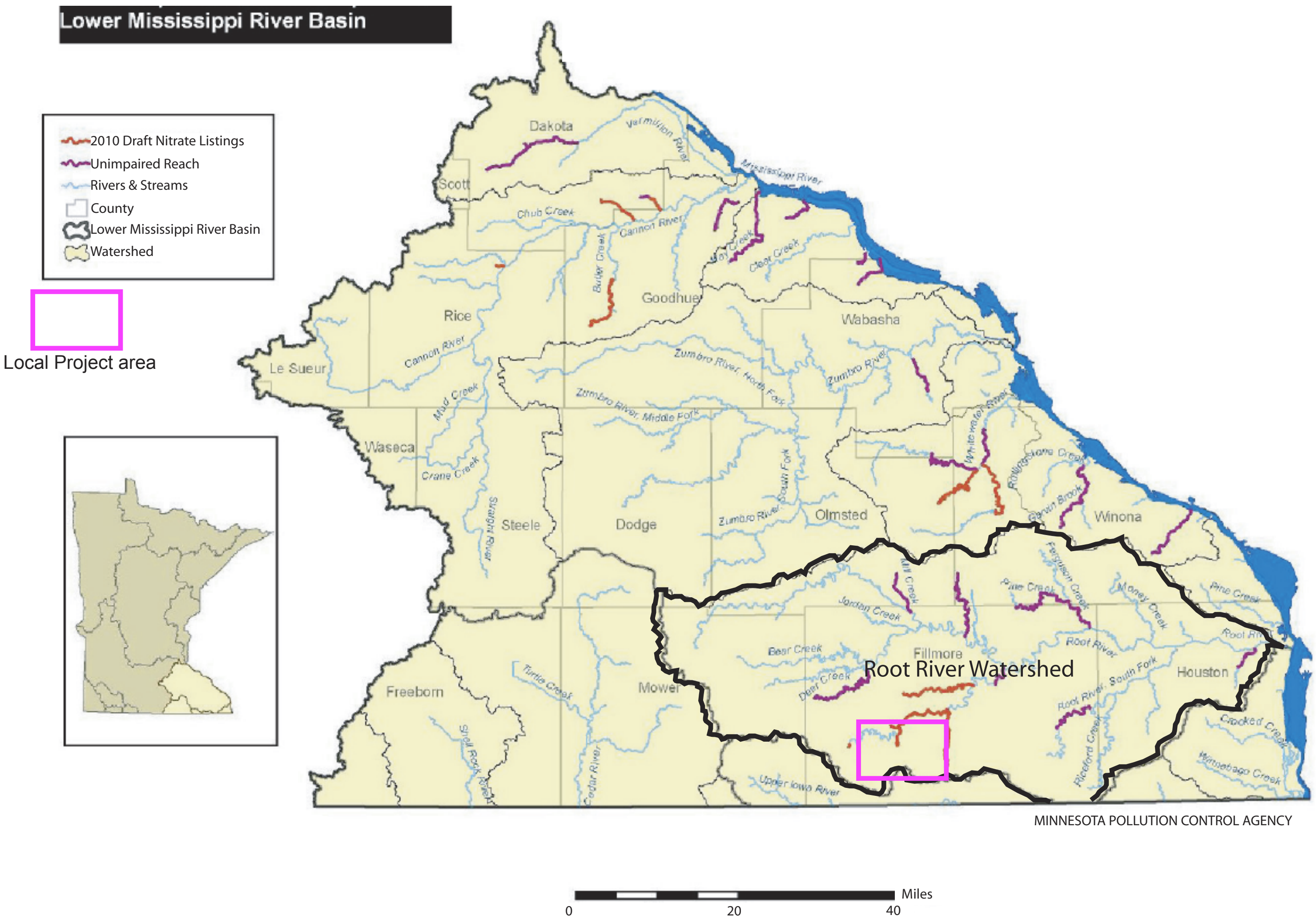


Figure 1. Lower Mississippi River Basin, southeastern Minnesota, showing stream reaches considered impaired, unimpaired, and those not yet evaluated, according to Minnesota Pollution Control Agency 2010 Draft Nitrate Listings. From the Minnesota Pollution Control Agency.

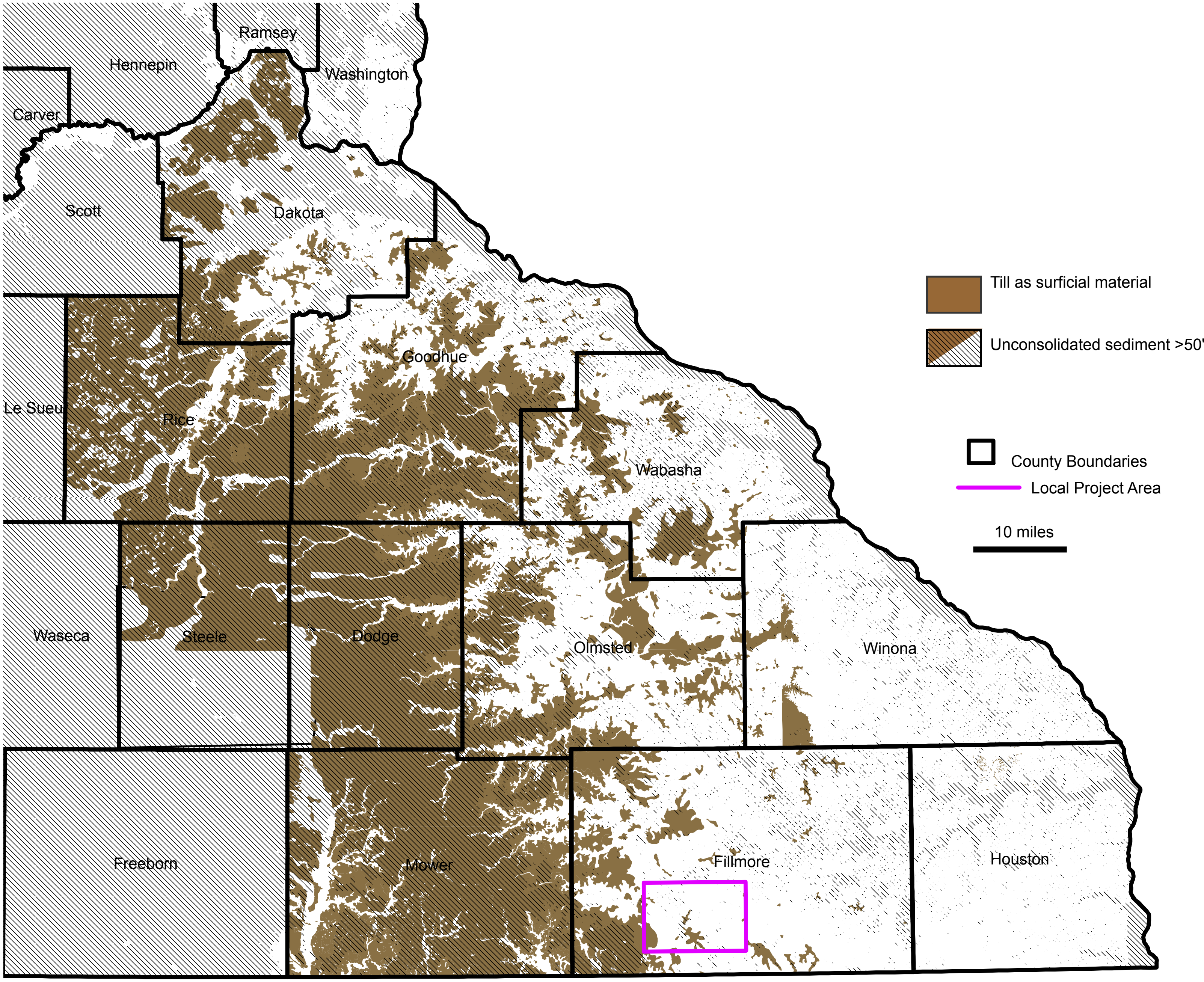


Figure 2. Example of map compilation for regional study area of southeastern Minnesota, here highlighting where unconsolidated sediment atop bedrock is greater than 50 ft in thickness, and where till (diamicton) is the surficial material. See text and Appendix B for methods and sources of information used in map compilation.

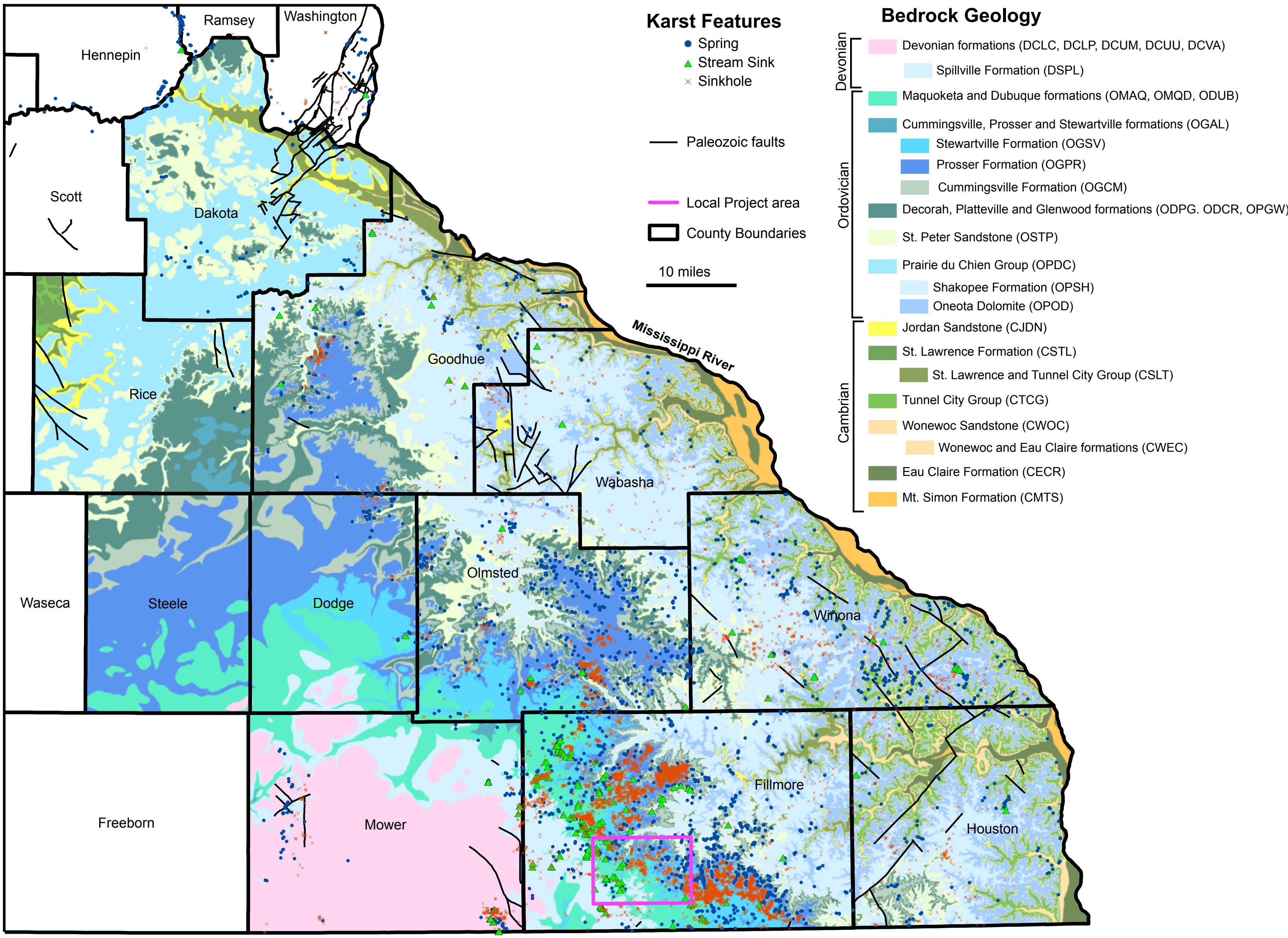


Figure 3. Bedrock Geology compilation map for regional study area of southeastern Minnesota. Shows bedrock units that are at the land surface or lie immediately below cover of unconsolidated sediment. Springs, stream sinks, and sinkholes from the Minnesota Department of Natural Resources/University of Minnesota Karst Features Data Base (KFDB) are also shown. See text and Appendix B for sources of information used in map compilation.

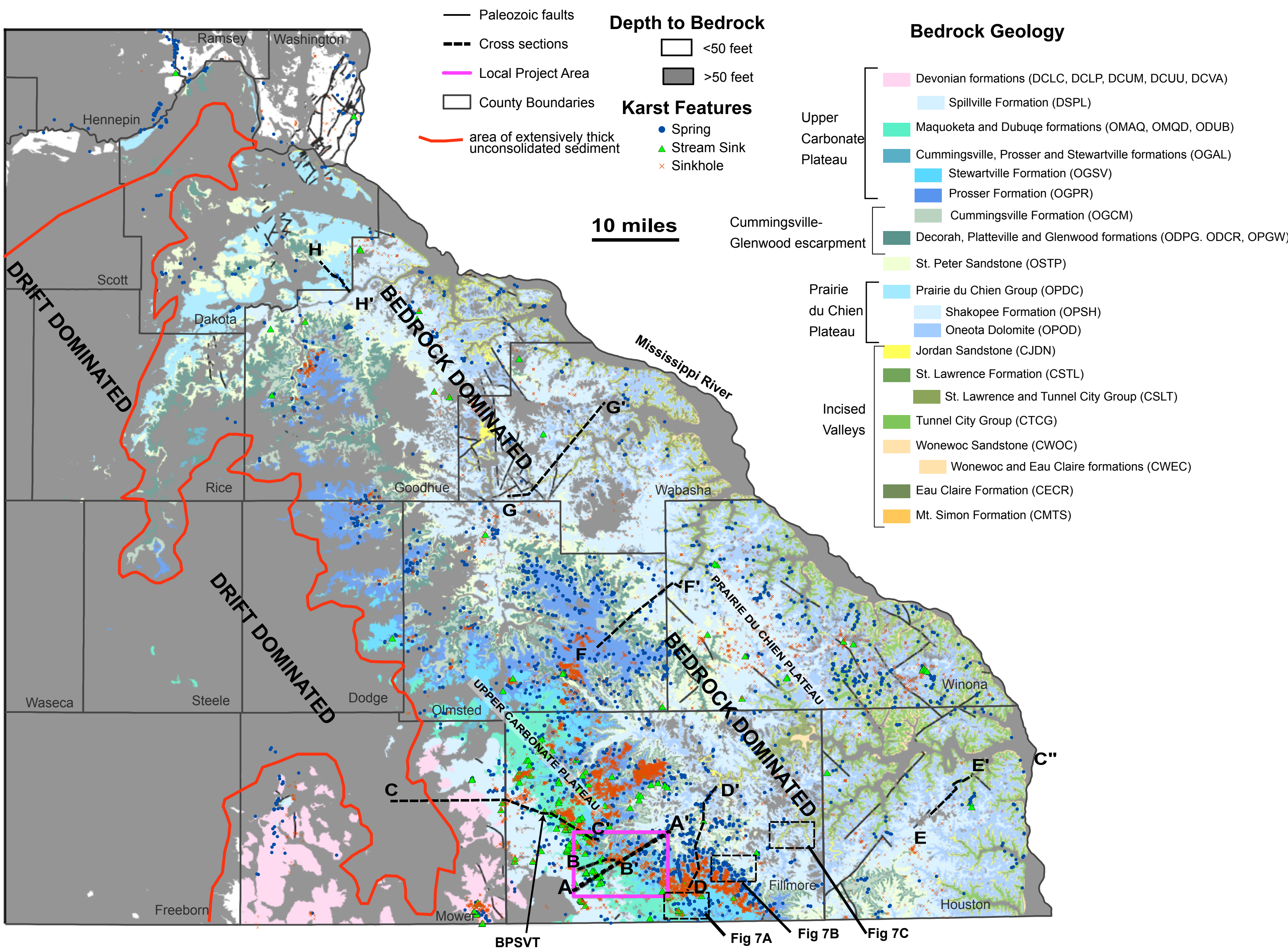


Figure 4. Compilation map of unconsolidated material and bedrock geology for the regional study area. The "drift dominated" landscape refers to areas where bedrock is covered by a relatively continuous blanket of unconsolidated sediment exceeding 50 ft in thickness. The "bedrock dominated" landscape has only a patchy cover of unconsolidated sediment that exceeds 50 ft. The bedrock dominated landscape can be generally divided into a Prairie du Chien Plateau and an Upper Carbonate Plateau. Lines of cross sections that appear in this report, and landscape illustrations in Figure 7, are also shown. BPSVT refers to British Petroleum Spring Valley Terminal contamination site.

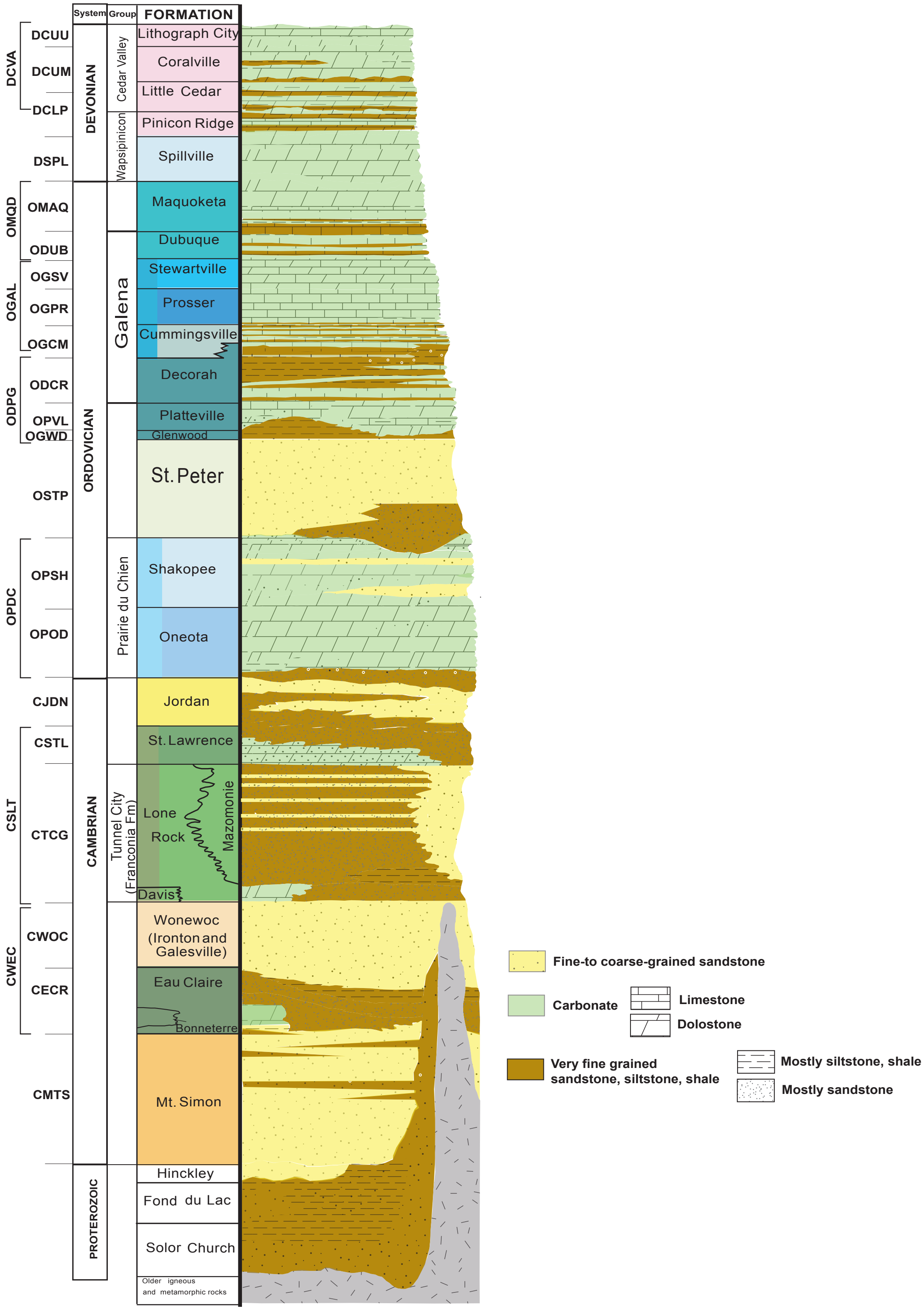


Figure 5. Stratigraphic column for bedrock of southeastern Minnesota. Modified from Mossler (2008). The thickness of the individual units vary, and are shown in Figure 6 and other cross sections from across the region in this report.

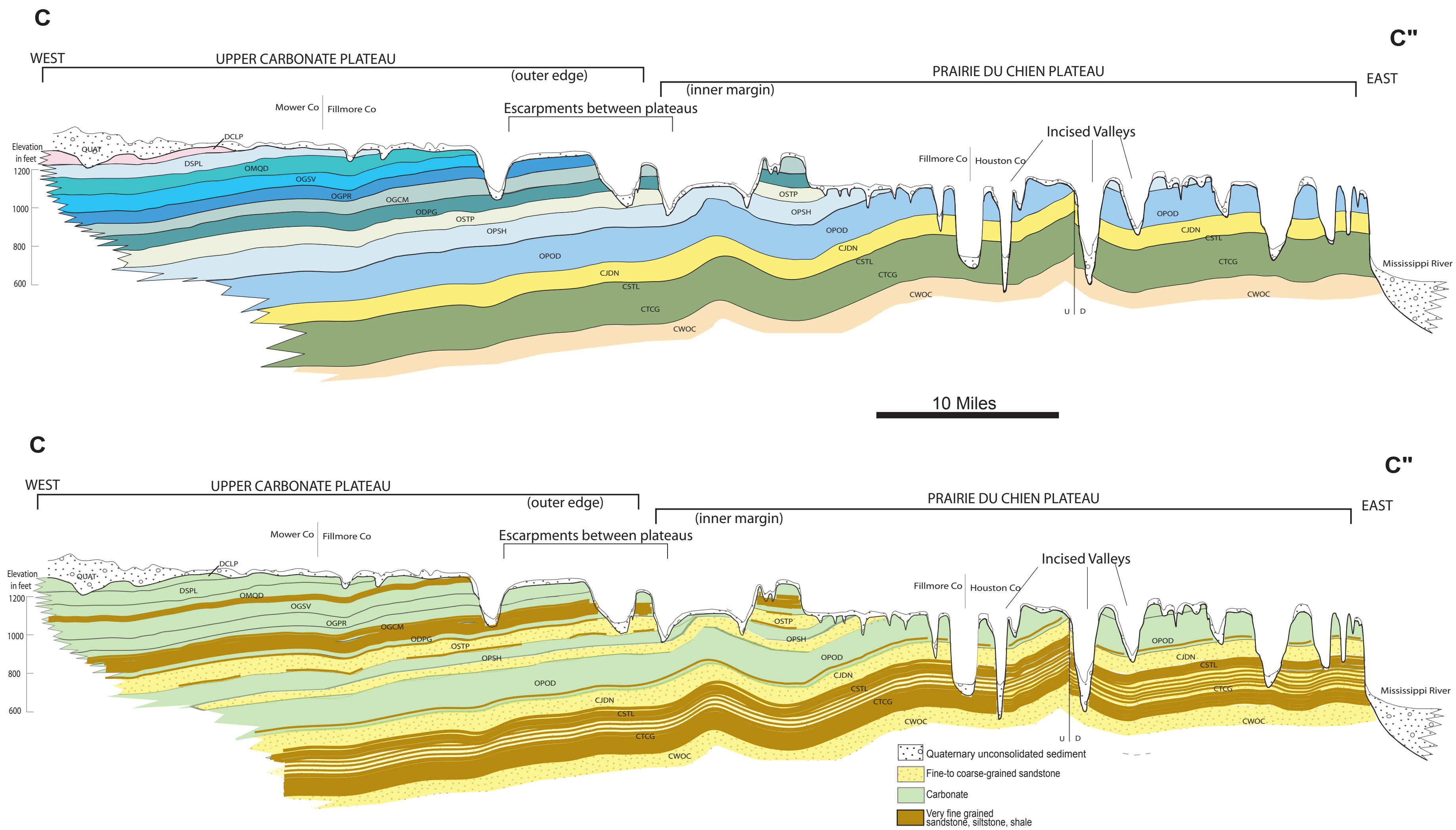


Figure 6. Highly generalized, regional-scale cross section from approximately central Mower County east to the Mississippi River across the Root River Watershed. The upper cross section shows the formal lithostratigraphic units that are also depicted on our geologic maps for the region (e.g. Figure 3), and the lower cross section shows a highly generalized characterization of the materials that make up these formations. Stratigraphic codes and colors corresponding to the individual formations can be found in Figure 5. Location of cross section (C-C”) is shown in Figure 4.

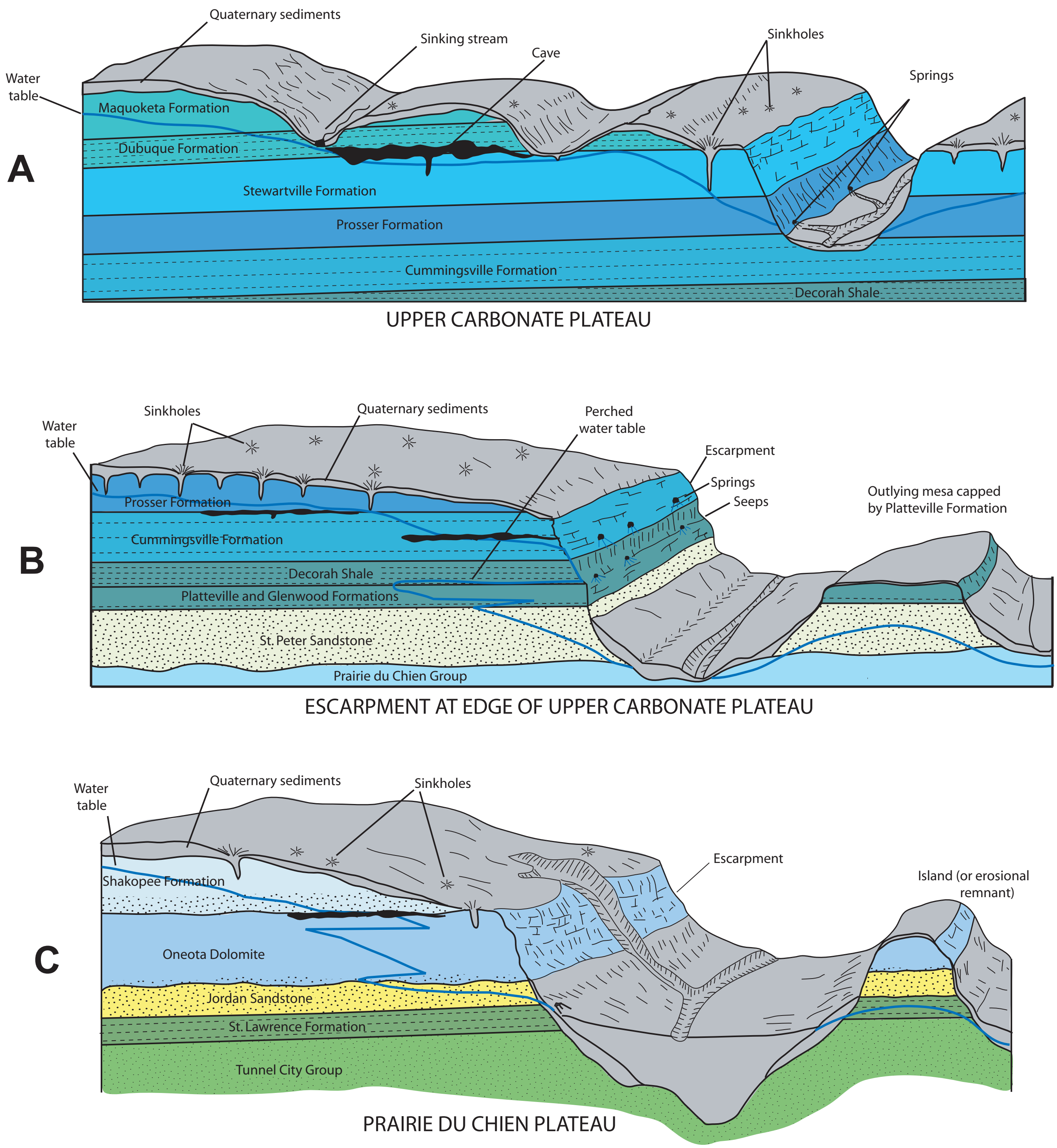


Figure 7. Typical landscape settings within the bedrock dominated landscape of southeastern Minnesota, with examples from the Upper Carbonate Plateau (A), its outer escarpment (B), and the Prairie du Chien Plateau (C). Each plateau is underlain by carbonate rock with solution-enhanced porosity reflected by karst features such as sinkholes and disappearing streams. See Figure 4 for map view of typical locations where these landscape types are present. Modified from Mossler and Hobbs (1995).

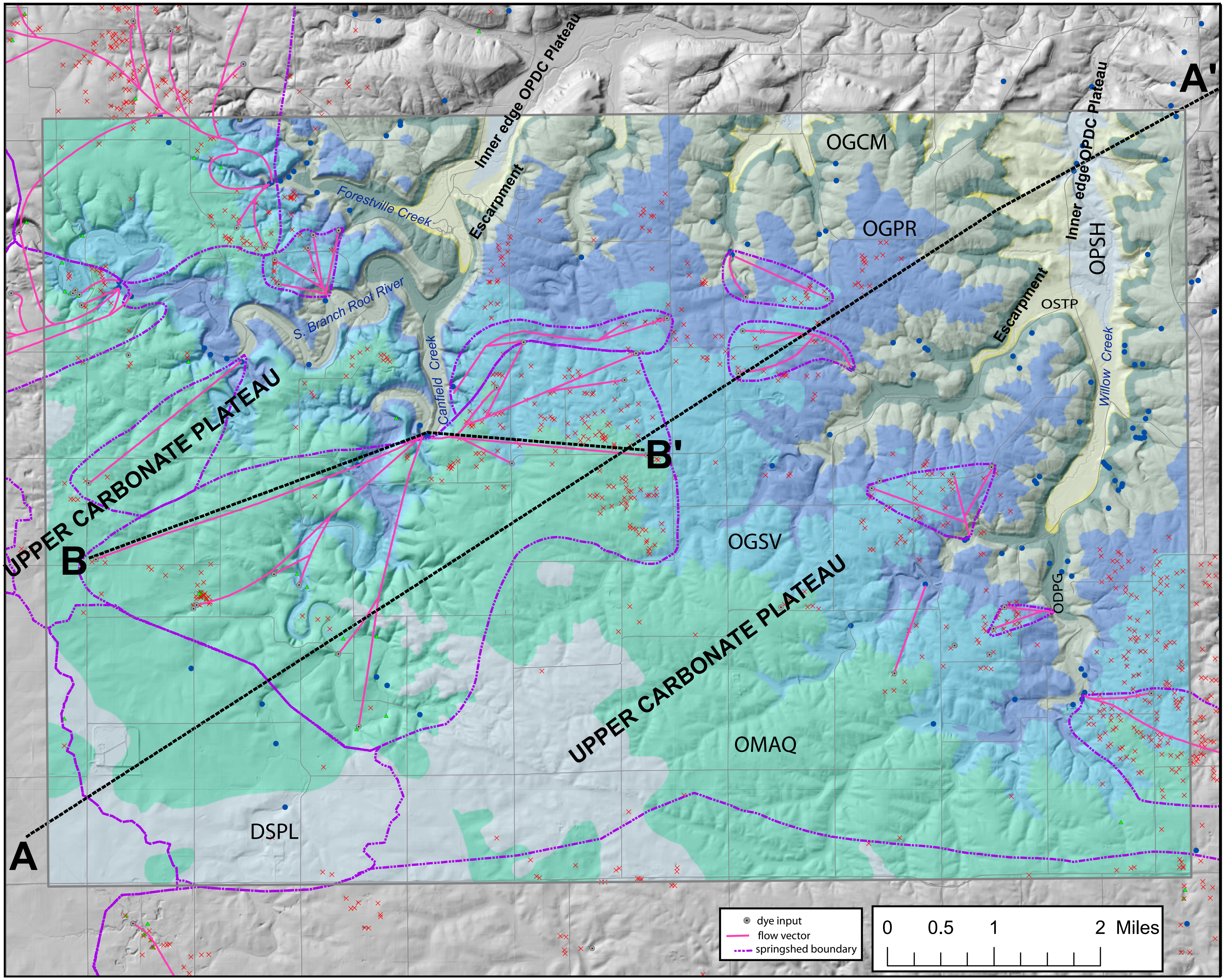


Figure 8. Bedrock geologic map for the local project area, southwestern Fillmore County. Map symbology and legend, and location of this project area, are shown in Figure 4. Codes for mapped units are in Figure 5. Also shown are results of dye trace investigations, from Alexander et al. (1996) supplemented with more recent information provided in 2013 by Jeff Green, Minnesota Department of Natural Resources.

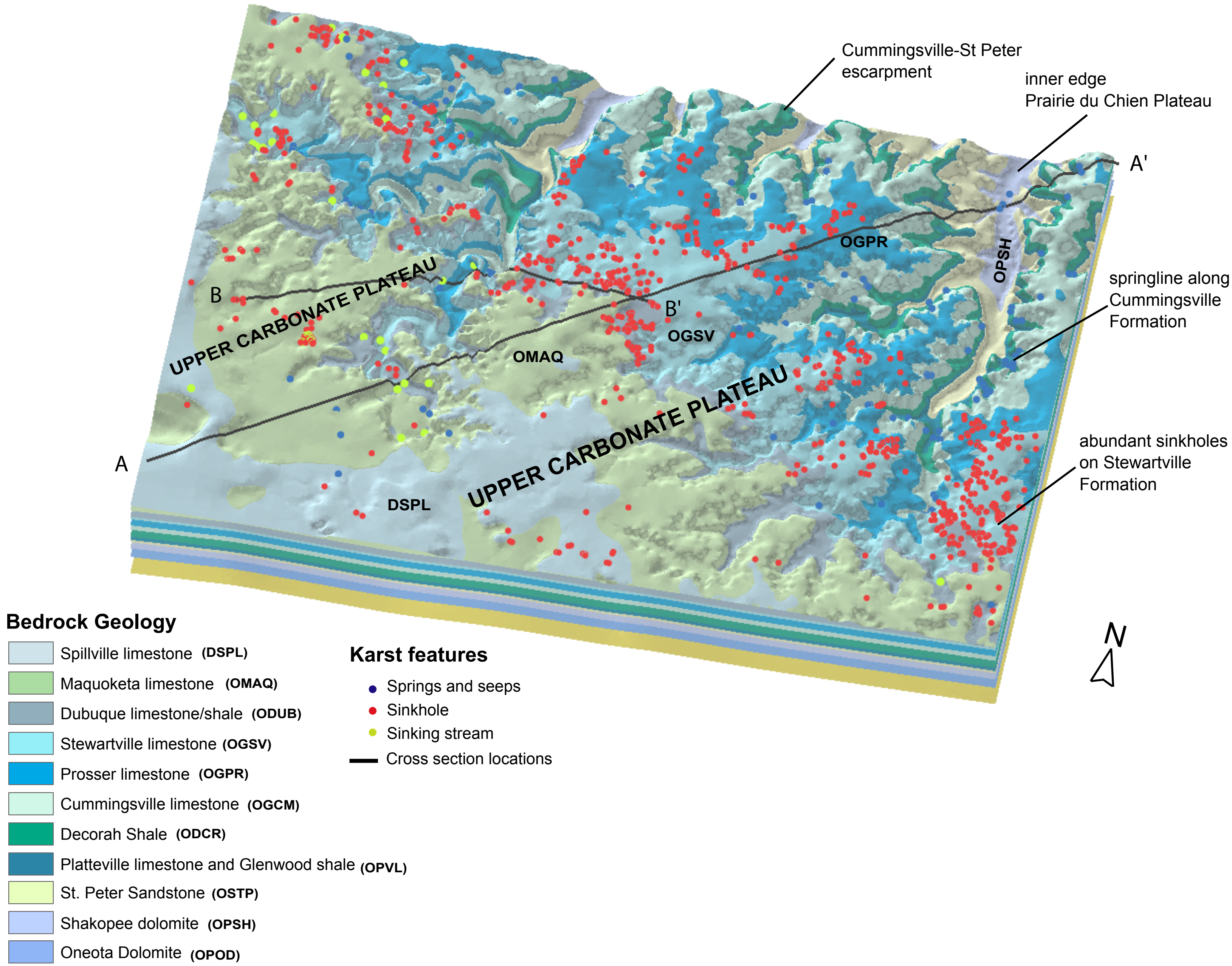


Figure 9. Three-dimensional model of the geologic map for the local project area, southwestern Fillmore County. Location of area shown in Fig. 4. See text for discussion.

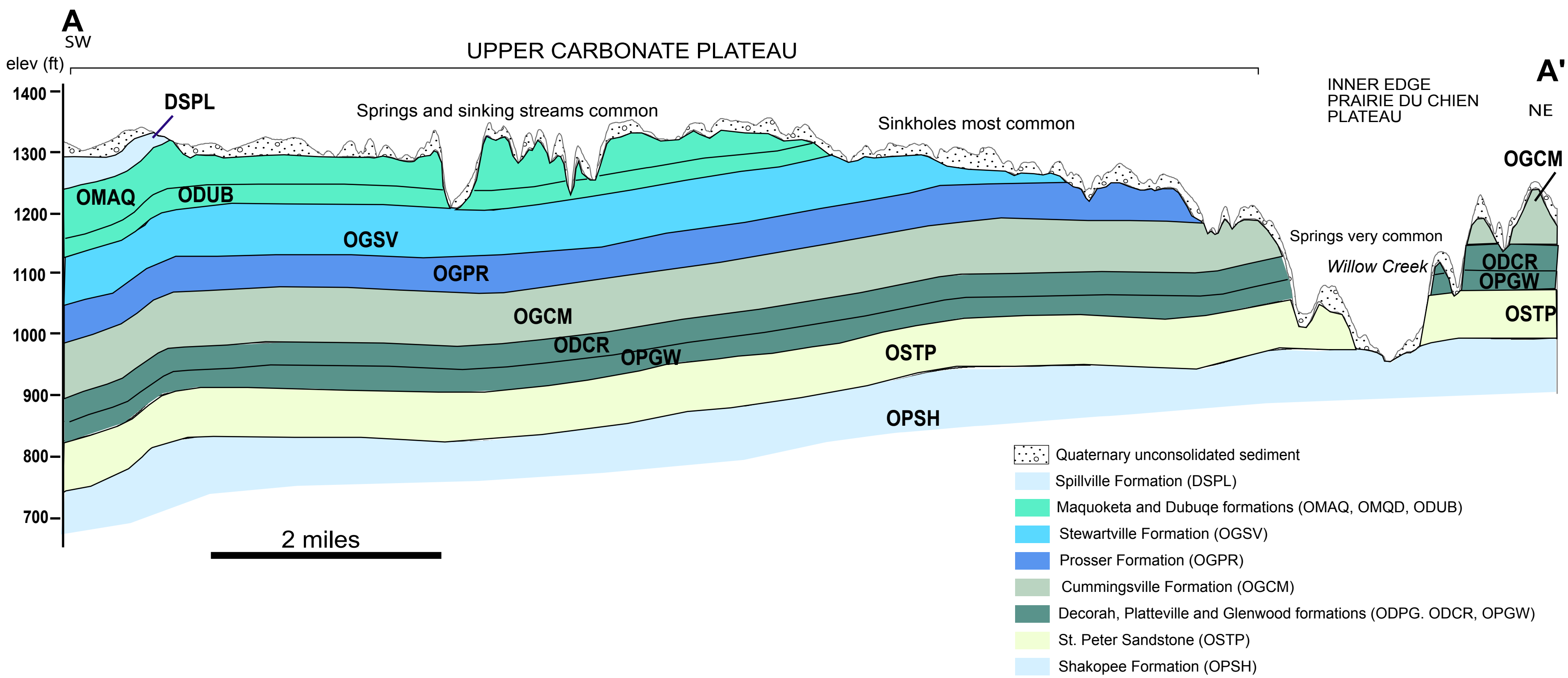


Figure 10. Cross sectional view of the formal lithostratigraphic units mapped in the local project area (Figures 8 and 9). See Figures 4 and 8 for cross section line.

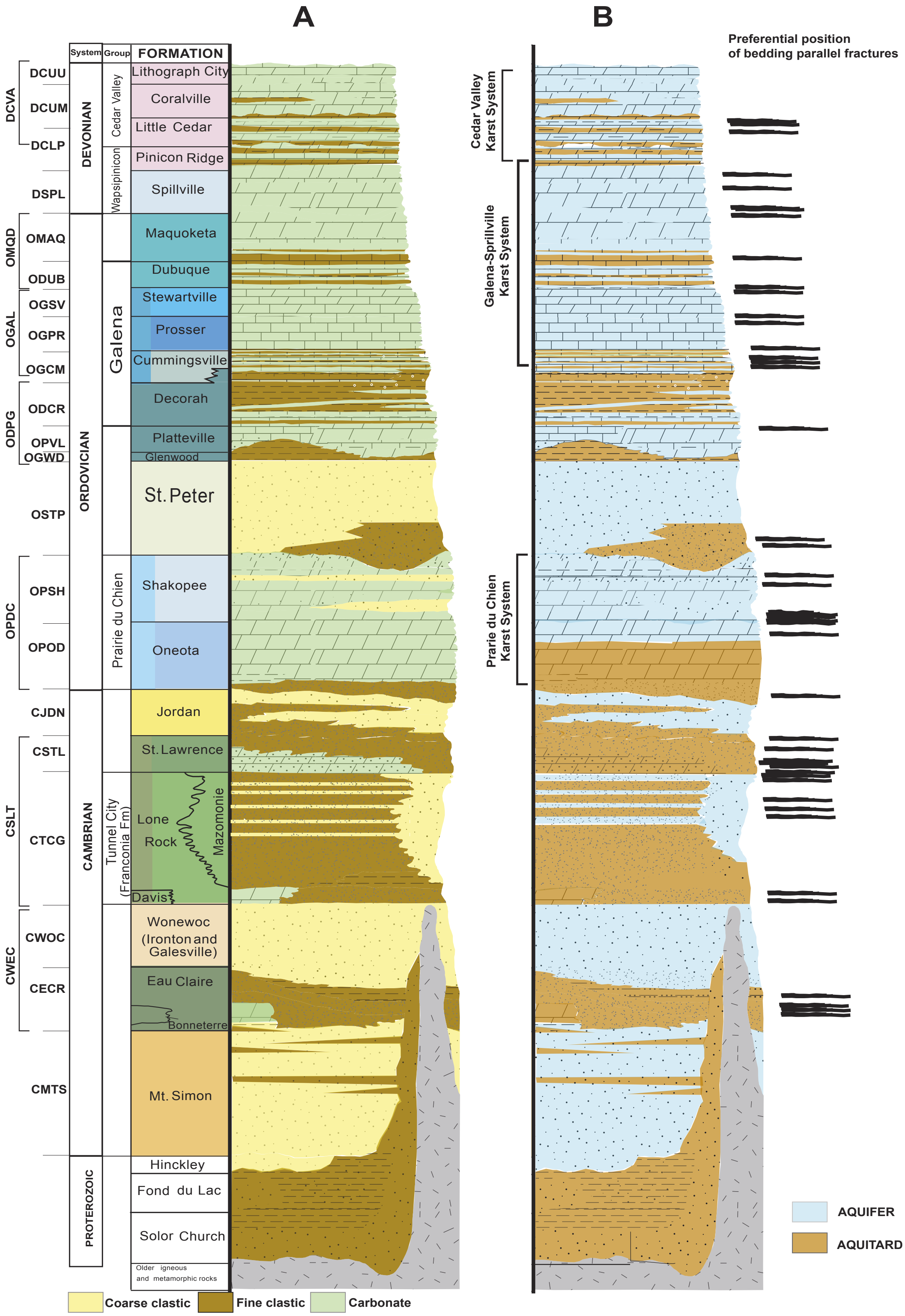


Figure 11. Stratigraphic columns for bedrock of southeastern Minnesota, highlighting matrix hydrostratigraphic components (A) and hydrogeologic units (B). Also shown are stratigraphic positions of the three major karst systems, and preferential positions of bedding parallel fracture networks.

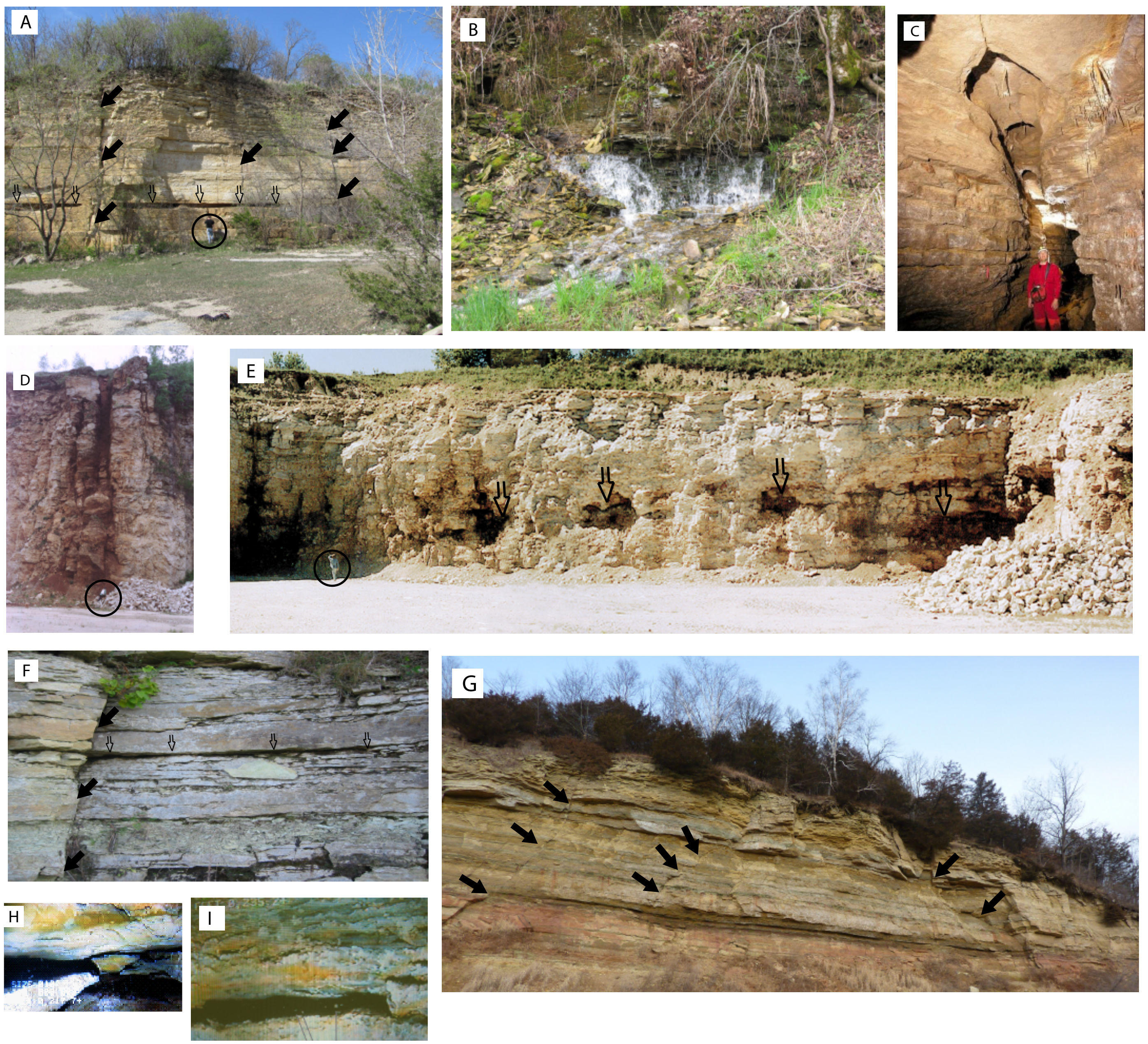


Figure 12. Outcrop examples of fractures in bedrock of southeastern Minnesota. (A) Quarry exposure of Prosser Formation in local project area showing prominent bedding parallel fractures (hollow arrows) enlarged by solution. Selected vertical joints also noted with solid arrows. Person circled for scale. (B) shows a spring emanating from bedding parallel fractures. Prosser Formation, western Fillmore County. (C) Solution enlarged vertical fracture in Dubuque Formation, Goliath Cave, western Fillmore County. Photo from Art Palmer. (D) Prominent solution-enlarged vertical fractures in Oneota Dolomite, northeast Fillmore County. Person circled for scale. (E) Large solution cavities (hollow arrows) aligned along the Oneota Dolomite-Shakopee Formation contact, Wabasha County. Person circled for scale. (F) Bedding parallel fracture (hollow arrows) and vertical fracture (solid arrows) in St Lawrence Formation, Goodhue County. (G) Vertical fractures (solid arrows) in Tunnel City Group, Houston County. (H) Bedding parallel fracture in St Lawrence Formation at depth of 218 ft. From borehole video log of water well, Dakota County. (I) Bedding parallel fracture in Tunnel City Group at depth of 235 ft. From borehole video log of water well, Anoka County. Examples in A-E are representative of karst, where porosity is significantly enhanced by solution of rock.

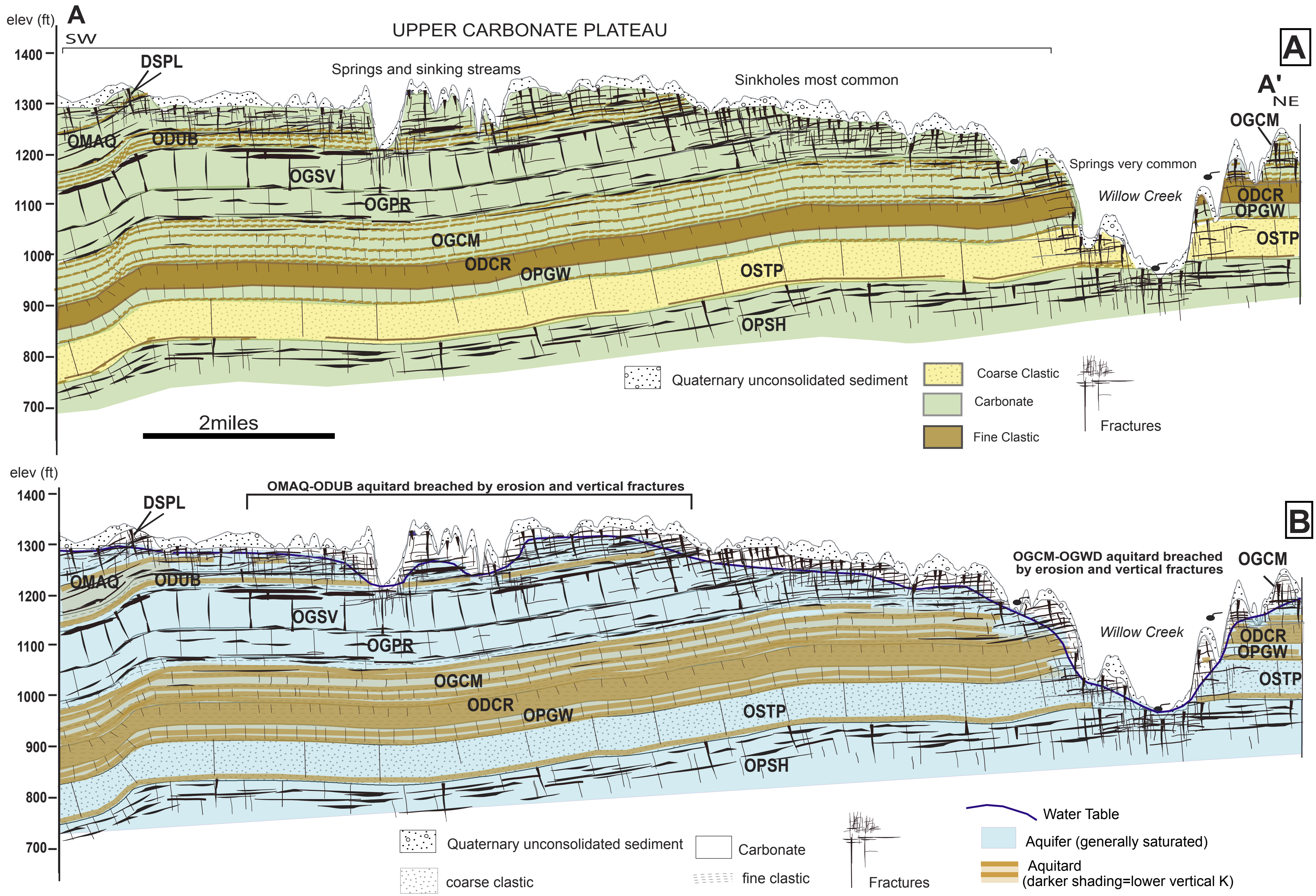


Figure 13. Cross sections from local project area. (A) shows typical distribution of hydrostratigraphic attributes including matrix components and fractures. Note higher density of fractures in the uppermost approximately 50 ft of bedrock and the preferential development of bedding parallel fractures along specific stratigraphic positions. (B) includes the distribution of aquifers and aquitards. See Figures 4 and 8 for location of cross section

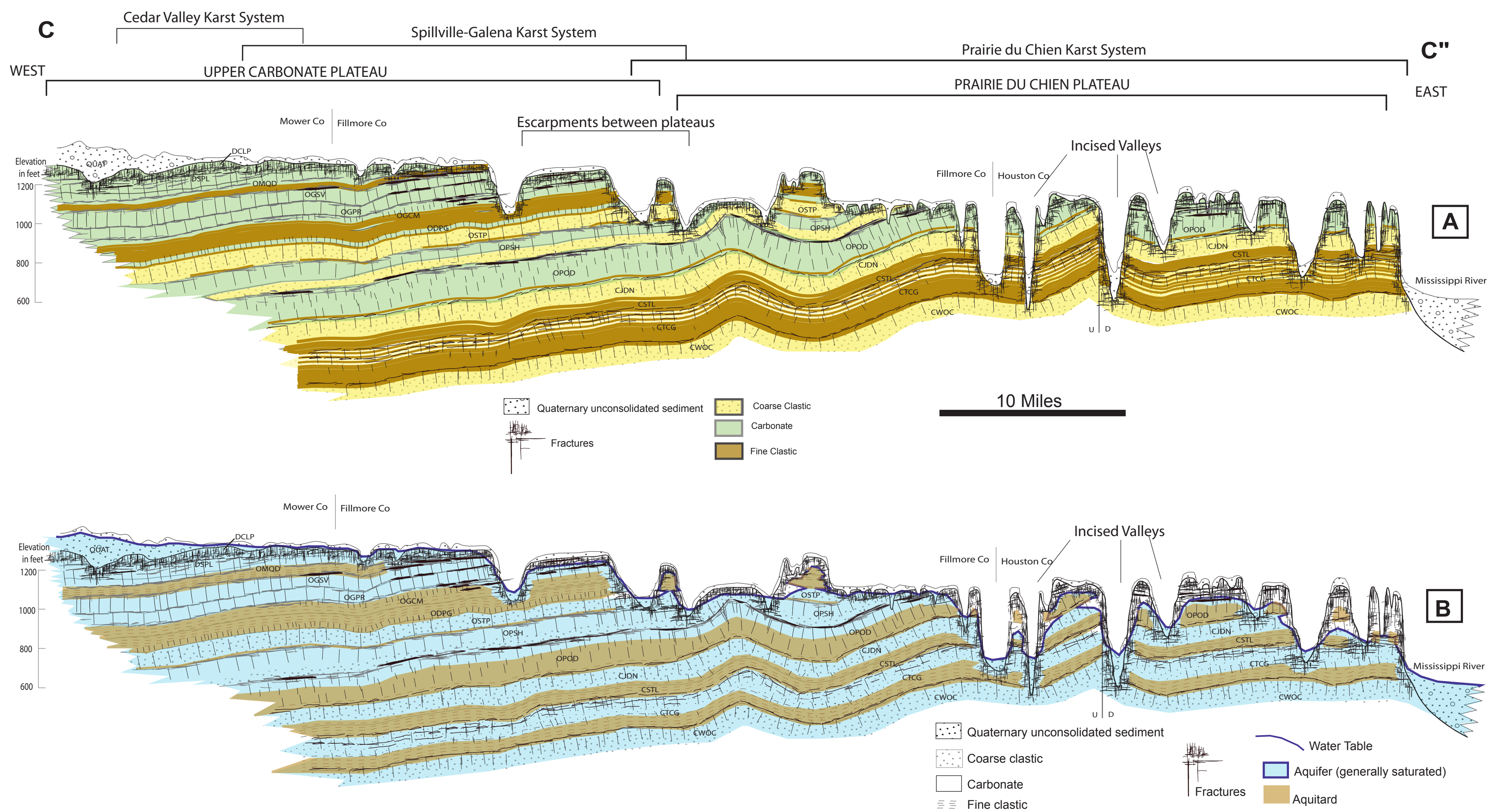


Figure 14. Generalized, regional scale cross section from approximately central Mower County, east to the Mississippi River in southeastern Minnesota. (A) shows typical distribution of hydrostratigraphic attributes including matrix components and fractures. Note higher density of fractures in the uppermost approximately 50 ft of bedrock and the preferential development of bedding parallel fractures along specific stratigraphic positions. (B) includes the distribution of aquifers and aquitards. Location of cross section (C-C") is shown in Figure 4.

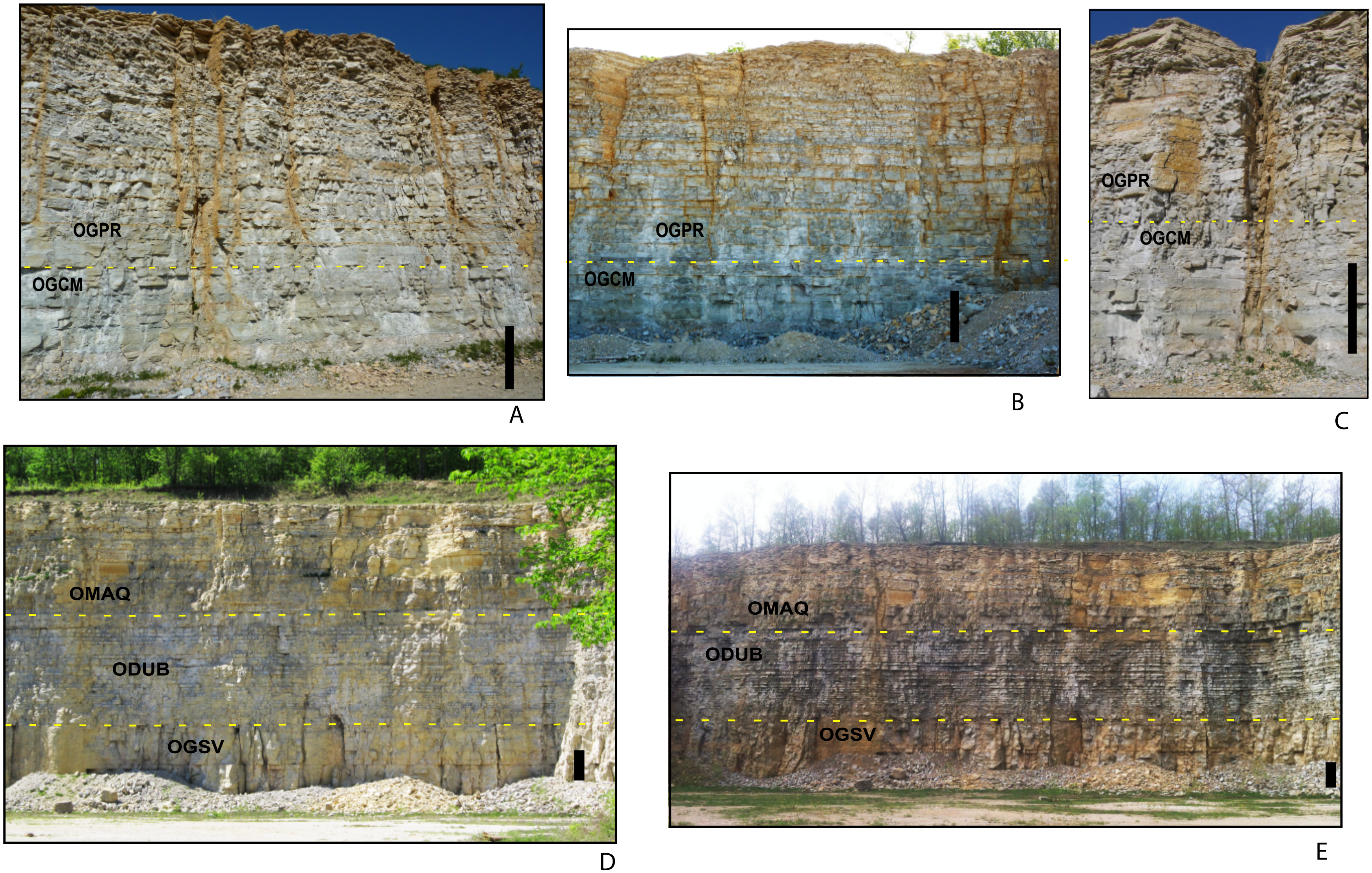


Figure 15. Examples of outcrops that show termination of vertical fractures at preferential stratigraphic positions. (A),(B), and (C), show termination, or significant aperture diminishment, of prominent vertical joints from the Prosser (OGPR) downward into the upper Cummingsville Formation (OGCM). Quarry near Fountain, Fillmore County. (D) and (E) show vertical joints in the Stewartville (OGSV) and Maquoketa (OMAQ) Formations that commonly terminate or have narrower apertures within intervening Dubuque Formation (ODUB). Black vertical bar is about 6 ft.

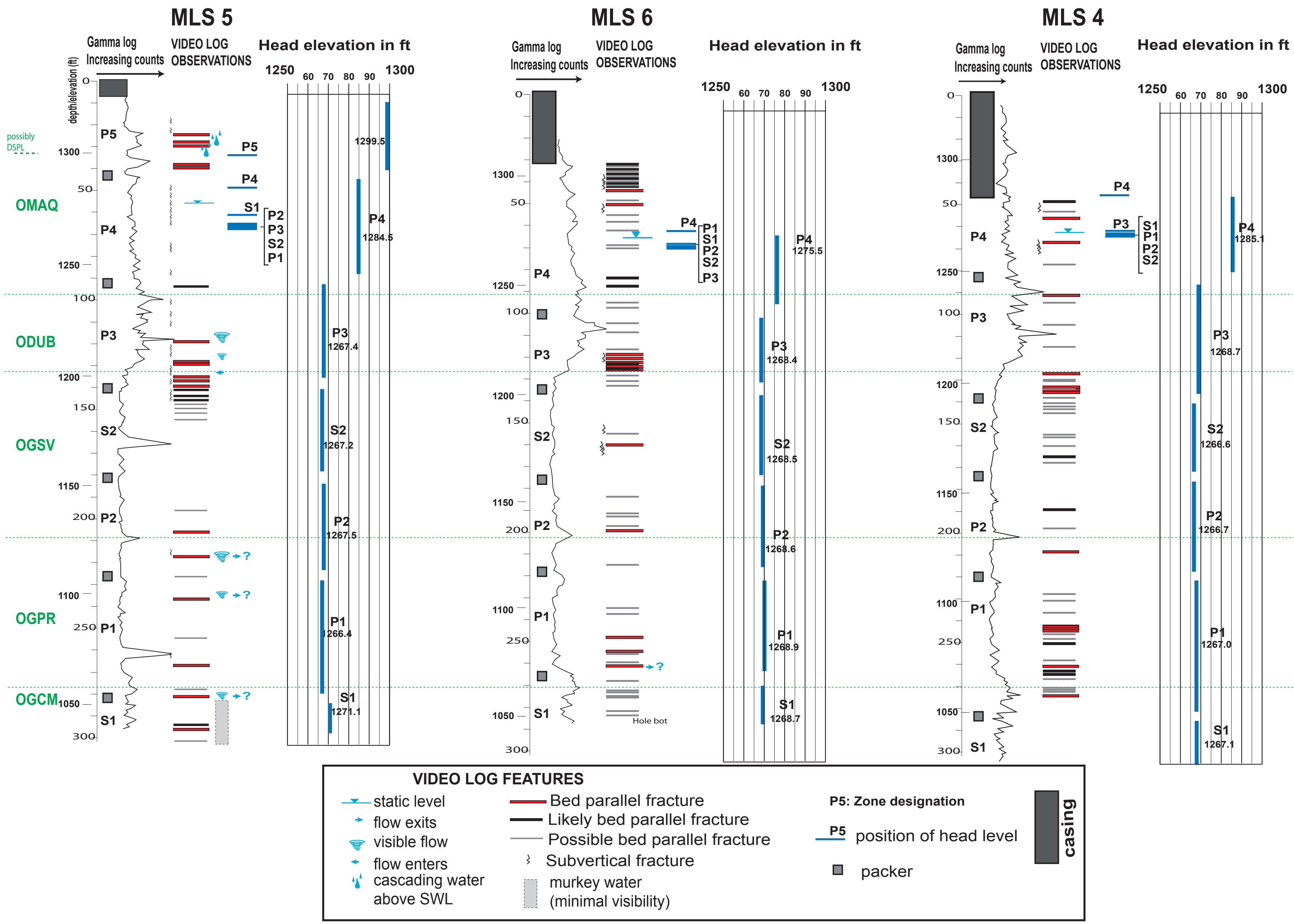


Figure 16. Representative examples of information acquired from wells with multilevel monitoring systems (MLS) at the British Petroleum (formerly Amoco) Spring Valley Terminal contamination site. Natural gamma logs, video logs, and discrete interval water level monitoring from these and 10 other MLS wells were used to better characterize the hydrogeologic characteristics of this part of the stratigraphic section, which forms much of the Upper Carbonate Plateau. Information is from Delta Environmental Consultants (now AnteaGroup) (1996, 2002), and copies of borehole videos provided to the authors by AnteaGroup in 2012. See text for discussion. Location of the site is shown in Figure 4.

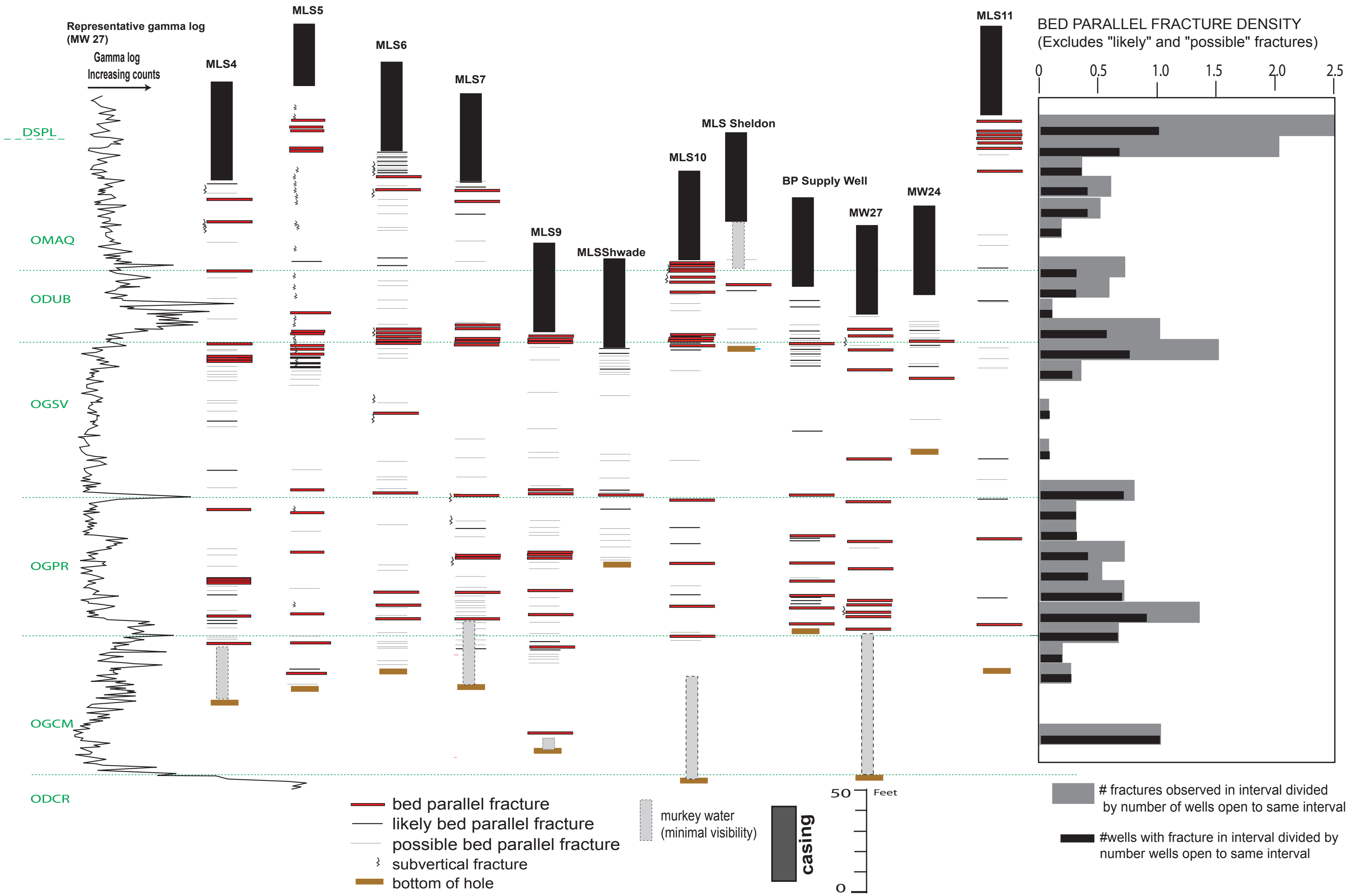
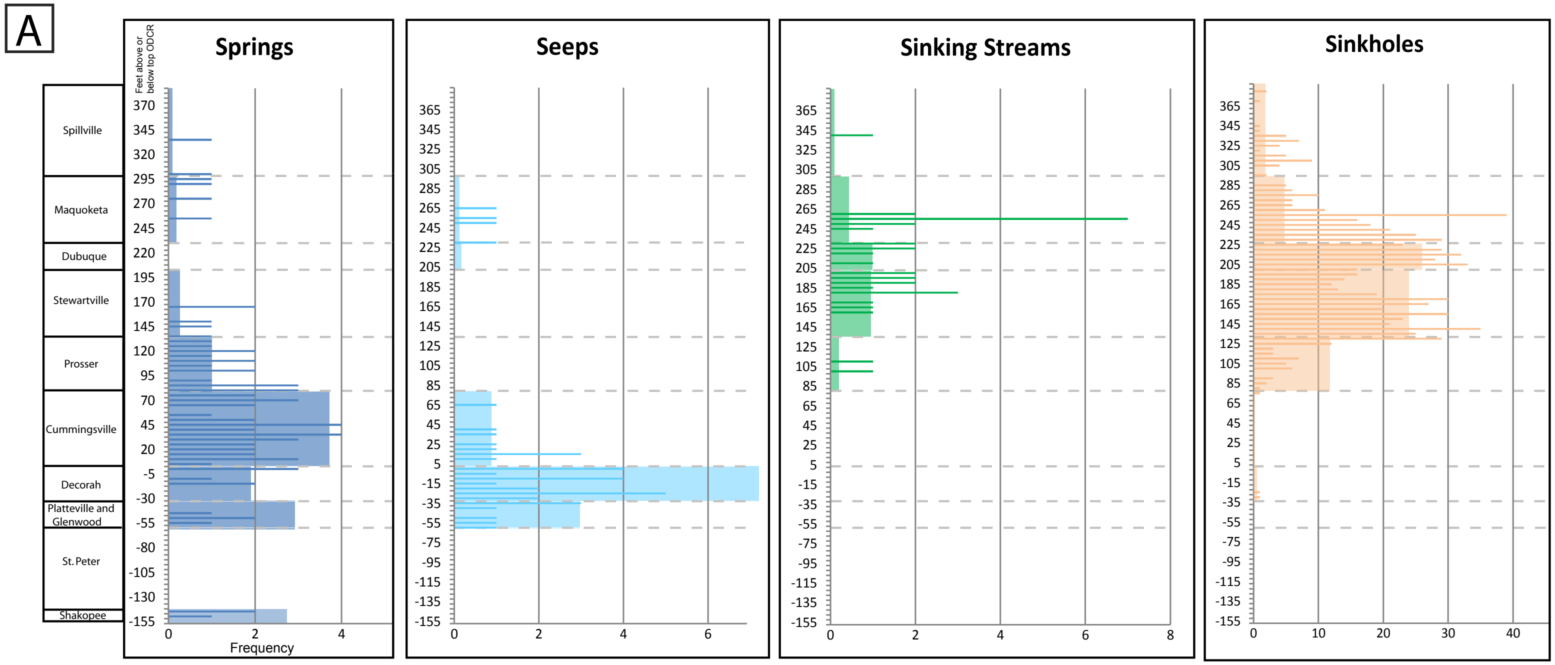


Figure 17. Summary of our observations of fractures in video logs of 12 boreholes from the British Petroleum (formerly Amoco) Spring Valley Terminal contamination site. Bedding parallel fractures are most densely distributed in uppermost Maquoketa/lowermost Spillville, Dubuque-Stewartville, and Prosser-Cummingsville contact strata. See text for discussion. Location of site is shown in Figure 4.



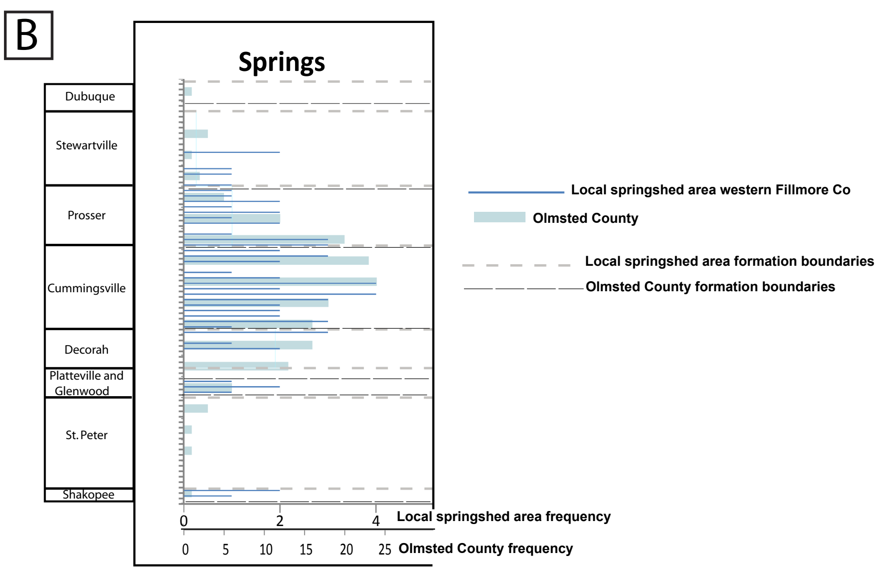


Figure 18. (A) Stratigraphic position of karst features in the local project area, western Fillmore County. Springs are preferentially located where Cummingsville Formation is uppermost bedrock, whereas seeps are most common where the Decorah Shale is uppermost bedrock. Sinking streams preferentially occur across the Maquoketa to Stewartville Formations, and sinkholes in the Stewartville and Dubuque formations. Darker solid lines are number of karst features within a five foot interval of strata. Lighter shading represents number of features per square mile for each formation to account for variable surface area of individual formations as uppermost bedrock across local project area. Location of local project area shown in Figure 4. Map view of karst features in local project area shown in Figure 8. (B) Stratigraphic position of springs in Olmsted County compared to local project area, western Fillmore County. Generally similar pattern indicates that stratigraphic control on springs can be considered a regional phenomenon.

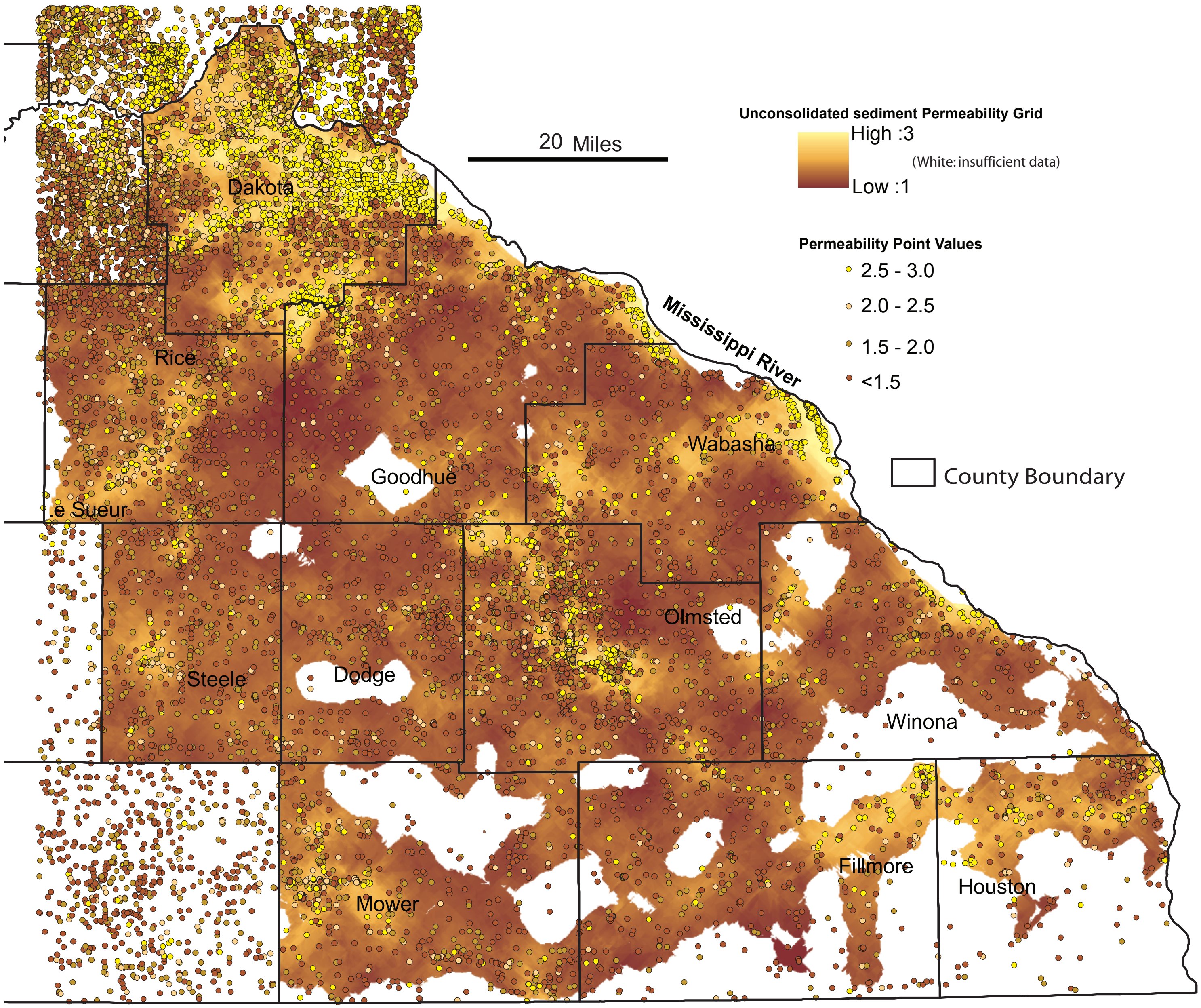


Figure 19. Illustration of raster grid depicting vertical permeability of unconsolidated sediment across the regional study area. See text for explanation.

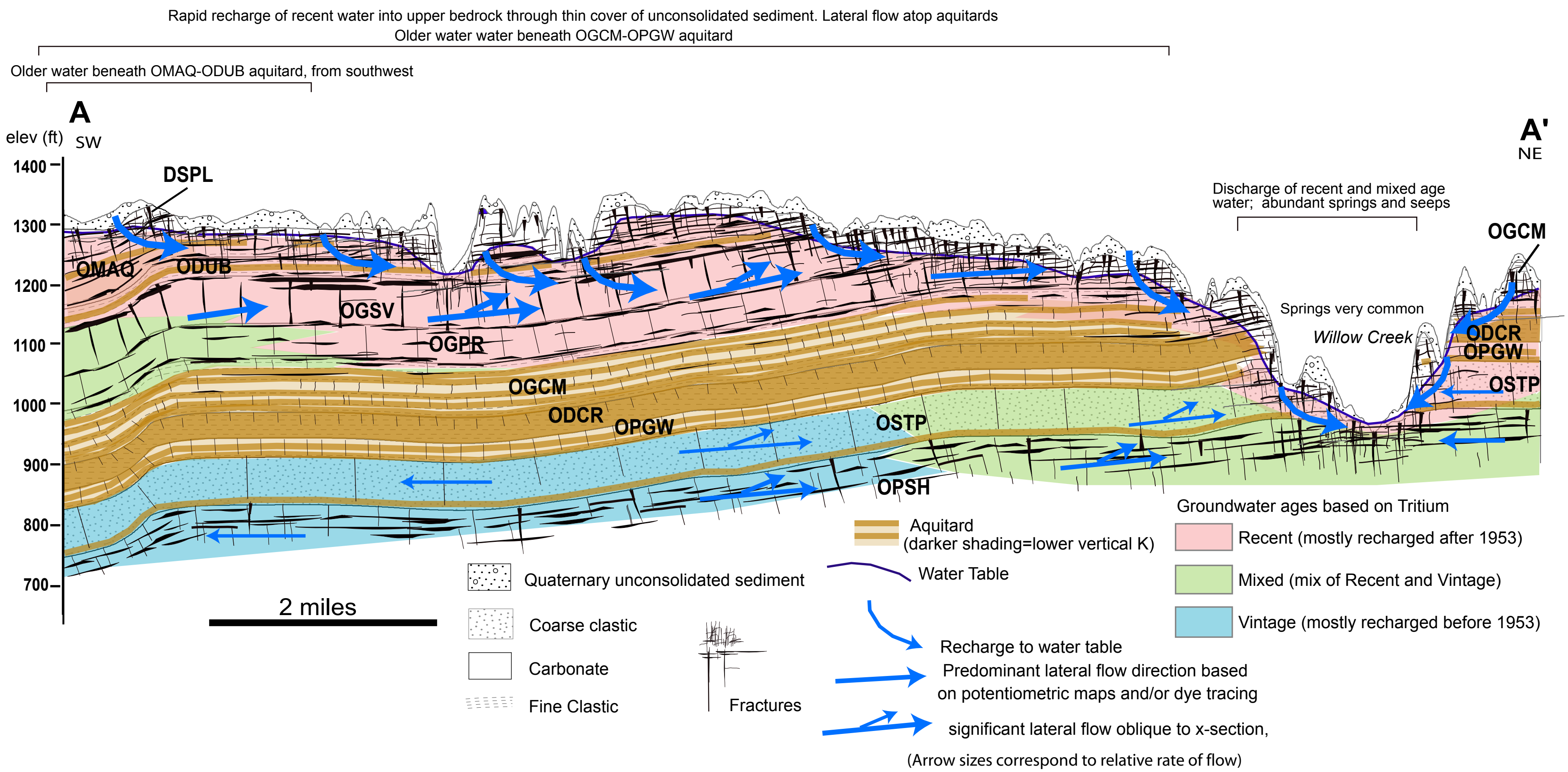


Figure 20. Cross section from local project area highlighting groundwater age as determined by tritium concentration, and showing dominant, bulk flow directions. Note especially age stratification whereby the Cummingsville-Glenwood aquitard separates mostly recent water above from vintage or mixed water below. Recent water moves downward to lower stratigraphic levels where the aquitard is breached by fractures and removed by erosion along valleys. The water of mixed age beneath the aquitard on the eastern edge of the cross section likely reflects the contribution of recently recharged in areas off the line of cross section, where the aquitard is absent, and subsequent lateral flow to this area. See text for discussion. Profile of groundwater ages modified from Zhang and Kanivetsky (1996), and flow directions (arrows) from Zhang and Kanivetsky (1996) and Alexander et al. (1996). Overall vertical gradient is downward and a component of overall downward flow that is present in most places, including leakage across aquitards, is not represented by arrows. See Figures 4 and 8 for location of cross section. Stratigraphic codes are in Figure 5.

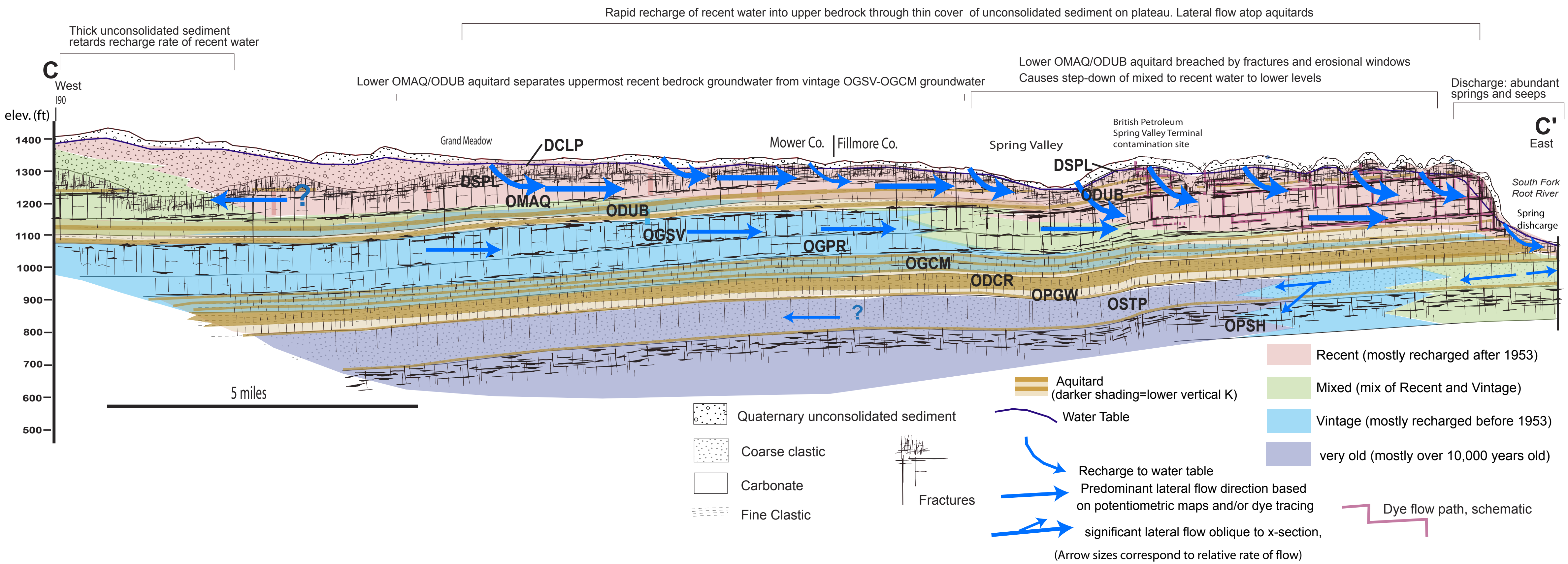


Figure 21. Cross section from central Mower to western Fillmore County highlighting groundwater age as determined by tritium concentration, and carbon 14 dating, and showing dominant, bulk flow directions. Note especially age stratification whereby the Maquoketa-Dubuque and Cummingsville-Glenwood aquitards separate younger water above from older water below. In each example water moves downward to lower stratigraphic levels where the aquitard is breached by fractures and removed by erosion along valleys. See text for discussion. Profile of groundwater ages and flow directions (arrows) for Mower County are from Campion (2002). For Fillmore County they are modified from Zhang and Kanivetsky (1996) and Alexander et al (1996). Arrows show dominant, bulk flow directions. (A component of downward flow that is present in most places because of overall downward vertical gradient is not represented by arrows). See Figure 4 for location of cross section. Stratigraphic codes are in Figure 5.

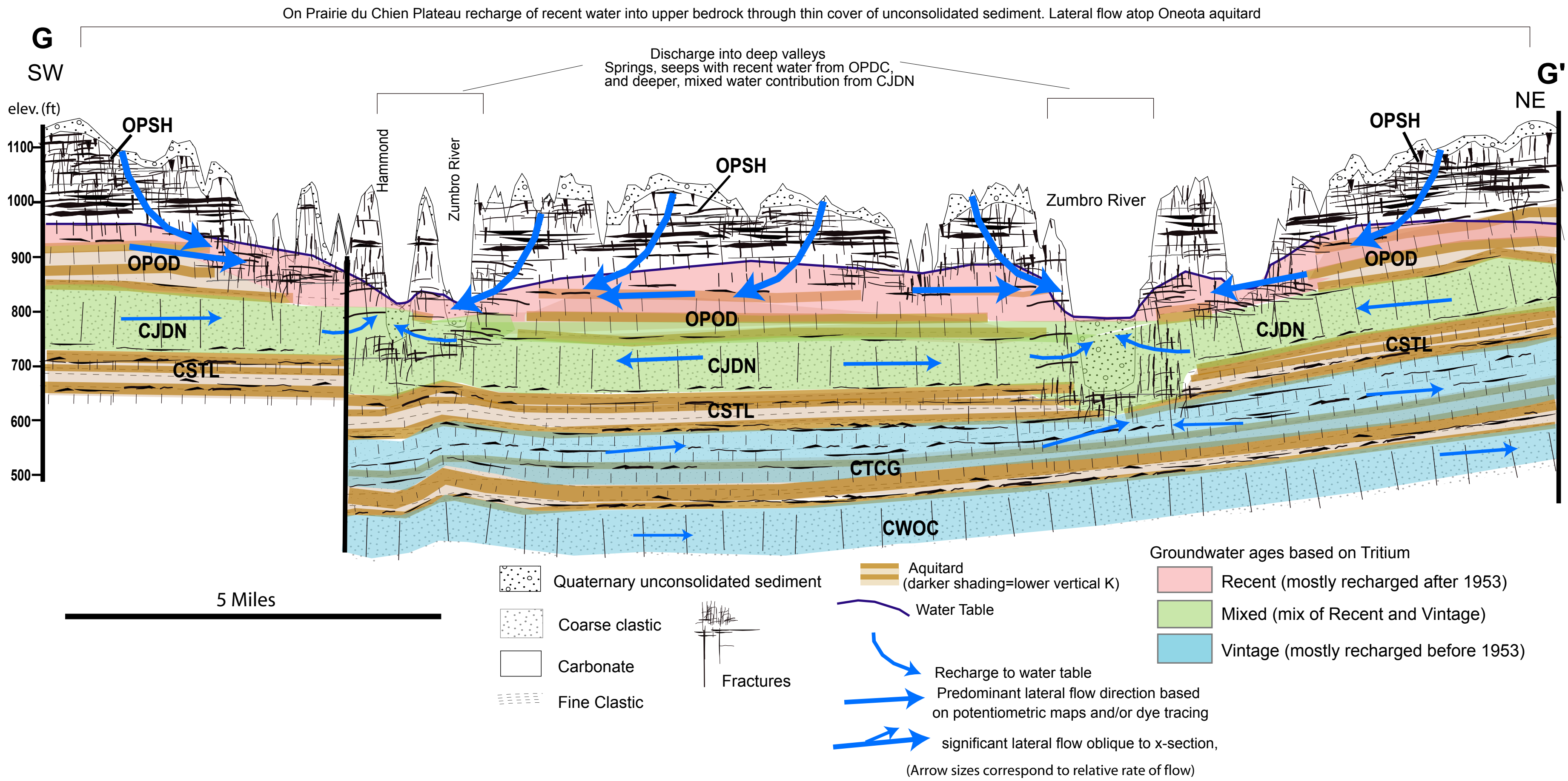


Figure 22. Cross section from Wabasha County highlighting groundwater age as determined by tritium concentration and showing dominant, bulk flow directions. Note especially age stratification whereby the Oneota and St Lawrence aquitards separate younger water above from older water below. Older water can discharge into valleys where the aquitards are breached by fractures and removed by erosion. See text for discussion. Cross section, including profile of groundwater ages and flow directions (arrows) are from Petersen (2005). Arrows show dominant, bulk flow directions. [A component of downward flow that is present in most places (except near valleys) because of overall downward vertical gradient is not represented by arrows]. See Figure 4 for location of cross section. Stratigraphic codes are in Figure 5.

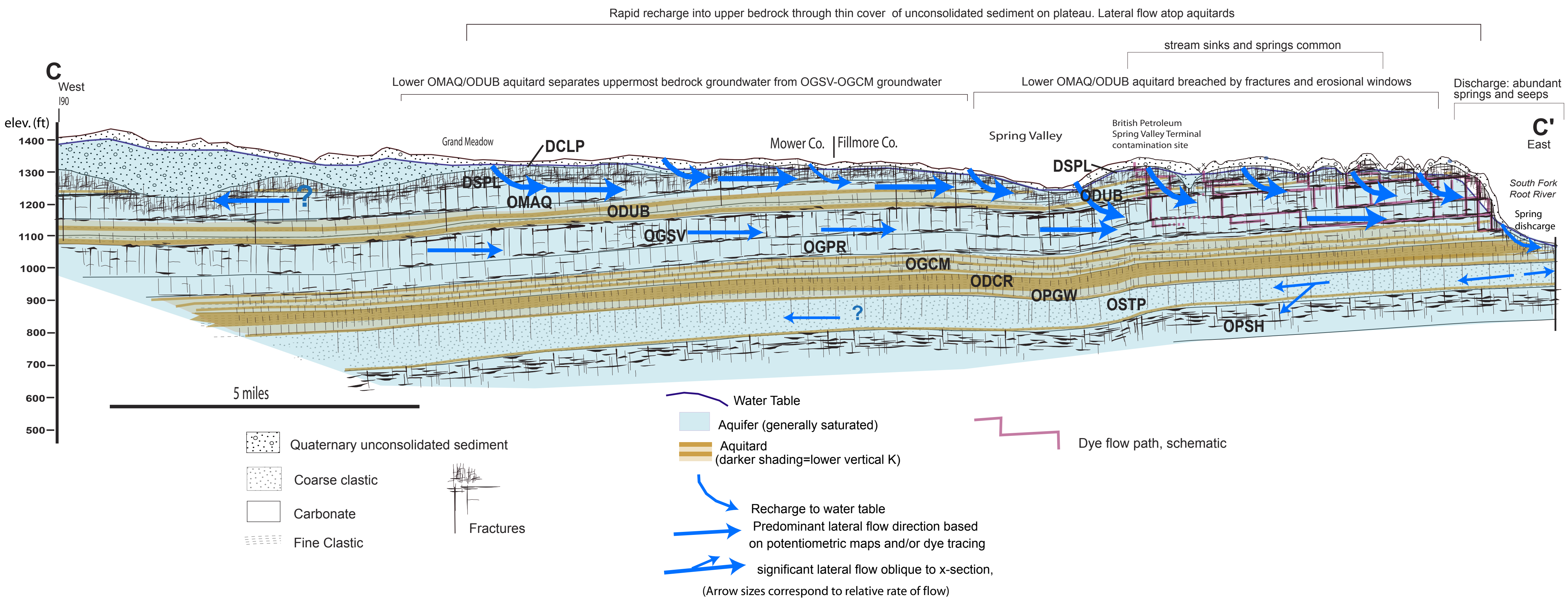


Figure 23. Cross section from central Mower to western Fillmore County showing example of flow system across Upper Carbonate Plateau, from edge of drift-dominated landscape (west) to bedrock-dominated landscape (east). Arrows show dominant, bulk flow directions. (A component of downward flow that is present in most places because of overall downward vertical gradient is not represented by arrows). Flow directions for Mower County are from Campion (2002). For Fillmore County they are modified from Zhang and Kanivetsky (1996) and Alexander et al. (1996). Dye trace depiction based on information from Alexander et al. (1996) and Alexander and Alexander (1998). See Figure 4 for location of cross section. Stratigraphic codes are in Figure 5.

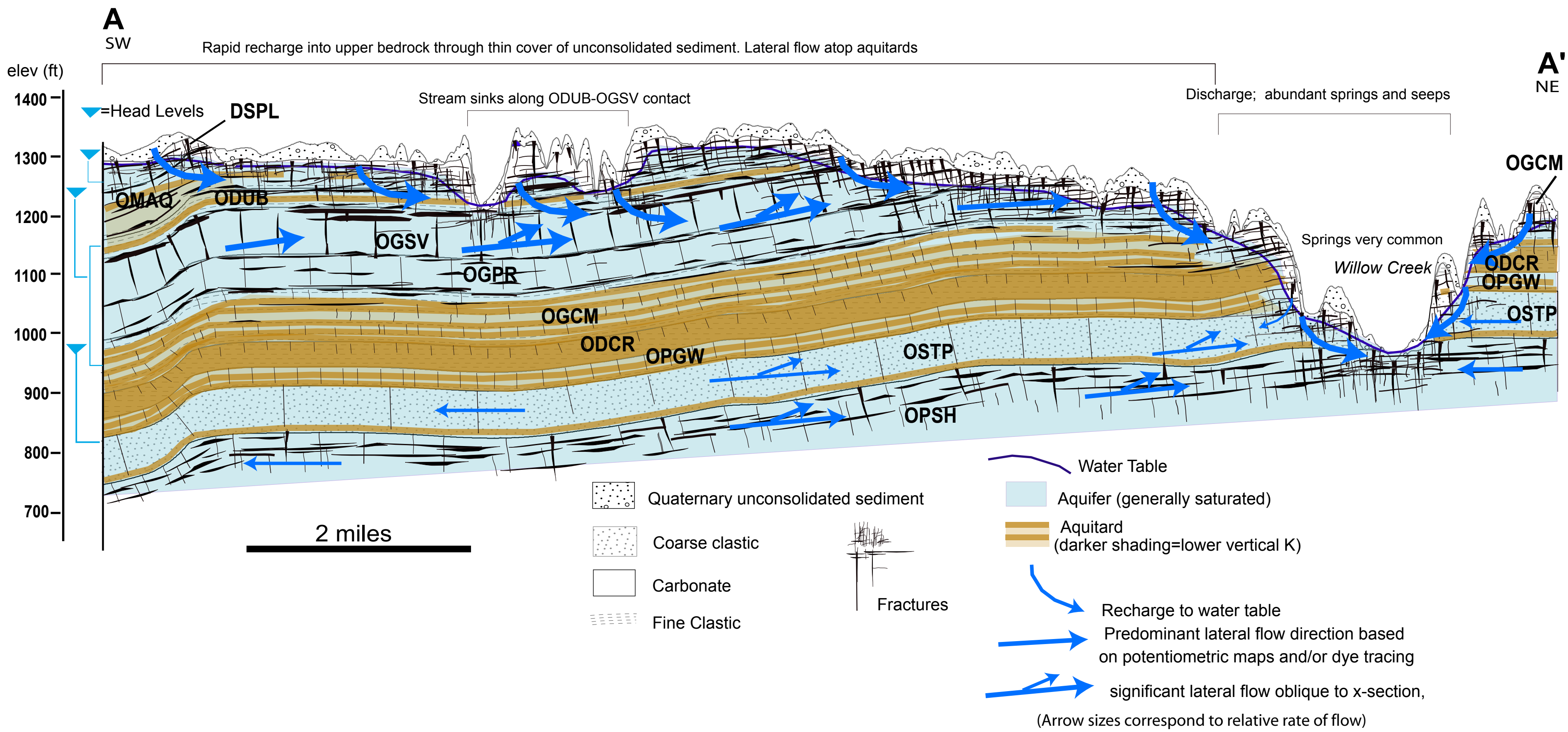


Figure 24. Cross section from the local project area showing example of flow system in Upper Carbonate Plateau setting to escarpment at outer edge of plateau. Arrows show dominant, bulk flow directions. (A more limited component of downward flow that is present in most places is not represented by arrows). Flow directions are modified from Zhang and Kanivetsky (1996) and Alexander et al. (1996). Head levels based on discrete level monitoring in a similar setting at the British Petroleum Spring Valley Terminal in nearby western Fillmore County. See Figures 4 and 8 for location of cross section. Stratigraphic codes are in Figure 5.

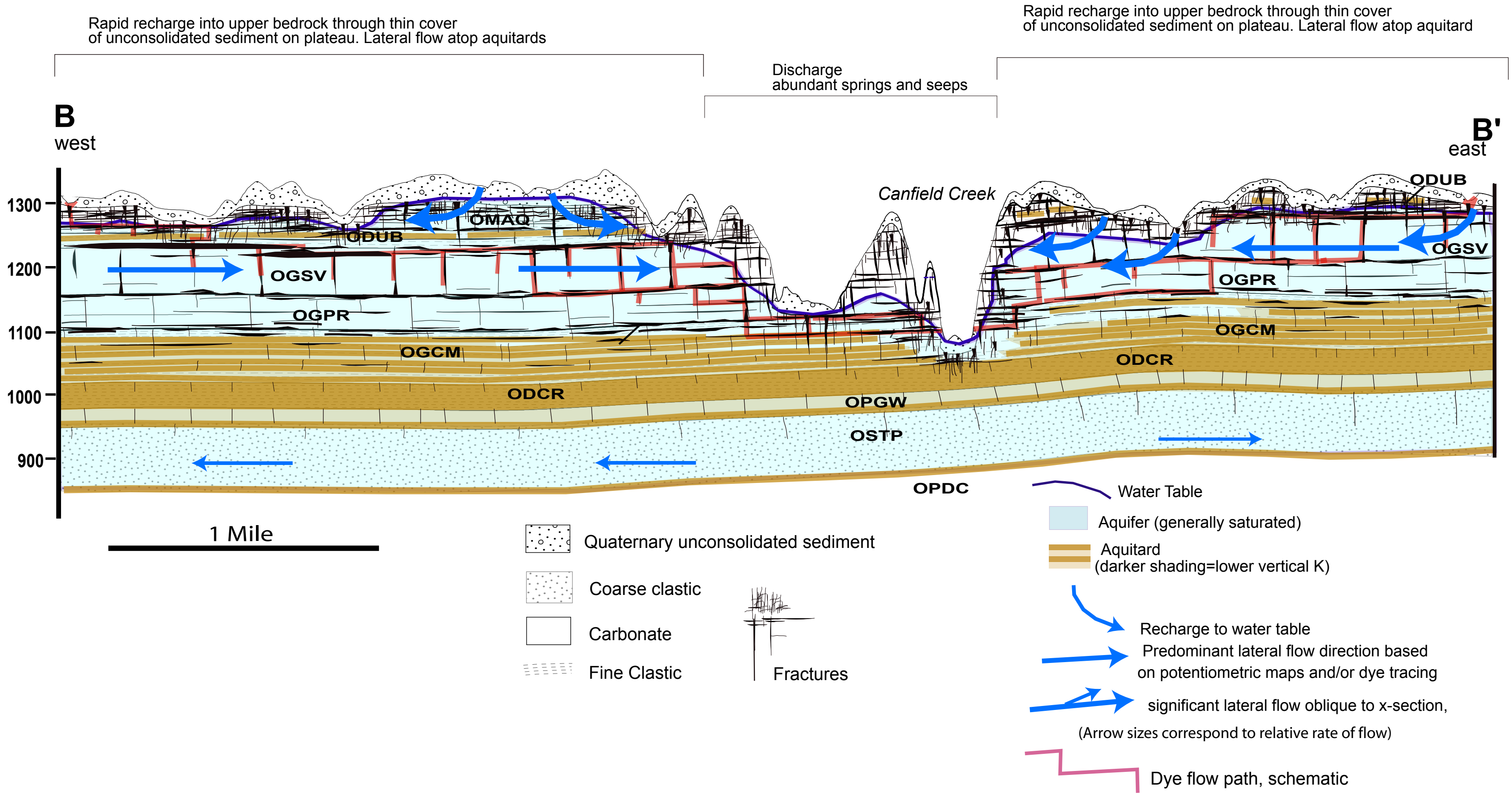


Figure 25. Cross section from the local project area showing example of flow system in Upper Carbonate Plateau setting with incised valley. Arrows show dominant, bulk flow directions. (A more limited component of downward flow that is present in most places is not represented by arrows). Flow directions are modified from Zhang and Kanivetsky (1996) and Alexander et al. (1996). Dye trace depiction based on information from Alexander et al. (1996). See Figures 4 and 8 for location of cross section. Stratigraphic codes are in Figure 5.

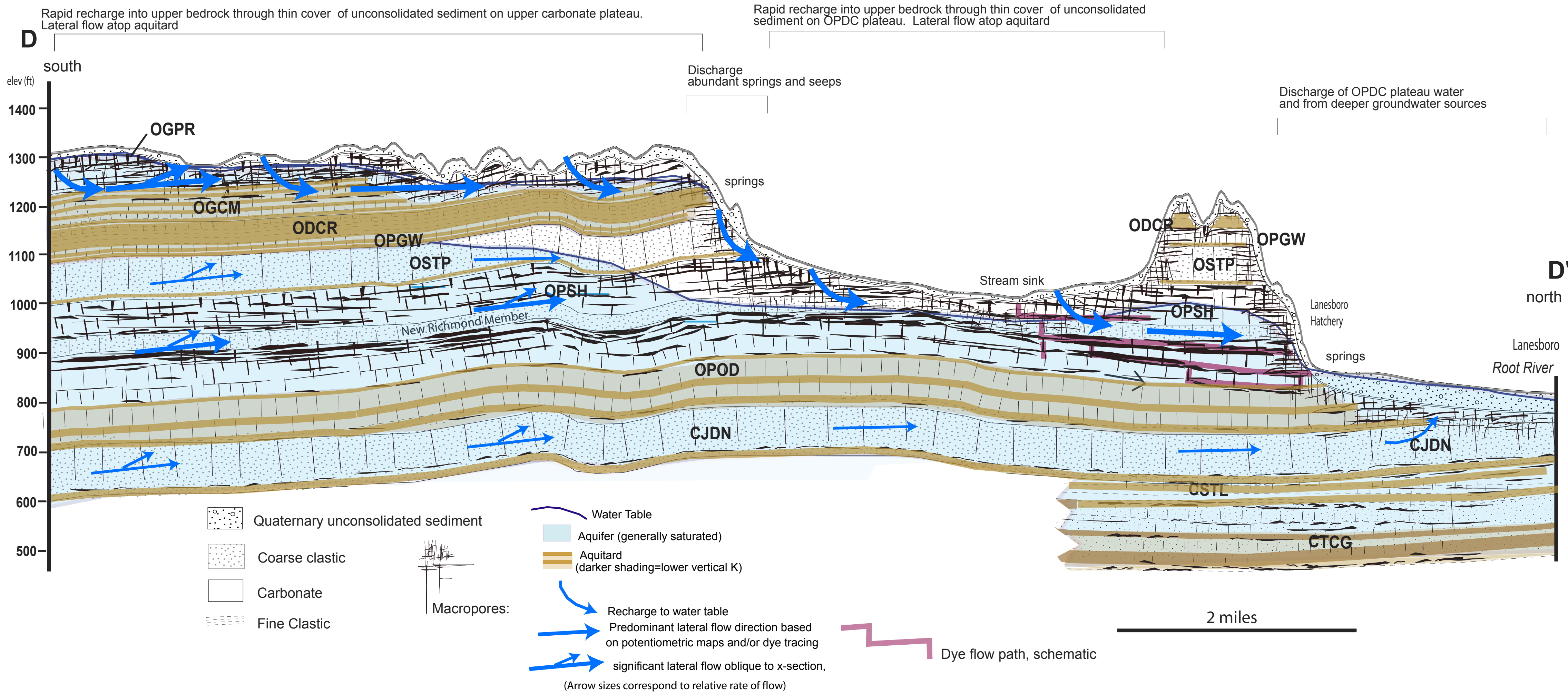


Figure 26. Cross section from south-central Fillmore County showing example of flow system from outer edge of Upper Carbonate Plateau (south), across escarpment, to the Prairie du Chien Plateau (north). Arrows show dominant, bulk flow directions. (A more limited component of downward flow that is present in most places is not represented by arrows). Flow directions are modified from Zhang and Kanivetsky (1996) and Alexander et al. (1996). Dye trace depiction based on information from Alexander et al. (1996) and Runkel et al. (2003). See Figure 4 for location of cross section. Stratigraphic codes are in Figure 5.

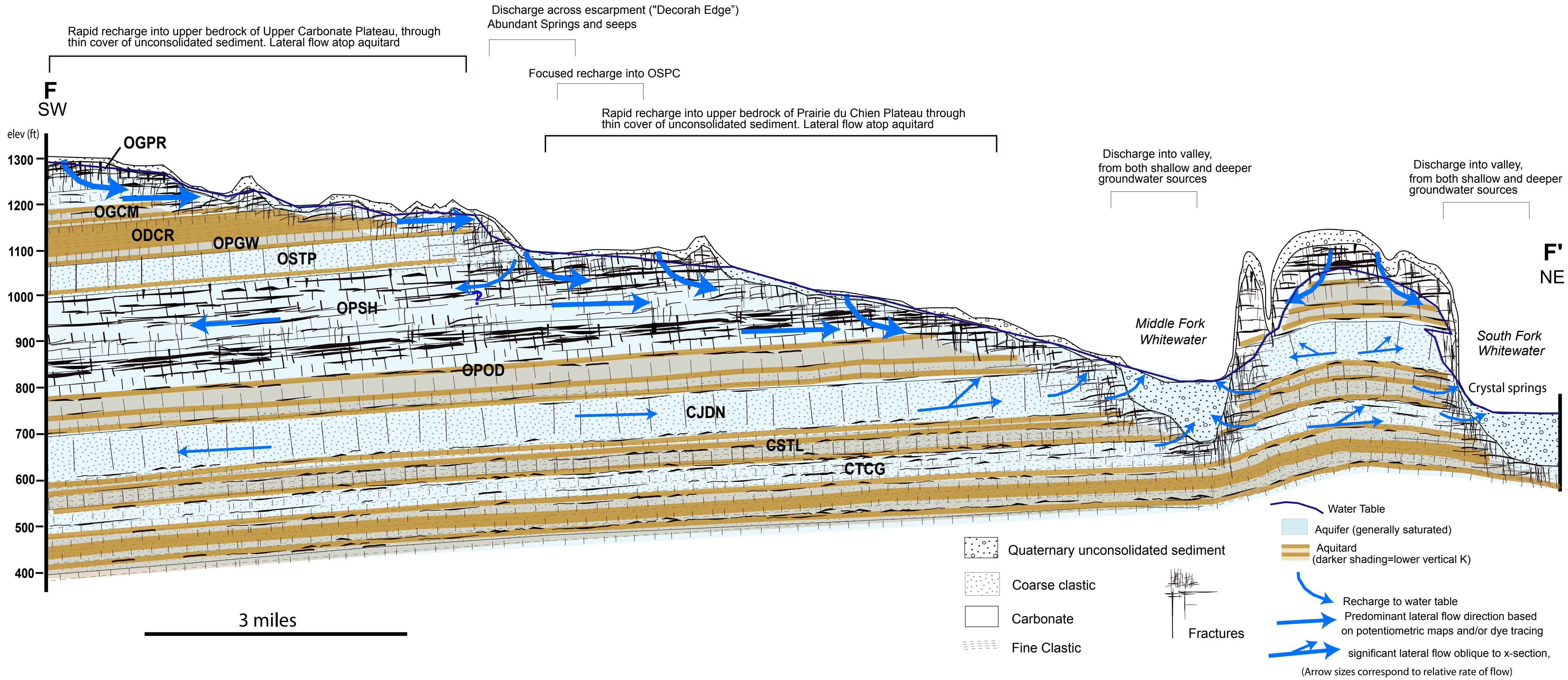


Figure 27. Cross section from eastern Olmsted and western Winona Counties showing example of flow system from outer edge of Upper Carbonate Plateau (southwest), across escarpment, to the Prairie du Chien Plateau (northeast). Arrows show dominant, bulk flow directions. (A more limited component of downward flow that is present in most places is not represented by arrows). Flow directions are modified from Kanivetsky (1984, 1988). See Figure 4 for location of cross section. Stratigraphic codes are in Figure 5.

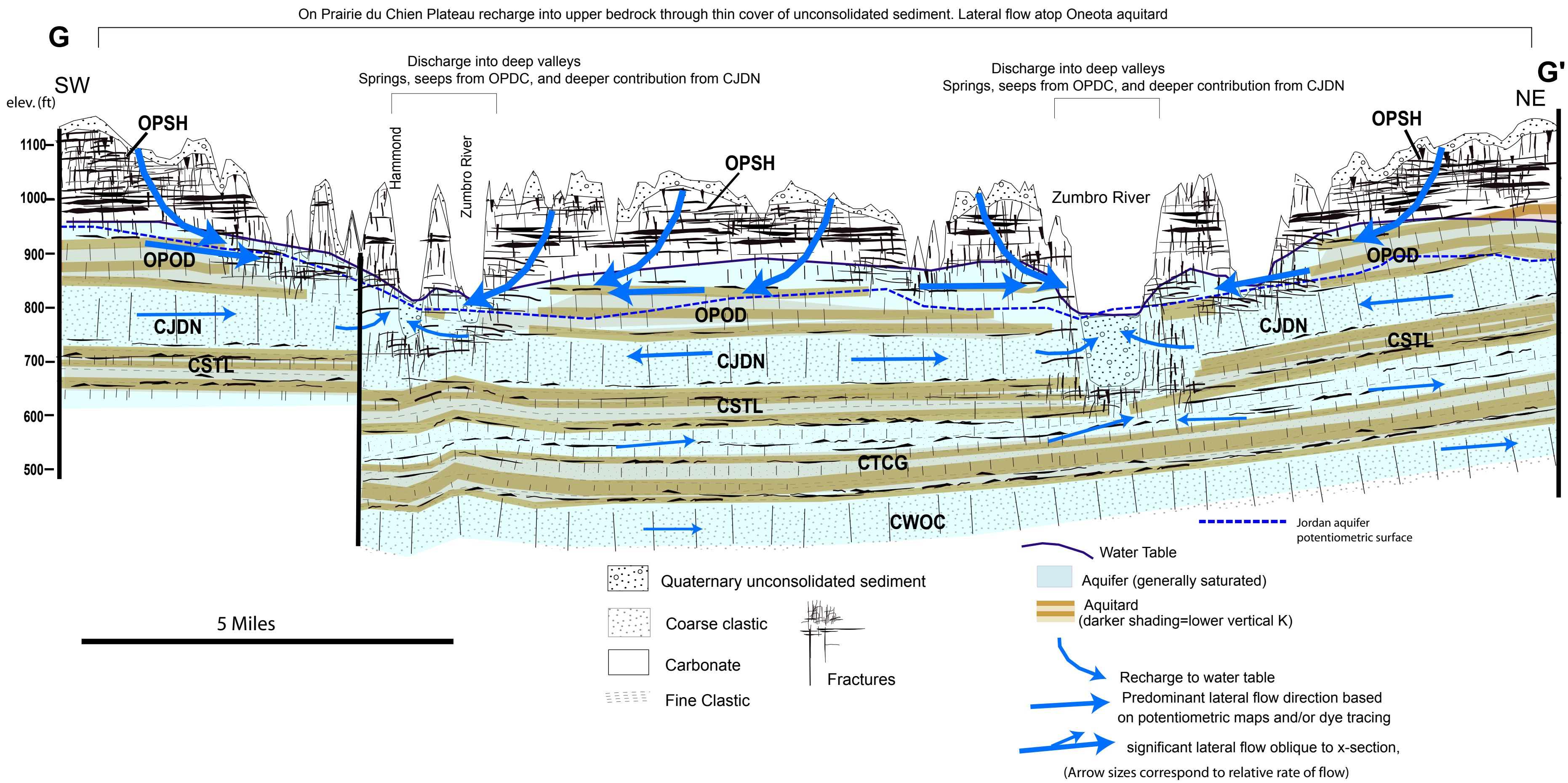


Figure 28. Cross section from Wabasha County showing example of flow system across Prairie du Chien Plateau, with deeply incised valleys. Arrows show dominant, bulk flow directions. [A more limited component of downward flow that is present in most places (with exception of near valleys) is not represented by arrows]. Cross section and flow directions are modified from Petersen (2005). See Figure 4 for location of cross section. Stratigraphic codes are in Figure 5.

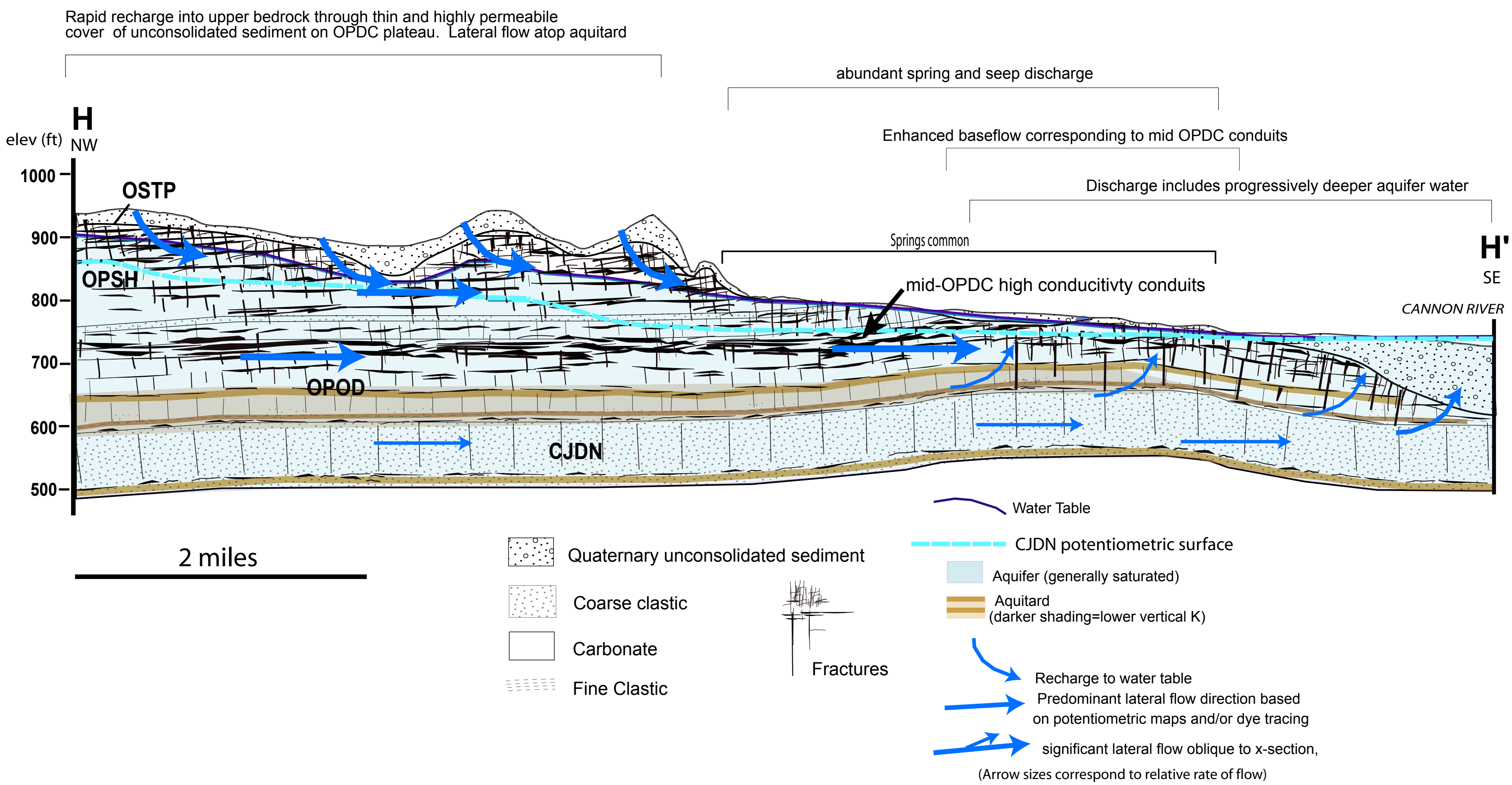


Figure 29. Cross section from Dakota County showing example of flow system across Prairie du Chien Plateau down to edge of incised valley. Arrows show dominant, bulk flow directions. [A more limited component of downward flow that is present in most places (with exception of near valleys) is not represented by arrows]. Flow directions are modified from Palen (1990). Some baseflow information is from Groten and Alexander (2013). See Figure 4 for location of cross section. Stratigraphic codes are in Figure 5.

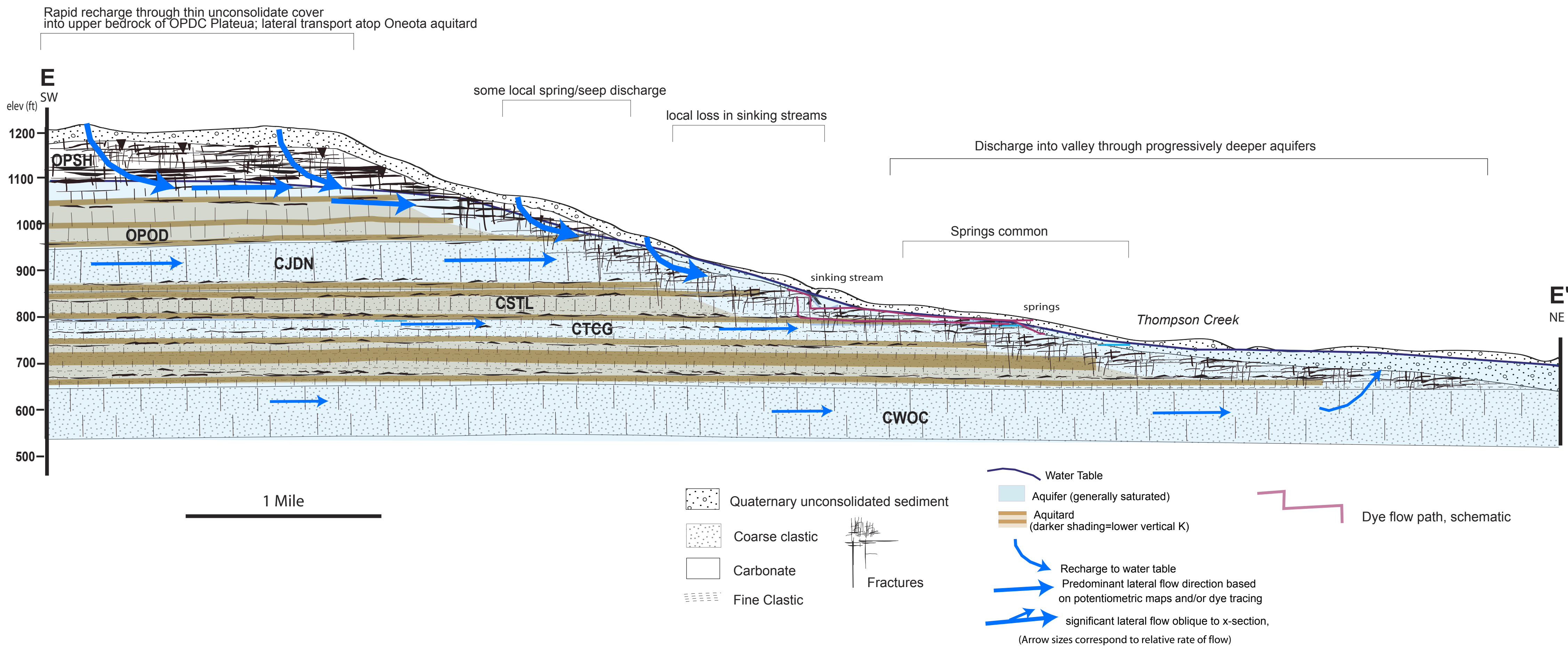


Figure 30. Cross section from Houston County showing example of flow system across Prairie du Chien Plateau (southwest) down the approximate axis of an incised valley. Arrows show dominant, bulk flow directions. [A more limited component of downward flow that is present in most places (with exception of near valleys) is not represented by arrows]. Flow directions are modified from Delin and Woodward (1984) and draw upon similar settings in other counties where hydrogeologic conditions have been studied in greater detail (e.g. Petersen, 2005). Dye trace depiction based on information from Jeff Green, MNDNR (e.g. Green et al., 2012). See Figure 4 for location of cross section. Stratigraphic codes are in Figure 5.

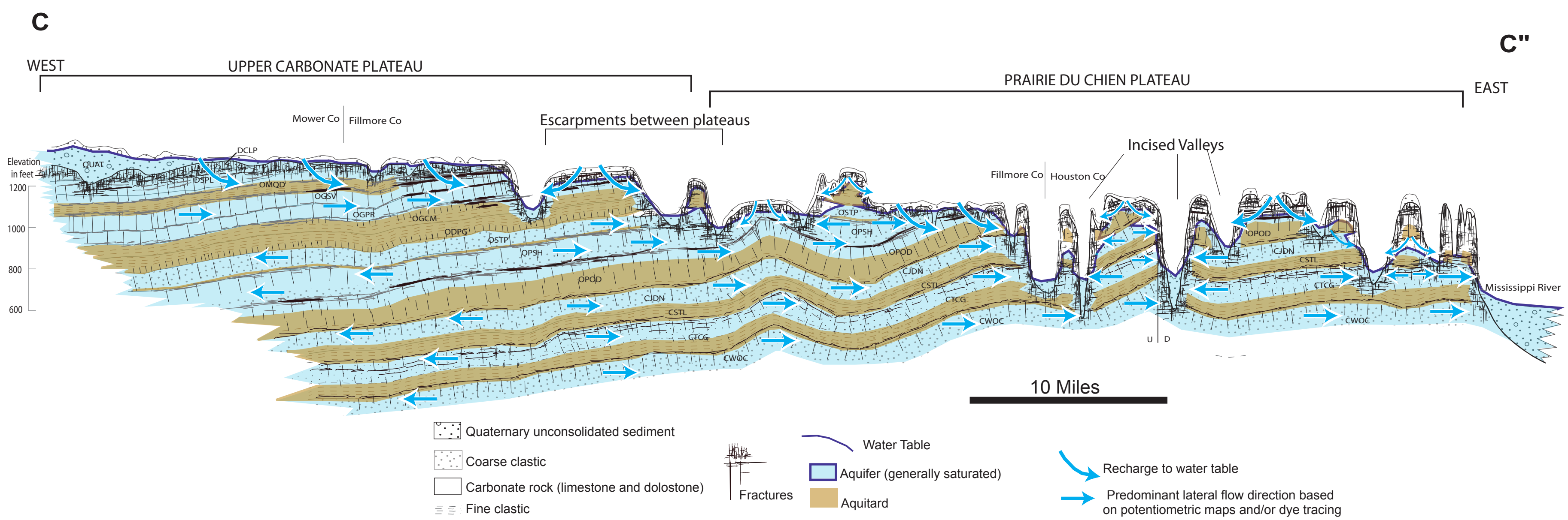


Figure 31. Highly generalized, regional-scale cross-section, from approximately central Mower County, east to the Mississippi River, showing example of flow system from the outer edge of the drift-dominated landscape (west), across the bedrock dominated landscape (east). Arrows show dominant, bulk flow directions. [A more limited component of downward flow that is present in most places (with exception of near valleys) is not represented by arrows]. Flow directions are modified from Delin and Woodward (1984), Campion (2002), Zhang and Kanivetsky (1996), and Alexander et al. (1996). Location of cross section (C-C”) is shown in Figure 4. Stratigraphic codes are in Figure 5.

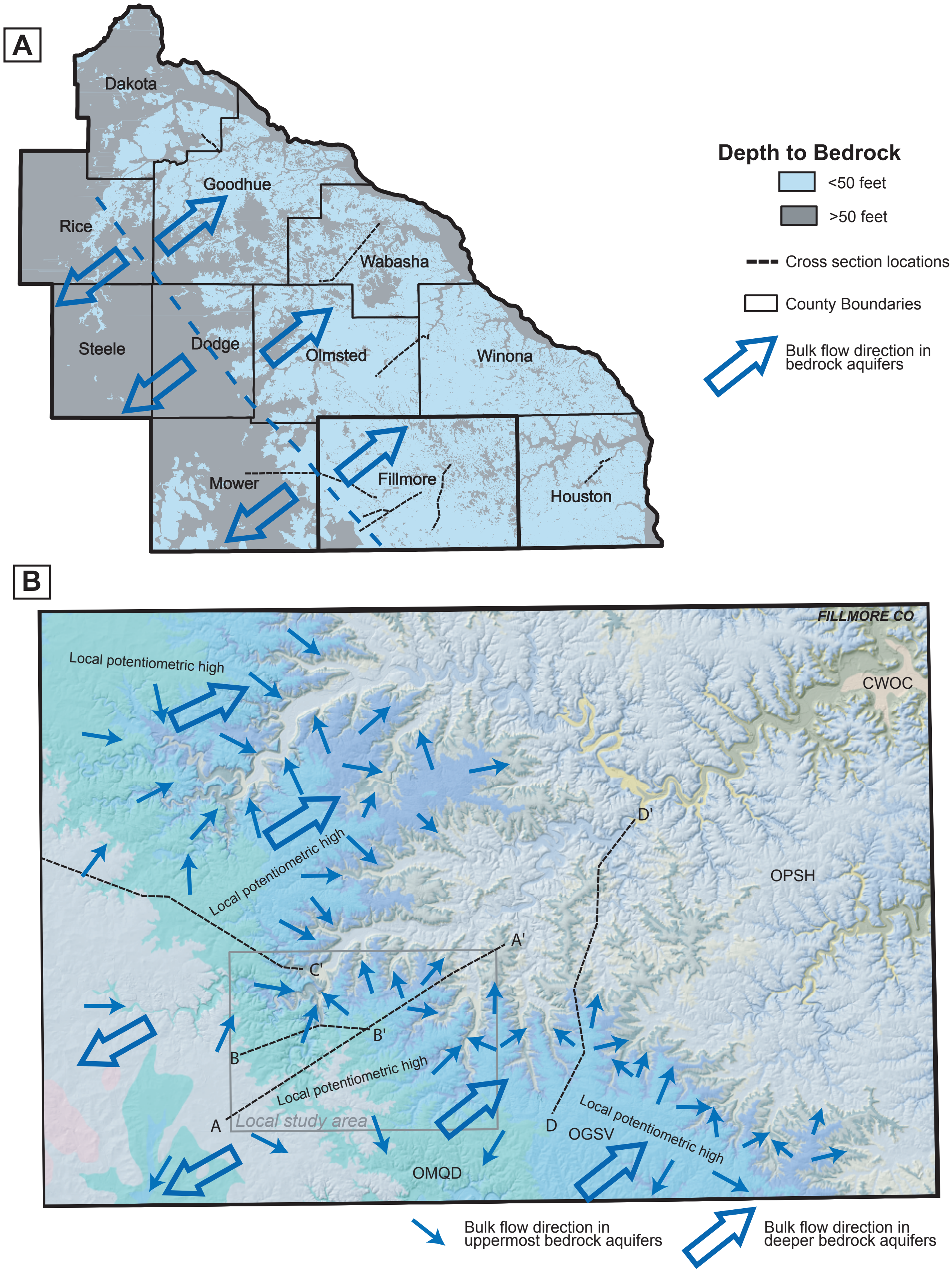


Figure 32. Map views of dominant, bulk groundwater flow directions in southeastern Minnesota. (A) shows dominant direction of groundwater flow in the bedrock at regional scale. (B) shows dominant direction of flow at more detailed scale, all of Fillmore County, contrasting bulk flow directions of deeper bedrock aquifers with more highly resolved and variable directions in uppermost bedrock. See text for discussion. Based on information from Delin and Woodward (1984), Kanivetsky (1988), Zhang and Kanivetsky (1996), Alexander et al. (1996), Berg and Bradt (2003), and Campion (1997, 2002). See figure 4 for legend to bedrock map and location of Fillmore County in (B).

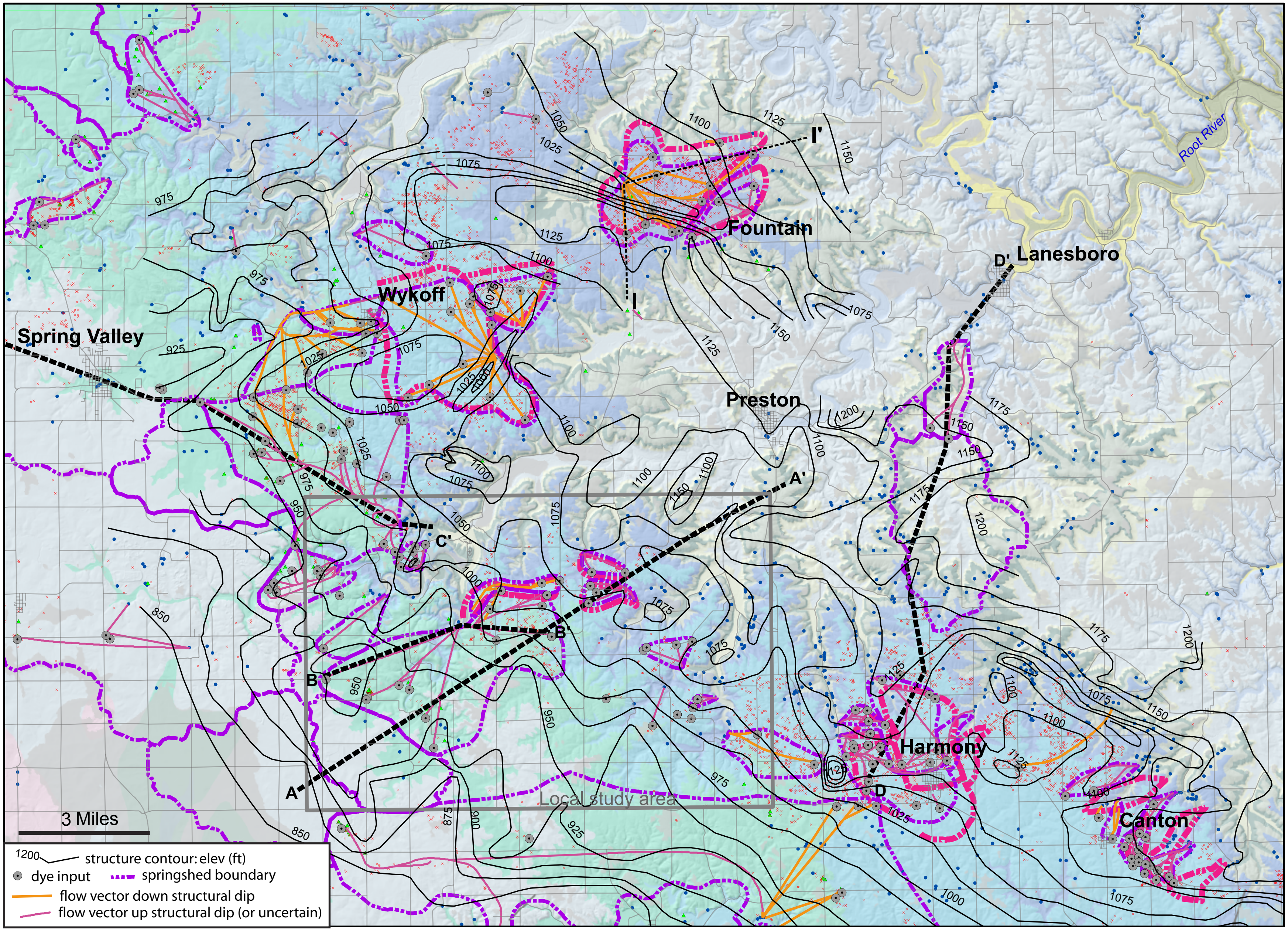


Figure 33. Bedrock geology of part of Fillmore County highlighting a comparison of springshed boundaries, dye trace flow vectors, and structure of the bedrock formations. The structure contours represent the elevation of the top of the St Peter Sandstone. In some springsheds flow is directed preferentially down structural dip, in others flow is up structural dip. See text for discussion. Most springshed boundaries, flow vectors, and dye input locations published originally by Alexander et al. (1996), and modified for this illustration with new information provided by Jeff Green, MNDNR, as part of an ongoing University of Minnesota and MNDNR project. See Figure 4 for legend to bedrock map.

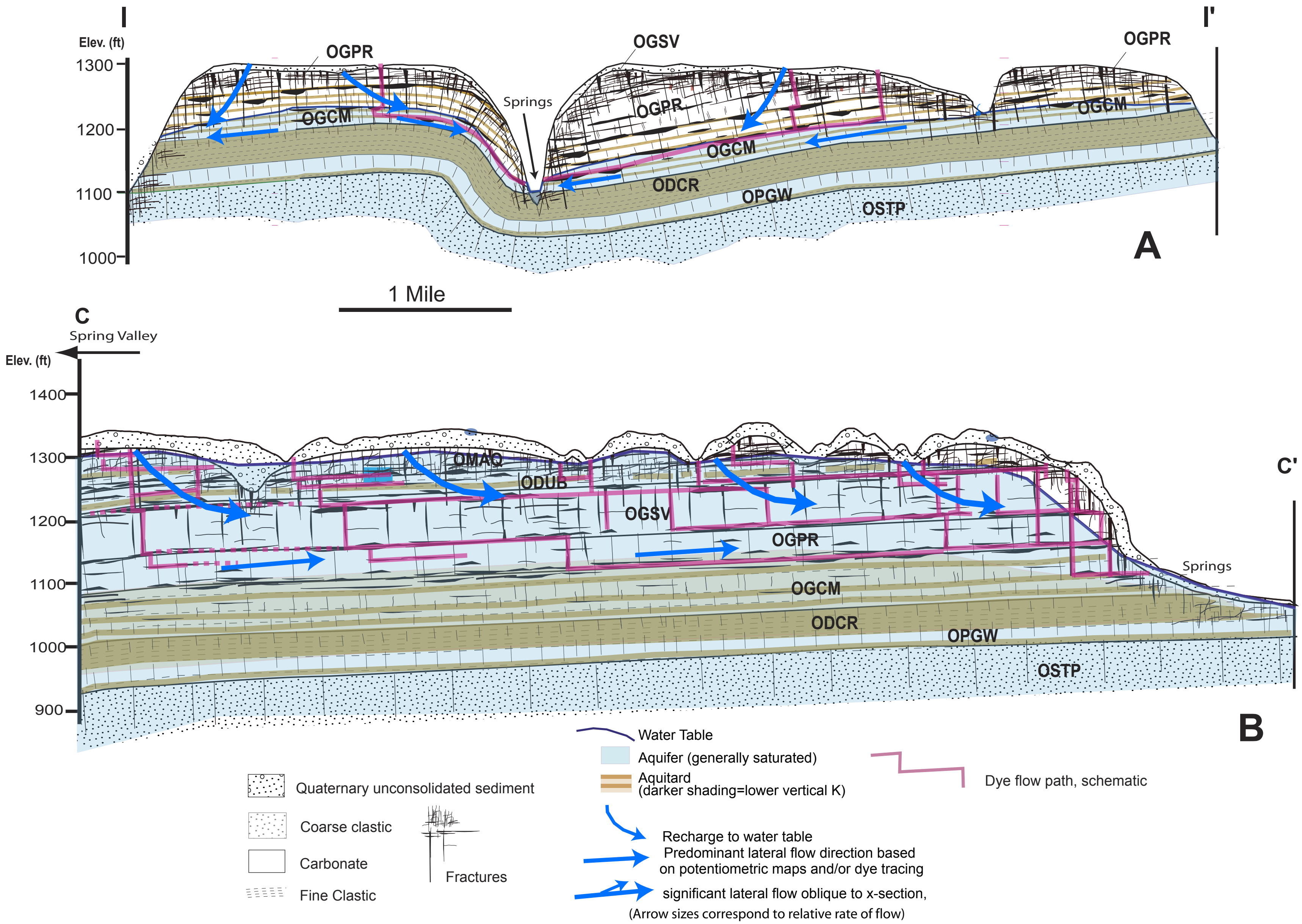


Figure 34. Cross sections from western Fillmore County showing representative examples of springsheds where (A) flow in uppermost bedrock flows preferentially down structural dip, and (B) where flow in upmost bedrock is up structural dip. See Figure 33 for cross section locations.

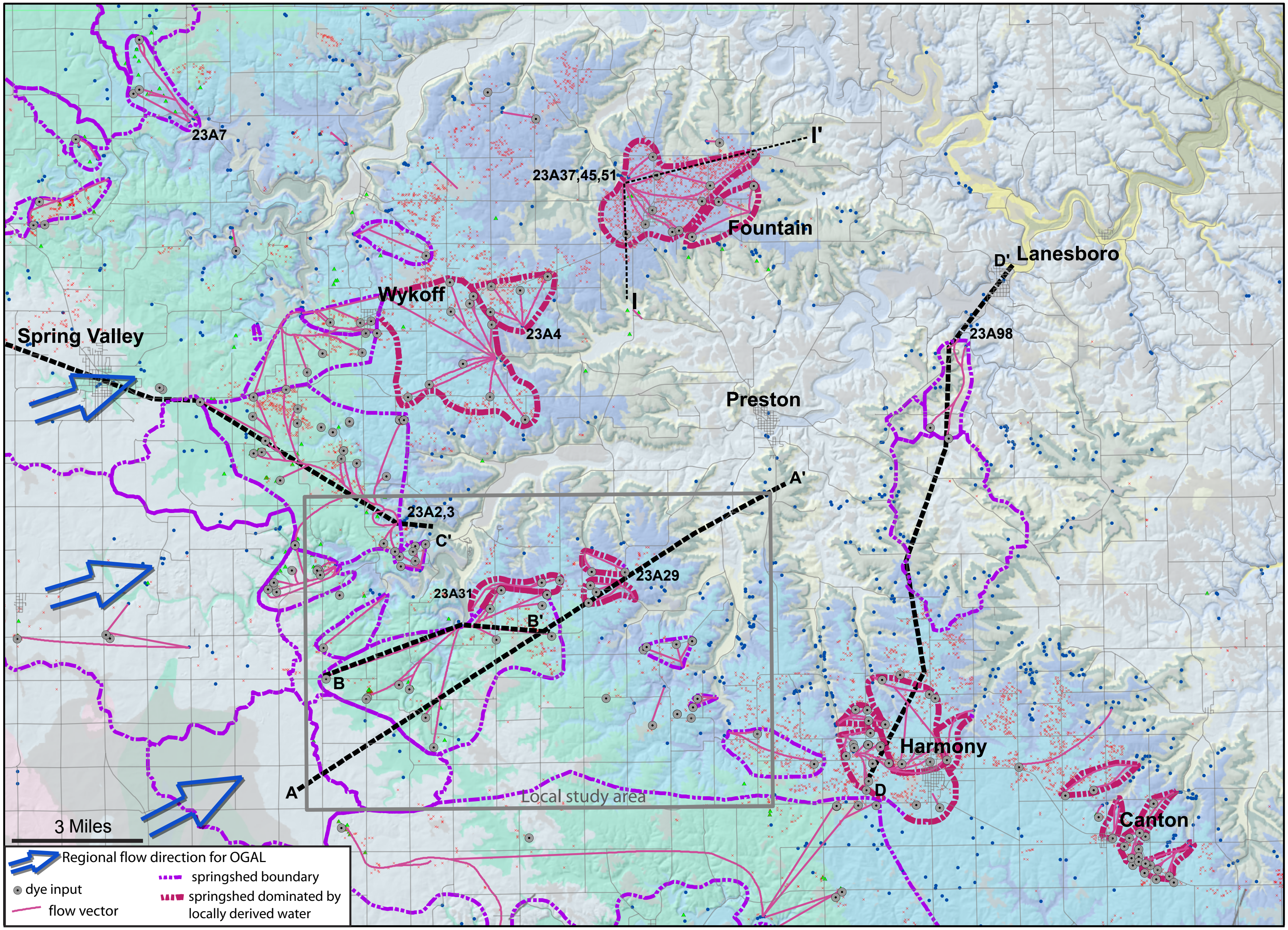


Figure 35. Bedrock geology of part of Fillmore County, highlighting springsheds likely to be dominated by locally derived water. See text for discussion. 23A identifiers refer to springs sampled and analyzed for nitrate concentration, discussed in the nitrate sections of this report, and illustrated in Figs. 58-60. Most springshed boundaries, flow vectors, and dye input locations published originally by Alexander et al. (1996) and modified for this illustration with new information provided by Jeff Green, MNDNR, as part of an ongoing University of Minnesota and MNDNR project. See Figure 4 for legend to bedrock map.

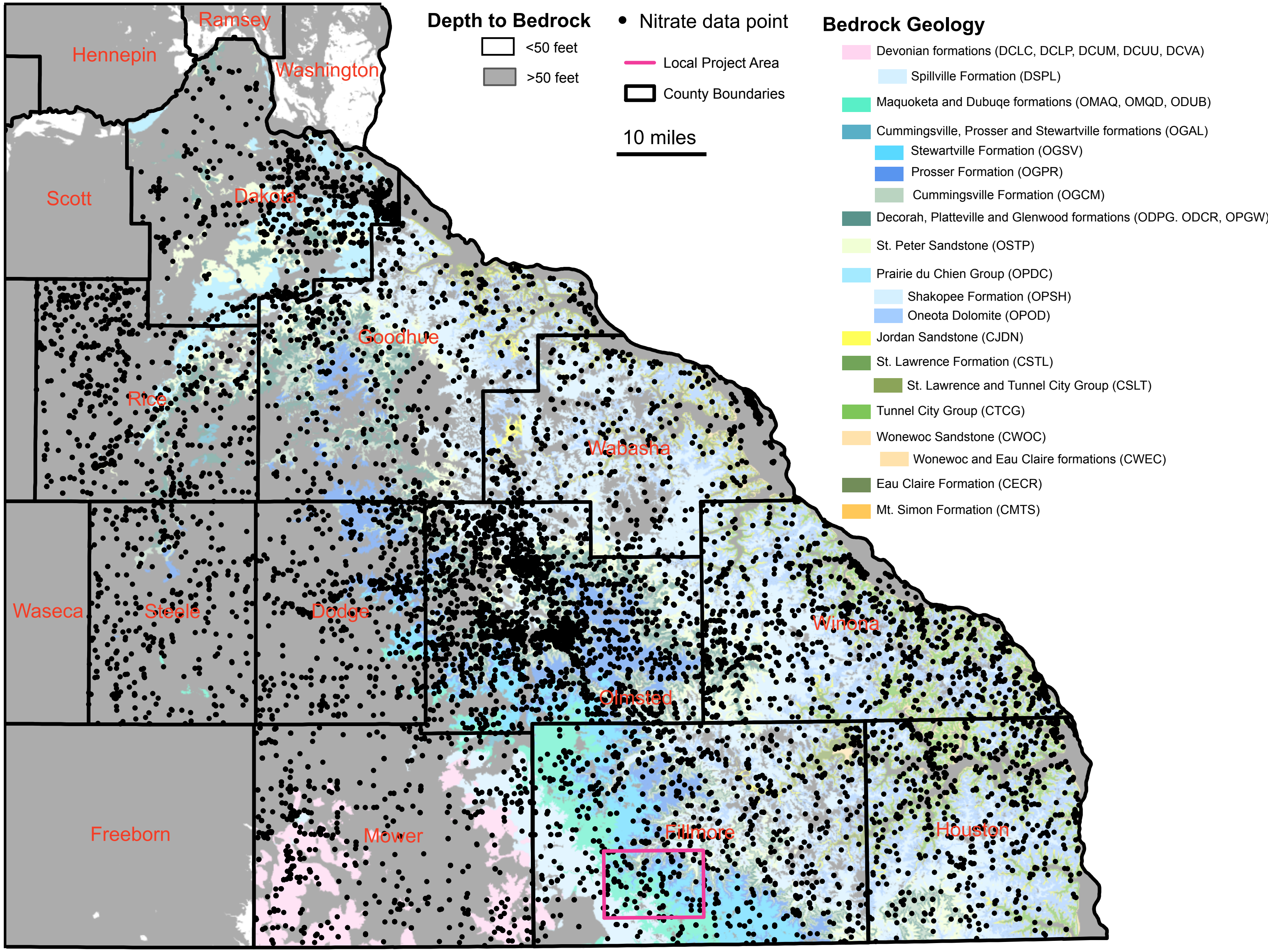


Figure 36. Regional geologic map for southeastern Minnesota showing distribution of water samples with nitrate concentrations in the database compiled for this report.

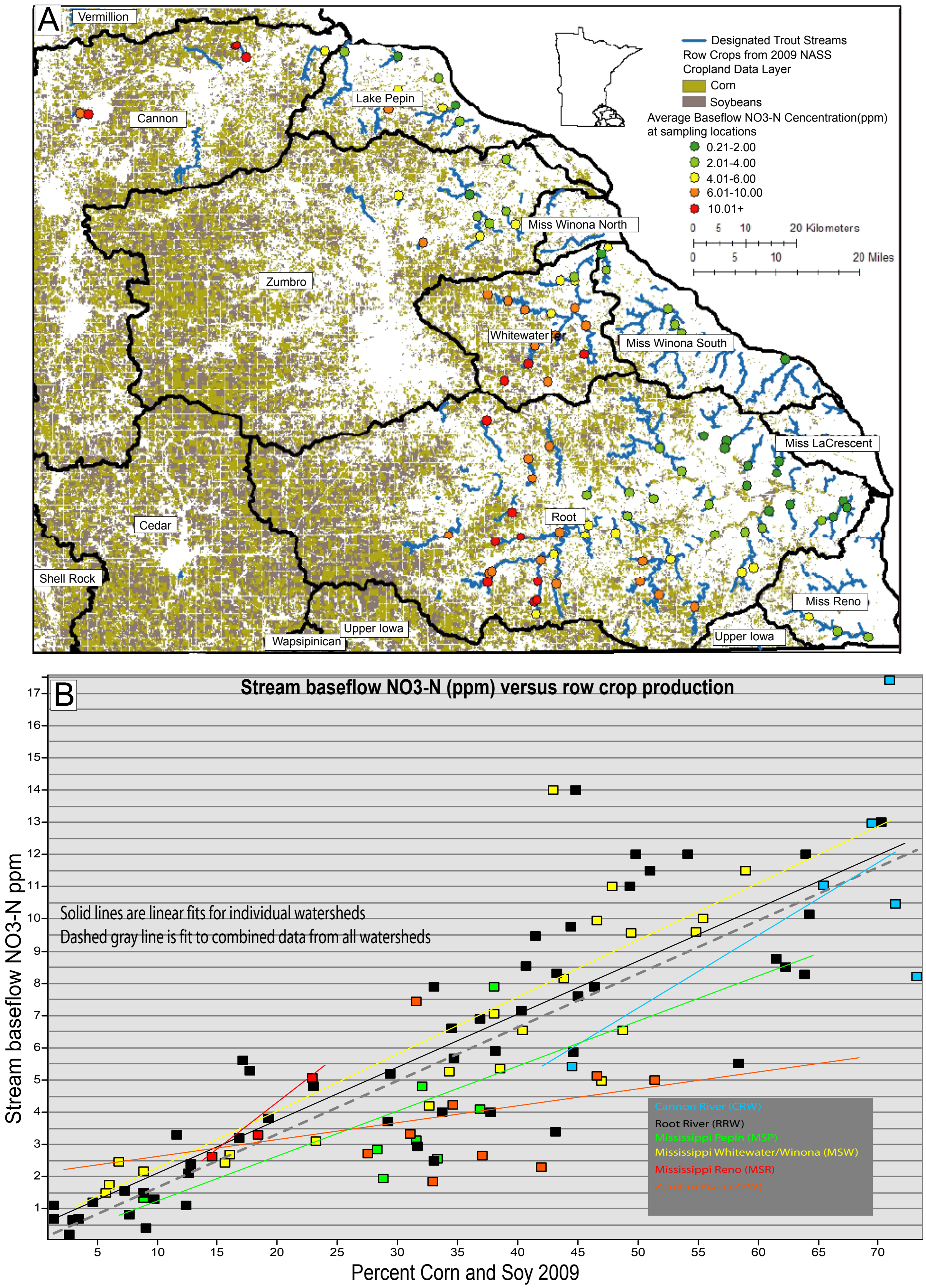
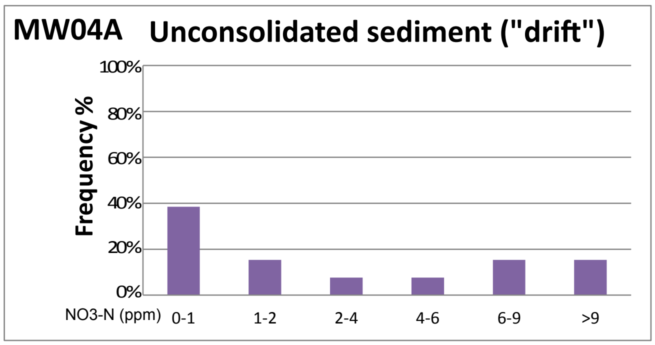
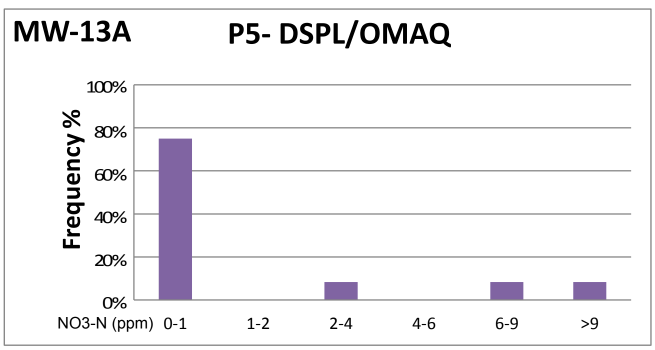


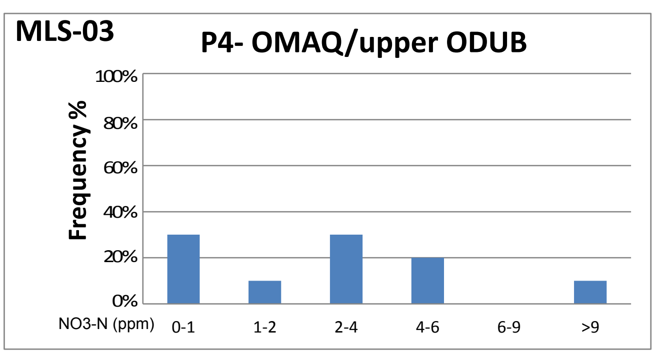
Figure 37. (A) Stream baseflow nitrate concentration sampling point locations on 2009 map of row crop land use for southeastern Minnesota. (B) Stream baseflow nitrate concentration plotted against 2009 row crop land use from Watkins et al. (2011). Stream samples are meant to be representative of baseflow or "non-event" conditions. Individual values are based on multiple samples, most collected between 2005-2010. Complete database available from the MPCA.



Well	Zone	Sample date	reported value	assigned value
MW-04A	Drift	11/20/2000	7.7	7.7
MW-04A	Drift	3/22/2001	9	9
MW-04A	Drift	8/28/2001	3	3
MW-04A	Drift	11/20/2001	0	0
MW-04A	Drift	3/26/2002	0	0
MW-04A	Drift	8/22/2002	>5.0	5
MW-04A	Drift	3/28/2003	10.7	10.7
MW-04A	Drift	7/22/2003	0.6	0.6
MW-04A	Drift	10/28/2003	0.3	0.3
MW-04A	Drift	3/17/2004	0	0
MW-04A	Drift	7/12/2004	8	8
MW-04A	Drift	10/20/2004	1.1	1.1



Well	Zone	Sample date	reported value	assigned value
MW-13A	Z-P5	11/21/2000	<0.1	0
MW-13A	Z-P5	3/21/2001	<0.1	0
MW-13A	Z-P5	8/28/2001	<1	0
MW-13A	Z-P5	11/20/2001	0	0
MW-13A	Z-P5	3/28/2002	0	0
MW-13A	Z-P5	8/21/2002	0	0
MW-13A	Z-P5	11/13/2002	0	0
MW-13A	Z-P5	4/3/2003	2.7	2.7
MW-13A	Z-P5	7/16/2003	10	10
MW-13A	Z-P5	3/16/2004	0	0
MW-13A	Z-P5	7/8/2004	6.3	6.3
MW-13A	Z-P5	10/19/2004	0	0



Well	Zone	Sample date	reported value	assigned value
MLS-03	Z-P4	11/2/2000	5.4	5.4
MLS-03	Z-P4	8/28/2001	2.3	2.3
MLS-03	Z-P4	12/5/2001	0.3	0.3
MLS-03	Z-P4	4/4/2002	0	0
MLS-03	Z-P4	8/22/2002	3.4	3.4
MLS-03	Z-P4	11/22/2002	2.4	2.4
MLS-03	Z-P4	7/31/2003	5.8	5.8
MLS-03	Z-P4	3/23/2004	0	0
MLS-03	Z-P4	7/21/2004	12.3	12.3
MLS-03	Z-P4	10/27/2004	1.1	1.1

Figure 38. Nitrate concentrations over time from wells open to relatively discrete intervals of unconsolidated sediment and bedrock at British Petroleum Spring Valley Terminal, Fillmore County Minnesota. These exemplify the variability in concentration over time that may be characteristic of other parts of southeastern Minnesota. See text for discussion. Data provided by AnteaGroup (formerly Delta Environmental) consultants. Samples analyzed in the field with a HACH colorimeter. Location of site is shown on cross section in Figure 23, and on map in Figures 4.

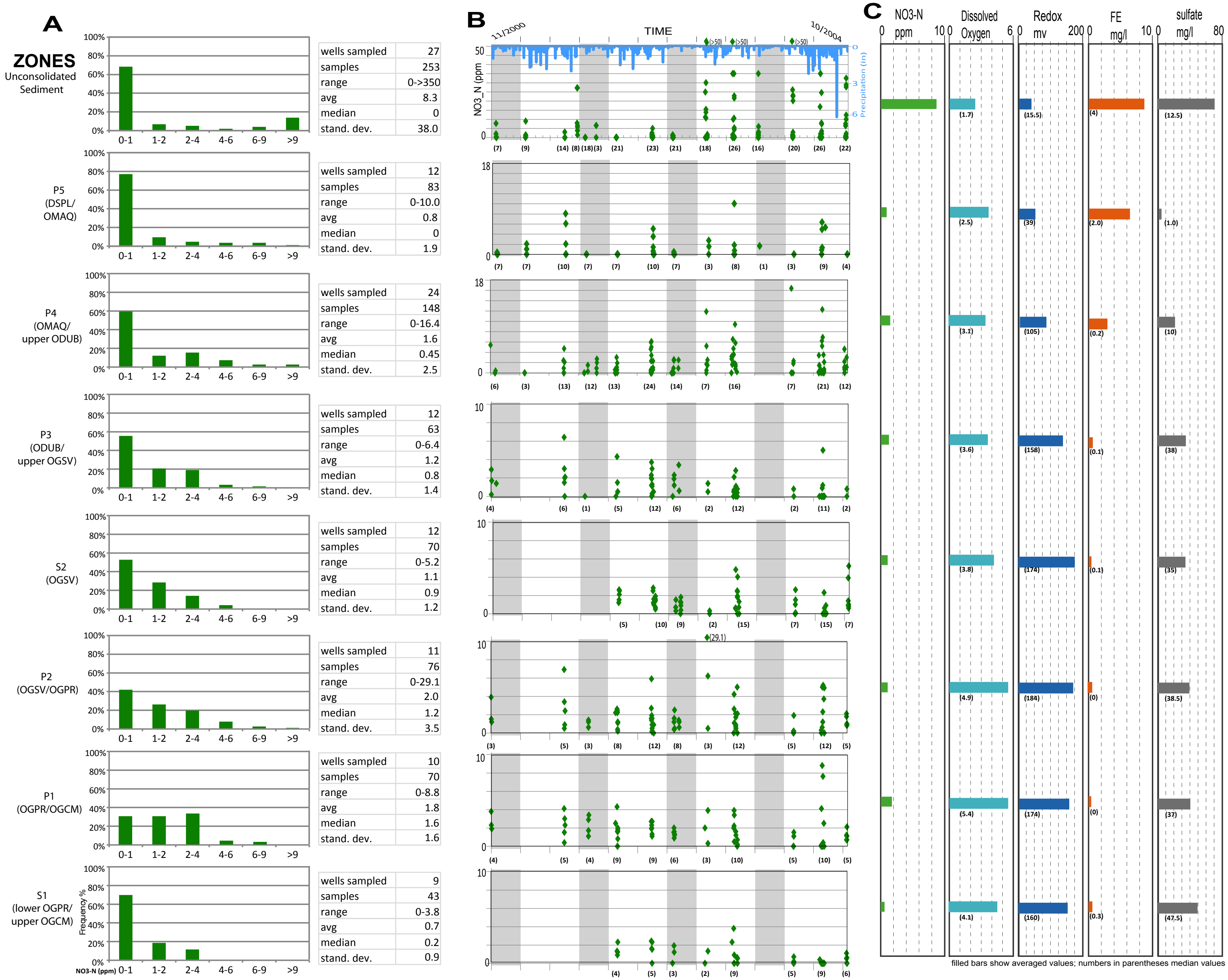


Figure 39. Nitrate concentrations (A, B) and associated chemical analyses (C) from wells open to discrete intervals of unconsolidated sediment and bedrock at British Petroleum Spring Valley Terminal, Fillmore County Minnesota. Histograms in (A) show frequency of samples within specific ranges of nitrate concentrations for individual zones. (B) shows concentrations of samples from individual zones over time. Samples collected from 65 wells approximately every 3-4 months from 2000 to 2004. Gray vertical bars on plots in (B) correspond to November-February, and numbers in parentheses are number of wells sampled. Individual sampling events typically occurred over about a two week period. Values shown as horizontal bars in (C) are averaged values and numbers beneath the bars are median values. Unconsolidated sediment ranges from about 10 to 50 ft thick, and zone S1 is at depth of about 300 ft. Location of site is shown on cross section in Fig. 23, and on maps in Figs. 4 and 45B. Stratigraphic codes in Figure 5. Data provided by AnteaGroup (formerly Delta Environmental) consultants. Samples analyzed in the field with a HACH colorimeter.

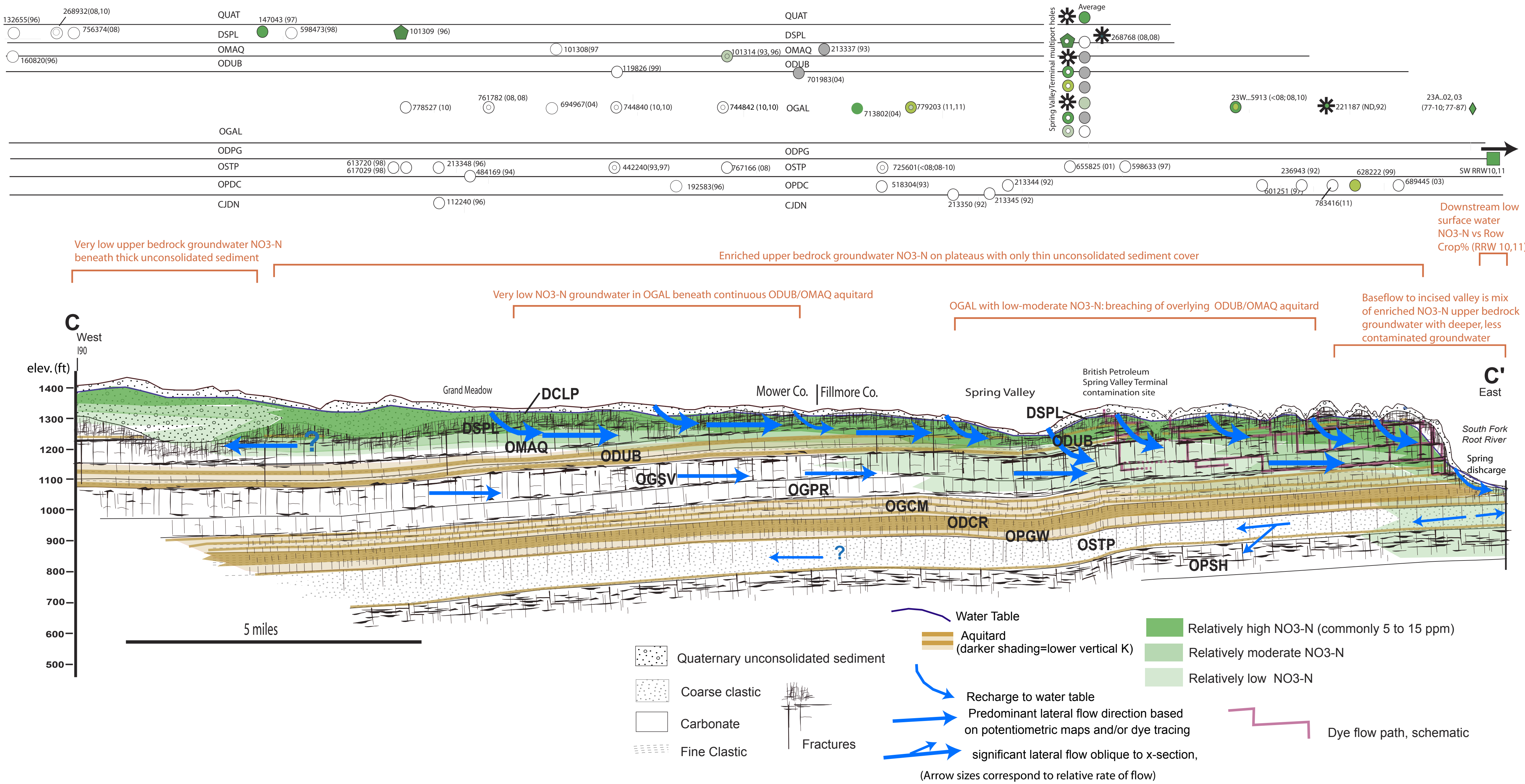


Figure 40. (A) Cross section showing ground and surface water nitrate concentrations in hydrogeologic context across the Upper Carbonate Plateau, from the edge of the drift-dominated landscape (west) to the bedrock-dominated landscape (east). Eastern Mower and western Fillmore Counties. Figure 23 provides additional information on flow conditions and sources of information. Full legend and explanation for cross section in Appendix A.

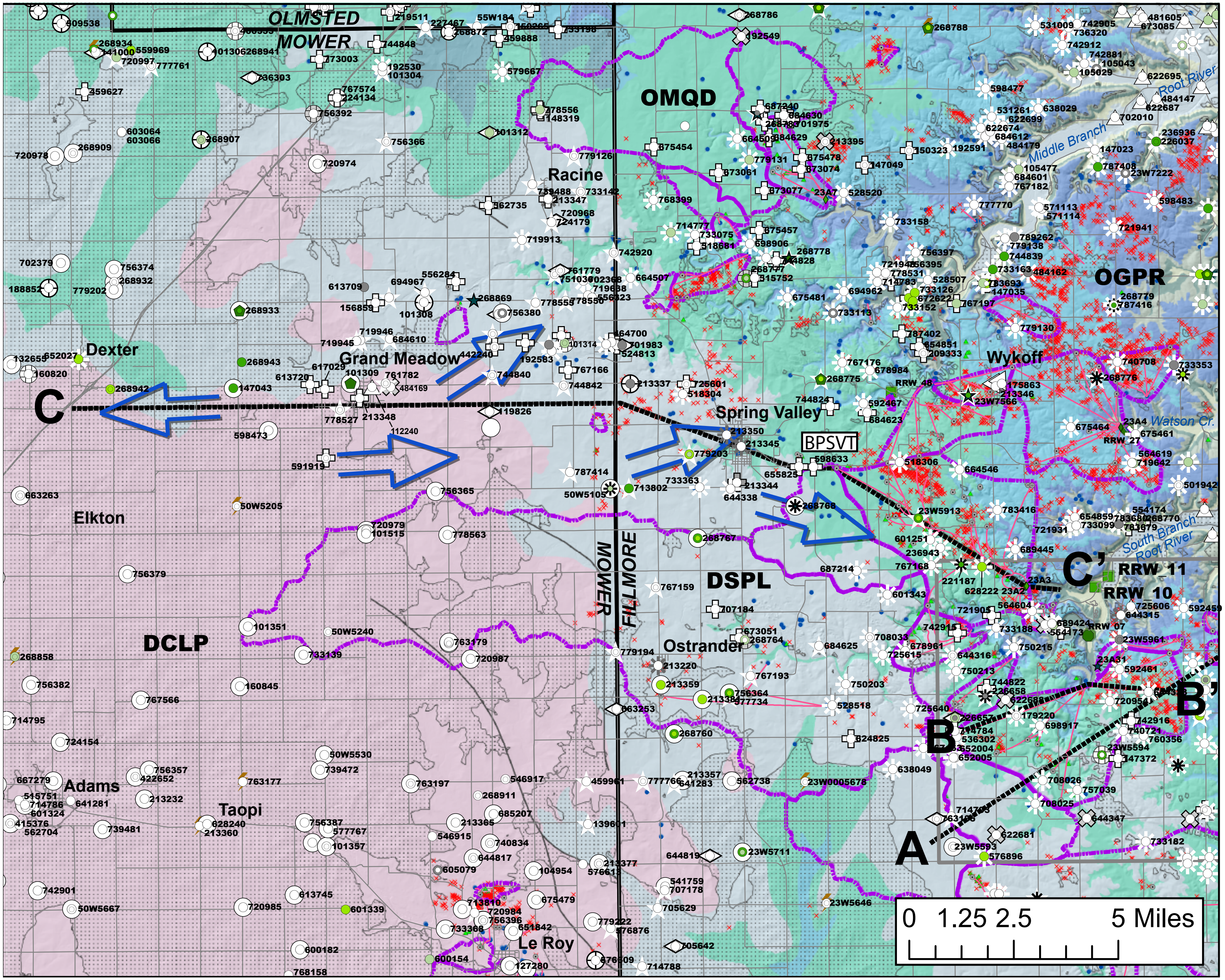


Figure 40 (B) Map showing cross section line, nitrate data, and other relevant information used to construct the cross section in Fig 40A. Arrows depict bulk dominant flow directions in Galena Aquifer. BPSVT=British Petroleum Spring Valley Terminal. Full legend and explanation for map in Appendix A.

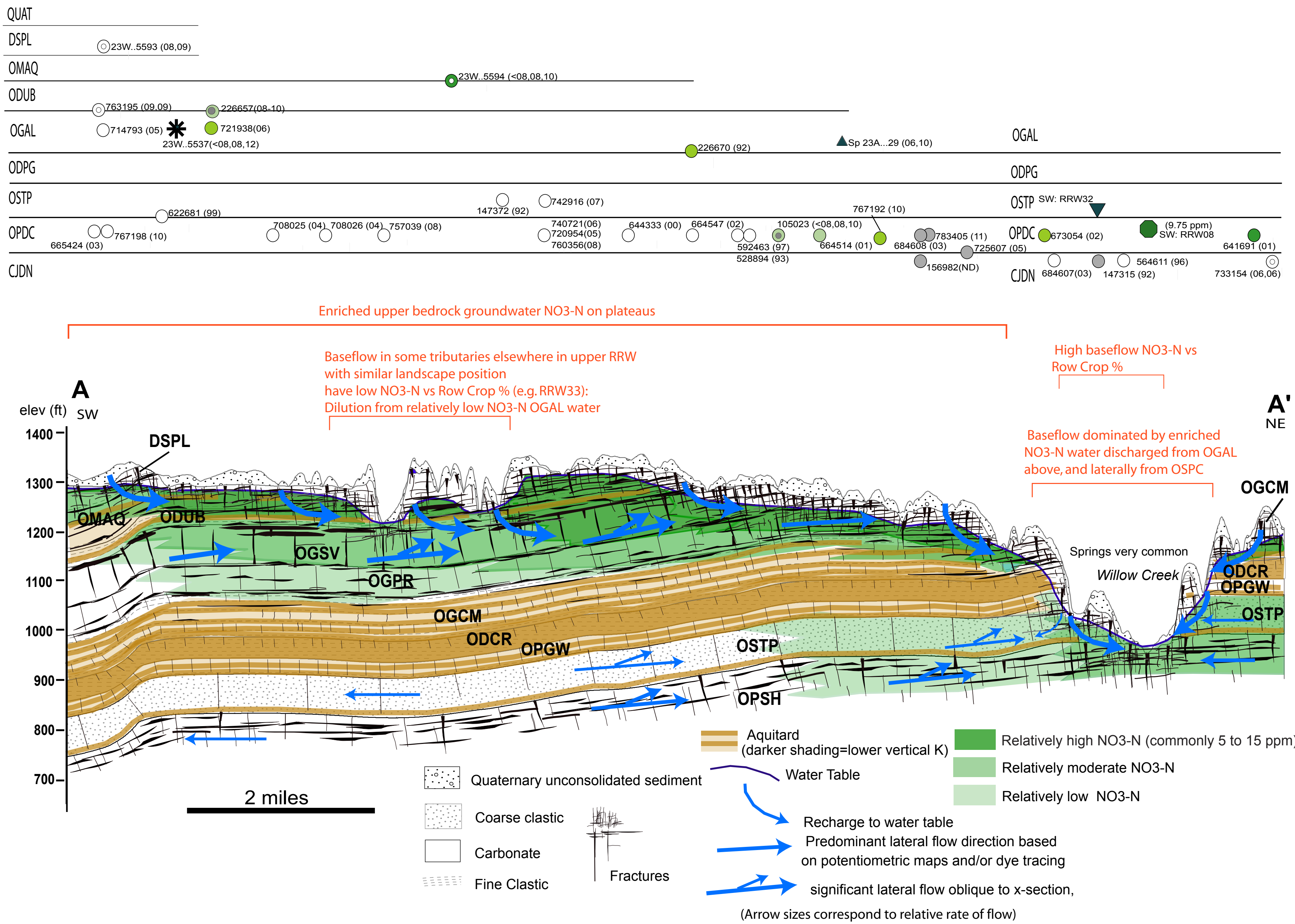


Figure 41. (A) Cross section showing ground and surface water nitrate concentrations in hydrogeologic context across Upper Carbonate Plateau setting to escarpment at outer edge of plateau. Local project area of Fillmore County. Figure 24 provides additional information on flow conditions and sources of information. Full legend and explanation for cross section in Appendix A.

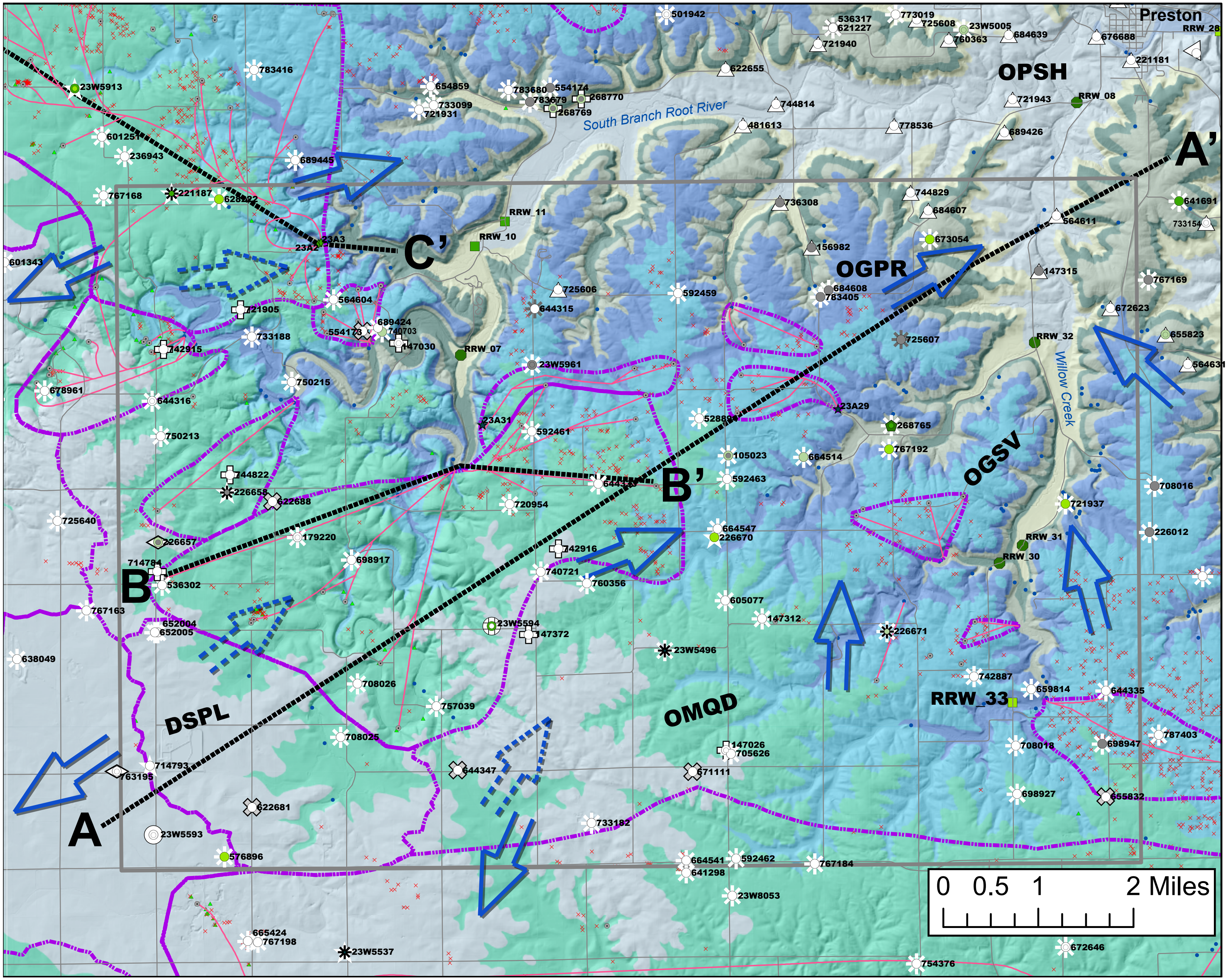


Figure 41 (B) Map showing cross section line, nitrate data, and other relevant information used to construct the cross section in Fig 41A. Solid line arrows depict bulk dominant flow directions for combined St Peter, Prairie du Chien and Jordan aquifers. Dashed line arrows depict dominant bulk flow in Galena aquifer. Distribution of unconsolidated sediment greater than 50 ft not shown on map, but occurs in isolated patches and in deeper stream valleys. It is depicted on cross section, on regional maps (e.g. Figure 4) and available in delivered GIS coverage. Full legend and explanation for map in Appendix A.

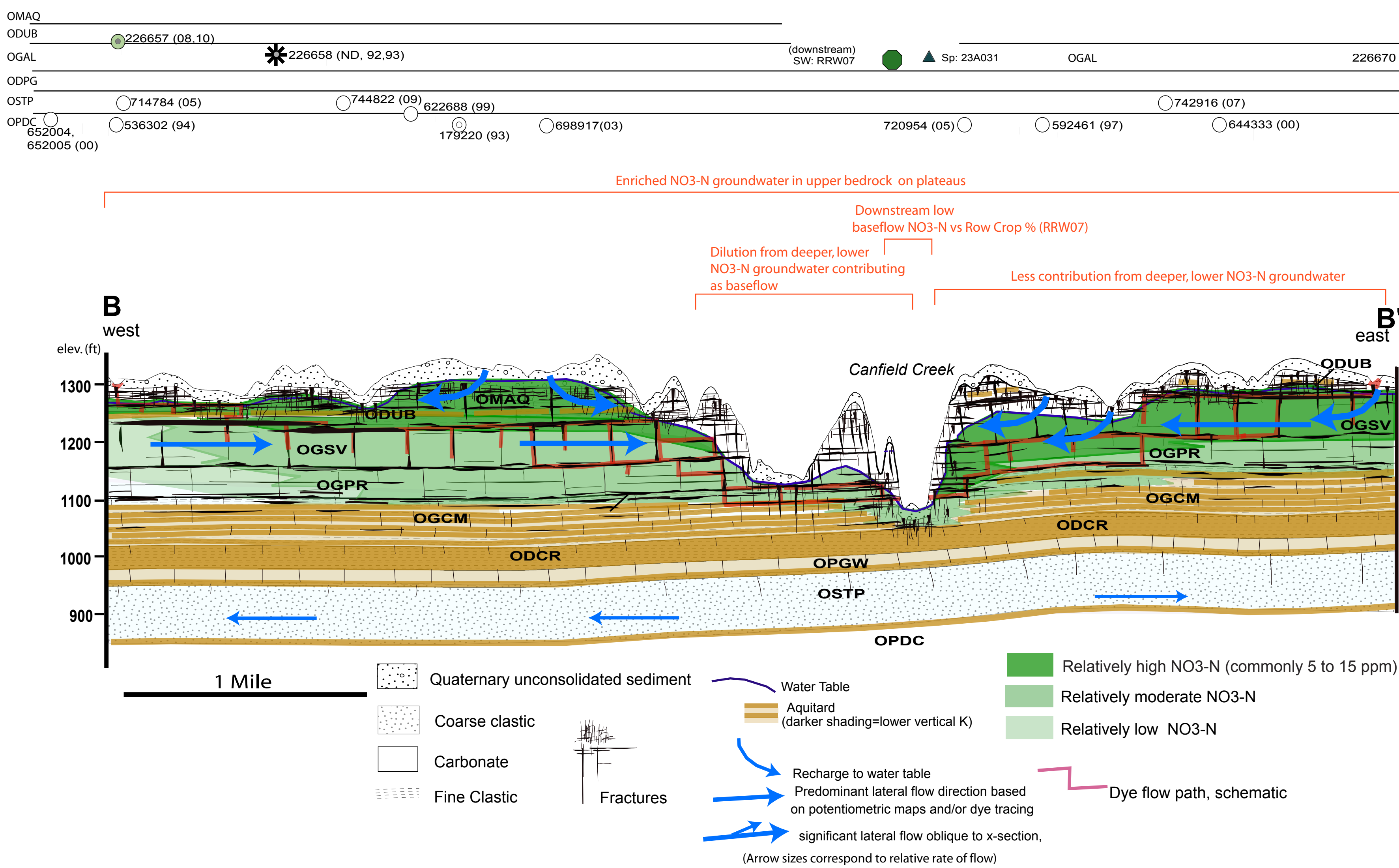


Figure 42. (A) Cross section showing ground and surface water nitrate concentrations in hydrogeologic context in Upper Carbonate Plateau setting with incised valley. Local project area of Fillmore County. Figure 25 provides additional information on flow conditions and sources of information. Full legend and explanation for cross section in Appendix A.

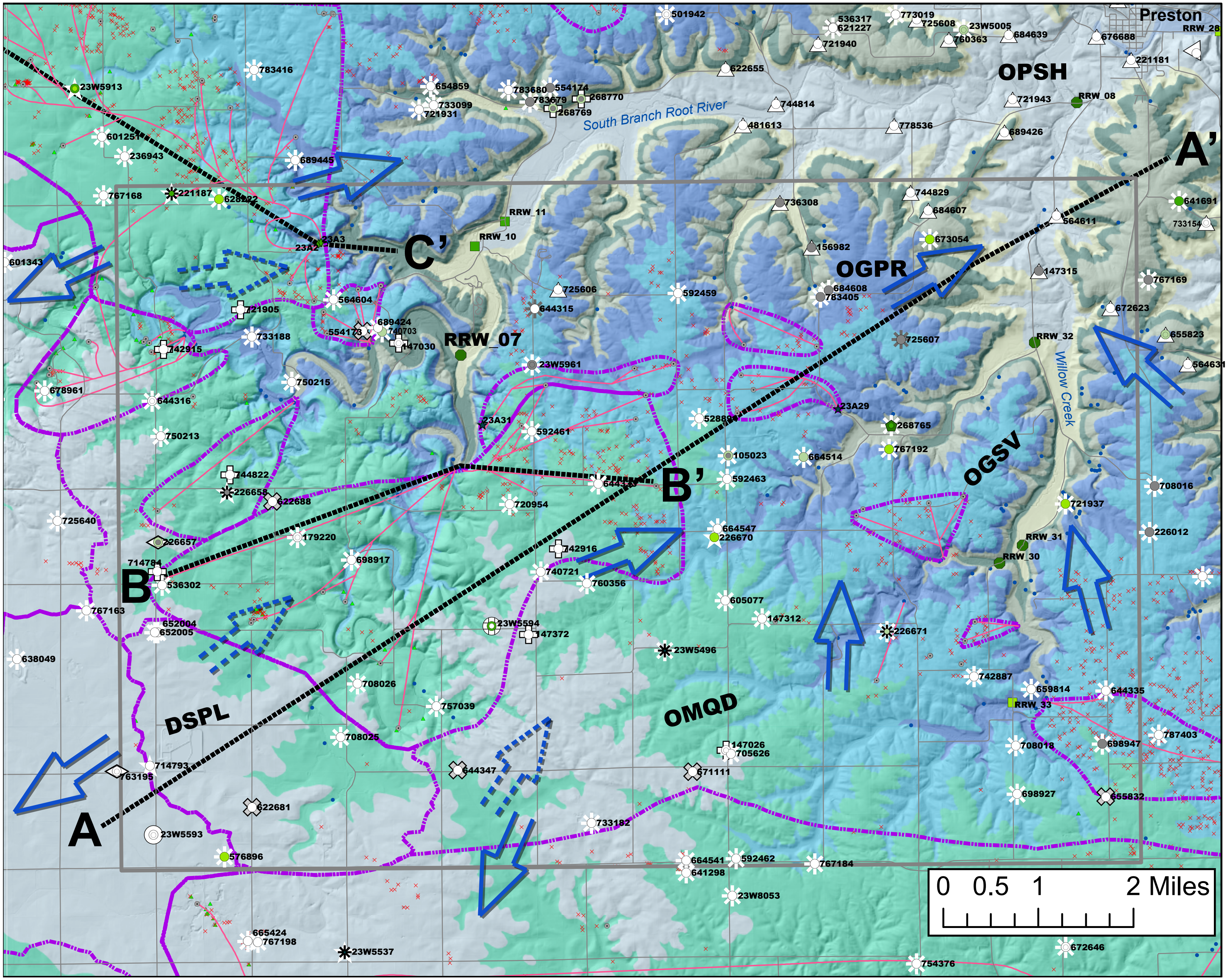


Figure 42 (B) Map showing cross section line, nitrate data, and other relevant information used to construct the cross section in Fig 42A. Solid line arrows depict bulk dominant flow directions for combined St Peter, Prairie du Chien and Jordan aquifers. Dashed line arrows depict dominant bulk flow in Galena aquifer. Distribution of unconsolidated sediment greater than 50 ft not shown on map, but occurs in isolated patches and in deeper stream valleys. It is depicted on cross section, on regional maps (e.g. Figure 4) and available in delivered GIS coverage. Full legend and explanation for map in Appendix A.

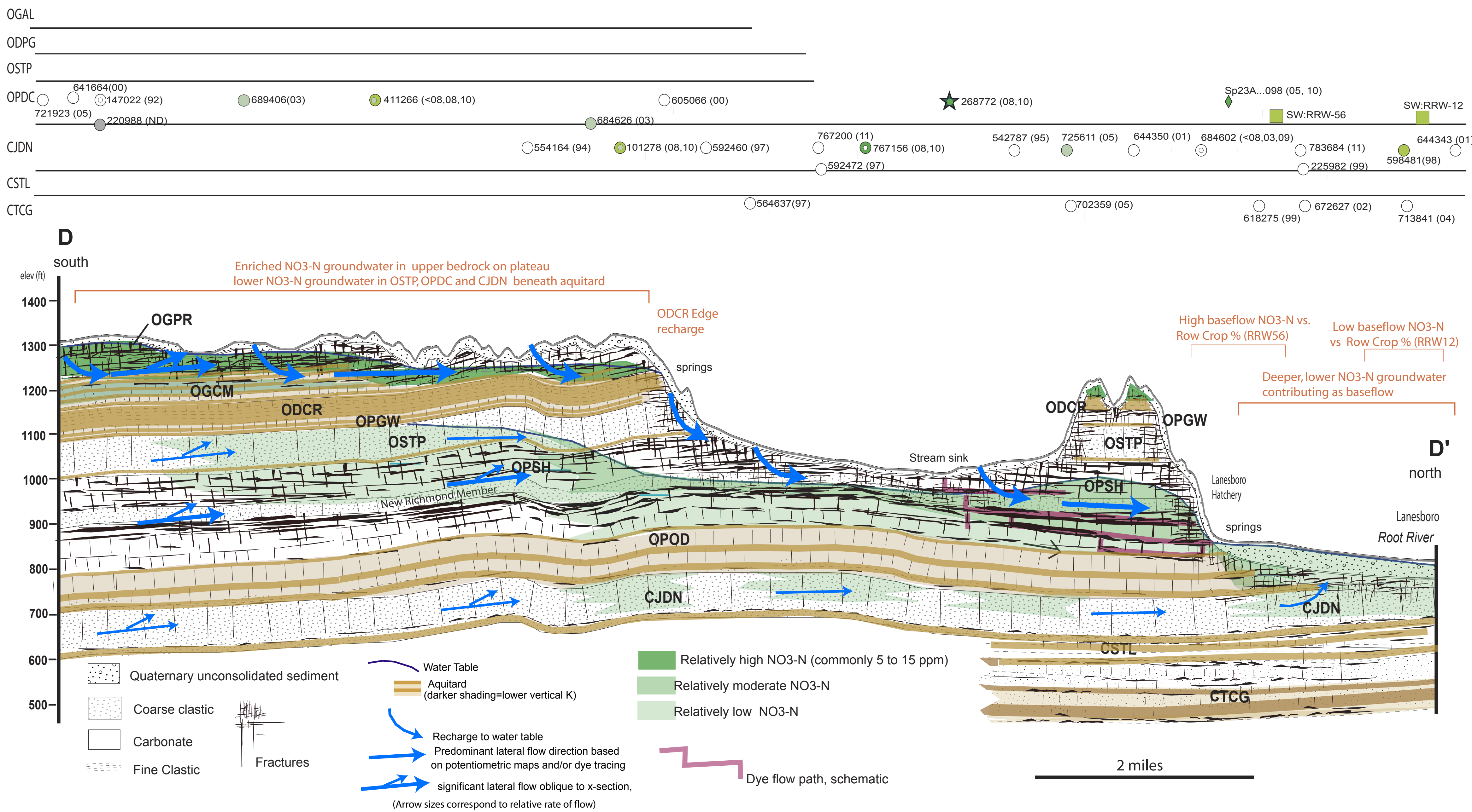


Figure 43. (A) Cross section showing ground and surface water nitrate concentrations in hydrogeologic context from outer edge of Upper Carbonate Plateau (south), across escarpment, to the Prairie du Chien Plateau (north). South-central Fillmore County. Figure 26 provides additional information on flow conditions and sources of information. Full legend and explanation for cross section in Appendix A.

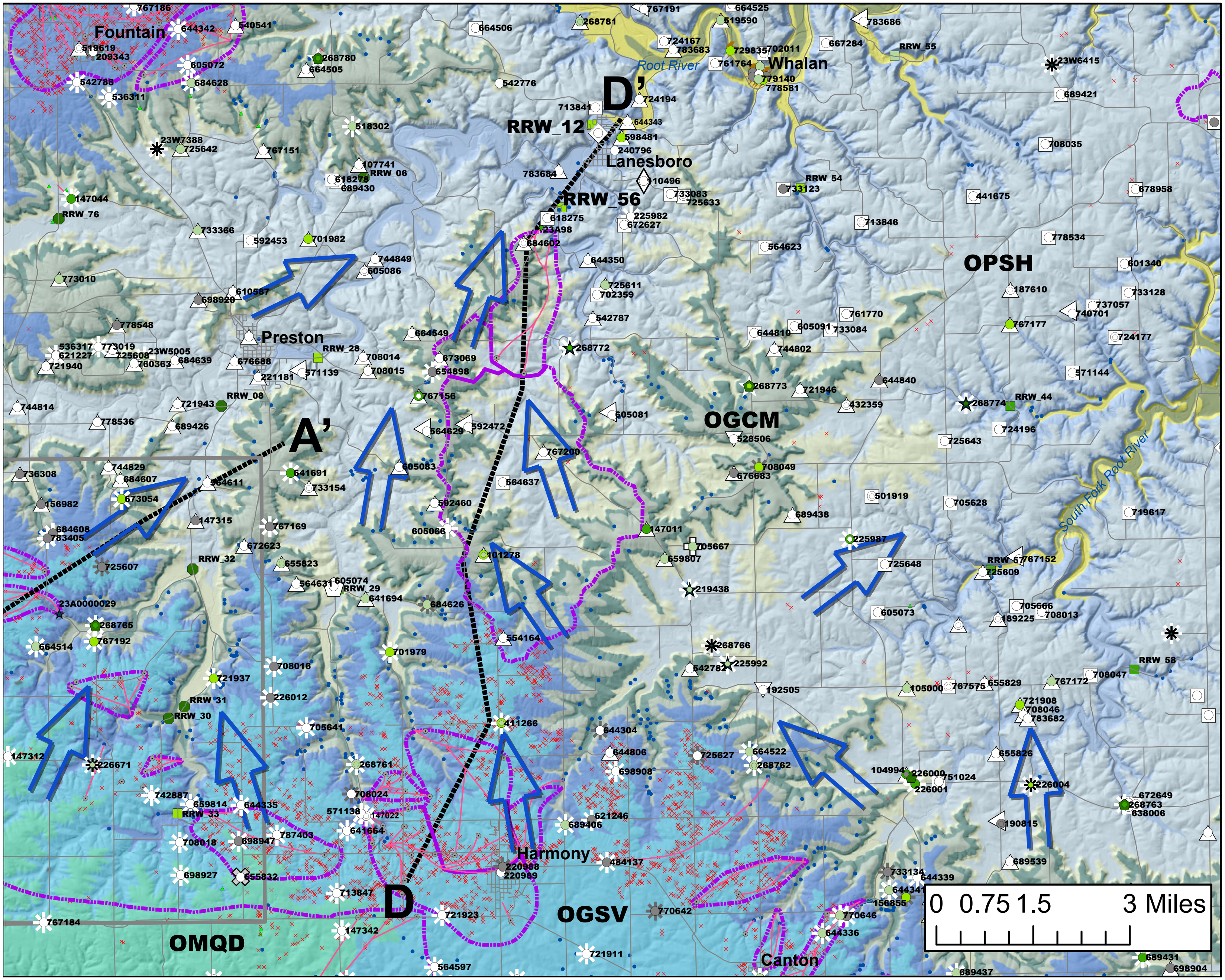


Figure 43 (B) Map showing cross section line, nitrate data, and other relevant information used to construct the cross section in Fig 43A. Arrows depict bulk dominant flow directions for combined St Peter, Prairie du Chien and Jordan aquifers. Distribution of unconsolidated sediment greater than 50 ft not shown on map, but occurs in isolated patches and in deeper stream valleys. It is depicted on cross section, on regional maps (e.g. Figure 4) and available in delivered GIS coverage. Full legend and explanation for map in Appendix A.

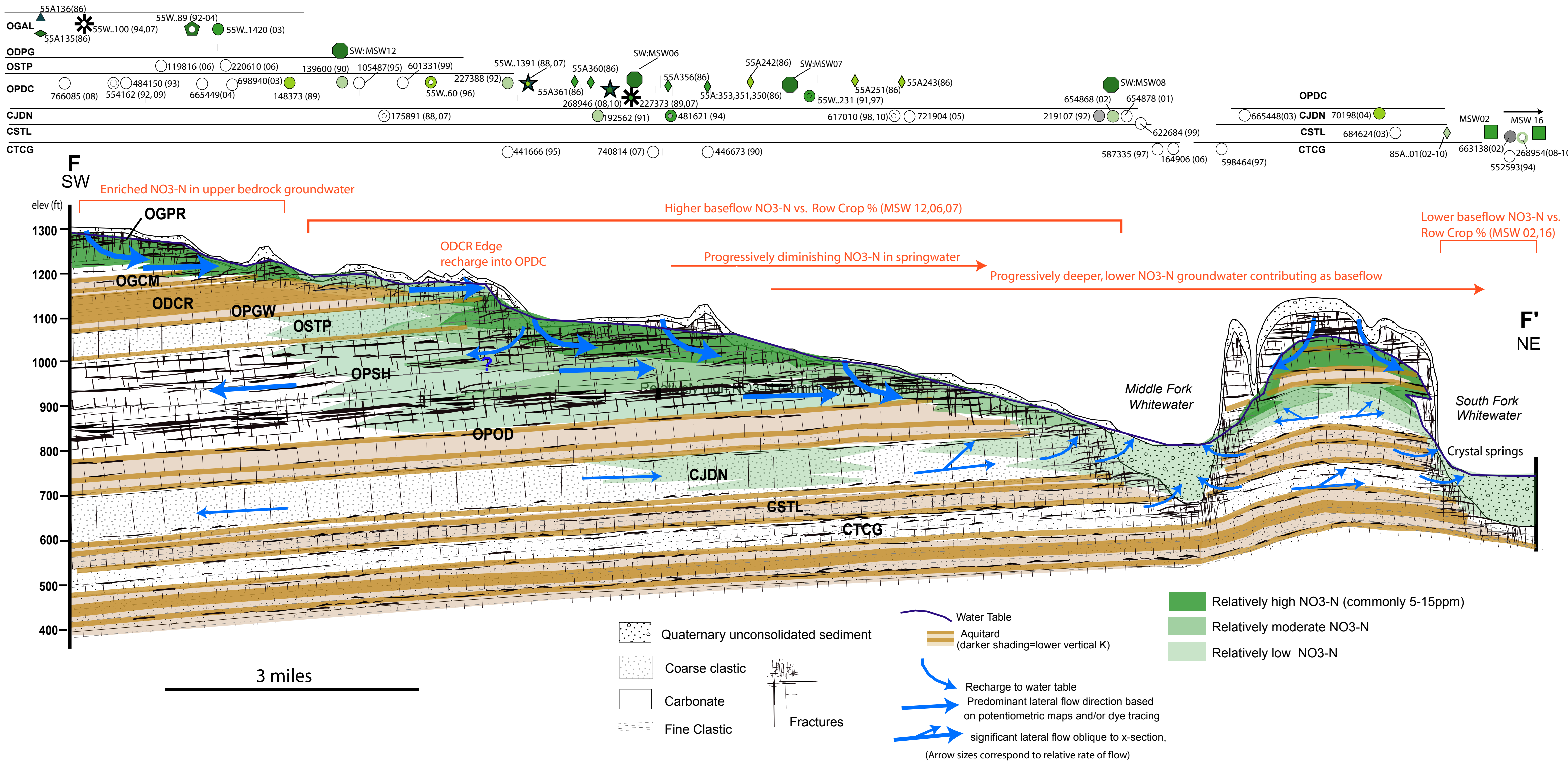


Figure 44. (A) Cross section showing ground and surface water nitrate concentrations in hydrogeologic context from outer edge of Upper Carbonate Plateau (southwest), across escarpment, to the Prairie du Chien Plateau (northeast). Eastern Olmsted and western Winona Counties. Figure 27 provides additional information on flow conditions and sources of information. Full legend and explanation for cross section in Appendix A.

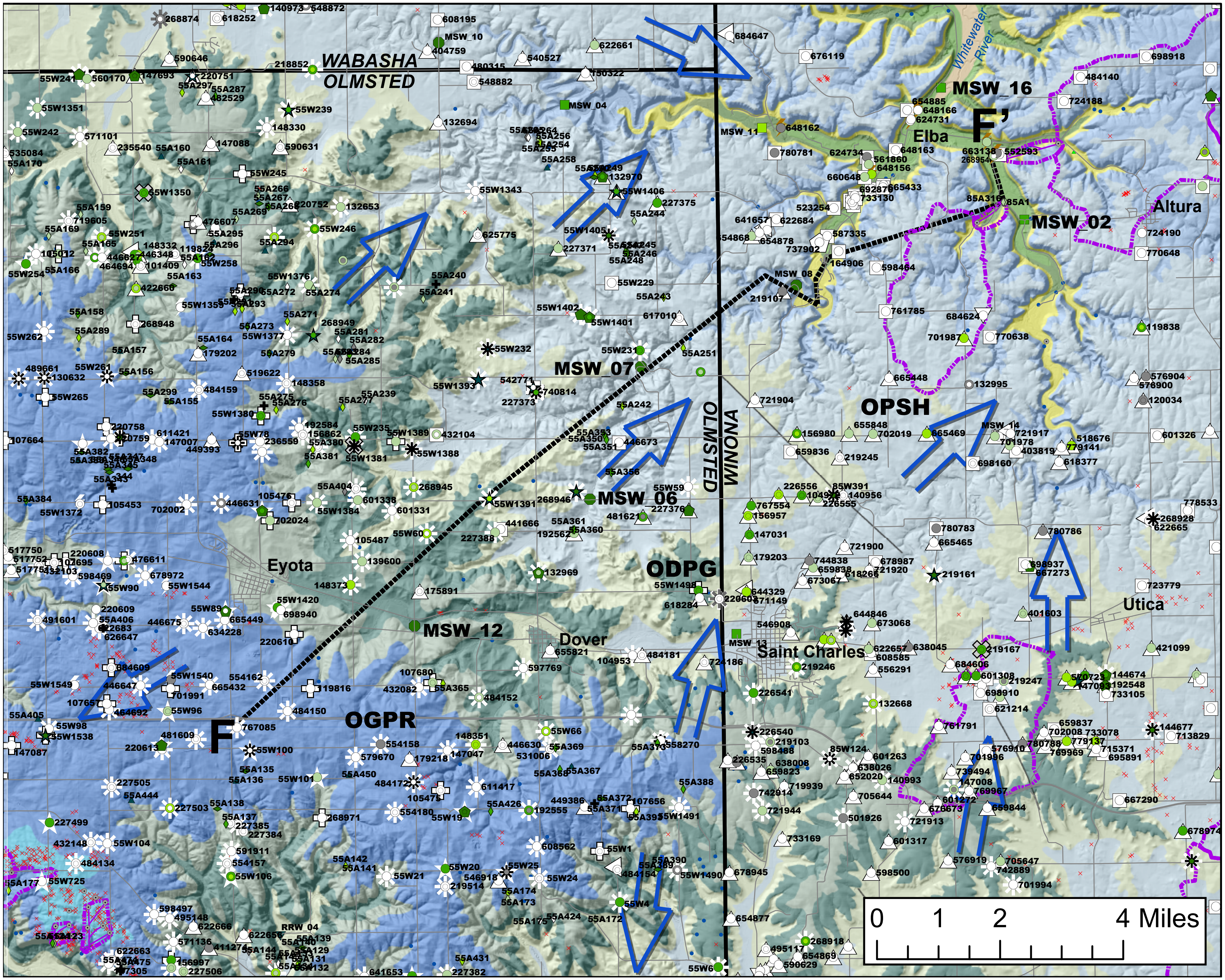


Figure 44 (B) Map showing cross section line, nitrate data, and other relevant information used to construct the cross section in Fig 44A. Arrows depict bulk dominant flow directions for combined St Peter, Prairie du Chien and Jordan aquifers. Distribution of unconsolidated sediment greater than 50 ft not shown on map, but occurs in isolated patches and in deeper stream valleys. It is depicted on cross section, on regional maps (e.g. Figure 4) and available in delivered GIS coverage. Full legend and explanation for map in Appendix A.

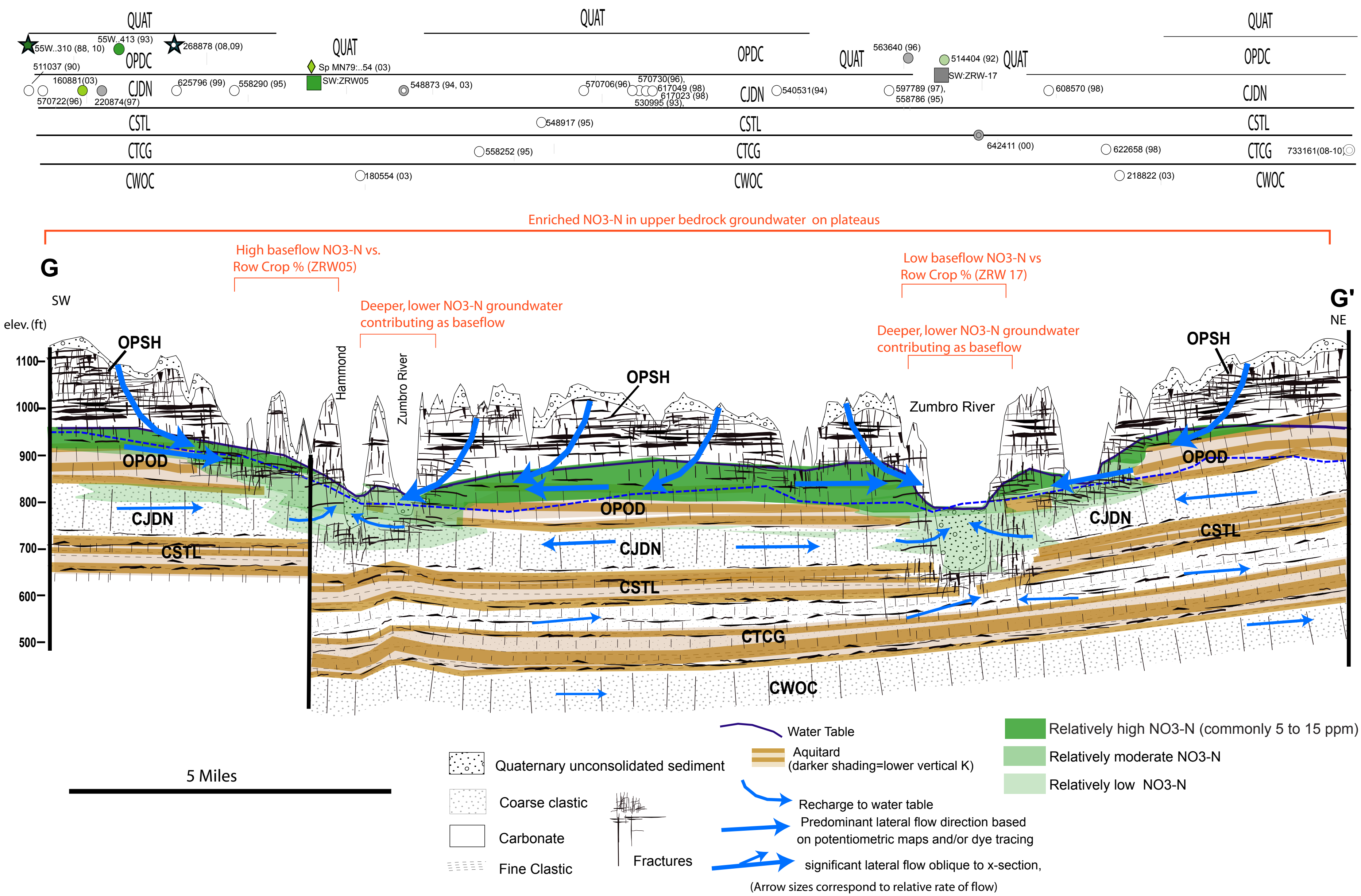


Figure 45. (A) Cross section showing ground and surface water nitrate concentrations in hydrogeologic context across Prairie du Chien Plateau, with deeply incised valleys. Wabasha County. Figure 28 provides additional information on flow conditions and sources of information. Full legend and explanation for cross section in Appendix A.

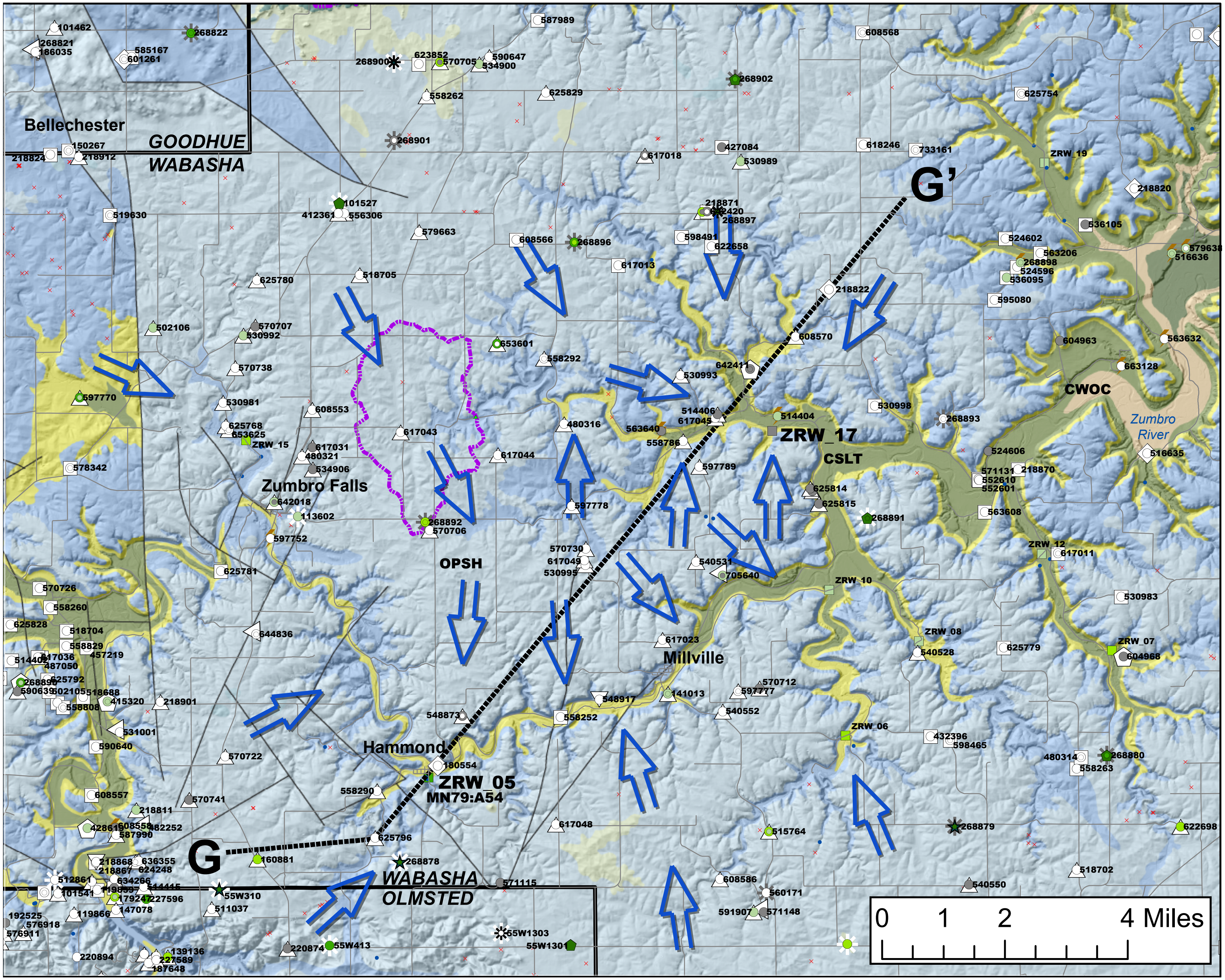


Figure 45(B) Map showing cross section line, nitrate data, and other relevant information used to construct the cross section in Fig 45A. Arrows depict bulk dominant flow directions in Jordan Aquifer. Distribution of unconsolidated sediment greater than 50 ft not shown on map, but occurs in isolated patches and in deeper stream valleys. It is depicted on cross section, on regional maps (e.g. Figure 4) and available in delivered GIS coverage. Full legend and explanation for map in Appendix A.

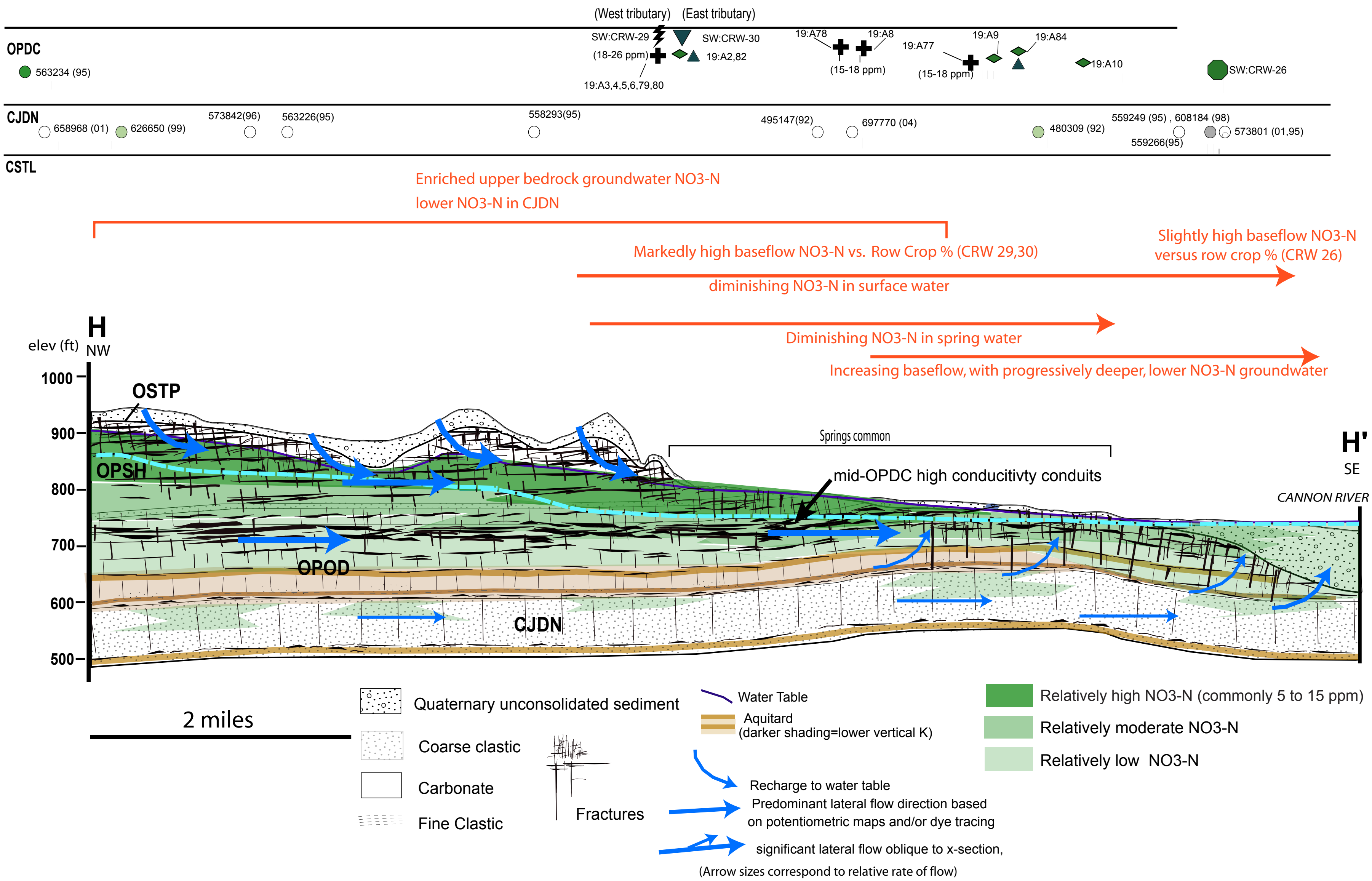


Figure 46. (A) Cross section showing ground and surface water nitrate concentrations in hydrogeologic context across Prairie du Chien Plateau down to edge of incised valley. Dakota County. Figure 29 provides additional information on flow conditions and sources of information. Full legend and explanation for cross section in Appendix A.

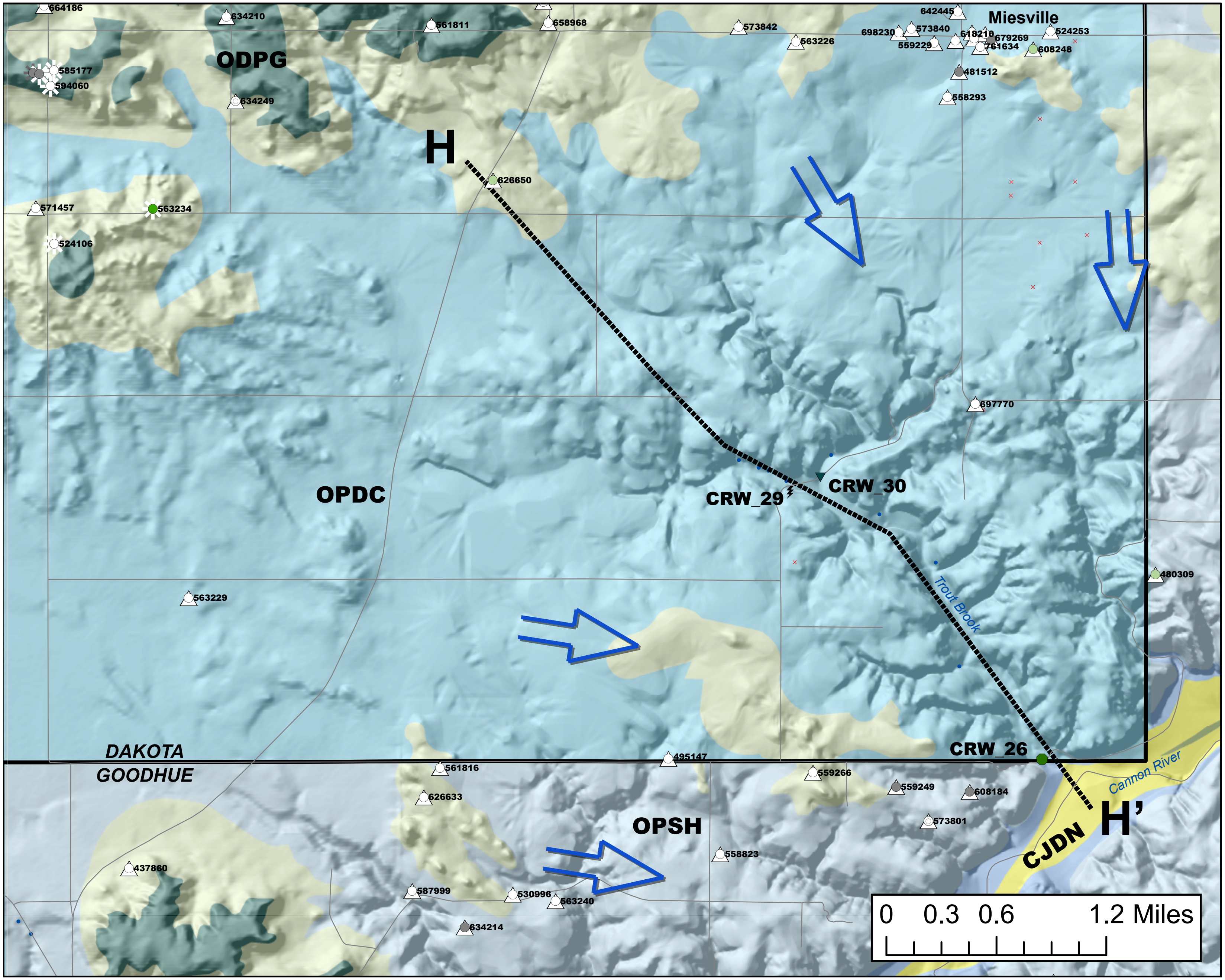


Figure 46 (B) Map showing cross section line, nitrate data, and other relevant information used to construct the cross section in Fig 46A. Arrows depict bulk dominant flow directions in Jordan Aquifer. Distribution of unconsolidated sediment greater than 50 ft not shown on map, but occurs in isolated patches and in deeper stream valleys. It is depicted on cross section, on regional maps (e.g. Figure 4) and available in delivered GIS coverage. Full legend and explanation for map in Appendix A.

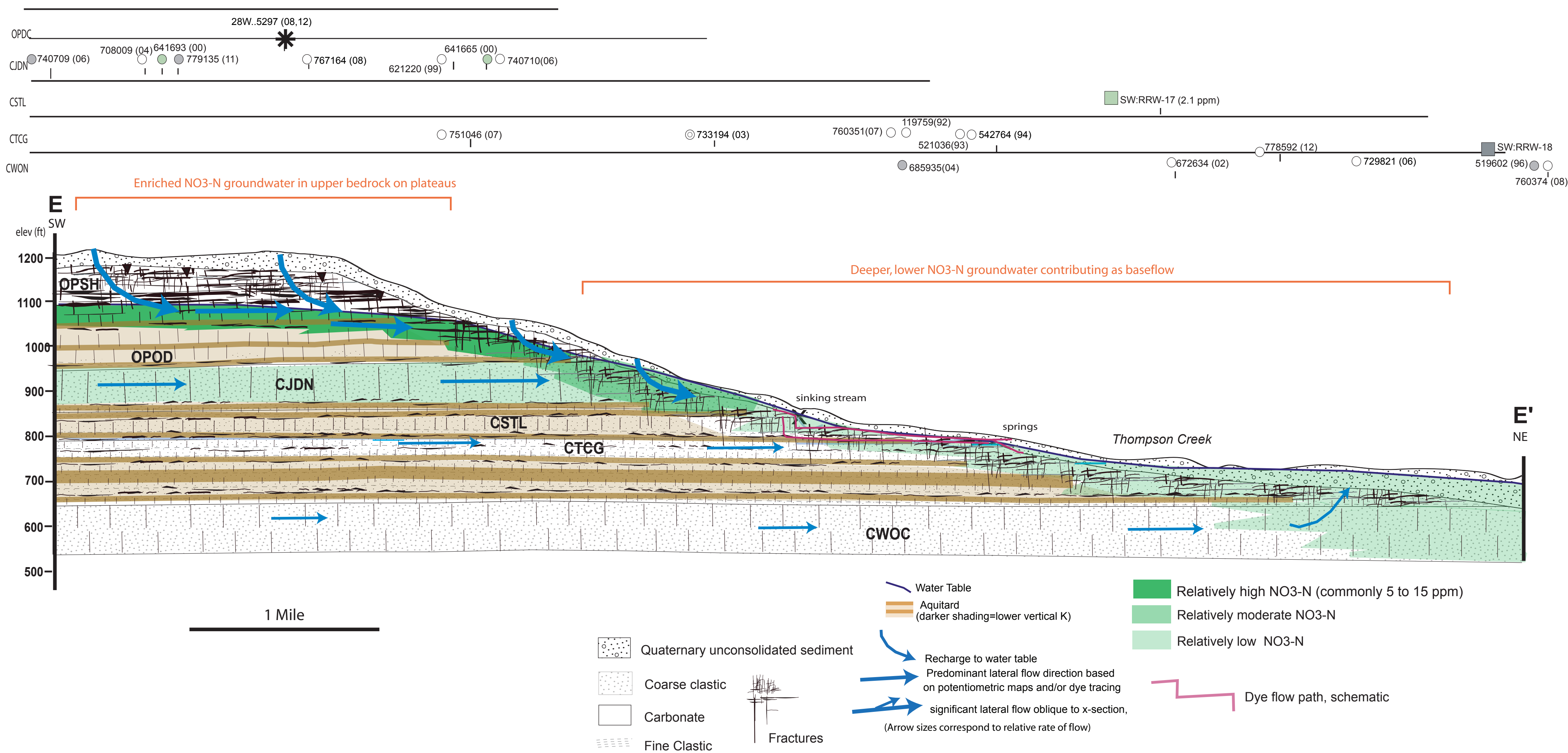


Figure 47. (A) Cross section showing ground and surface water nitrate concentrations in hydrogeologic context across Prairie du Chien Plateau (southwest) down the approximate axis of an incised valley. Houston County. Figure 30 provides additional information on flow conditions and sources of information. Full legend and explanation for cross section in Appendix A.

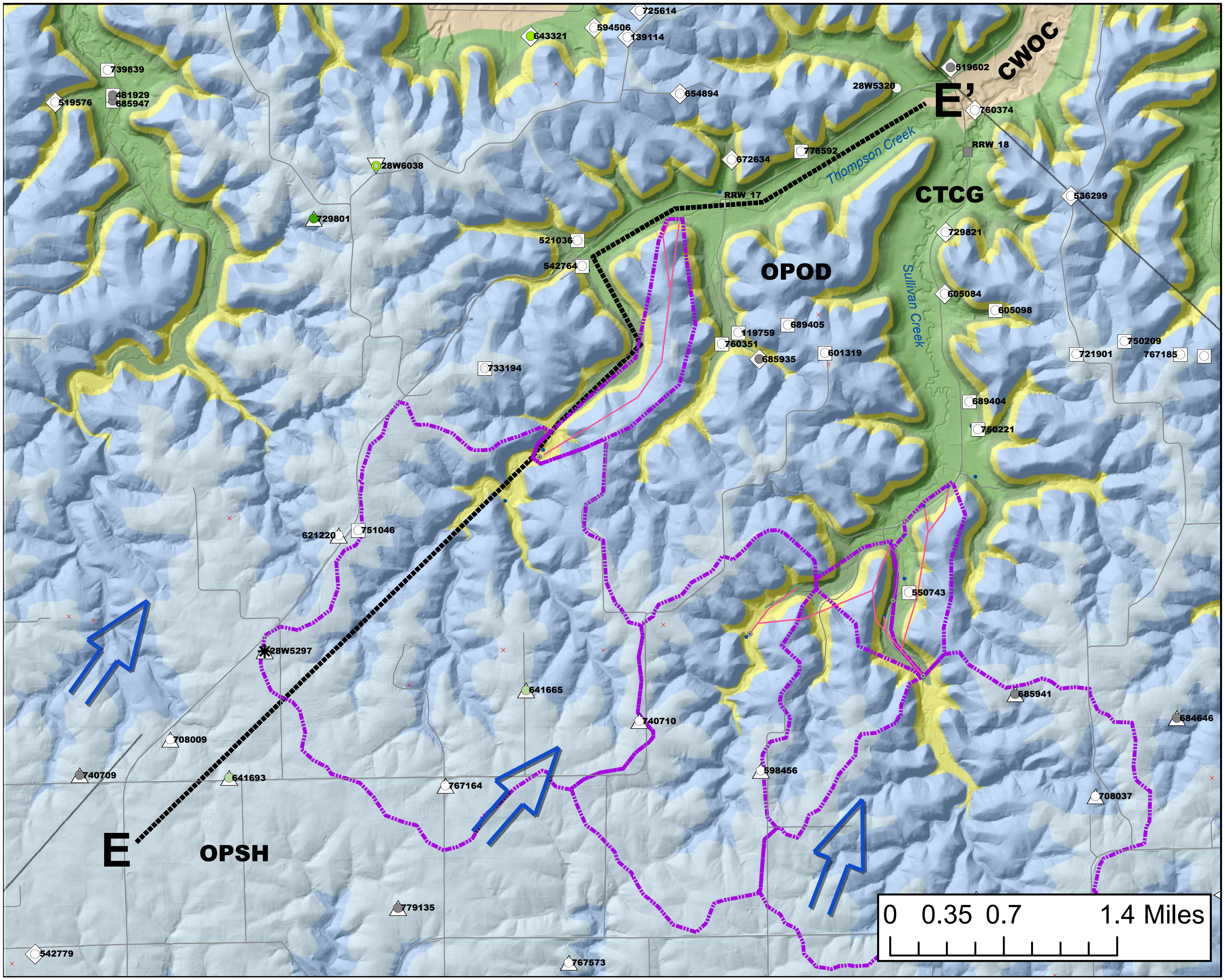


Figure 47 (B) Map showing cross section line, nitrate data, and other relevant information used to construct the cross section in Fig 47A. Arrows depict bulk dominant flow directions in Jordan Aquifer. Distribution of unconsolidated sediment greater than 50 ft not shown on map, but occurs in isolated patches and in deeper stream valleys. It is depicted on cross section, on regional maps (e.g. Figure 4) and available in delivered GIS coverage. Full legend and explanation map in Appendix A.

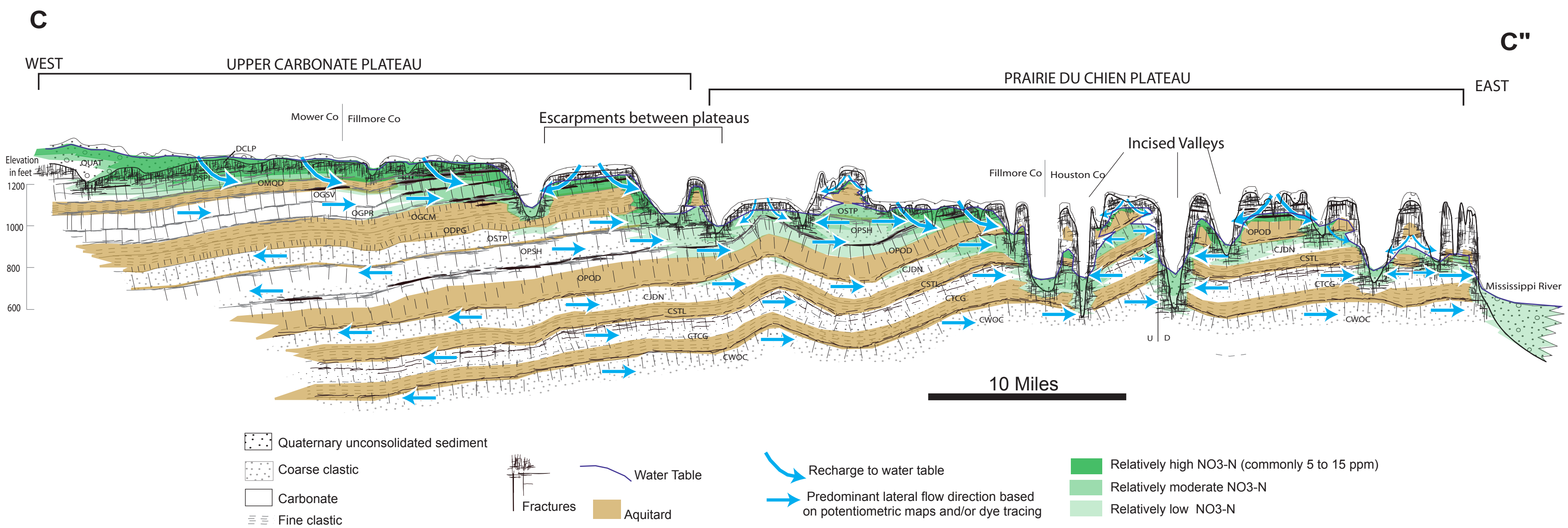


Figure 48. Generalized, regional scale cross section showing groundwater nitrate concentrations in hydrogeologic context from the outer edge of the drift-dominated landscape (west), across the bedrock dominated landscape to the Mississippi River (east). Location of cross section shown in Figure 4. Full legend and explanation for cross sections and maps in Appendix A. Figure 31 provides additional information on flow conditions and sources of information

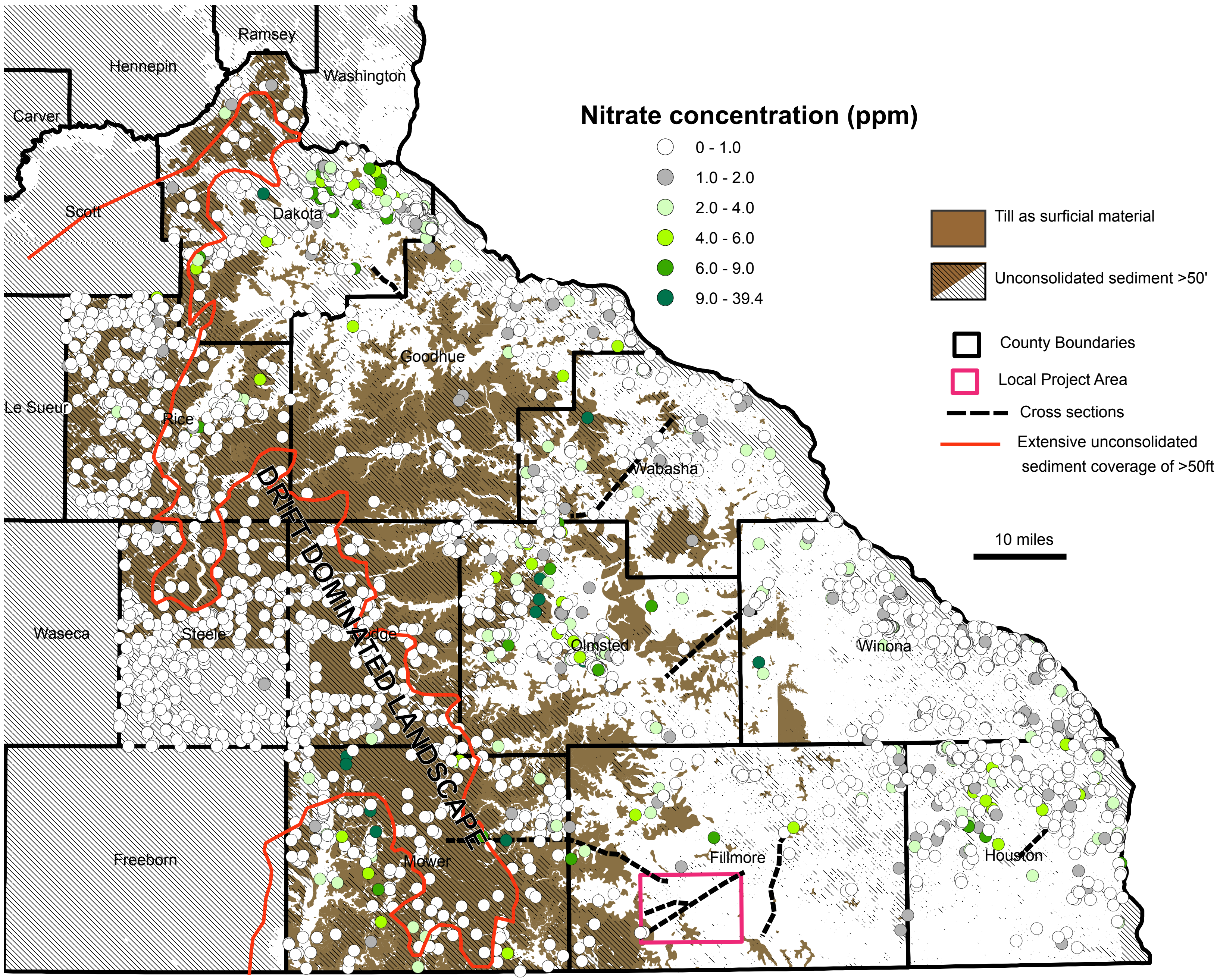
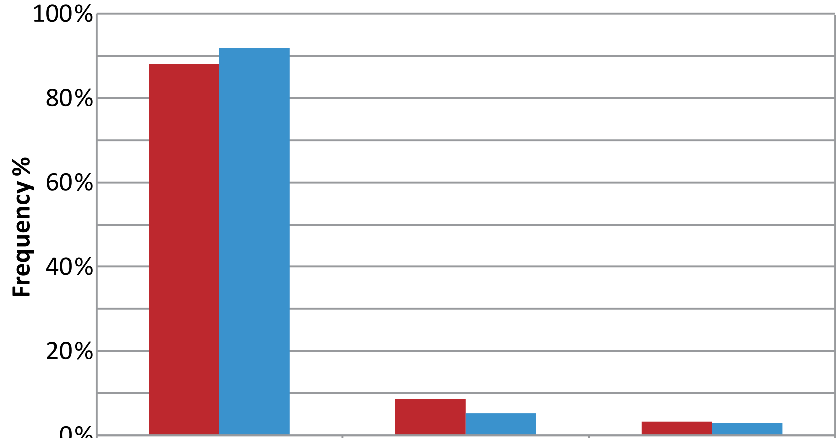


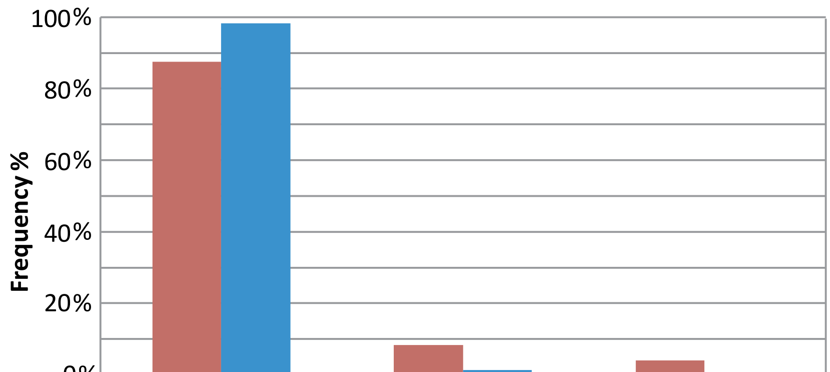
Figure 49. Nitrate concentrations from individual wells open to uppermost bedrock across southeastern Minnesota, compared against thickness and distribution of unconsolidated sediment. Note that wells within the extensive coverage of unconsolidated sediment greater than 50 ft in thickness (the interior of the drift dominated landscape) only rarely exceed 2 ppm nitrate. Includes only grouted wells cased less than 200 ft below the bedrock surface, and excludes wells cased below the Decorah Shale. Histograms depicting this evaluation shown in Figure 50.

A **Nitrate concentration in wells vs. unconsolidated sediment thickness**



	NO3-N (ppm)	<2	2-4.99	≥5
n= 803	<50thick	88.15%	8.64%	3.21%
n=1699	>50thick	91.84%	5.27%	2.89%

B **Nitrate concentration in wells vs. extensive thick unconsolidated sediment**



	NO3-N (ppm)	<2	2-4.99	≥5
n= 711	Outside of extensive thick unconsol. sediment	87.56%	8.39%	4.06%
n=179	Within extensive thick unconsol. sediment	98.24%	1.36%	0.41%

Figure 50. Histograms showing nitrate concentrations from individual wells open to uppermost bedrock across southeastern Minnesota, compared against thickness and distribution of unconsolidated sediment. Includes only grouted wells cased less than 200 ft below the bedrock surface and excludes wells cased below the Decorah Shale. (A) Histograms of nitrate concentrations, comparing samples from wells constructed where unconsolidated sediment exceeds 50 ft in thickness versus where it is less than 50 ft. Note that higher nitrate concentrations are less common where unconsolidated sediment is relatively thick. (B) Histograms of nitrate concentrations, comparing samples from wells constructed in areas of relatively continuous, extensive cover of unconsolidated sediment that exceeds 50 ft in thickness versus areas with thin or only patchy thick sedimentary cover. In this second analysis, wells located where thick (>50 ft) drift is present only as isolated patches or along the irregularly eroded margin of the transition from drift to bedrock dominated landscape are combined with wells located where sedimentary cover is less than 50 ft thick. Note higher nitrate concentrations are markedly less common across areas with extensive thick cover of unconsolidated sediment. See text for details. Data are shown in map view in Figure 49.

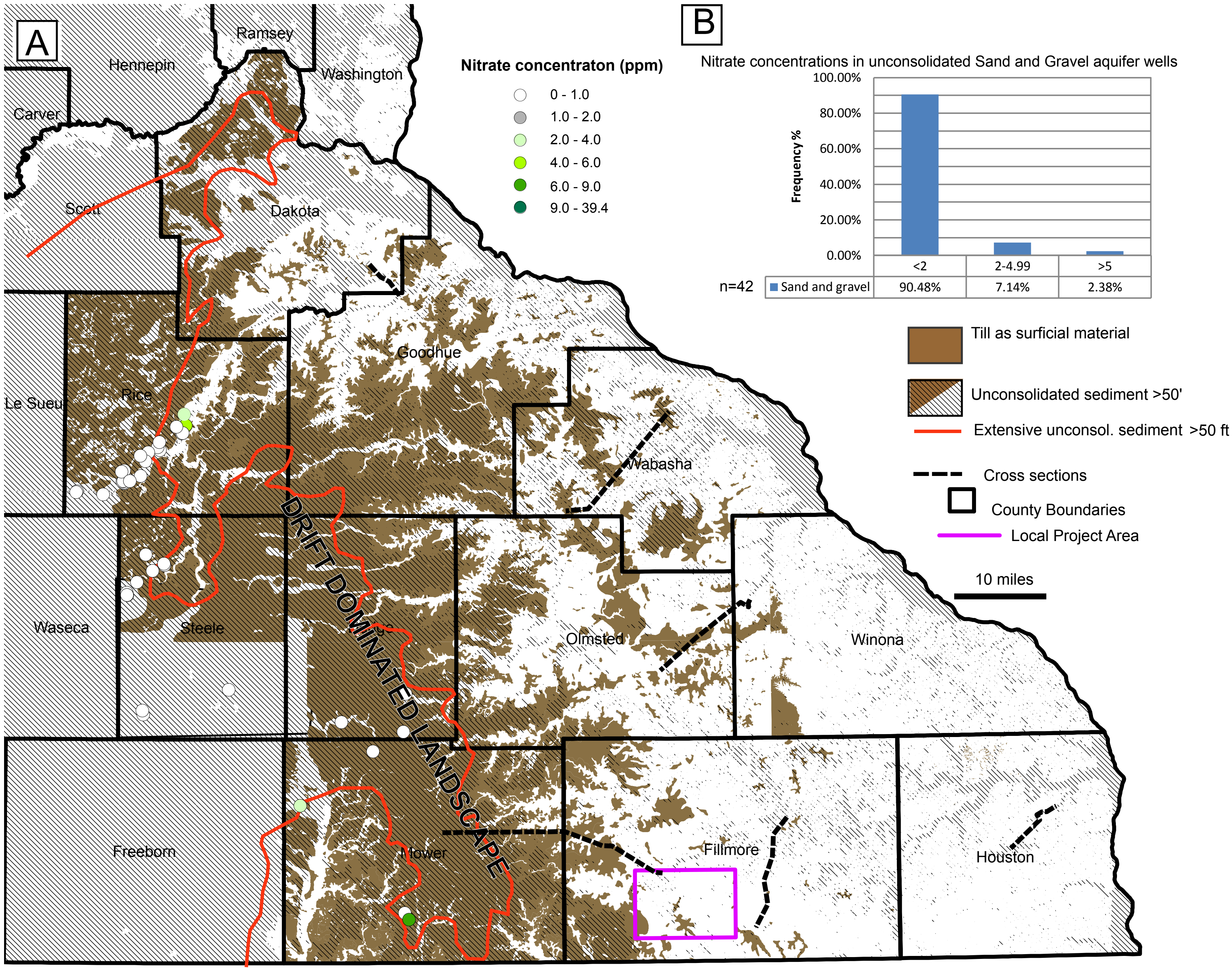


Figure 51. Nitrate concentrations of samples from wells drawing from unconsolidated sand and gravel aquifers within and along the margins of the drift dominated landscape. (A) Concentrations plotted on map that depicts where unconsolidated sediment that lies on top of bedrock is greater than 50 ft in thickness, and where till (diamicton) is the surficial material. (B) Histogram of nitrate concentrations from these wells. See text for discussion.

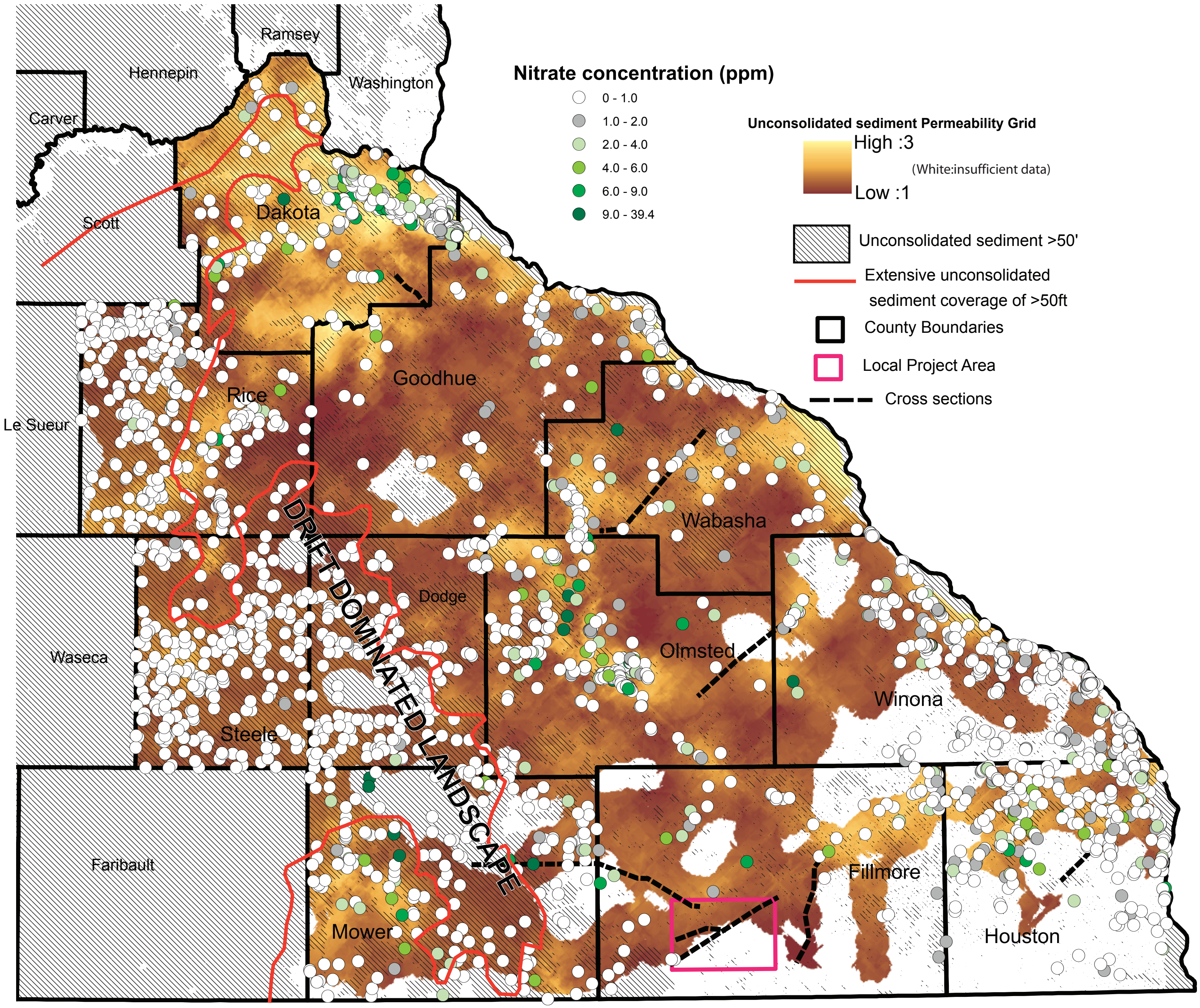
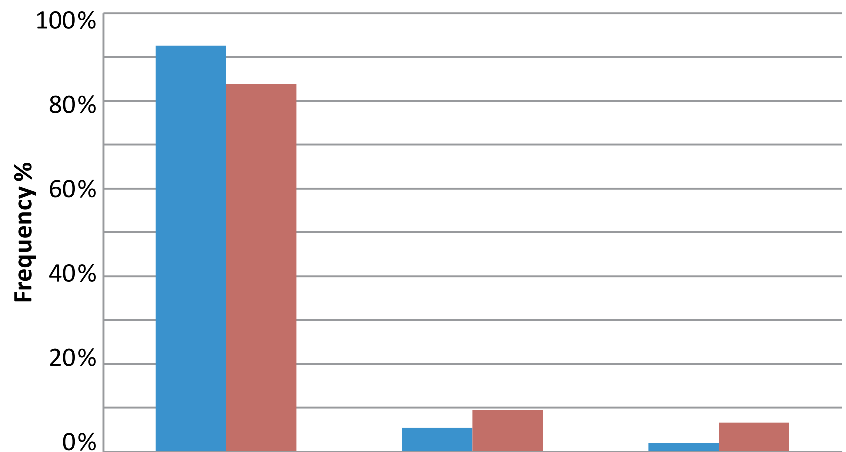


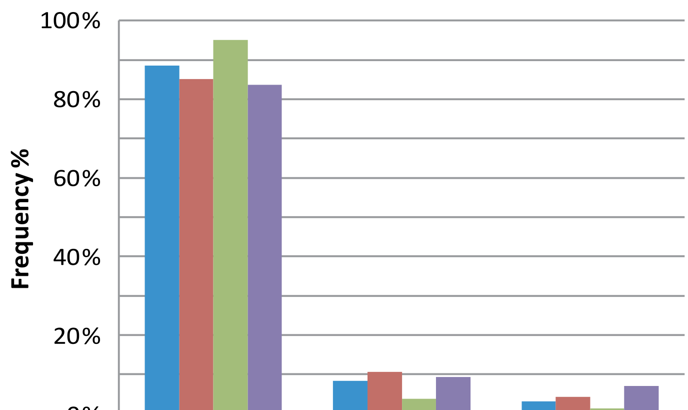
Figure 52. Nitrate concentrations of samples from wells drawing water from upper bedrock aquifers plotted on map of calculated permeability of unconsolidated sediments. As summarized in histograms of Figure 53, wells constructed in areas with relatively high permeability more commonly have high nitrate concentrations than wells constructed in areas of low permeability. Includes only grouted wells cased less than 200 ft below the bedrock surface, and excludes wells cased below the Decorah Shale.

A **Nitrate concentration in wells vs. weighted unconsolidated sediment permeability**



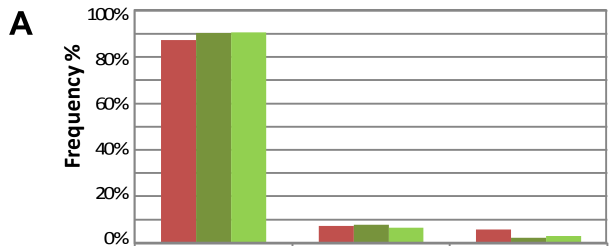
NO3-N (ppm)		<2	2-4.99	≥5
n=1962	perm. <2	92.66%	5.40%	1.94%
n=576	perm. >2	83.85%	9.55%	6.60%

B **Nitrate concentration in wells vs. unconsolidated sediment permeability, and thickness**

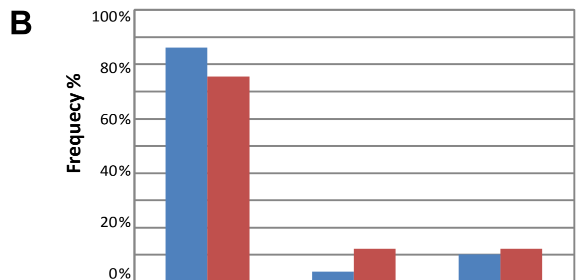


	NO3-N (ppm)	<2	2-4.99	≥5
n= 716	<2 drift perm and < 50 feet of unconsol. sed.	88.55%	8.38%	3.07%
n=94	>2 drift perm and < 50 feet of unconsol. sed.	85.11%	10.64%	4.26%
n=1246	<2 drift perm and >50 feet of unconsol. sed.	95.02%	3.69%	1.28%
n=482	>2 drift perm and >50 feet of unconsol. sed.	83.61%	9.34%	7.05%

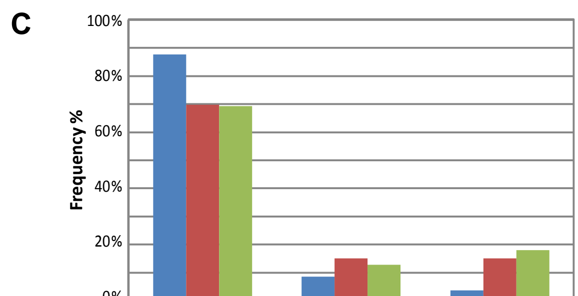
Figure 53. (A) Histogram showing the effect of the drift permeability on nitrate concentrations. Note that wells constructed in areas with less permeable drift (<2) have lower nitrate concentrations than those constructed where drift is more permeable (>2). (B) Histogram showing the effect of both drift permeability and drift thickness on nitrate concentrations for the same data set. Note that wells constructed where unconsolidated sediments are of relatively high permeability (>2) more commonly have high nitrate concentrations, even where the thickness of the sediment exceeds 50 ft. See text for additional discussion. Dataset includes only grouted wells cased less than 200 ft below the bedrock surface, and excludes wells cased below the Decorah Shale. Data shown in map view in Figure 52.



	NO3-N (ppm)	<2	2-4.99	≥5
n=252	open hole above aquitard	87.30%	7.14%	5.56%
n=506	open hole w/in, below aquitard	90.32%	7.71%	1.98%
n=3772	open hole below aquitard	90.72%	6.42%	2.86%



	NO3-N (ppm)	<2	2-4.99	≥5
n= 79	ODCR cased off	86.08%	3.80%	10.13%
n=114	ODCR not cased off	75.44%	12.28%	12.28%



	NO3-N (ppm)	<2	2-4.99	≥5
n=601	OPDC first bedrock <50 feet of unconsol. sed., CJDN wells	87.69%	8.65%	3.66%
n=33	OPDC first bedrock <50 feet of unconsol. sed., OPDC wells	69.70%	15.15%	15.15%
n=39	OPDC first bedrock <50 feet of unconsol. sed., OPDC and OPCJ wells	69.23%	12.82%	17.95%

Figure 54. Evaluation of effect of bedrock aquitards on groundwater nitrate concentrations in water well samples. (A) Histogram showing the nitrate concentration for wells in which the open hole is: above a bedrock aquitard; within an aquitard (and underlying aquifer); entirely below an aquitard. Analysis includes only grouted wells open to bedrock, and does not consider thickness of overlying unconsolidated sediment. Limitations to database led to exclusion of most wells necessary to evaluate Oneota aquitard in this manner (drilling records and stratigraphic codes were too generalized to determine if Oneota Dolomite is cased off in the well). Most wells drawing from the Devonian and uppermost Galena Group were excluded from the analysis as well because of similar limitations. Despite these limitations, the results show that wells not cased below an aquitard more commonly have relatively high nitrate concentrations. (B) Histogram comparing nitrate concentrations of St Peter and Prairie du Chien water drawn from below Decorah Shale to water where Decorah is absent or not cased off. This analysis used only grouted wells drawing water from bedrock within 200 ft of the bedrock surface, and where unconsolidated sedimentary cover is less than 50 ft thick. (C) Histogram comparing nitrate concentrations from wells constructed to draw water only from the Jordan Sandstone versus wells drawing only from any part of the Prairie du Chien Group (including the Oneota aquitard). Wells drawing from Prairie du Chien are twice as likely to yield water with nitrate concentration above 2 ppm. Analysis included only grouted bedrock wells located where Prairie du Chien is uppermost bedrock and unconsolidated sedimentary cover is less than 50 ft thick.

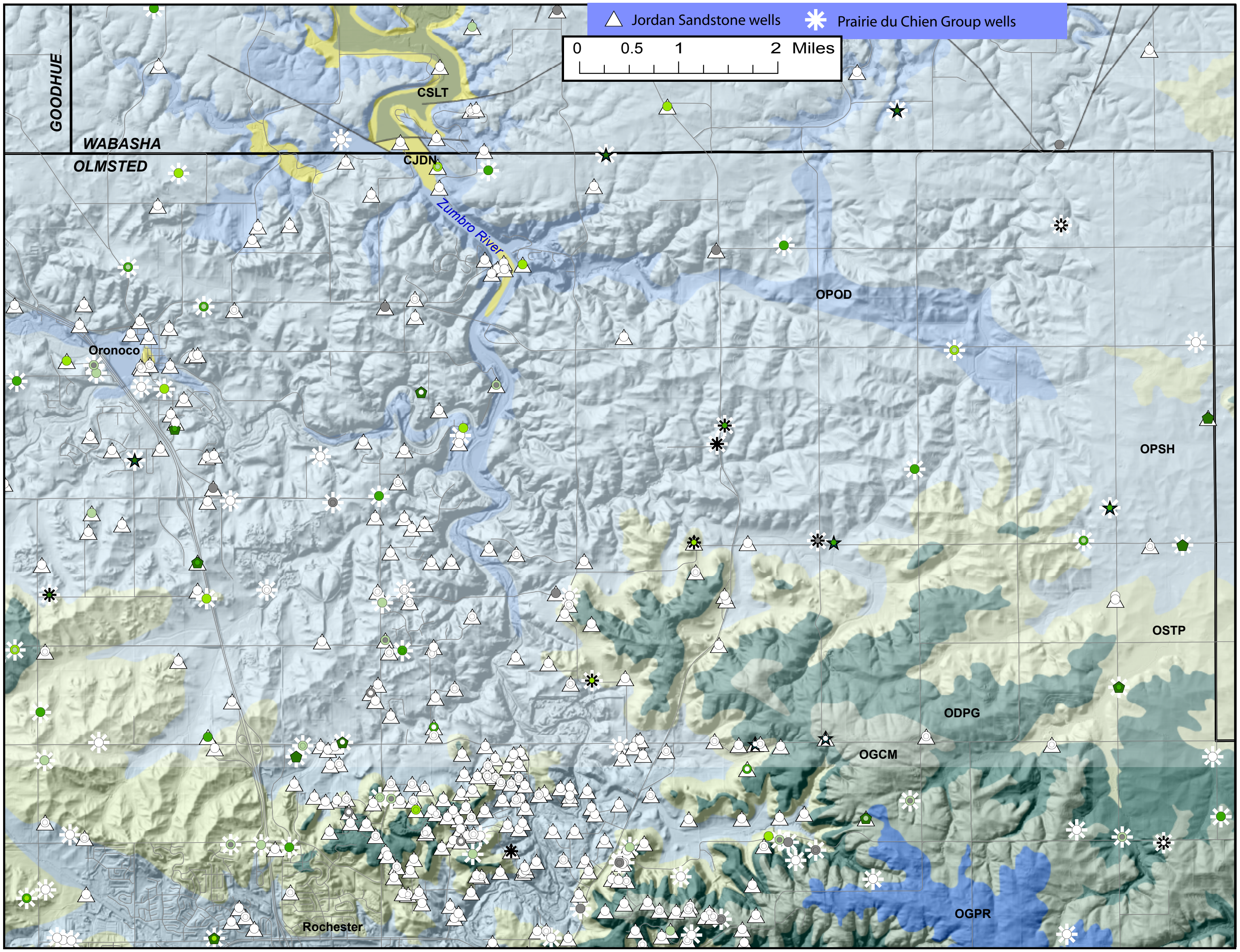
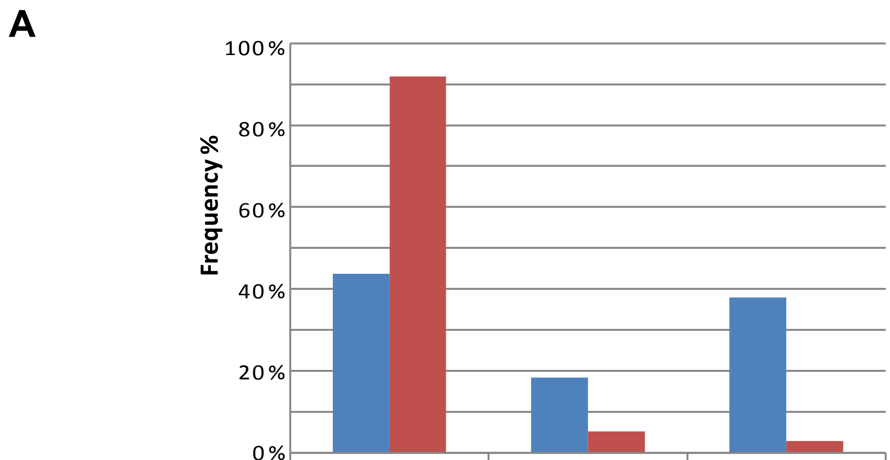
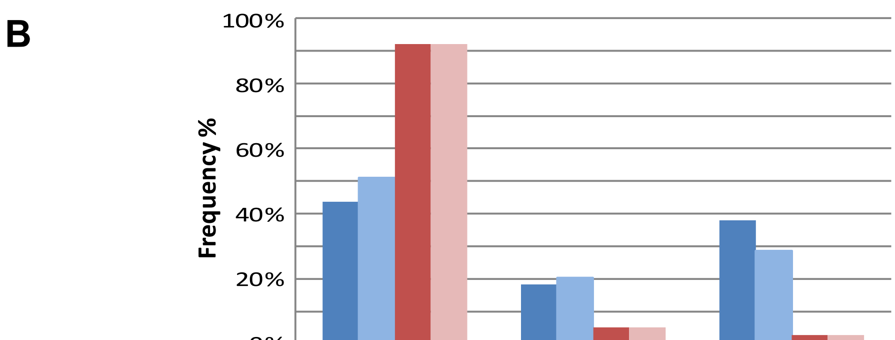


Figure 55. Comparison of nitrate concentrations of water from wells open to the Jordan Sandstone versus wells open only to Prairie du Chien Group in northern Olmsted and southern Wabasha County. Note that relatively high nitrate concentrations are common in the Prairie du Chien wells, and scarce in the Jordan wells, which is depicted in the histograms of Figure 56. See Appendix A for map legend.



NO3-N (ppm)		<2	2-4.99	≥5
n=87	Prairie du Chien Aquifer	43.68%	18.39%	37.93%
n=286	Jordan Aquifer	91.96%	5.24%	2.80%



NO3-N (ppm)		<2	2-4.99	≥5
n=87	Prairie du Chien Aquifer	43.68%	18.39%	37.93%
n=49	OPDC w/o Wseries	51.02%	20.41%	28.57%
n=286	Jordan Aquifer	91.96%	5.24%	2.80%
n=285	Jordan w/o Wseries	91.93%	5.26%	2.81%

Figure 56. (A) Histograms comparing nitrate concentrations of water from wells open to the Jordan Sandstone versus wells open only to Prairie du Chien Group in northern Olmsted and southern Wabasha County. Note that high nitrate concentrations are much more common in the Prairie du Chien than in the Jordan. This analysis includes 38 W-series wells open to the Prairie du Chien that have incomplete well construction records (including lack of grouting information). (B) Analysis of same dataset, but excluding all W-series wells. A markedly greater proportion of Prairie du Chien wells with relatively high nitrates also revealed in this analysis. (see text for additional information). Map view of data shown in Fig. 55.

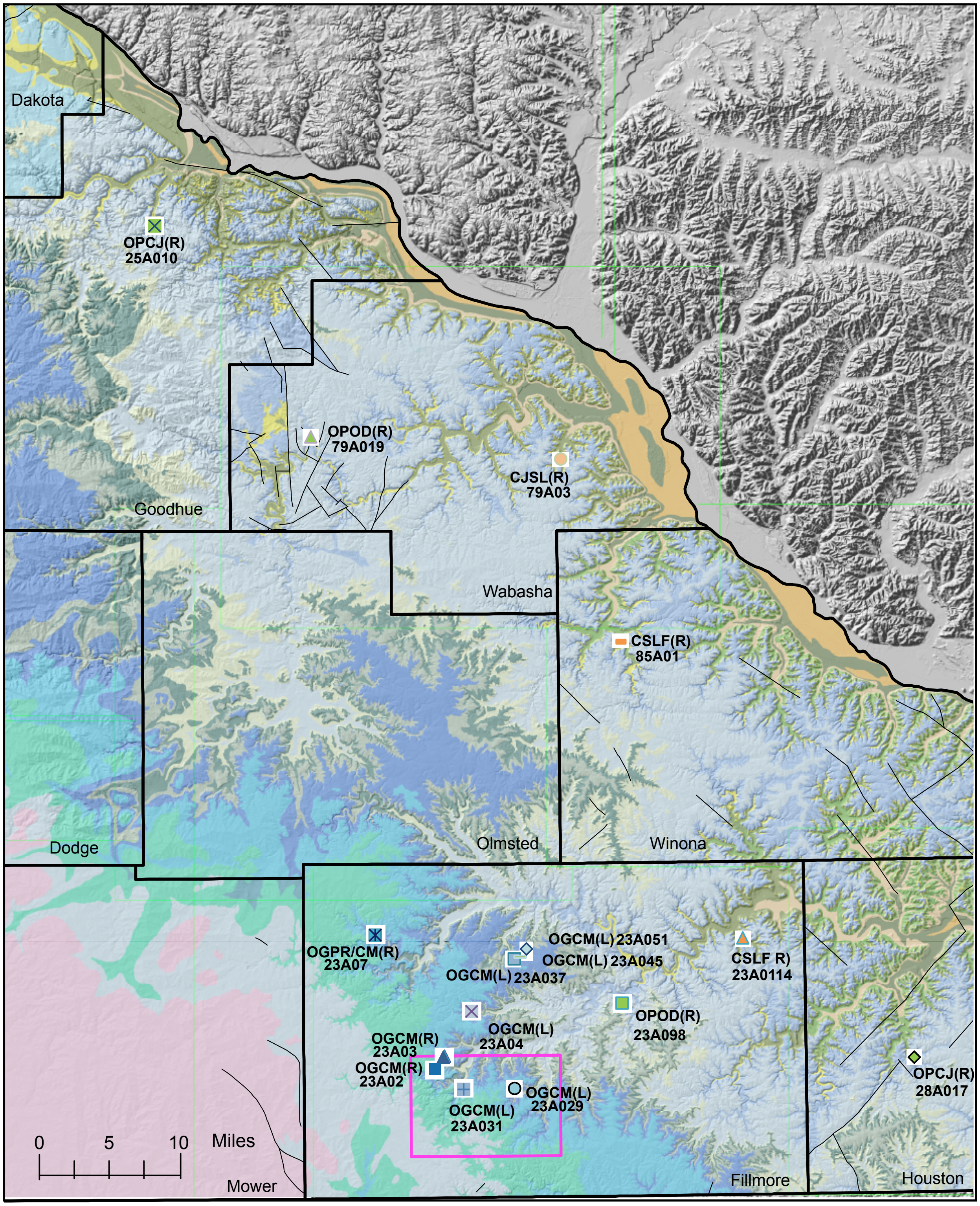


Figure 57. Locations of springs with nitrate concentrations evaluated in this report. Stratigraphic position of spring is provided (see Figure 5 for stratigraphic codes). (L) designates "locally dominated" springs where regional contribution of water to the spring is unlikely to be significant based on hydrogeologic setting. (R) designates springs where regional contribution of water to spring is likely to be significant compared to the locally dominated springs, based on hydrogeologic setting. Analyses of the nitrate concentrations in these springs, identified by symbols KFDB identifier, are illustrated in Figures 58-60.

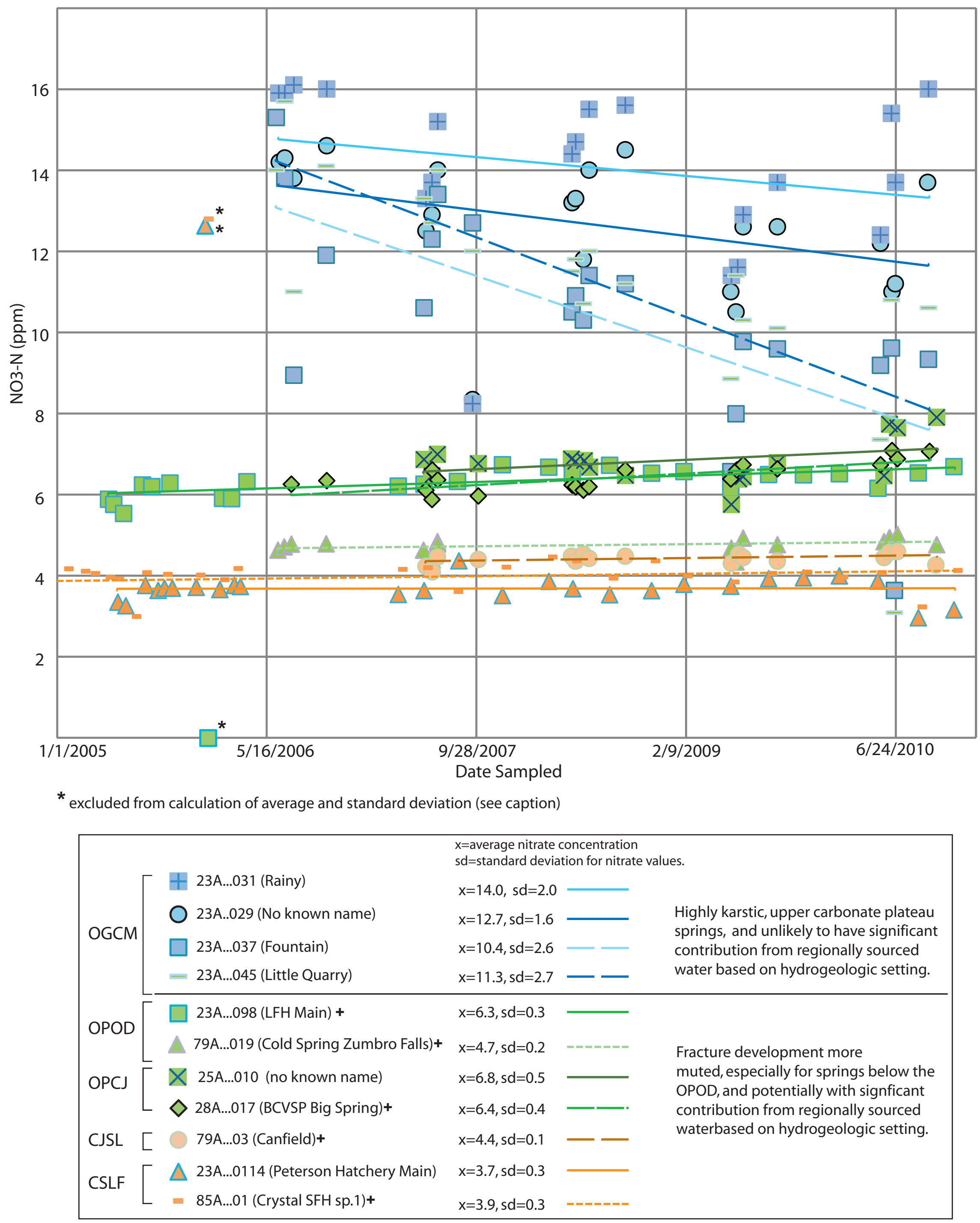
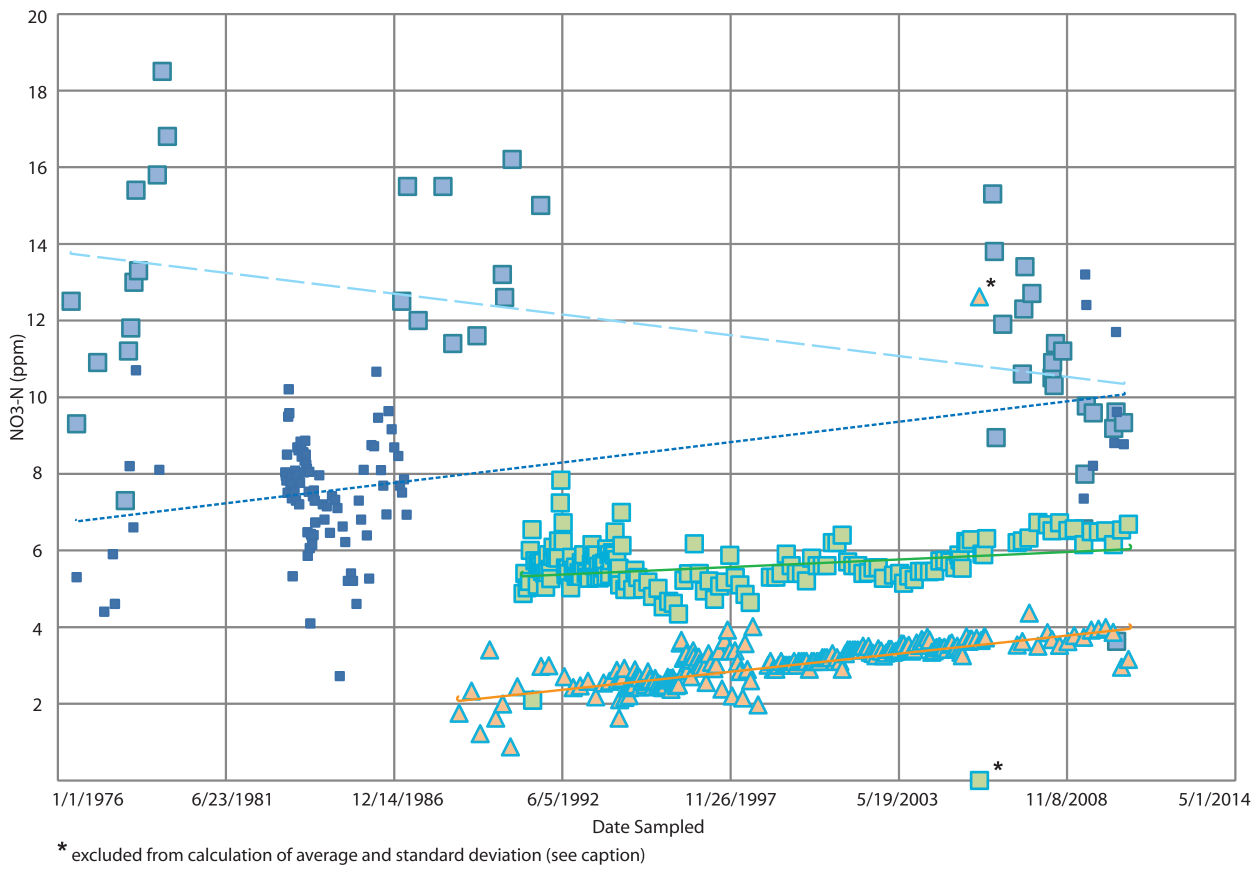


Figure 58. Nitrate concentrations in selected springs in southeastern Minnesota from 2005 to 2011. Note that variability through time in nitrate concentrations differs significantly among the springs and reflects hydrogeologic setting. Springs emanating from the Oneota Dolomite and lower stratigraphic levels are in hydrogeologic settings that lead to relatively little variability in nitrate concentration. See text for additional discussion. Figure 57 shows location of springs. "+" designates springs monitored as part of research summarized in Luhmann et al. (2011). Single, outlying values of nitrate concentration for each of three springs (23A098, 23A0114, 85A01) were not included in the calculation of standard deviation and average, nor used in the calculation of the trend lines. These values are regarded as spurious, and possibly are associated with sampling or analytical errors.



x=average nitrate concentration over this time.
sd=standard deviation for nitrate values.

OGCM ▢ 23A...037 (Fountain)	x=11.9, sd=2.9	light blue dashed line	Unlikely to have significant contribution from regionally sourced water based on hydrogeologic setting. Highly karstic
OGCM ■ 23A...02 (Moth)	x=7.6, sd=1.5	blue dotted line	Potentially with significant contribution from regionally sourced water based on hydrogeologic setting. Highly karstic
OPOD ▢ 23A...098 (LFH Main)	x=5.6, sd=0.6	green line	Potentially with significant contribution from regionally sourced water based on hydrogeologic setting. Fracture dominated but to lesser degree than karstic units above
CSLF △ 23A...0114 (Peterson Hatchery Main)	x=3.0, sd=0.5	orange line	

Figure 59. Nitrate concentrations in selected springs in southeastern Minnesota from 1976 to 2011. Note that variability through time in nitrate concentrations differs significantly among the springs and reflects hydrogeologic setting. See text for discussion. Figure 57 shows location of springs. Single, outlying values of nitrate concentration for each of two springs (23A098, 23A0114) were not included in the calculation of standard deviation values.

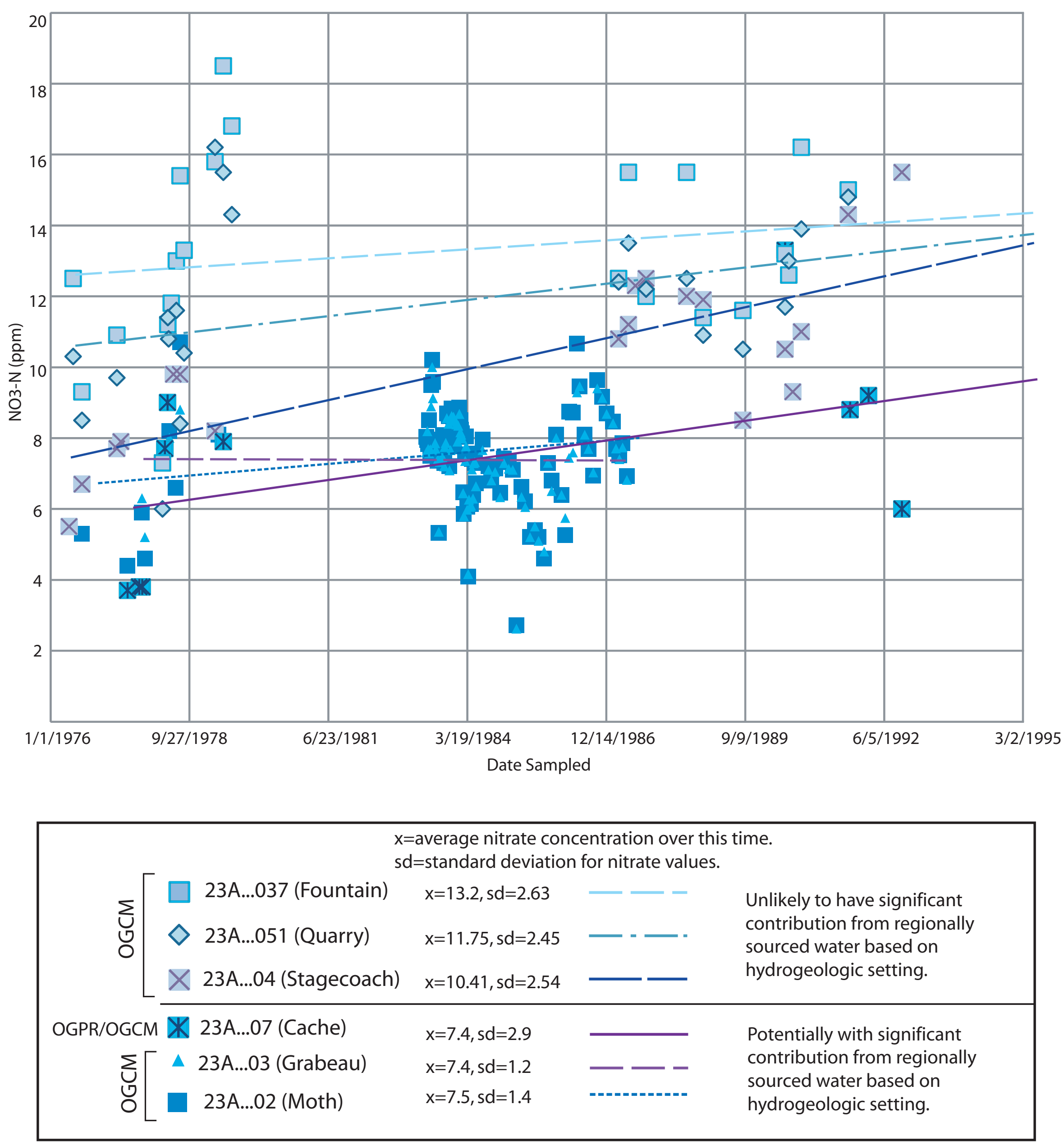


Figure 60. Nitrate concentrations in selected springs on the Upper Carbonate Plateau in western Fillmore County, from 1976 to 1995. Note that variability through time in nitrate concentrations differs significantly among the springs and reflects hydrogeologic setting. See text for discussion. Figure 57 shows location of springs.

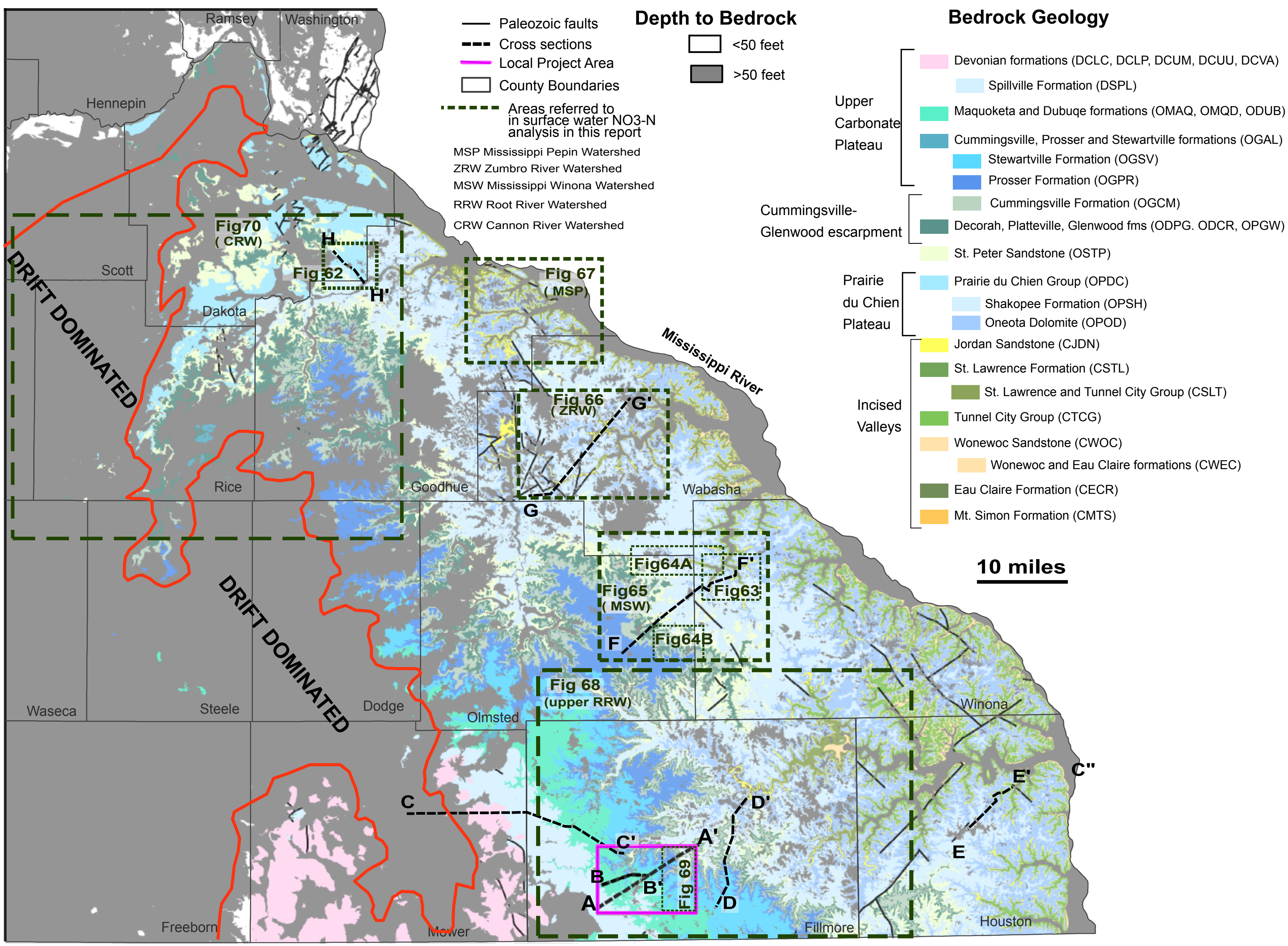


Figure 61. Compilation map for regional study area combining map of unconsolidated material and bedrock geology, and showing location of maps and cross sections used as illustrations (Figs 62-70) in our analysis of geologic controls on baseflow stream water nitrate concentrations. See Figure 4 for map explanation.

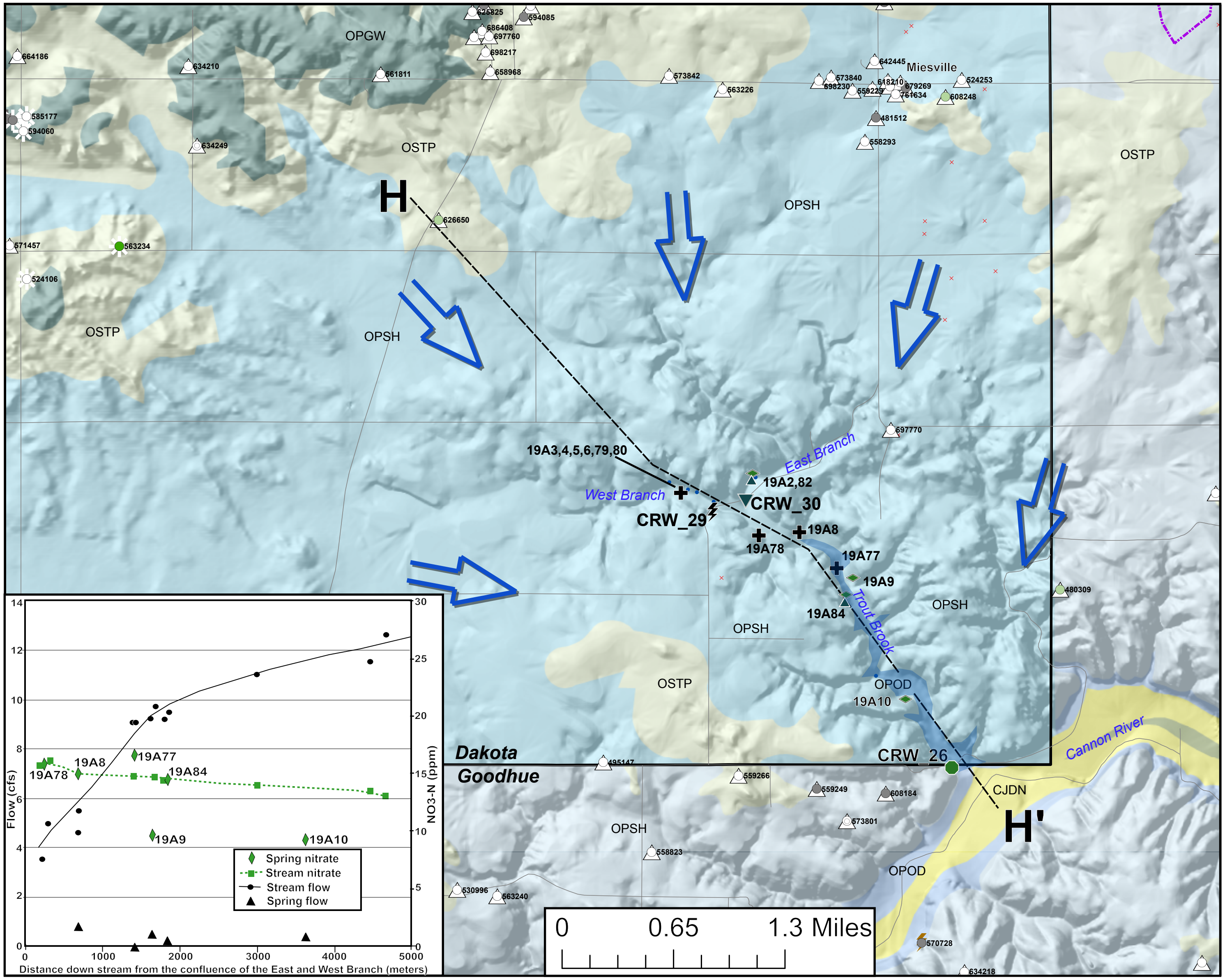


Figure 62. Trout Brook area, southeastern Dakota County, showing nitrate concentrations of water from wells, springs, and streams. On the map, note overall decrease in springwater nitrate concentration downstream of the confluence of the east and west branches of Trout Brook (springs from 19A78 downstream to 19A10). Stream water nitrate concentration is also diminished on the downstream end of Trout Brook due to dilution from these springs, and from more distributed baseflow emanating from lower in the Oneota and Jordan Formations (see also cross section H-H' in figure 46). Spring water nitrate values depicted by symbology on map are averages from 2011-2012 measurements in Groten and Alexander (2013). Stream water nitrate values from Watkins et al 2011 and are averaged from samples taken between 2005 and 2010. The inset illustration shows nitrate concentrations and flow rates from springs and stream water along Trout Brook downstream of the confluence of the east and west branches measured on October 28 and 29, 2011 (modified from Groten and Alexander, 2013). These synoptic data also indicate progressive downstream diminishment of stream nitrate concentration. The Oneota Dolomite has not been mapped across Dakota County, and was added to this illustration within Trout Brook based on field visits to the area and water well drilling records. Appendix A provides map legend and explanation. Large blue arrows depict bulk dominant flow in Jordan aquifer. Location in regional context in Figure 61.

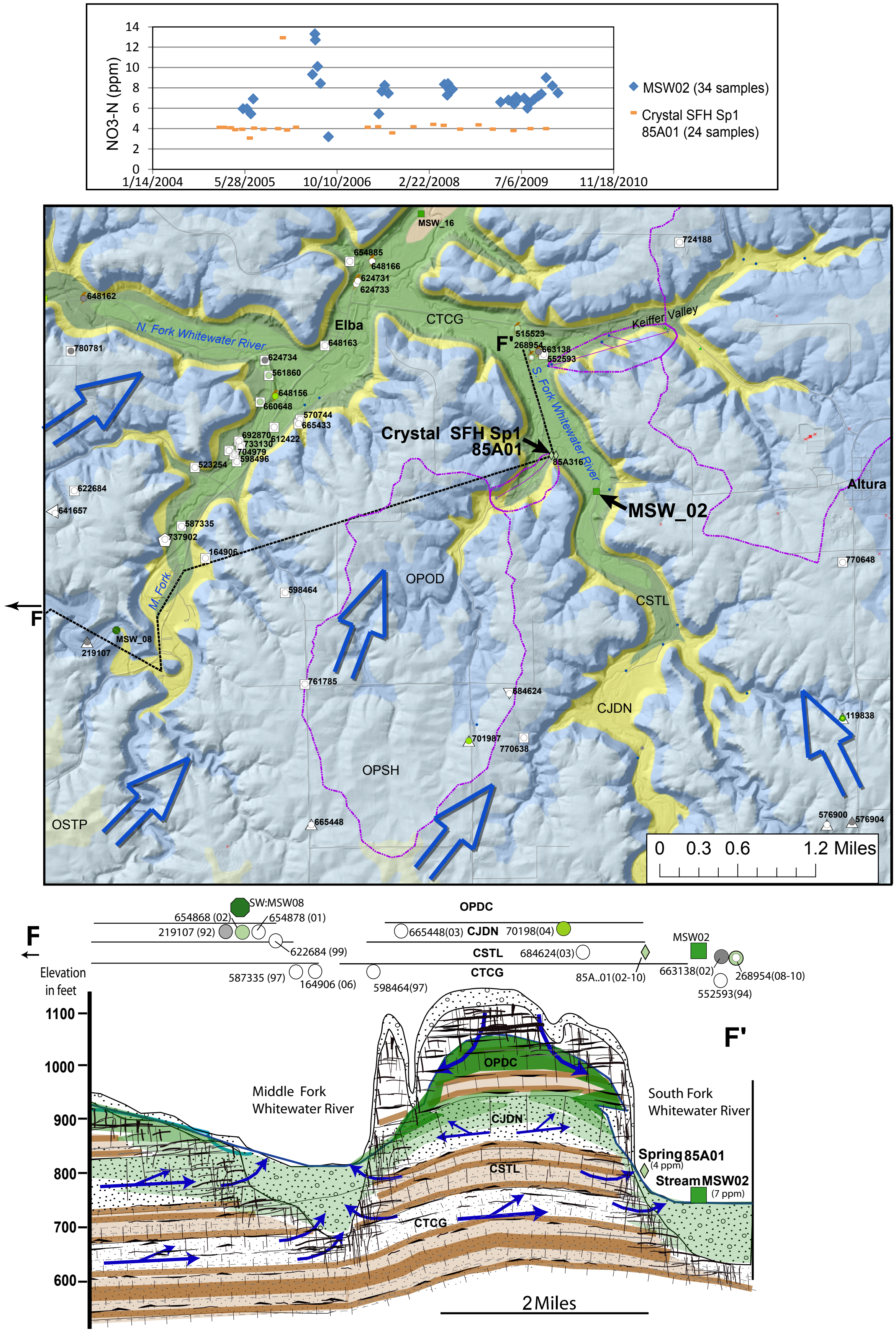


Figure 63. Comparison of stream baseflow nitrate concentration to nearby spring water nitrate concentration downstream. Measured over the same approximately five year period, the water from Crystal Springs Fish Hatchery Spring 1, with rare exception, has a lower nitrate concentration than the nearby upstream surface water. Springs emanating from the lower parts of incised valleys, such as this one sourced through the St Lawrence Formation, commonly dilute the nitrate concentration of streams. Appendix A provides legends to maps and cross section. Large blue arrows depict bulk dominant flow in Jordan and lower aquifers. Stream water nitrate concentration from Watkins et al. (2011). Cross section F-F' shown in its entirety in Figure 44. Location in regional context in Figure 61.

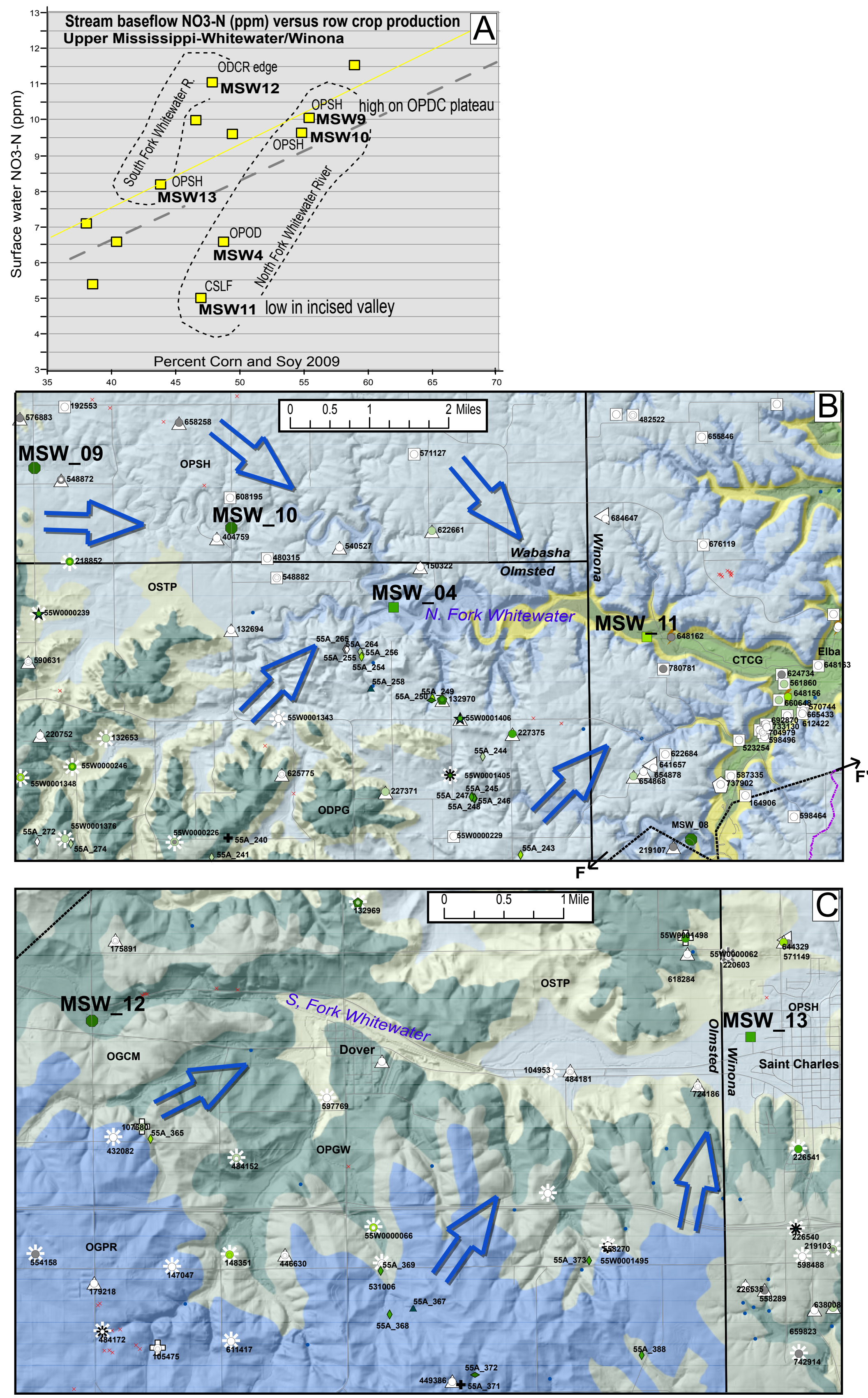


Figure 64. Variability in stream water nitrate concentration relative to row crop production (A) along two stream reaches in the upper part of the Mississippi-Whitewater River (MSW) watershed. The downstream decrease in surface water nitrate concentration relative to row crop production along the North (B) and South (C) Forks of the Whitewater River likely reflect at least in part dilution via baseflow derived from progressively deeper groundwater. See text for discussion. Appendix A provides legend to map. Large blue arrows depict bulk dominant flow in Prairie du Chien Group and Jordan Sandstone. The plot of stream baseflow nitrate concentration versus 2009 row crop land use (A) is modified from Watkins et al. (2011). See Figure 37 for complete plot of all sample points, and additional explanation. Solid yellow line on plot is linear fit for all MSW data and dashed straight gray line is fit to combined data from all watersheds. Location in regional context in Figure 61.

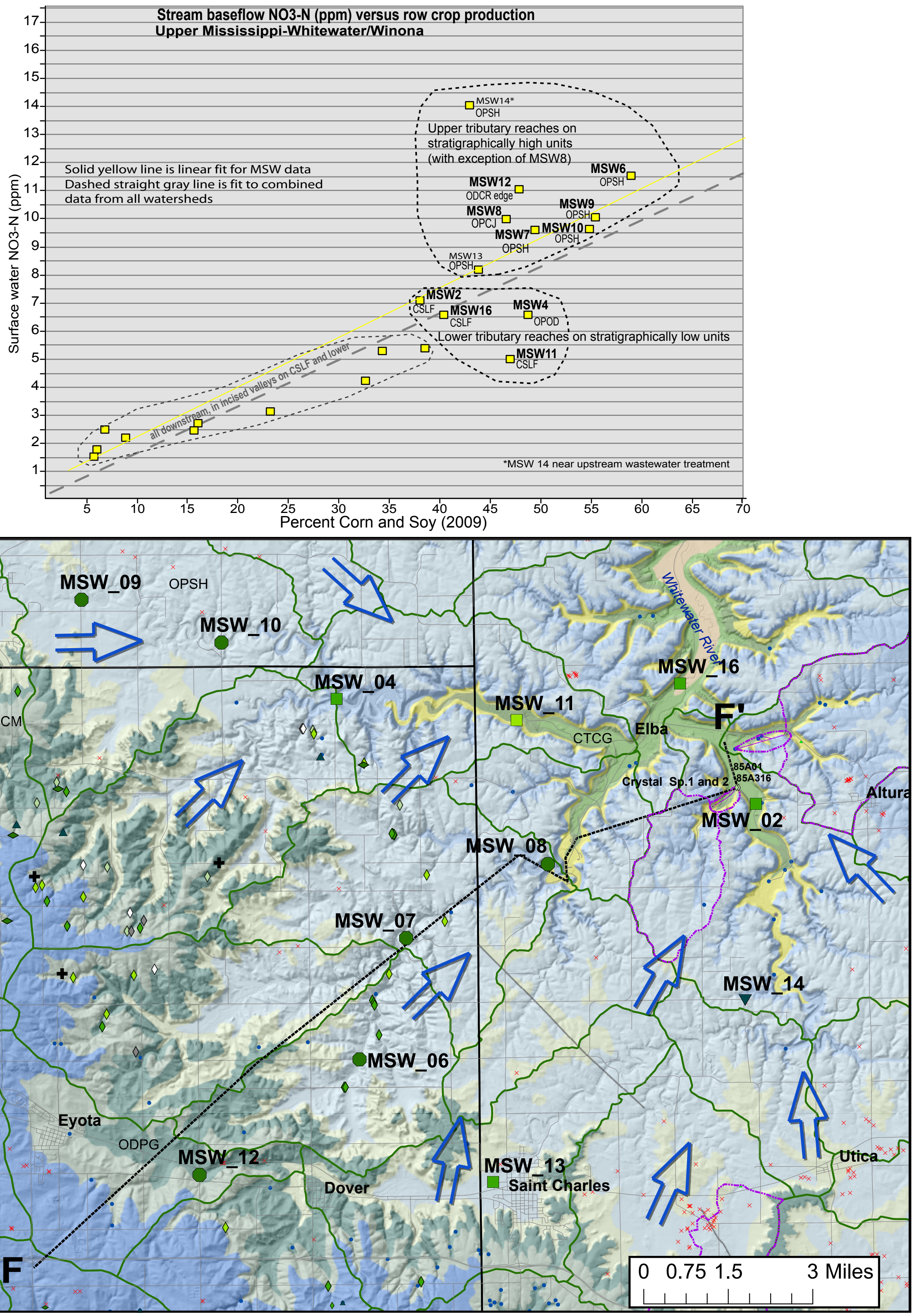


Figure 65. Variability in stream water nitrate concentration relative to row crop production, compared against hydrogeologic setting in the upper part of the Mississippi-Whitewater River (MSW) watershed. Relatively high concentrations are mostly (exception is MSW8) from stream samples high on the Prairie du Chien Plateau (OPSH and higher). Relatively low concentrations are samples from stream reaches lower in the plateau or in incised valleys (OPOD and lower). This relationship likely reflects, at least in part, dilution from nitrate poor groundwater being significantly lower in the stratigraphic section. Appendix A provides legend to map. Large blue arrows depict bulk dominant flow in Prairie du Chien Group and Jordan Sandstone. See also cross section F-F' in Figure 44. Location in regional context in Figure 61. The plot of stream baseflow nitrate concentration versus 2009 row crop land use modified from Watkins et al. (2011). See Figure 37 for complete plot of all sample points, and additional explanation.

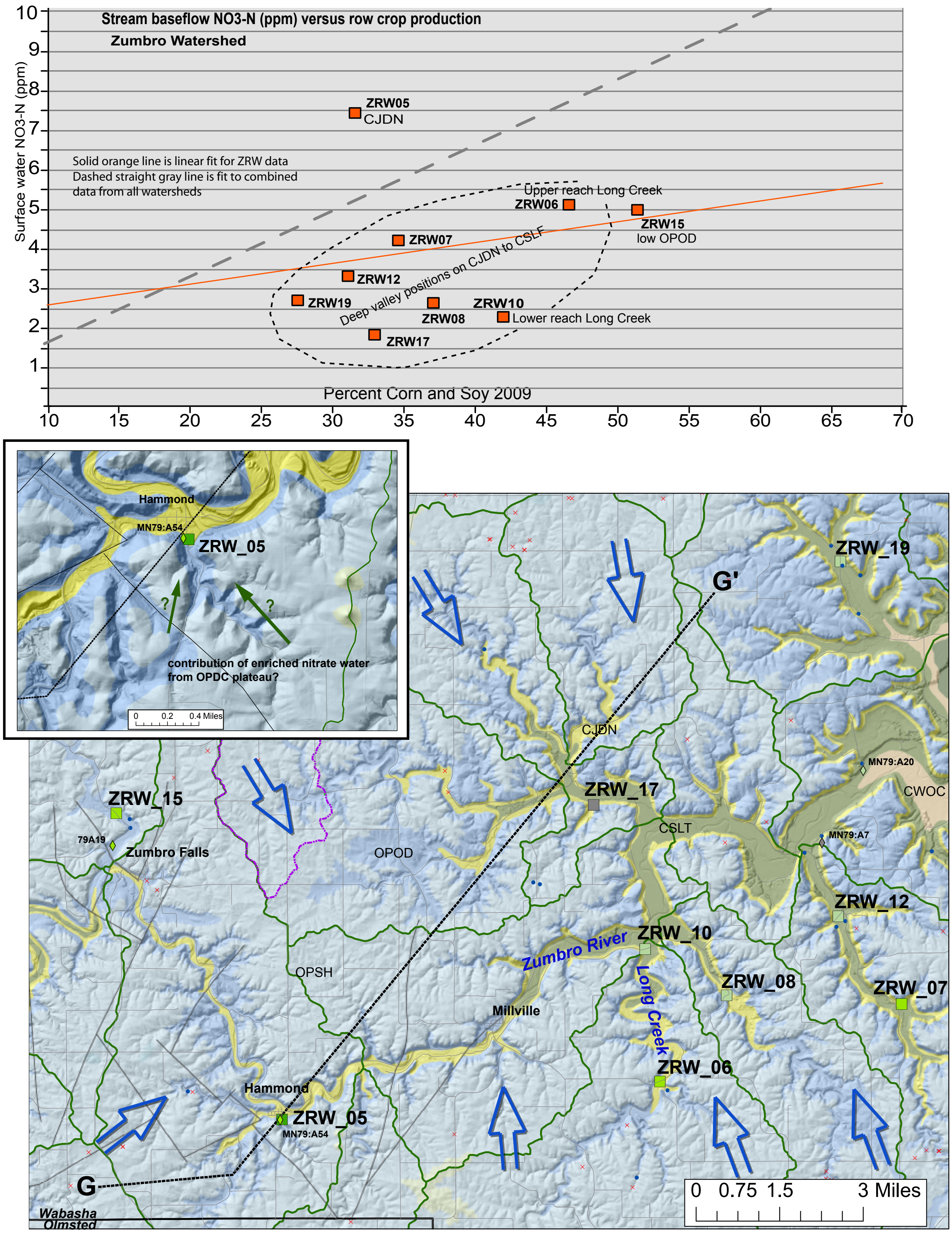
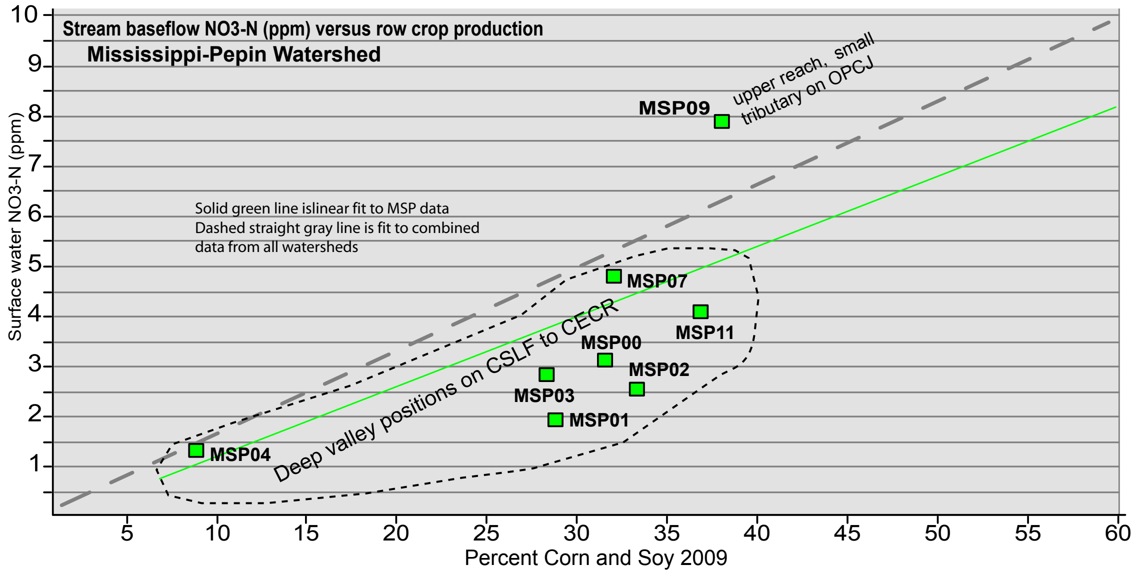


Figure 66. Variability in stream water nitrate concentration relative to row crop production, compared against hydrogeologic setting, in part of the Zumbro River watershed (ZRW). With a single exception, samples show an overall low stream nitrate concentration versus corn-soy production compared to correlation for combined watersheds. This can be attributed to the dominance of sampling stations located deep in valleys where baseflow sourced from bedrock is likely to be nitrate-poor. Note also the decrease in nitrate concentration relative to row crop production downstream along Long Creek, which also may reflect dilution from deeper aquifers. The exception to low nitrate concentrations, ZRW05, is on a small tributary (inset map) that may receive a significant contribution of enriched nitrate water from the Prairie du Chien Plateau compared to other sampling sites. See text for discussion. See also cross section G-G' in Figure 45. Appendix A provides legend to map. Large blue arrows depict bulk dominant flow in Jordan Sandstone and lower units. Location in regional context in Figure 61. The plot of stream baseflow nitrate concentration versus 2009 row crop land use modified from Watkins et al. (2011). See Figure 37 for complete plot of all sample points, and additional explanation.



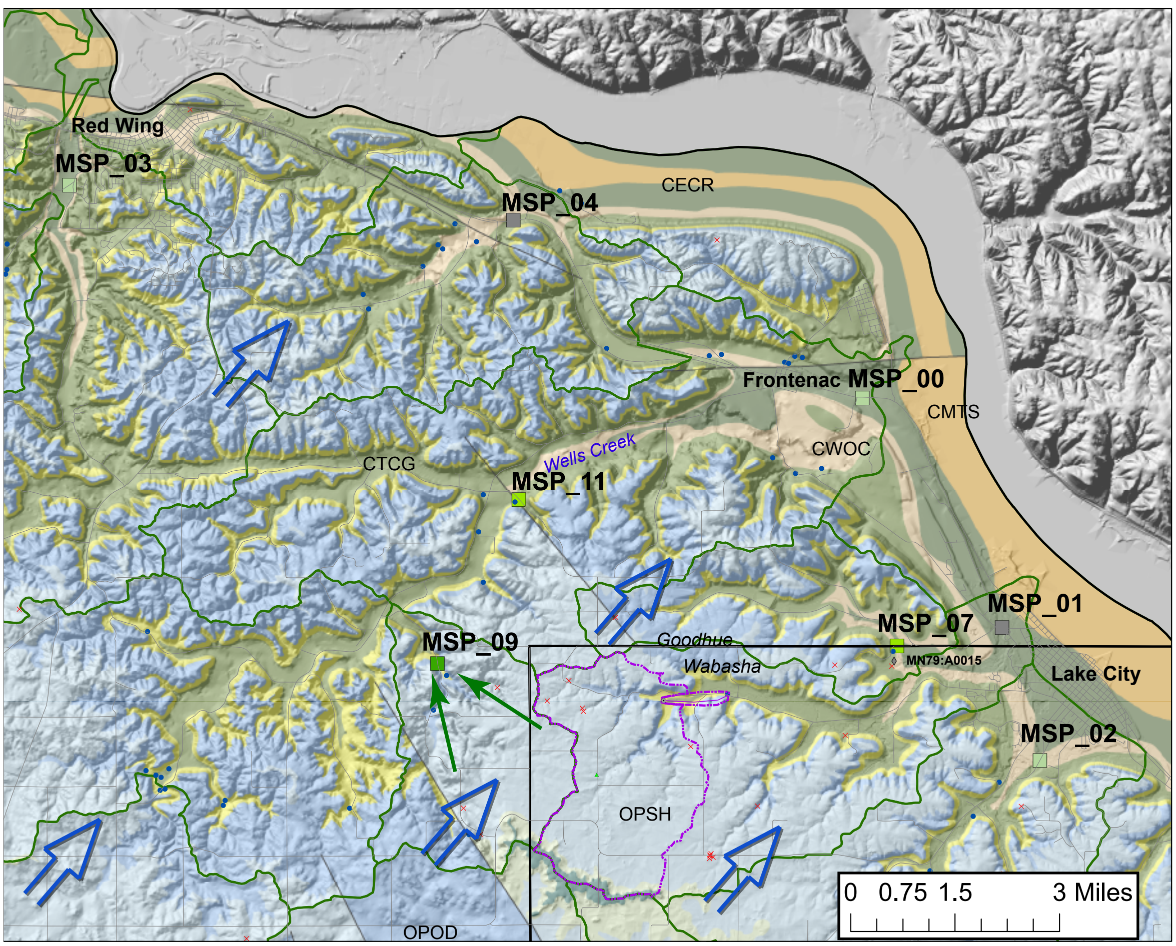


Figure 67. Variability in stream water nitrate concentration relative to row crop production, compared against hydrogeologic setting, in part of the Mississippi Pepin watershed (MSP). With a single exception, these samples show an overall low stream nitrate concentration versus corn-soy production compared to correlation for combined watersheds. This can be attributed to the dominance of sampling stations located deep in valleys where the baseflow sourced from bedrock is likely to be nitrate-poor. The exception to low nitrate concentrations, MSP09, contrasts to the others in its position high up a small tributary valley, on Prairie du Chien-Jordan contact strata. See text for discussion. Appendix A provides legends to map. Large blue arrows depict bulk dominant flow in Jordan Sandstone and lower units. Location in regional context in Figure 61. The plot of stream baseflow nitrate concentration versus 2009 row crop land use modified from Watkins et al. (2011). See Figure 37 for complete plot of all sample points, and additional explanation.

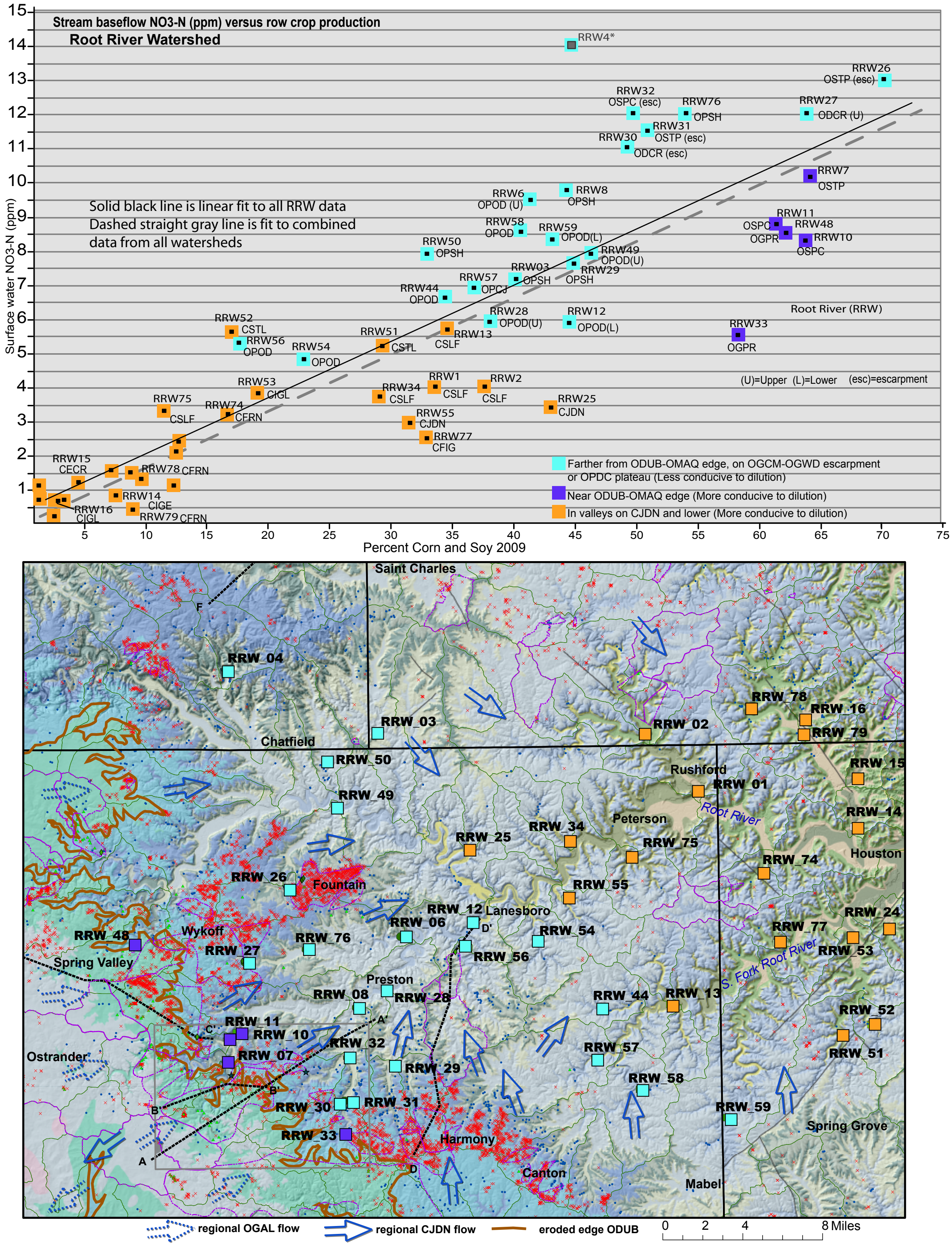


Figure 68. Variability in stream water nitrate concentration relative to row crop production, compared against hydrogeologic setting, in upper part of the Root River Watershed (RRW). Sample points with low nitrate relative to row crop production mostly located in one of two settings: 1) deep in valleys where Oneota aquitard and units below contribute baseflow, and 2) near eroded edge of Maquoketa-Dubuque aquitard, where Galena aquifer water sourced regionally from the west contributes to baseflow. Samples with relatively high nitrate concentrations are dominated by locations along higher reaches of tributaries on the Prairie du Chien Plateau and along lower part of OGCM-OGWD escarpment. See text for discussion. See also cross sections in Figures 40-43. Appendix A provides legend to map. Location in regional context in Figure 61. Plot of stream baseflow nitrate concentration versus 2009 row crop land use modified from Watkins et al. (2011). Only sampling points within the map area are labeled with identifiers on the plot. Others are lower in the watershed, off of map area. RRW 4 was not included in the evaluation because of uncertainties over calculation of row crop percentage (Watkins, personal communication). See Figure 37 for complete plot of all sample points of Watkins et al. (2011), and additional explanation.

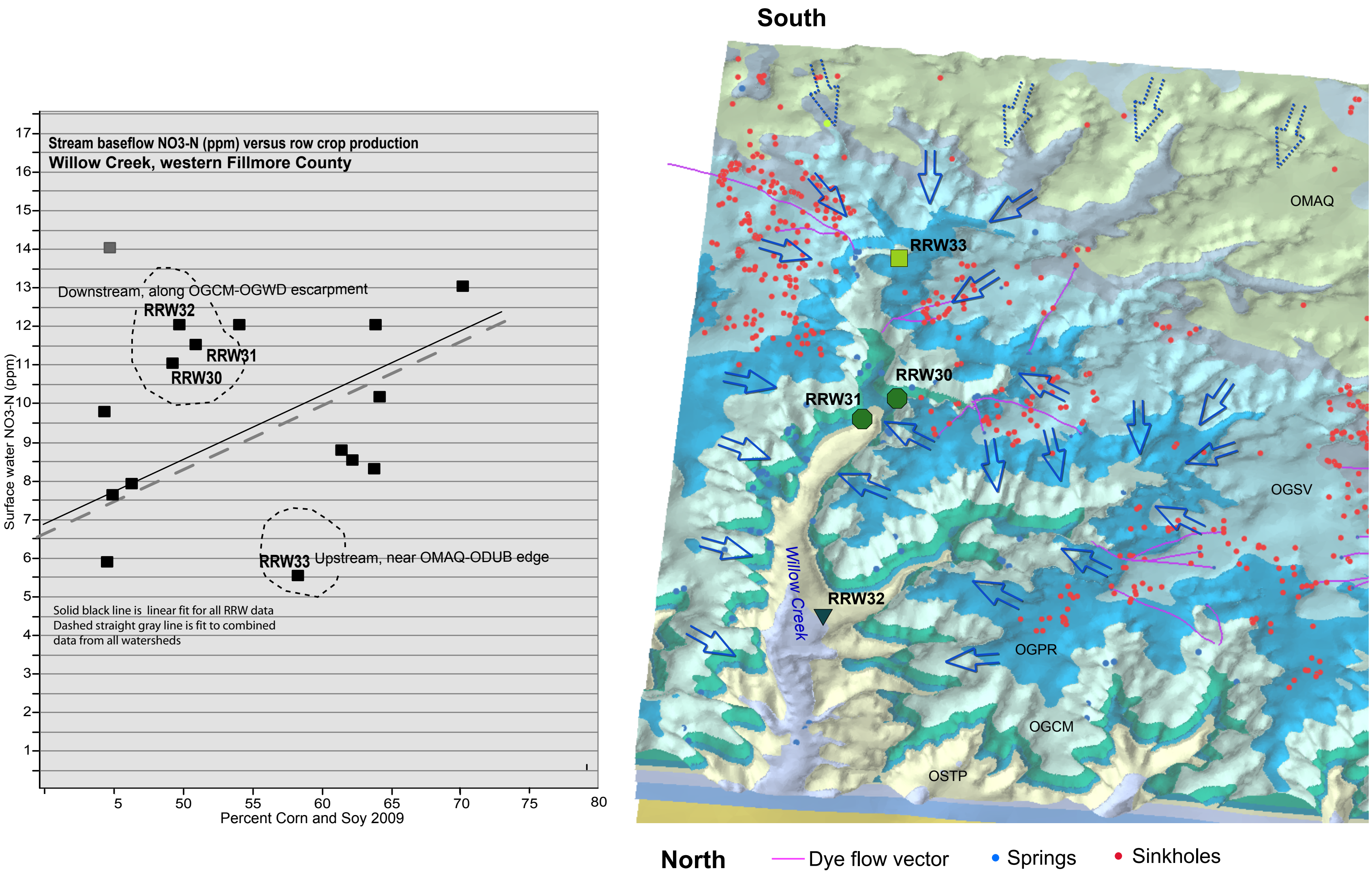


Figure 69. Variability in stream water nitrate concentration relative to row crop production along Willow Creek in the upper part of the Root River Watershed (RRW). Four sampling stations show a systematic down valley increase in stream water nitrate concentration relative to row crop production. See text for discussion. Appendix A provides legend to map. Large, dashed blue arrows depict bulk dominant flow of water in Galena sourced in part by the regional system to the west. Smaller arrows depict flow directions in Galena of water that includes significant local recharge. The plot of stream baseflow nitrate concentration versus 2009 row crop land use modified from Watkins et al. (2011). See Figure 37 for complete plot of all sample points, and additional explanation. Location in regional context in Figure 61.

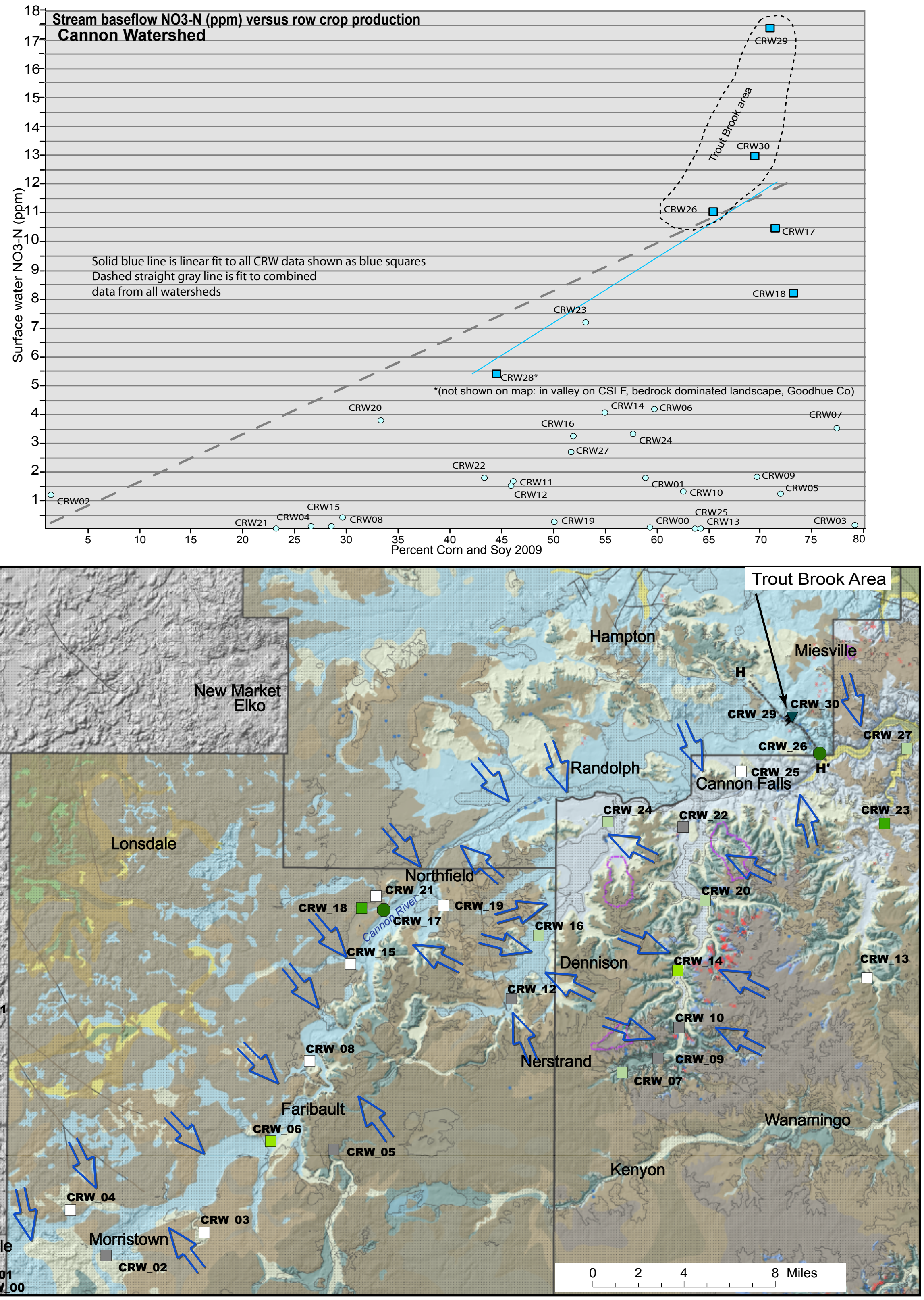


Figure 70. Variability in stream water nitrate concentration relative to row crop production, compared against hydrogeologic setting, in Cannon River Watershed (CRW). The two locations with highest nitrate concentration relative to row crop production (CRW29,30) are along Trout Brook, where surficial tills and thick unconsolidated sedimentary cover are present only as patches. CRW 26, at the downstream end of Trout Brook has relatively low nitrate concentration, resulting from dilution (presented earlier in this report). Most other sample locations are from valleys cut into extensive areas of thick unconsolidated sedimentary cover with till. These are dominated by relatively low stream nitrate concentrations versus corn-soy production compared to the correlation for combined watersheds. See text for discussion. Appendix A provides legend to map. Blue arrows show flow directions in unconsolidated sediment and uppermost bedrock, based on Palen (1990), Campion and Wetzel (1997), Berg and Bradt (2003). Location in regional context in Figure 61. Plot of stream baseflow nitrate concentration versus 2009 row crop land use modified from Watkins et al. (2011). Includes sampling sites Watkins et al. (2011) considered to be outside of bedrock dominated, cold-water stream landscape of southeastern Minnesota, and therefore not part of the dataset used to statistically test the relationship between row crop production and nitrate concentrations. These sites distinguished as small blue circles on plot in this figure. See Figure 37 for complete plot of all sample points of Watkins et al. (2011), and additional explanation.

APPENDIX A: LEGENDS
Legend of Aquifer Codes

(units exposed in open hole interval)

- Quaternary sediments (QBAA, QBUA, QUUU, QWTA)
- Devonian rocks (DCLP, DCLS, DCOG, DCOM, DCVA, DCVL, DCVU, DPOM, DSOG, DSOM, DSPL, DWAP)
- Maquoketa Formation (OMAQ)
- Maquoketa and Dubuque Formations (OMQD)
- Maquoketa, Dubuque and Galena units (OMQG)
- Dubuque Formation (ODUB)
- Dubuque and Galena units (ODGL)
- Galena Group (OGAL, OGSV, OGCM, OGDC)
- Decorah, Platteville, Glenwood (ODCR, OPVL, OPGW, OPSP)
- St. Peter Sandstone (OSTP)
- St. Peter and Prairie du Chien units (OSPC)
- St. Peter, Prairie du Chien and Jordan units (OSPJ)
- Prairie du Chien Group (OPSH, OPWR, OPNR, OPOD, OPDC)
- Prairie du Chien and Jordan units (OPCJ)
- Jordan Sandstone (CJDN)
- Jordan Sandstone and St. Lawrence Formation (CJSL)
- St. Lawrence Formation (CSTL)
- St. Lawrence and Tunnel City (Franconia) units (CSLF, CSLT)
- Tunnel City (Franconia) and Tunnel City and Wonewoc (Ironton-Galesvile) (CFRN, CTCG, CFIG, CTCW)
- Wonewoc (Ironton-Galesvile) Sandstone (CIGL, CWOC, CGSL, CIGE, CWEC, CIGM, CWMS)
- Eau Claire Formation (CECR)
- Eau Claire and Mt. Simon Formations (CEMS)
- Mt. Simon Formation (CMTS)

APPENDIX A: LEGENDS
Master legend to maps

Quaternary Till deposit (shown only on Figure 70B)

Depth to Bedrock
(shown only on Figs. 45B and 70B)

- <50 feet
- >50 feet

Bedrock Geology

- Devonian formations (DCLC, DCLP, DCUM, DCUU, DCVA)
  - Spillville Formation (DSPL)
- Maquoketa and Dubuqe formations (OMAQ, OMQD, ODUB)
- Cummingsville, Prosser and Stewartville formations
  - Stewartville Formation (OGSV)
  - Prosser Formation (OGPR)
  - Cummingsville Formation (OGCM)
- Decorah, Platteville and Glenwood formations (OGAL) (ODPG. ODCR, OPGW)
- St. Peter Sandstone (OSTP)
- Prairie du Chien Group (OPDC)
  - Shakopee Formation (OPSH)
  - Oneota Dolomite (OPOD)
- Jordan Sandstone (CJDN)
- St. Lawrence Formation (CSTL)
  - St. Lawrence and Tunnel City Group (CSLT)
- Tunnel City Group (CTCG)
- Wonewoc Sandstone (CWOC)
  - Wonewoc and Eau Claire formations (CWEC)
- Eau Claire Formation (CECR)
- Mt. Simon Formation (CMTS)

Karst Features

- Spring
- Stream Sink
- Sinkhole

- Paleozoic faults
- Cross sections
- Local Project Area
- County Boundaries
- Dye trace, input
- Dye trace, flow vector
- springshed boundary
- watershed boundary
- groundwater flow direction

Water wells
NO3-N (ppm)

Maximum / Minimum

- 0-1
- 1-2
- 2-4
- 4-6
- 6-9
- 9-12
- 12-15
- >15

221187 23W...5913 unique well number

Spring water
NO3-N (ppm)

- 0 - 1.0
- 1.0 - 2.0
- 2.0 - 4.0
- 4.0 - 6.0
- 6.0 - 9.0
- 9.0 - 12.0
- 12.0 - 15.0
- >15.0 (value in ppm)

23A29 spring identifier

Surface water
NO3-N (ppm)

- 0 - 1.0
- 1.0- 2.0
- 2.0 - 4.0
- 4.0 - 6.0
- 6.0 - 9.0
- 9.0 - 12.0
- 12.0 - 15.0
- >15

RRW_11 Sample identifier

Watershed code

MSP Mississippi Pepin Watershed
ZRW Zumbro River Watershed
MSW Mississippi Winona Watershed
RRW Root River Watershed
CRW Cannon River Watershed

Maps that accompany cross sections in Figures 45-52 show lines of section and data points with nitrate values used to show distribution of relative nitrate concentrations on the cross sections. Areas on the maps with a high density of point data may not clearly show all points and identifier labels.The GIS project delivered with this report can be used to visualize and access all data points. Aquifer codes and symbols that appear on maps are shown on next page of this legend.

APPENDIX A: LEGENDS

Master legend to cross sections

- Quaternary unconsolidated sediment
- Fine to coarse grained sandstone
- Carbonate rock (limestone and dolostone)
- Very fine grained sandstone, siltstone, shale
- Coarse Clastic
- Carbonate
- Fine Clastic
- Fractures
- Aquifer (generally saturated)
- Aquitard (darker shading=lower vertical K)
- Water Table
- Predominant lateral flow direction based on potentiometric maps and/or dye tracing
- significant lateral flow oblique to x-section,
- Recharge to water table
- Discharge to surface water

(Variable arrow sizes on cross sections correspond to relative rate of flow)

- Dye flow path, schematic

Water wells

NO3-N in ppm

Maximum | Minimum

- 0-1
- 1-2
- 2-4
- 4-6
- 6-9
- 9-12
- 12-15
- >15

221187
23W...5913 unique well number

Surface water NO3-N (ppm)

- 0 - 1.0
- 1.0- 2.0
- 2.0 - 4.0
- 4.0 - 6.0
- 6.0 - 9.0
- 9.0 - 12.0
- 12.0 - 15.0
- >15

RRW_11, Sample identifier

Watershed code

MSP Mississippi Pepin Watershed
ZRW Zumbro River Watershed
MSW Mississippi Winona Watershed
RRW Root River Watershed
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Spring water NO3-N (ppm)

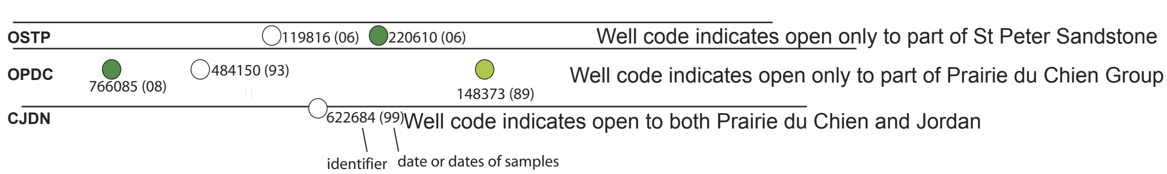
- 0 - 1.0
- 1.0 - 2.0
- 2.0 - 4.0
- 4.0 - 6.0
- 6.0 - 9.0
- 9.0 - 12.0
- 12.0 - 15.0
- >15.0 (value in ppm)

23A29 spring identifier

Relative nitrate concentrations within each area of cross-section

- Relatively high NO3-N (commonly 5 to 15 ppm)
- Relatively moderate NO3-N
- Relatively low NO3-N

Example of data points projected on to cross sections



Each cross section is accompanied by a map view illustration showing location of cross section line, and point data with nitrate values that were projected on to the line of section. Stratigraphic position of water well samples is based on aquifer code, and illustrated in the above format. Relative stratigraphic position of the samples within individual stratigraphic units is not discerned.