Springshed Assessment Methods
for Paleozoic Bedrock Springs
of Southeastern Minnesota

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Acknowledgements

Cover Photo: Camp Winnebago Spring, Houston County, Minnesota

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Introduction

Springs are the natural discharge points for groundwater. They provide baseflow for streams and in the case of trout streams are critical sources of isothermal water. They are commonly found emerging from the Paleozoic sedimentary rocks of southeastern Minnesota where river valleys cut deeply through the water-bearing bedrock layers. The different lithology and hydraulic properties (hydrostratigraphy) of the rock types makes some settings more likely for springs. Our research on springs focused on areas with cold-water streams that support trout populations within the bedrock-dominated landscape of southeastern Minnesota (Figure 1). In that region, carbonate (limestone, dolostone) and carbonate-cemented sandstone rock layers dissolve in slightly acidic groundwater and have developed a system of conduits that allow water to be routed quickly through the enlarged passages (karst). Other units, while not exhibiting all of the characteristics of traditional carbonate karst, do share some of the key hydrologic properties.

A springshed is defined as "those areas within ground- and surface-water basins that contribute to the discharge of a spring" (Florida Geological Survey, 2003). Precipitation falling on the surface usually infiltrates through the soil. Where karst features are present, surface water enters the groundwater more quickly through sinkholes and stream sinks, the point at which a surface stream sinks into the ground (Figure 2). The boundaries of groundwater springsheds do not necessarily correspond to those on the surface. They are dynamic, changing as groundwater levels rise and fall.

In order to conserve and protect springs and the surface water bodies they supply, it is necessary to understand their geologic setting and where they derive their water. The University of Minnesota (U of M), the Minnesota Department of Natural Resources (DNR), and a group of experienced local cavers have been actively working on mapping springsheds in southeastern Minnesota for several decades. Funding from the Environment and Natural Resources Trust Fund (ENRTF) has allowed these researchers to accelerate and formalize efforts to delineate springsheds by injecting fluorescent organic dyes into sinkholes or sinking streams to determine the general flow path to springs. This time- and labor-intensive method has only been applied to a small portion of the known springs in southeastern Minnesota. However, if combined with an understanding of the geology, dye-tracing provides experienced geologists and hydrologists with a powerful tool for interpreting undelineated springsheds. This ultimately improves our ability to assess the vulnerability of springs to activities on the land surface.

Spring vulnerability

Our focus is on the sources of water to the uppermost bedrock springs because they are most susceptible to degradation in water quality, flow rate, and temperature. Furthermore, the uppermost bedrock aquifer is more amenable to springshed extent estimation than the deeper systems.

High-volume water appropriations can disrupt or decrease groundwater flow to springs depending on the number of wells, their distance to the spring, the pumping rate of the well, and the hydrogeologic characteristics of the particular unit. Landscape alteration from mining operations and road construction can disrupt the flow of groundwater to a spring by intercepting it (Green and others, 2003). An increase in impervious surface area in a watershed increases runoff and decreases infiltration, affecting water quality and temperature with potentially detrimental effects on biota (Wang and others, 2003). Agricultural nonpoint-source pollution (fertilizers, herbicides, insecticides and runoff) and point-source pollution from discrete chemical releases can impact a spring's chemistry and quality. Additional information on the impacts of human activities on springs is presented by Drew and Hotzl (1999).

Geologic background

An overview of the regional geologic setting, hydrostratigraphy, and the groundwater-surface water flow system across the bedrock-dominated landscape of southeastern Minnesota was recently presented by Runkel and others (2013) (Figures 1, 3 and 4). The major points relevant to understand springsheds and springs are summarized below.

Physiography

The landscape of southeastern Minnesota is bedrock dominated and highly dissected by tributaries to the Mississippi River. There are two broad, dissected bedrock plateaus that are formed in resistant carbonate rock units (Figure 5) (Mossler and Hobbs, 1995). Less resistant sandstone and shale layers crop out or are shallowly buried along escarpments and valley walls and in the floors of entrenched streams. Although previously glaciated, unconsolidated glacial and related sediment on top of bedrock is generally less than 50 feet thick. Exceptions include isolated areas on top of the plateaus or where thick alluvial sediment fills the lower parts of narrow bedrock valleys (Figure 1).

The Upper Carbonate Plateau (also called the Galena–Cedar Valley Plateau) is comprised 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 (Figure 5A). It is generally between 1200-1300 feet in elevation. The outer, eroded edge of the Upper Carbonate Plateau is an escarpment exposing from bottom to top, the St. Peter Sandstone, Glenwood and Platteville formations, Decorah Shale, and Cummingsville Formation
(Figure 5B).

The Prairie du Chien Plateau forms the next step down, ranging from 1200-900 feet in elevation and extends generally eastward to the edge of the Mississippi River where it forms the resistant bluff tops. Relatively smaller mesas of St. Peter Sandstone are capped by remnants of the Platteville Formation and are scattered across the Prairie du Chien Plateau
(Figure 5C).

The regionally extensive plateaus of different elevation (Figures 1, 4, 5) have been dissected by pre-glacial, inter-glacial, and to a lesser extent, recent streams.

Bedrock geology

The Paleozoic bedrock of southeastern Minnesota was primarily deposited in a marine setting during Cambrian to Devonian time (505 to 350 million years ago). The resulting layers of quartz-rich sandstone, very fine-grained sandstone, siltstone and shale, and limestone or dolostone rock layers range from 50 to 200 feet thick (Figures 1, 3, 4). The lower part of the stratigraphy that is relevant to this discussion is Cambrian in age and dominated by siliciclastic material (sandstone, siltstone and shale). The upper layers are Ordovician and Devonian units dominated by carbonate rock units and shale. The bedrock is described in detail by Mossler (2008).

The bedrock formations, although nearly flat-lying, have dips of less than two degrees and form a subtle structural depression called the Hollandale embayment. The eastern margin of the depression is exposed along the Mississippi River and its tributaries where the bedrock dips generally west and southwest (Figure 4). Along the Minnesota River north of Mankato, the western side of the bowl dips gently to the east. Faults are locally common, especially in areas where underlying Proterozoic bedrock contains faults related to the Midcontinent Rift System (Mossler, 2008). Older strata form the uplifted western and eastern limbs of the Hollandale Embayment (Figures 1 and 4) with progressively younger bedrock preserved toward the center.

The bedrock has been potentially exposed to weathering processes since the Devonian, a period of hundreds of millions of years. The material left after rock has dissolved is a red, clay-rich residuum. This material washes into joints in the bedrock surface on the plateau; it is commonly eroded from hillsides.

Glacial and recent geology

The unconsolidated sediment that overlies the bedrock in southeastern Minnesota is primarily Quaternary in age (less than about 2.6 million years old) and was deposited by processes related to glaciation. Sediment preserved at the surface includes the following:

1. Sand-and-gravel-dominated glacial stream sediment

2. Finer-grained, silty, windblown sediment (loess)

3. Poorly sorted sediment with a fine matrix texture but containing coarser clasts (diamicton and when known to be deposited by glaciers, till)

4. Mixed rocky deposits along steep slopes (colluvium)

The Quaternary sequence on the plateaus is commonly loess overlying thin, patchy remnants of till and stream sediment, overlying the clayey weathered bedrock residuum described above. Thicker deposits partly filling bedrock valleys are mostly sand-dominated stream sediment. More recently, natural and human-accelerated erosion and sedimentation have further eroded plateau tops, modified steep slopes, and in-filled river valleys with silt-dominated alluvium.

Hydrostratigraphy

When studying groundwater movement it is helpful to define bodies of rock on the basis of their characteristic porosity and permeability, instead of using traditional rock-property descriptions (hydrostratigraphy as opposed to lithostratigraphy) (Seaber, 1988). The formal classification of Paleozoic bedrock into aquifers and aquitards used in this report is based on hydraulic data interpreted within the context of hydrostratigraphic attributes, summarized in Runkel and others (2003, 2006a, 2013, 2014) Figures 3 and 4).

Porosity

The greatest volume of water is stored within the small pore spaces of a rock matrix. The Paleozoic strata are divided into three hydrostratigraphic units based on matrix characteristics (Runkel and others, 2003, 2006b): 1) The fine clastic and carbonate rock components are generally moderately to well cemented, with small, relatively poorly connected intergranular pores spaces. These materials are of low to very low permeability. (2) The coarse clastic component is fine- to coarse-grained sandstone with large, well-connected pore spaces, and has a markedly higher permeability. The greatest flux of water in the bedrock occurs through (3) secondary pores that are larger than intergranular spaces, collectively referred to as macropores. Capillary action is relatively insignificant (e.g., Pfannkuch, 1971) and aperture widths range from a few tens-of-microns to caves large enough for humans to pass.

The two fundamental kinds of macropore networks are those aligned with bedding and those intersecting bedding (Figures 4, 6 and 7). Bedding-parallel macropores form anastomosing networks at discrete stratigraphic intervals (Runkel and others, 2003, 2006b). Macropores intersecting bedding include vertical to subvertical fractures such as systematic joints that commonly penetrate several feet to tens-of-feet. Some stratigraphic intervals have been shown to be resistant to the through-going development of vertical fractures (e.g., Anderson and others, 2011; Runkel and others, 2014).

Both bedding-parallel and vertical macropores are common in all Paleozoic bedrock formations across southeastern Minnesota and southern Wisconsin and play a major role in flow (e.g., Muldoon and others,

2001; Runkel and others, 2003, 2006a, 2006b; Tipping and others, 2006; Swanson and others, 2006; Meyer and others, 2008; Anderson and others, 2011). Averaged across thick intervals (tens-of-feet), bulk hydraulic conductivities of Paleozoic bedrock range from tens to hundreds of feet per day, significantly greater than matrix permeability alone would accommodate (Runkel and others, 2003). Individual macropores intersected by boreholes have conductivities measured as high as thousands of feet per day (e.g., Runkel and others, 2003; 2006a, 2007, 2014). Dye traces demonstrate that macropore networks commonly accommodate flow speeds measured in tens of feet to miles per day (e.g., Alexander and Lively, 1995; Runkel and others, 2003; Green and others, 2012).

The degree to which macropores are developed in bedrock varies with its depth of burial (Runkel and others, 2003) (Figures 4, 6, and 7). In conditions of relatively deep burial by younger bedrock (50 feet or greater), macropores are typically limited to discrete intervals with abundant, bedding-plane parallel openings and subvertical fractures. These macropores have relatively narrow apertures compared to those in bedrock that is shallowly buried. Where there is less than 50 feet of overlying material, macropores are more abundant, better connected, and have larger apertures. The change from shallow to deep bedrock conditions is transitional but these categories generally hold for the 1:100,000 scale of the mapping in the region.

In addition to depth of burial, the composition of the bedrock has an impact on the development of macropore networks. Macropore apertures in both coarse- and fine-grained siliciclastic-dominated rock layers are rarely greater than a few inches (Runkel and others, 2006a, 2006b) and vertical fractures have limited trace lengths. In contrast, apertures in carbonate rock range upward to cave networks and commonly have vertical fractures that extend for over 100 feet (Runkel and others, 2013).

The carbonate rock layers forming the Upper Carbonate and Prairie du Chien plateaus across southeastern Minnesota contain large, solution-enhanced macropores and other cavities that are expressed at the surface as a karst landscape (Figure 5) (Alexander and Lively, 1995; Alexander and others, 1996; Green and others, 1997, 2002). Karst landscapes are characterized by features such as sinkholes, caves, closed depressions, and sinking streams.

Aquifers and aquitards

All parts of the Paleozoic bedrock section are known to yield water in economic quantities in a horizontal direction. Therefore, the hydrogeologic classification is based on first identifying aquitards that limit flow in a vertical direction. Intervals of strata between these aquitards are classified as aquifers.

Local variability in both matrix and fracture characteristics may result in conditions which are not entirely consistent with the regional-scale classification. For example, the lower Jordan-St. Lawrence aquitard (Runkel and others, 2014) internally contains discrete intervals with bedding-parallel fracture networks or coarse-clastic interbeds that have moderate to high horizontal conductivity even in deep bedrock conditions (Runkel and others, 2006b). In shallow bedrock conditions, many springs emanate through macropores in the units classified herein as aquitards, and therefore can be a significant source of water to springs by way of fast-flowing conduit networks (Green and others, 2008, 2012), just as aquifers are.

Classification of aquifers and aquitards in shallow bedrock conditions is especially difficult because of the abundance of macropores and the limited number of studies conducted. 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 can be expected to be highly variable.

The unconsolidated sediment on top of bedrock in southeastern Minnesota is divided into aquifer and aquitard units: sand and gravel is classified as an aquifer and sediment with significant silt and clay is classified as an aquitard. Conductivity in glacial and non-glacial stream deposits range from 10^{-1} feet per

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day to a few thousand feet per day. Glacial till in the region is a diamicton with a silty, clayey matrix texture and ranges in conductivity from about 10^{-1} feet per day to 10^{-6} feet per day, even with macropores (Tipping and others, 2010).

Surface to groundwater flow

Flow in the bedrock-dominated landscape of southeastern Minnesota is characterized by a large volume of water that moves rapidly through bedrock macropores that directly connect groundwater to surface water. The 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 and others, 2011).

Macropore-dominated flow, including turbulent flow through conduits, is not limited to carbonate rock; it also is present in siliciclastic bedrock (e.g., Runkel and others, 2003, 2006a; Swanson and others, 2006; Green and others, 2012). Siliciclastic rock can have sufficiently well-developed macropore systems to cause stream sinks and rapid transport of the losing water to individual spring discharge points that have been described as karst conduit flow (Green and others, 2012). However, the proportional volume of flow through individual conduits versus matrix blocks is likely to be lower than in karstic carbonate rock, reflecting narrower, more poorly connected macropores, and relatively high matrix porosity and permeability.

Groundwater age

Aquitards also influence flow paths, rate 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) across southeastern Minnesota has helped quantify the impacts of aquitards on the flow system (Zhang and Kanivetsky, 1996; Campion, 1997, 2002; Berg, 2003; Petersen, 2005). Results indicate that where the uppermost bedrock aquitard is buried by more than 50 feet of rock, vertical recharge is limited. This produces groundwater bodies that are stratified in age across extensive, mappable areas (Figures 6 and 7).

Uppermost bedrock groundwater commonly contains constituents such as chloride and nitrate indicating human impact and recharge in the past few decades through shallow, well-connected bedrock macropores. This water is classified as recent.

Deeply buried aquitards that are not significantly breached by interconnected vertical fractures or erosional windows separate the 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 (some or no anthropogenic constituents, namely tritium, a fallout radionuclide) and part of a flow system that is of more regional extent. Successively lower aquitards can produce additional age-stratified water bodies, commonly culminating with water that is at least several thousands of years old (Figure 6).

How water travels through the layered succession of fractured bedrock aquifers and aquitards in two local settings is representative of much of the bedrock-dominated landscape of southeastern Minnesota (Figures 4, 6 and 7). Across the Upper Carbonate and Prairie du Chien plateaus the combination of a thin, patchy cover of unconsolidated sediment, a well-developed, uppermost-bedrock fracture network leads to rapid recharge from the land surface to the bedrock water table. Downward flow is retarded where the uppermost bedrock aquitard is relatively deeply buried. This leads to the greatest volume of water travelling horizontally across the top of the aquitard rather than vertically through it, and discharging along valley walls.

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Relatively rapid recharge of recent water to deeper aquifers occurs where aquitards lose their vertical integrity. This includes where they are cut by buried bedrock valleys and anywhere they are breached by well-connected vertical fractures where the aquitards are less deeply buried by younger bedrock in shallow bedrock conditions (Figure 6).

Groundwater-to-surface-water flow paths (baseflow)

The uppermost bedrock groundwater that travels laterally across the top of an aquitard will discharge at escarpments and into valleys (Figures 4, 6, 7). This discharge forms the baseflow to streams and may emerge in a seep, spring, or in the shallow subsurface through unconsolidated sediment. Some baseflow will be dominated by recently recharged water within a relatively localized area, whereas other settings are more likely to have a significant component of older water sourced from more extensive regional flow systems.

If valley incision is sufficiently deep, multiple aquifers and aquitards may be breached, and the baseflow can be a mixture of both discharge from uppermost bedrock aquifers and more deeply sourced, regional water. This is particularly common in valleys on the Prairie du Chien Plateau where the Jordan aquifer has a potentiometric level that exceeds the elevation in the valleys (Figure 7).

In western Fillmore County flow to springs in the upper reaches of tributary valleys to the Root River system along the outer margins of the Upper Carbonate Plateau is dominated by locally sourced water recharged relatively recently into the Galena aquifer (Figure 9). The springsheds near the town of Fountain are two such examples (Figure 9, 10). Farther west on the plateau, near the eroded edge of the Maquoketa–Dubuque aquitard, flow to springs deep in the tributary valleys in the Root River watershed has a component of locally derived water. However, there is also contribution from deeper, more regionally sourced aquifers that are capped by aquitards. Similarly, the Prairie du Chien Plateau has stream reaches in which the source of flow to springs is dominated by locally derived, relatively recent recharge, and other stream reaches where the flow to springs includes a significant component of more deeply derived, older, regional water.

Hydrostratigraphic observations by physiographic region

The surface and groundwater paths 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 occurs where the Cummingsville Formation is present along the upper part of the escarpment and separates the Upper Carbonate Plateau from the Prairie du Chien Plateau (Figures 5 and 6). 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 position in the landscape. This phenomenon is referred to as the "Decorah Edge" (Delin, 1991).

Particularly extensive and well-integrated fracture networks accommodating significant horizontal flow are also present along the lower Spillville and 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 and others, 2003, 2006a, 2006b; Tipping and others, 2001, 2006; Tipping, 2002; Luhmann and others, 2011; Green and others, 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.

In this type of anisotropic, fracture-dominated system in the bedrock-dominated landscape there may be multiple paths for water to move from the surface into the ground and back to the surface again (Figure

4). 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 (Figures 4 and 6). Water lost to the underlying Galena Group aquifer system may emerge as discharge along the Cummingsville-Glenwood escarpment farther to the east, where it recharges the uppermost bedrock along the inner part of the Prairie du Chien Plateau. Laterally flowing water within the Prairie du Chien Group may emerge along deeply incised valleys closer to the Mississippi River. The Cambrian siliciclastic-dominated uppermost bedrock in these valleys is also a macropore-dominated system of alternating aquifers and fractured aquitards in which sinking and emergence of water is common. Water preferentially sinks where valleys intersect the uppermost St. Lawrence Formation and emerges in the lower St. Lawrence and underlying Tunnel City Group (Green and others, 2008, 2012). Surface-to-ground-to-surface paths 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.

Groundwater flow direction

A regional groundwater divide extends from the southwestern corner of Fillmore County northwest to central Rice County (Delin and Woodward, 1984) and separates generally northeastward flow from southwestward flow (Figure 8A). At a more local scale, flow in dissected bedrock settings may be significantly different owing to a number of factors, such as the influence of local topography (Figure 8B, C). For example, in dissected portions of the Upper Carbonate Plateau, the flow of the uppermost bedrock aquifer is towards bedrock valleys with groundwater divides approximately midway between valleys (Figure 8B). Water table aquifers may therefore have boundaries that generally approximate surface watershed boundaries in this setting.

Methods

The approaches described here have been developed specifically for the layered, Paleozoic sedimentary bedrock of southeastern Minnesota. They have not been tested in other settings.

Surface-watershed delineation

Surface water basins were mapped topographically where they contribute surface runoff to a sinkhole or stream sink. The upstream boundaries of surface water basins were identified using digital elevation models (DEM) created with Light Detection and Ranging (LiDAR) data or topographic maps.

Locating karst features

The location of many of the mapped springs, sinkholes, and sinking streams in southeastern Minnesota are stored by the Minnesota Geological Survey (MGS) in a database that describes their location and additional attributes (Minnesota Karst Features Database, KFDB). Although not an exhaustive inventory, it provided a useful starting point that was verified and augmented with primary and interpreted data sets in a Geographic Information Systems (GIS) environment.

Primary resources used to verify the locations of features listed in the KFDB and to locate unmapped karst features included:

- County Geologic Atlases published by the Minnesota Geological Survey (MGS) and the Minnesota DNR (Alexander and others, 1996; Berg and Bradt, 2003; Green and others, 2002; Green and others, 1996; Mossler, 1995; Mossler, 1984; Petersen, 2005; Tipping, 2001).

- The County Well Index (CWI) for well locations, interpreted stratigraphy, and additional information regarding water chemistry (Minnesota Department of Health, 2010).

- A hydrography coverage (Minnesota Department of Natural Resources, 2014a) including trout stream locations (Minnesota Department of Natural Resources, 2014b).

- One-meter black and white digital aerial imagery (U.S. Department of Agriculture, 2010).

- Reflected infrared aerial photography, 50cm resolution Color Infrared Imagery (Minnesota Department of Natural Resources, 2011).

- U.S. Geological Survey 1:24,000-scale topographic maps, (U.S. Geological Survey and Minnesota DNR, 2006)

- High resolution LiDAR-based digital elevation models (Minnesota Department of Natural Resources, 2005-2014).

Potential karst features were recorded and landowners contacted to request a site visit to field-verify the features.

Field characterization

The stratigraphic position of a spring is essential information for assessing its characteristics and vulnerability. At the springs we noted bedrock outcrops. These observations were compared to nearby well logs, spring elevation data extracted from LiDAR surfaces, and with existing bedrock maps. We described the morphology of the spring and whether it was a discrete location or a series of points. We noted if it discharged directly from bedrock, was a boiling sand spring, or if it was flowing out of the base of a stream bank or through bedrock rubble.

We measured or recorded temperature and specific conductivity using a calibrated meter. Many springs have highly variable temperature and conductivity, making data collected from continuous data loggers more informative. We measured or estimated the spring's discharge with the intent to characterize base-flow conditions where possible.

Dye tracing

Dyes were selected that travel at approximately the same velocity as water and are not lost to chemical or physical processes (conservative tracers). These were introduced to the groundwater flow system to determine flow direction and rate. Specific traces were designed to establish connections between recharge points (sinkholes and stream sinks) and discharge points (springs). Multiple traces were used to delineate the boundaries of springsheds for the shallowest part of the bedrock-groundwater system.

The fluorescent dyes used in these investigations were readily obtainable, non-toxic, simple to analyze, detectable at very low concentrations, and not naturally present in the groundwater. We typically used eosine (Chemical Abstract Service [CAS] 17372-87-1), rhodamine WT (CAS 37299-86-8), and/or uranine C (CAS 518-47-8). The use of multiple dyes for groundwater-springshed mapping increased the speed and efficiency of the field work. Traces generally used between 200 and 1200 grams of dye. The dyes were introduced into sinking stream reaches of surface waters, snow melt running into sinkholes, and into dry sinkholes. Dry sinkholes were flushed with water from a tanker truck (typically 500–2000 gallons) during the introduction of dye.

Dye traces were conducted in two modes: 1) with passive charcoal detectors or 2) with direct water samples. Passive charcoal detectors (often called "bugs") are integrating dye detectors. They are small permeable envelopes that contain activated charcoal that are anchored in a stream. The charcoal in the envelopes has a strong affinity for the organic dyes and will adsorb dye that flows through the packet. After exposure to the water, the dye was removed in the lab and measured.

Charcoal packets were used as a qualitative way of determining if a dye had passed a specific monitoring point. The detectors were deployed several weeks prior to introducing dye to determine background levels of fluorescence in the groundwater. After the dye was introduced the packets were changed periodically until the trace was terminated. The time resolution of the dye arrival at the monitored point was limited by how long the charcoal packets were left in the water before being analyzed, typically several days to a few weeks.

In direct-water-sample dye traces water was collected from the springs, streams or wells at time intervals ranging from a days to minutes using automatic water samplers programmed to collect specific volumes of water at specific time intervals. Analysis of each water sample gave a quantitative measure of the dye concentration when the water sample revealing the dye concentration through time (break through curve) (Figure 15). Break through curves are typically asymmetric; the dye concentration rises rapidly from background to a peak and then falls slowly to background. Break through curves also provide information about the maximum concentration and dye dispersal, allowing a better understanding of the groundwater flow system.

Passive dye detectors and water samples were sent to the University of Minnesota, Department of Earth Sciences for analysis. The charcoal detectors were analyzed by placing about 1 gram (dry weight) activated carbon into a disposable test tube and the adsorbed dye was extracted with a mixture of water, sodium hydroxide and isopropanol. The remaining carbon was stored for later use. The solution was analyzed using a Shimadzu RF5000 scanning spectrofluorophotometer that uses a synchronous scan mode which varies the peak emission and excitation wavelengths. Fluorescent dyes absorb light and remit it at longer wavelengths, the peak-emission wavelength, which is different for each dye.

Spectrofluorophotometers allow dyes to be detected below the part-per-billion level, far below visual levels. The spectrofluorophotometer supplies light at the peak-excitation wavelength and then measures the intensity of the light at the peak-emission wavelength (Alexander, 2005).

The resultant dye peaks were analyzed with PeakFit, a non-linear curve-fitting software. All three dyes were analyzed at the same time and distinguished from naturally occurring fluorescent materials. Some water samples were analyzed in the field using a scanning spectrofluorophotometer and a small portion of the water sample; the rest was saved for additional analysis.

Results

Mapping and approximating springsheds

In southeastern Minnesota the groundwater springsheds were mapped in areas where porous and permeable bedrock, limestone, dolostone, and coarse sandstone are the uppermost bedrock and are overlain by less than 50 feet of surficial sediments. Areas where the Galena and Prairie du Chien are first bedrock are characterized by the near absence of surface water flow, except during and immediately after the largest recharge events (heavy rains and major snow melts). Their groundwater springsheds may have sinkholes and losing or sinking streams but many do not have obvious surface karst features. Recharge areas without evident surface karst features can form valleys that lack a permanent surface stream. Dry valleys are common on carbonate rocks with good primary permeability and occur on other permeable rocks such as sandstone. Even where abundant surface karst features are present most of the groundwater recharge is typically through distributed recharge through soil macropores and infiltration.

Sinkholes and stream sieves or sinks may empty directly into the major conduits. Distributed recharge may recharge to the matrix storage or into the fractures, joints and bedding planes connecting the matrix and the conduits. During dry periods the pressure heads in the conduits may drop below those in the matrix allowing the matrix to drain through fractures, joints and bedding planes to the conduits that support the base flow to springs. During major recharge high flow events, the pressure heads in the conduits may quickly rise far above the pressure heads in the matrix and the matrix is recharged from the conduits through fractures, joints and bedding planes.

Where a surface watershed is underlain by low-permeability sediment or is sloping and significant surface runoff occurs, surface flow may form perennial or ephemeral surface streams that flow into the groundwater springsheds. Where that surface runoff reaches the groundwater portion of the springshed it may sink in stream sieves (a reach of stream that may extend for several hundred feet over which water sinks) or stream sinks (discrete points where a stream enters the ground). During extreme dry periods the surface water flow may cease entirely.

Regional springshed flow was found beneath one or more aquitards. Water may have entered the system by way of continued downward transport of some fraction of the recharge that infiltrated beneath the surface water springshed, or it may have come from regional groundwater recharge far beyond the surface water springsheds. It has had a significantly longer underground residence time and is more significant in springs that drain from the deeper parts of the hydrostratigraphic section in the incised valleys along the Mississippi River valley. These regional springshed components may, in principle, be mapped by identifying flow divides in detailed potentiometric maps of the deeper aquifers. However, sufficiently detailed potentiometric maps are often not available.

Example of springshed estimation for the St. Lawrence-Tunnel City aquifers

The springshed mapping and spring characterization work that was done on these aquifers over the past seven years has altered our understanding of groundwater flow in these geologic units in the dissected landscape of the Prairie du Chien plateau. Specifically, we have documented that water sank at discrete points or in losing reaches of streams into the upper St. Lawrence in valley settings (Green and others 2008; Green and others, 2012). That water then moved rapidly to St. Lawrence and Tunnel City springs. This consistent pattern made dye tracing a reliable method for estimating the shallow flow regimes. Results showed that surface-water basins up to several thousand acres fed a single stream sink in a valley (Green and others, 2008; Green and others 2012), sending water at a rate of hundreds to over a thousand feet per day to a spring. Also, streams that did not sink lost flow more gradually to the St. Lawrence and

Tunnel City Group. This water then emerged from the units at springs located along lower stratigraphic intervals.

Large precipitation events also had no visible impact on spring turbidity. The flow increase and stable turbidity were interpreted to mean that water was infiltrating the overlying Jordan Sandstone on the hillslopes and uplands above the springs and then moved into the underlying St. Lawrence and Tunnel City Group. This increased the flow by raising the potentiometric surface in these units with a concomitant increase in flow. There was also a strong regional flow component to these springs where valleys dissect the formations and served as regional groundwater discharge points. The regional flow component was evidenced through volumetric gain in flow and reduced concentrations of nitrate at these springs. The nitrate-poor water has been shown to be older water that has not been influenced by activities on the land surface (Runkel and others, 2013). Discharge of springs that received flow from sinking streams exceeded the discharge in the sinking stream.

In a hypothetical example, a St. Lawrence Formation -Tunnel City Group spring discharges from the base of a large bedrock promontory (Figure 22). The adjacent valleys were included in the estimated catchment area because dye-tracing work completed in this hydrostratigraphic group showed that water sank in valleys and flowed to St. Lawrence Formation-Tunnel City Group springs. The groundwater springshed was extended into the upland to account for groundwater flow from the units there. Several other springs emanated from the St. Lawrence Formation-Tunnel City Group. The estimation process took into account the fact that those springs also had groundwater springsheds. The St. Lawrence and Tunnel City bedrock layers extend many miles to the west. The easterly regional flow brings an unquantified flux of old water into southeastern Minnesota.

Potentiometric-surface mapping

The accuracy of mapping springsheds using potentiometric surfaces is limited by the availability of water-level information. Drilling multiple holes to acquire more water level measurements would improve mapping but is costly and time-consuming. Inferred bulk-flow directions may differ significantly from local flow directions revealed through dye traces. This difference has been demonstrated in the Upper Carbonate Plateau in western Fillmore County and is likely caused by a wide range of potentiometric levels in bedrock wells due to a stacked series of aquifers and aquitards (Figure 3). Vertical head differences may be large within even the upper few tens- of-feet of saturated bedrock due to the presence of regional (Figure 3) as well as local aquitards (Runkel and others, 2003, 2006a, 2013, 2014, and references within). As a result, without careful analysis of hydrostratigraphic context, potentiometric maps may be based on water-level elevations at individual control points (wells) that in reality represent multiple, hydraulically separated aquifers that may differ from one another in flow directions (Meyer and others, 2008, 2014; Delta Environmental, 1995, 1996). The accuracy of inferred groundwater flow directions will be compromised for potentiometric maps using such data. Hydrostratigraphic context of individual wells must therefore be taken into careful consideration in producing potentiometric maps (Runkel and others, 2003, 2006a; Meyer and others, 2008, 2014).

Dye tracing

Dye traces were effective for mapping the groundwater portions of the springsheds of springs draining the Upper Carbonate Plateau in southeastern Mower County (Green and others, 2002), western Fillmore County (Alexander and Lively, 1995), and southern Olmstead County. Due to the complexity of the flow systems, dye traces in the Prairie du Chien had a mixed record of success (Green and Alexander, 2011). Dye traces have been used very successfully to delineate the local groundwater springsheds for St. Lawrence springs (Green and others, 2012).

Each successful dye trace demonstrated an underground connection between the dye input point and the spring in which the dye was detected. As additional traces reached a given spring the resulting dye trace vectors better defined the groundwater springshed. Dye traces were conducted further and further away from a given spring until the dye was detected in a different spring. Sometimes when the dye input point was on the boundary between two or more springsheds the dye went to two or more springs in different directions. Such traces defined the boundaries between two or more springsheds. With a sufficient number of traces the entire surface area can be apportioned to contiguous springsheds.

Dye trace vectors were drawn as curvilinear, converging, down-flow vectors. The convergent pattern of the underground flow was evident in those cases where the conduits carrying the water were mapped in cave streams.

Influence of geologic structure

Ongoing research has indicated that geologic structure can have a significant impact on flow directions, specifically the gentle dip of beds of the Hollandale Embayment. Maps of geologic structure thereby have the potential to serve as a predictive tool for estimating springsheds. This was most applicable to water-table-dominated aquifers with thin saturated thickness overlying aquitards of relatively high integrity (very low, field-scale, vertical hydraulic conductivity) where flow direction is controlled largely by gravity. Dye-trace investigations in western Fillmore County delineated springshed boundaries and local flow directions in uppermost bedrock aquifers across a significant part of the Upper Carbonate Plateau (Figure 9) (Alexander and others, 1996). Springshed flow was preferentially directed down structural dip, springshed divides corresponded to anticlinal crests, and water emerged as springs along synclinal axes (Figures 9 and 10). Several of these springsheds occurred near the outer margins of the Upper Carbonate Plateau, where the Galena aquifer is high on ridges forming a karst interfluve separated by deeply entrenched bedrock valleys. This creates water-table dominated aquifers with thin saturated thickness near the lower part of the Galena Group aquifer system (Alexander and others, 2008). Flow direction in such a setting is controlled largely by gravity, with most water flowing down dip on top of the underlying Cummingsville-Glenwood aquitard (Figure 10).

Other springsheds did not appear to be strongly controlled by geologic structure. In these, flow was commonly up structural dip, springshed boundaries did not correspond closely to anticlinal axes, nor did spring locations appear to be preferentially located in synclines (Figure 9). Many of these springsheds were 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 supplies water to the springs. This leads to conditions where the configuration of the water table and hydrostatic heads of individual aquifers have a greater impact on flow direction than dip of the aquitards.

Discussion

The dye traces and spring field investigations that have been completed targeted specific bedrock units. Each unit has its distinctive hydrologic properties.

Bedrock unit properties and charactaristics

This section describes hydrologic properties, characteristics of lithostratigraphic units, and spring vulnerability for units that are present across southeastern Minnesota. This information is summarized in Table 1. The units are listed from youngest (Devonian) to oldest (Cambrian).

Strati-graphic Unit	Age	Rock Type	Conduit Characteristics	Spring Disharge Pattern	Springshed Karst Features	Dye Trace	Breakthrough Response Curve	Groundwater Velocity
Lithograph City Formation	Devonian	Limestone, dolomite, and minor shale	Conduit flow through solution-enlarged joints and fractures	Highly variable, with large changes in level, temperature, and turbidity	Sinkholes, springs, solution-enlarged joints and fractures. Interconnected network of macro scale pores.	Multiple traces in LeRoy, MN area of Mower County	Rapid with recovery tails lasting up to 12 months	1–3 miles/day
Little Cedar Formation	Devonian	Limestone, dolomitic limestone, dolomite, and shale	Conduit flow, integrated system of sub-surface conduits and sinkholes	Highly variable, with large changes in level, temperature, and turbidity	Sinkholes, springs, and solution voids	None	N/A	Not measured
Spillville Formation–Galena Group	Devonian-Ordovician	Dolomite and minor shale	Conduit flow through solution-enlarged joints and fractures. Where near the land surface, caves commonly develop in the Dubuque & Stewartville Formations and in the middle to lower Cummingsville Formation	Highly variable, with large changes in level, temperature, and turbidity	Sinkholes, springs, solution-enlarged joints and fractures. Wells intersecting the network of solution-enlarged voids have very high yields.	Numerous (200+) traces in Fillmore County, MN	Rapid with short recovery tails ranging from 1–2 weeks	1–3 miles/day
St. Peter Sandstone – Prairie du Chien Group	Ordovician	The St. Peter is primarily coarse clastic, with fine clastic beds in basal unit. The Prairie du Chien Group is predominately dolomite with fine and coarse clastic interbeds	The St. Peter is dominated by flow through coarse clastic interbeds but has been documented to exhibit large scale fractures. Flow through the Prairie du Chien is through solution-enlarged joints and fractures and through matrix rock. A regional scale integrated conduit system within the unit lies at the contact of the Shakopee and Oneota Formations	Discharge from the St. Peter primarily occurs along seepage faces in the basal member. Discharge from the Prairie du Chien is variable with large changes in level, temperature, and turbidity	Sinkholes, springs, solution-enlarged joints and fractures predominately located in the Shakopee Member of the Prairie du Chien Formation. Interconnected network of macro-scale pores and regionally significant high conductivity zone.	Approx. 15 across SE MN	Variable with three general patterns: 1) rapid with recovery tails lasting up to 12 months; 2) slow recovery with long recovery tails, and 3) no recovery. In traces with no dye recovery the dye is believed to have moved vertically downward into the Jordan aquifer.	Miles/day to miles/week in well-connected networks to miles/year in less connected networks for those traces that were recovered.
Jordan Sandstone	Cambrian	Coarse clastic and fine clastic components	Primarily intergranular with well-developed secondary conduit flow through a system of fractures and systematic jointing	Only slight and muted changes to precipitation and runoff events	Not present	N/A	N/A	Pump tests have shown velocities of tens of feet per day in matrix rock to hundreds of feet per day in wells connected to macropores.

St. Lawrence Formation–Tunnel City Group	Cambrian	St. Lawrence is predominately carbonate rock in its lower section, and fine clastic its upper section. Tunnel City is predominately fine clastic, with subordinate beds of carbonate strata	Flow through an integrated system of sub-surface fractures and conduits and through porous media	Highly variable, with large changes in discharge.	Sinking stream points and diffuse losing stream reaches, springs.	15 dye traces primarily in Houston and Winona Counties	Rapid with recovery with recession limbs lasting months to years	300–1500 feet/day

Table 1. Bedrock unit properties and characteristics in southeastern Minnesota.

Devonian Lithograph City Formation

This unit subcrops near the city of LeRoy in Mower County, Minnesota. Spring and springshed characterization was completed by DNR hydrologists working on the Mower County Geologic Atlas karst plate (Green and others, 2002). Dye traces have been conducted for all of the major springs in the area (Figure 12). Based on the level of detail of the mapping work, it is highly likely that all of the significant springs have been located.

Hydrologic

Groundwater flow through this unit is dominantly through macropores, many with substantial solution enlargement. The low permeability of the rock matrix relative to the formation of macropores results in negligible flow through the matrix. This formation exhibits varying degrees of karst-feature development and density. Multiple dye-tracing investigations conducted here demonstrated breakthrough travel velocities of 1 to 3 miles per day (Figure 11), followed by a steep rise to peak concentration over a period of hours, followed by a tailing off of dye concentrations for up to 12 months (Green and others, 1997).

Spring characteristics

Discharge varies widely with fluctuations following precipitation events, indicating that a conduit system connects springs to surface karst features such as sinkholes and sinking streams. Many of these springs discharge directly from bedrock or bedrock rubble. Several major springs occur as sand boils in the bed of the Upper Iowa River near LeRoy. The groundwater springsheds typically have less than 50 feet of cover over bedrock and commonly have sinkholes, a good indicator of direct recharge for surface water and for conduit flow in the subsurface. Recharge water also moves through the thin sediment cover. The landscape between the sinkholes and springs may lack surficial expression of karst but high velocity conduit flow is present in the subsurface.

Spring vulnerability

Springs are vulnerable to groundwater flow diversion by quarrying of rock. This can occur by physical disruption of the conduits and by dewatering a quarry to provide a dry mining environment. Because the thin sediment cover provides little filtering or buffering, the quality and chemistry of springs can be severely impacted by point source pollution from discrete chemical releases and nonpoint source pollution. High-volume pumping from wells can decrease groundwater flow to springs and has been proven to dewater one significant spring on the Upper Iowa River (Green and others, 2003).

Devonian Little Cedar Formation

This unit is found in shallow conditions along the Cedar River and lower Otter Creek in Mower County. Extensive spring mapping and chemistry work has been completed in this area (Green and others, 2002). No dye-tracing work has been done and there are few data on spring flow.

Hydrologic

Groundwater flow through this unit is dominated by flow through macropores that are solution-enlarged joints and fractures. The formation has varying degrees of surface-karst-feature development and density.

Spring and springshed characteristics

Discharge varies widely following snow melt and precipitation events indicating that the springs are connected through conduit systems to the surficial karst features such as sinkholes and losing streams. Groundwater chemistry and age dating suggest there is a strong regional flow component (Figure 14) (Green and others, 2002). These springs commonly discharge from the toe of river and stream banks and in the bed of the Cedar River. The groundwater springsheds typically have less than 50 feet of unconsolidated cover over bedrock and exhibit sinkholes.

Spring vulnerability

The quality and chemistry of springs can be severely impacted by point-source pollution from discrete chemical releases and nonpoint-source pollution because the thin sediment cover provides very little attenuation of contaminants. Springs that discharge from these springsheds are very vulnerable to groundwater flow diversion by quarrying of rock. High-volume pumping from wells can decrease groundwater flow to springs.

Devonian Spillville Formation and Ordovician Galena Group

This unit is found in shallow conditions from western Fillmore County through western Olmsted County, northeastern Dodge County and western Goodhue County.

Hydrologic

The Stewartville and Prosser formations of the Galena Group exhibit the densest sinkhole development of all formations in Minnesota. Groundwater flow through these units is dominantly through macropores such as conduits, solution-enlarged joints, and fractures. The low permeability of the rock matrix provides negligible flow.

Multiple dye-tracing investigations have demonstrated breakthrough travel velocities of 1 to 3 miles per day (Green and others, 2005). The initial dye breakthrough is followed by a steep rise over a period of hours to peak concentration followed by dye concentrations returning to near-background levels in 1 to 2 weeks.

Groundwater flow velocities can be very high and the conduit systems can extend for miles into the upland. The longest connection documented by dye tracing is in Fillmore County (Alexander and others, 1996). Dye introduced into a stream sink in the York Blind Valley was recovered 10.5 miles to the southeast at Odessa Spring on the Upper Iowa River. Dye introduced into the Galena limestone near Forestville State Park in Fillmore County (Figure 16) traveled 1600 feet in 6 hours.

Tracer tests have demonstrated that sinkholes and stream sinks on the boundaries of multiple groundwater springsheds are dynamic and their flow direction changes with precipitation trends. Groundwater flow paths from sinkholes and stream sinks to springs in the Galena often cross surface watershed boundaries.

Spring and springshed characteristics

Discharge varies widely in these springs with flows increasing by a factor of 10 or more from baseflow to flood-flow conditions. Temperature, conductivity and turbidity also change significantly after runoff events. In springs connected to sinkholes, the temperature has been shown to drop from 48°F to 37°F overnight during snowmelt runoff. Springs that directly connect to conduits become visibly turbid during runoff events (Figure 16).

Many of these springs discharge directly from bedrock or bedrock rubble. In the Galena Group, many springs are found in the upper Cummingsville Formation where they are fed by the overlying limestone formations. The regional flow contribution to springs is substantial in settings near the eroded Maquoketa–Dubuque edge (Runkel and others, 2013). Major springs are often found at steepheads (steep-sided, generally short valley in karst terrain that has an abrupt upstream termination); other typical landscape positions include sideslopes, head slopes and toe slopes.

The springsheds vary greatly in size ranging from several hundred acres to many square miles (Green and others, 2005) and have thin cover over bedrock and commonly have sinkholes. Stream sinks and sinkholes serve as direct recharge points for surface water to enter the limestone aquifer and are good indicators of conduit flow in the subsurface. Recharge water also infiltrates through the sediment cover and into the carbonate bedrock. Work in Iowa (Hallberg and others, 1984) has demonstrated that 95 percent of the nitrates reach the first karst aquifer by this means. The landscape between the sinkholes and stream sinks and the springs they are connected to may lack surface-karst features but is characterized by high velocity conduit flow in the subsurface.

Spring vulnerability

Springs that discharge from these springsheds are vulnerable to groundwater flow diversion by quarrying of rock by and by dewatering to provide a dry mining environment. Since these springs are often connected to the surface by sinkholes and stream sinks, they are very vulnerable to land-surface activities. Many of these springs have elevated nitrate levels and turn turbid after precipitation events, illustrating their connection to the land surface. Agricultural nonpoint-source and point-source pollution from discrete chemical releases can severely impact the quality and chemistry of springs. The thin soils provide very little filtering or buffering making the springshed area vulnerable to contamination events which can quickly enter the aquifer.

Ordovician St. Peter Sandstone and Shakopee Formation, Oneota Dolomite of the Ordovician Prairie du Chien Group

These units are found in shallow conditions in Houston County, Winona County, eastern Fillmore County, eastern and northern Olmsted County, Wabasha County, Goodhue County and Dakota County.

Hydrologic

Solution enlargement of macropores is common in the Prairie du Chien Group. Significant flow can also be accommodated through the coarse-clastic matrix that dominates the St. Peter Sandstone, and as a subordinate component in the Prairie du Chien Group. The ratio of conduit to matrix flow varies between the three formations. Surface-karst-feature development and density vary. Multiple dye traces, including seven that were conducted as part of this study, have demonstrated that there are three flow regimes (Green and others, 2011): 1) breakthrough travel velocities of miles per day or week; 2) one to two miles per year, and 3) indeterminate. The indeterminate (no tracer recovered) tracing work is likely explained by dye-laden water moving downward through the Prairie du Chien into the Jordan sandstone. This phenomenon doesn't occur uniformly because where the Prairie du Chien is not dissected, the lower part of the Oneota Dolomite appears to act as an aquitard separating

the Shakopee aquifer from the underlying Jordan sandstone. Where the Shakopee is the first bedrock aquifer, there is a higher density of surface karst features than where the Oneota aquitard is first bedrock, with the greatest density corresponding to where two major bedding-plane parallel conduit systems are near the land surface: 1) the St. Peter Sandstone–Shakopee contact (Figures 1 and 18) the Shakopee–Oneota contact (Dalgleish and Alexander, 1984; Tipping and others, 2001).

Spring and springshed characteristics

Discharge varies widely in the Prairie du Chien springs. Flows can increase by at least a factor of ten from baseflow to flood-flow conditions. Temperature, conductivity and turbidity can also change significantly after runoff events with breakthrough travel velocities of miles per day or week (Alexander and others, 2011). Major springs are on sideslopes, head slopes and toe slopes. Many of these springs discharge directly from bedrock or bedrock rubble. The regional groundwater flow contribution is especially common close to the "Decorah Edge", where protected, older water flowing through the St. Peter and Prairie du Chien aquifers flows from beneath the Decorah towards the incised valleys in the Prairie du Chien (Runkel and others, 2013).

The springsheds vary greatly in size ranging from several hundred acres to multiple square miles. Recharge water infiltrates through the sediment which is commonly less than 50 feet into the bedrock. Sinkholes are common but there are large areas with only isolated stream sinks and dry valleys (Tipping, 2002). The St. Peter Sandstone has limited sinkhole development but often has dry valleys. In the vicinity of Spring Grove in Houston County, springs emanating from the Decorah Shale flow onto the St. Peter Sandstone and commonly sink. Stream sinks and sinkholes directly recharge the aquifer. The Prairie du Chien Group is largely dewatered near its edges where valleys have cut through it into the underlying Jordan Sandstone.

Spring vulnerability

Springs that are connected to the surface by sinkholes and stream sinks are very susceptible to land-surface activities. Thin sediment cover provides little filtering or buffering capacity making the entire groundwater springshed vulnerable to contamination. The quality and chemistry of springs is impacted by agricultural nonpoint-source pollution in the catchment area from broad application of agricultural chemicals, and runoff and point-source pollution from discrete chemical releases. The zone of particularly high conductivity approximating the Shakopee-Oneota contact is especially sensitive. Four catastrophic failures of three wastewater treatment lagoons occurred where this zone lay directly beneath a thin cover of sediment (Alexander and Book, 1984; Jannik, 1992; Alexander and others, 1993). Springs that discharge from these springsheds are also vulnerable to groundwater flow diversion by quarrying of rock and by dewatering to provide a dry mining environment.

Cambrian Jordan Sandstone

This units subcrops in the deeply dissected blufflands of southeastern Minnesota. There are limited data and observations for Jordan Sandstone springs. Temperature monitoring has shown that Jordan springs do not fluctuate in response to precipitation events or seasonal temperature changes (Luhmann and others, 2011). This indicates that they are not directly connected to the surface by sinkholes or stream sinks. Jordan springs are still be susceptible to chemical constituents moving through the sediment cover, would be influenced by high-capacity pumping, and sensitive to flow disruption due to quarrying of bedrock.

These springsheds are found in the deeply dissected blufflands of southeast Minnesota.

Hydrologic

Groundwater flow through these units is through macropores that include modified bedding-parallel fractures, nonsystematic vertical fractures, and the bedrock matrix (Runkel and others, 2003). Dye tracing has shown that, while not exhibiting all of the characteristics of traditional carbonate karst, the St. Lawrence Formation and the Reno Member of the Tunnel City Group have a karst-conduit-flow component. Multiple dye-tracing investigations in the St. Lawrence Formation and Tunnel City Group have demonstrated breakthrough travel velocities of 300 to 1500 feet per day (Green and others 2008, 2012) (Figures 18 and 19). Recessional limbs for dye traces show that recovery lasts months to years. Dye was still being detected in the springs three years after the first St. Lawrence dye trace in southern Winona County.

Spring and springshed characteristics

Streams commonly sink into the upper St. Lawrence in valleys but the locations often move up and down the valley depending on stream stage. In these settings, the streams are a series of pools and riffles with the pools functioning as the stream sinks. In locations where the streams flow along bedrock exposures, the stream sinks are discrete points. There are also streams that lose flow but do not totally disappear as they cross the upper St. Lawrence. Surface-water springsheds that are thousands of acres may drain into one set of stream sinks in a valley. Dye tracing has demonstrated that most of the groundwater springsheds align with surface topography but there are examples where dye traces have crossed surface divides. Multiple springs may be connected to single sinking points of streams in valleys. Through a series of separate investigations (Barry and Green, 2014), springs stratigraphically positioned in the Tunnel City Group have been shown to be connected to sinking points in the St. Lawrence Formation. In four traces, dye introduced into the St. Lawrence was detected at Tunnel City springs.

Discharge varies widely in springs located in these Upper Cambrian formations. Flows can increase by at least a factor of ten from baseflow to flood-flow conditions (Figure 20). Flow calculations, dye dilution, and environmental tracers show that surface water that disappears into stream sinks accounts for only a fraction of the total discharge at these springs. Continuous, high-resolution temperature monitoring of these springs has demonstrated that they have only slight diurnal fluctuation but have temperature signatures that are out-of-phase with the seasons. Water temperatures are warmest in the winter and coolest in the summer (Luhmann, 2011).

Springs of the St. Lawrence Formation and Tunnel City Group are often found at the base of ridges and steep hillsides. Based on this landscape position of these springs it is assumed that there is a hillslope flow component carrying local recharge to these springs. Discharge measurements of selected St. Lawrence and Tunnel City springs have shown that they respond within 24 hours to extreme precipitation events. This response is more rapid than the breakthrough velocities observed in dye traces. St. Lawrence springs emanate from the middle or more commonly lower part of the unit. The Tunnel City has a prominent spring line in the upper one-third of the unit in the Reno Member. Low permeability strata separate that spring line from a lower spring line found in the Birkmose Member.

Spring vulnerability

The large surface-water springsheds that send runoff water into the valleys (Figure 21) where it sinks into the St. Lawrence Formation are very vulnerable to surface activities. The long recovery period

demonstrated in dye-trace curves demonstrate that any contamination entering these aquifers will be present for an extended period. The upland areas of the surface water springsheds commonly have thin sediment cover which provides little buffering of agricultural chemicals. Springs that discharge from these springsheds are vulnerable to groundwater flow diversion by quarrying of rock and by dewatering to provide a dry mining environment. Removal of the overlying Jordan Sandstone could disrupt the groundwater flow paths to springs on a hillside setting, leading to loss of flow or a change in the location of springs.

Conclusions

Southeast Minnesota's many springs provide baseflow to all of its streams and rivers. The flow from those springs comes from precipitation. It reaches the springs by a variety of paths through the groundwater system. Surface water that flows varying distances before sinking can be mapped with watershed mapping tools, most recently LiDAR elevation models. Groundwater recharged by precipitation infiltrating more or less directly to the shallow groundwater flow system can be mapped with dye tracing, hydrogeologic and geomorphic mapping, and continuous water-quality monitoring.

Dye tracing in the Upper Carbonate Plateau and the Prairie du Chien groundwater springsheds has shown that they are heavily influenced by surface topography, geomorphology, local hydrostratigraphy and geologic structure. The well-mapped springsheds under Fountain, Minnesota are examples of springsheds dominated by locally recharged groundwater. St. Lawrence and Tunnel City springs have a significant conduit-flow component that transmits water rapidly from stream sinks to springs. These springs are also influenced by local recharge into the overlying aquifers.

Regional groundwater flow that may have recharged at more distant locations and at much earlier times is the most problematic to map. In principle, high resolution potentiometric maps could be used to map the regional groundwater flow to a specific spring, but such information is rarely available at sufficient accuracy. The St. Lawrence and Tunnel City springs in the deeply incised valleys along the eastern edge of southeast Minnesota, appear to have the largest components of regional groundwater flow. That regional flow is, so far, less impacted by modern anthropogenic pollutants.

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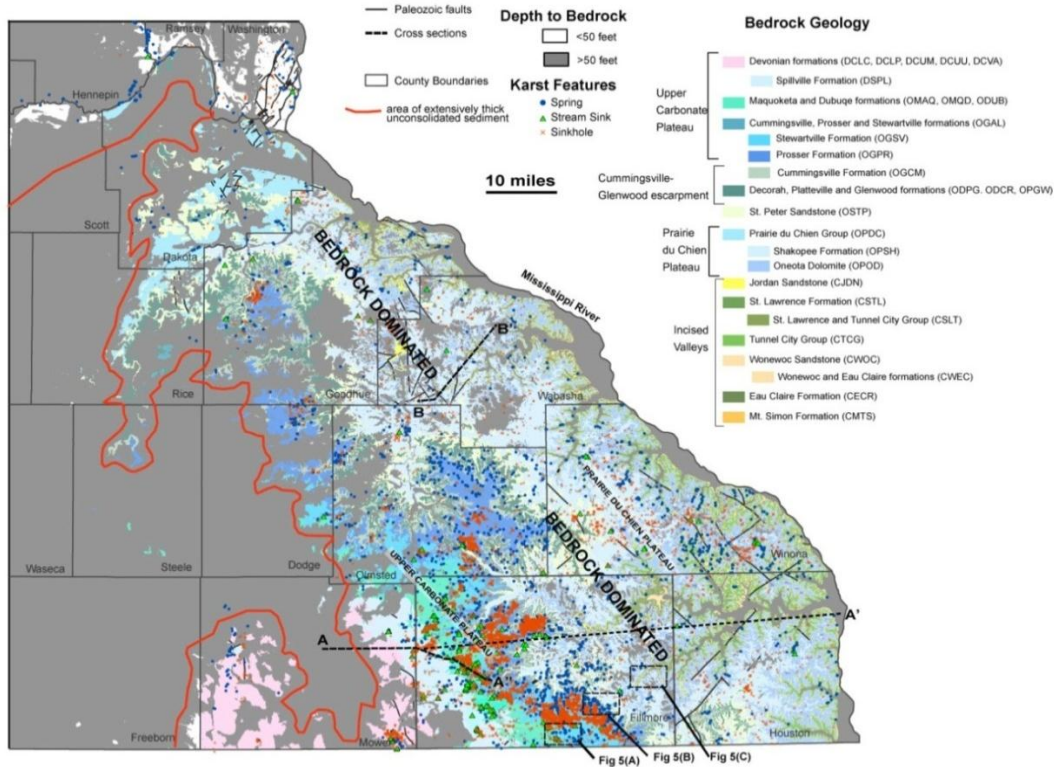
Figures

Figure 1. Generalized surficial geology of southeastern Minnesota showing first bedrock units and locations of karst features

The bedrock-dominated landscape of southeastern Minnesota can be divided into the Prairie du Chien Plateau and the Upper Carbonate Plateau. Areas where bedrock has less than 50 feet of sediment cover have abundant karst features. Certain bedrock units are more prone to karst development. Where bedrock is buried by more than 50 feet of Quaternary unconsolidated sediment (gray) karst is not common. Locations of cross sections and landscape illustrations in Figure 5 are shown. Modified from Runkel and others (2013).
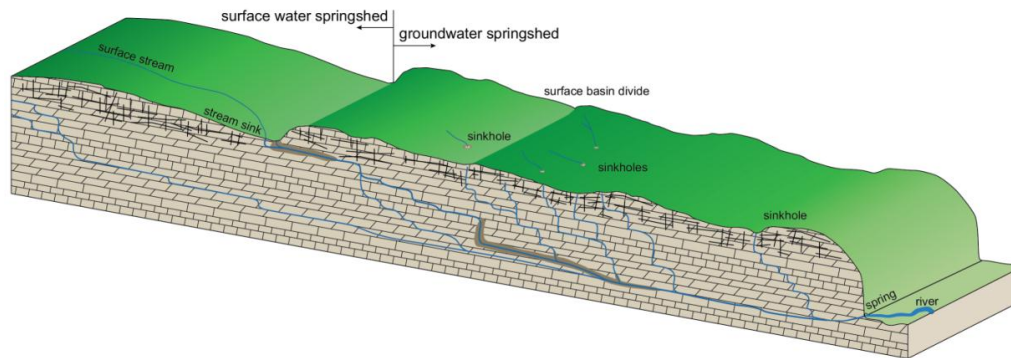
Figure 2. Springshed block diagram

Perennial and intermittent streams flowing across the surface descend into stream sinks or sinkholes, labeled. Those sinking points mark the beginning of the groundwater springshed carrying flow to a spring. The black lines in the upper horizon of the bedrock represent macropores in the subsurface such as vertical and horizontal joints and fractures that control the general direction of flow. The gray-shaded linear features represent larger conduits carrying groundwater flow. Another springshed component is regional flow (blue lines coming in from left side of the diagram) wherein water infiltrates from the surface and flows laterally from areas far beyond the surface water springsheds.
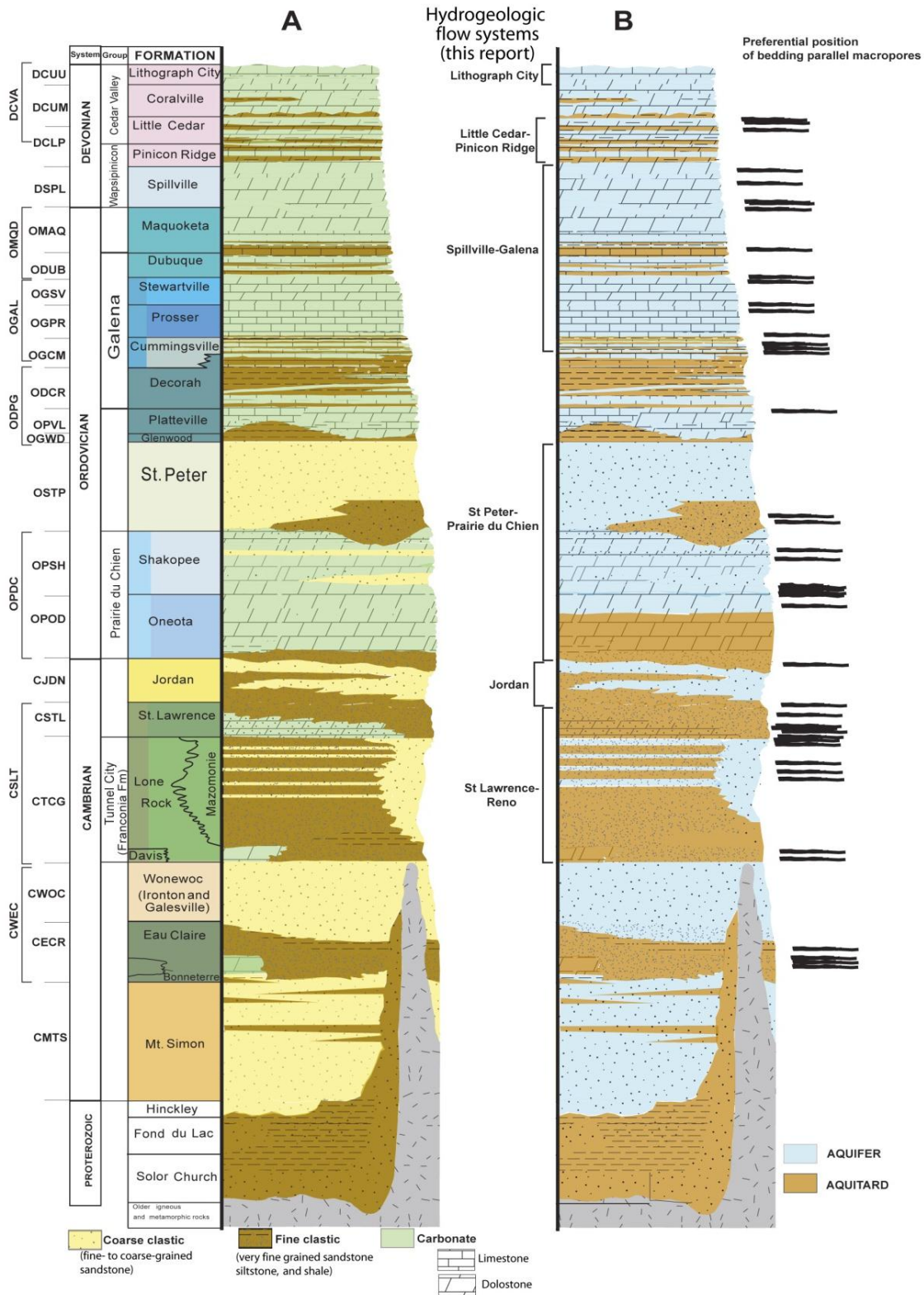
Figure 3. Stratigraphic columns for bedrock
This bedrock sequence for southeastern Minnesota highlights the lithostratigraphic attributes of the rock and includes lithostratigraphic, hydrostratigraphic (A) and hydrogeologic units (B). Also shown are the stratigraphic positions of the flow systems described in this report and horions of bedding-parallel macropore networks. Modified from Runkel and others (2013).
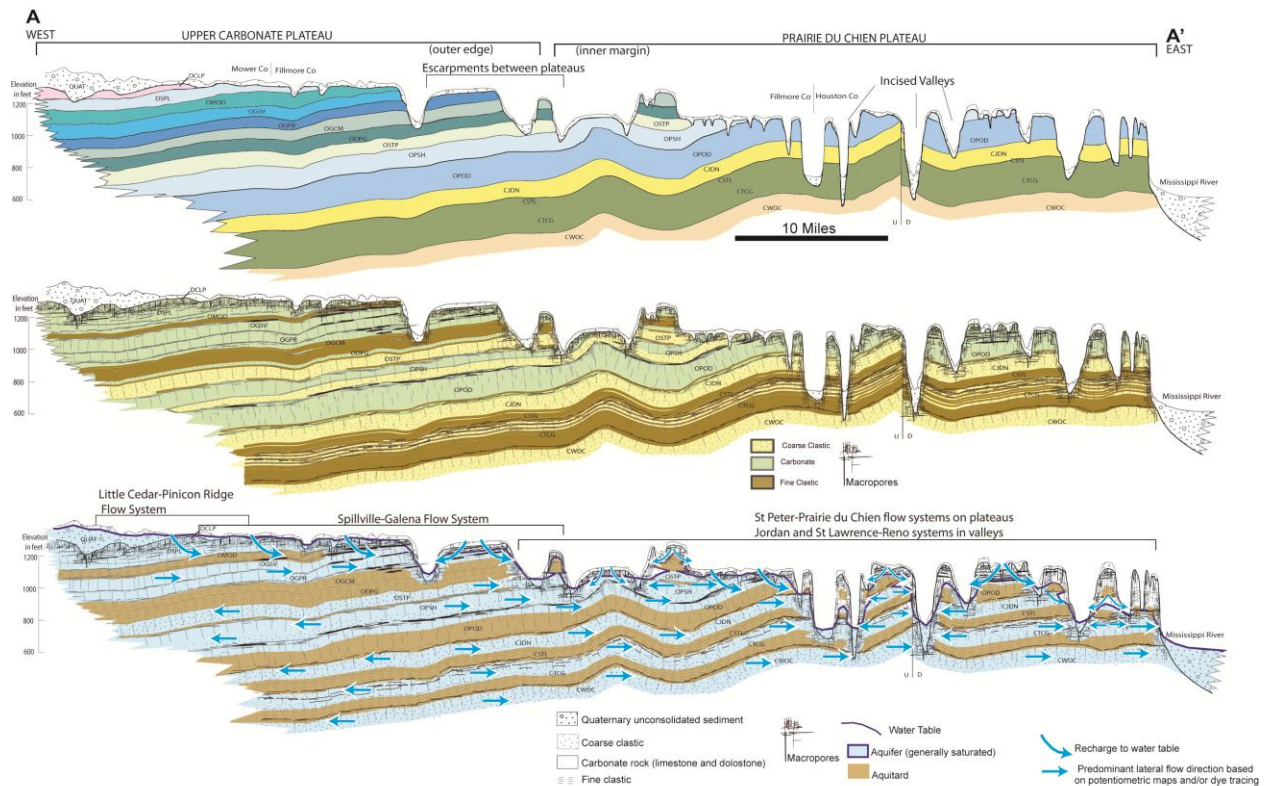
Figure 4. Regional cross sections

Highly generalized, regional-scale cross sections 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 geologic maps for the region (Figure 1). The middle cross section shows a highly generalized characterization of the materials that make up these formations, highlighting the distribution of hydrostratigraphic features including matrix components and fractures. Note higher density of fractures in the uppermost 50 feet of the bedrock and the preferential development of bedding-parallel fractures along specific stratigraphic positions. The lower cross section shows generalized flow system from the outer edge of the sediment-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 and others (1996). Stratigraphic codes and colors corresponding to the individual formations can be found in Figure 3. Location of cross section (A-A') is shown in Figure A. Modified from Runkel and others (2013).
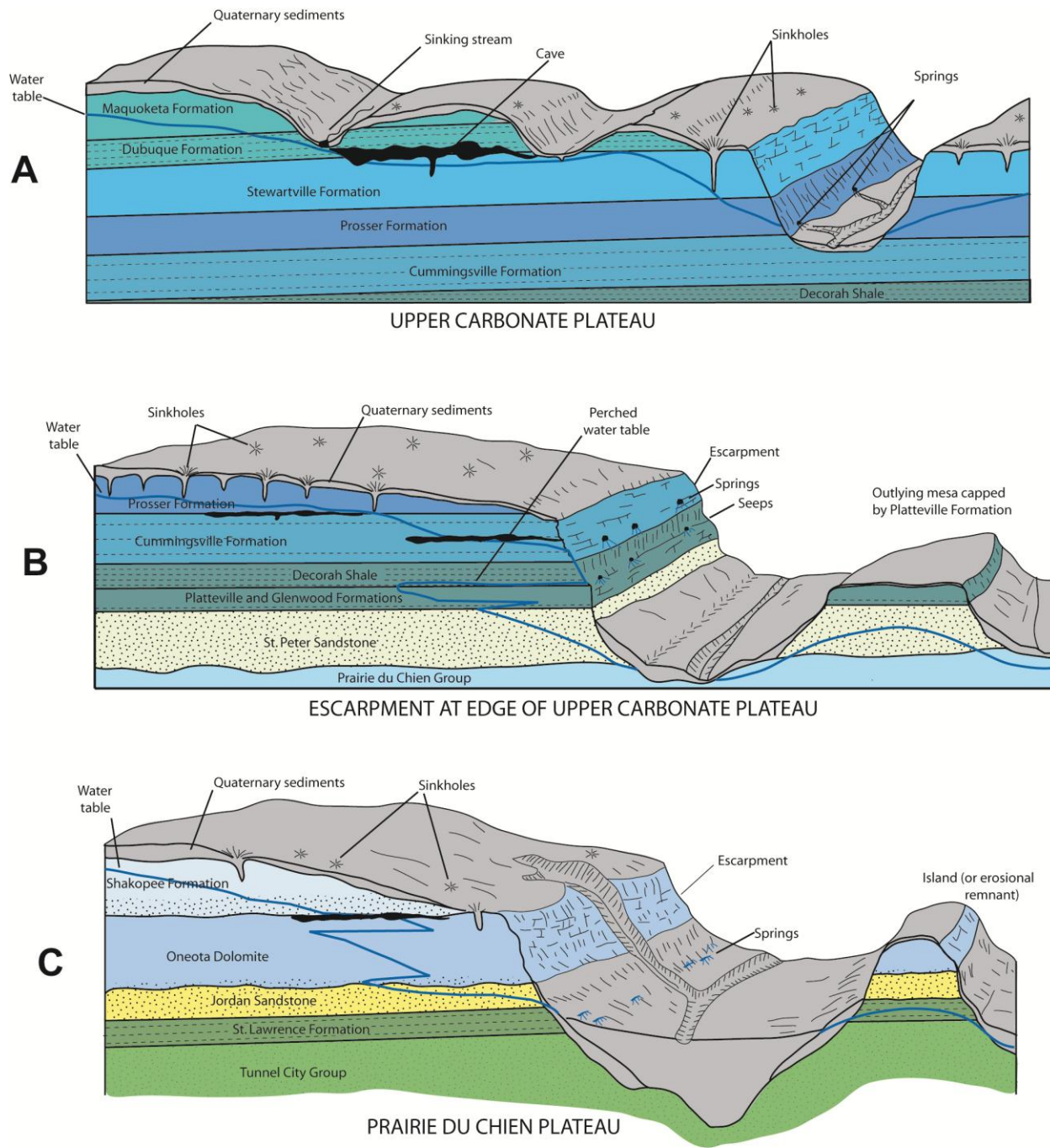
Figure 5. Block diagrams of typical landscape setting of bedrock units in southeastern Minnesota
Typical landscapes within the bedrock-dominated region of southeastern Minnesota with examples from the Upper Carbonate Plateau (A), its outer escarpment (B), and the Prairie du Chien Plateau (C). Each plateau is underlain by carbonate rock with solution-enhanced porosity reflected by karst features such as sinkholes and disappearing streams. See Figure 2 for map view of typical locations where these landscape types are present. Modified from Mossler and Hobbs (1995), Runkel and others (2013).
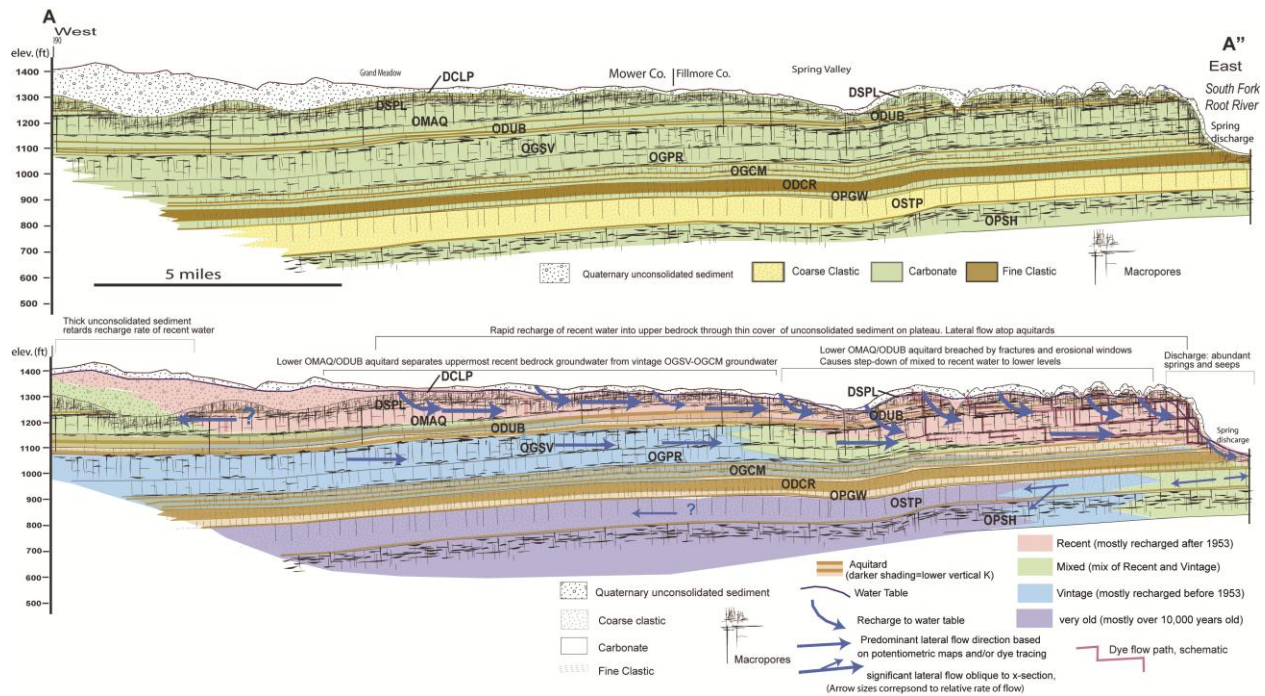
Figure 6. Cross sections, Mower to Fillmore counties

Cross section from central Mower to western Fillmore counties highlighting hydrostratigraphic components of the Paleozoic section (upper diagram) and groundwater age as determined by tritium concentration, and carbon-14 dating, and showing dominant, bulk-flow directions (lower diagram). Note especially the 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. The source of water to springs that emerge along the escarpment on the east side of the cross section is a mix of water dominated by recent recharge from uppermost bedrock groundwater, and deeper, more regionally derived water. 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 and others (1996). A component of downward flow that is present in most places because of overall downward vertical gradient is not represented by arrows. See Figure 2 for location of cross section. Stratigraphic codes are shown in Figure 3. Modified from Runkel and others (2013).

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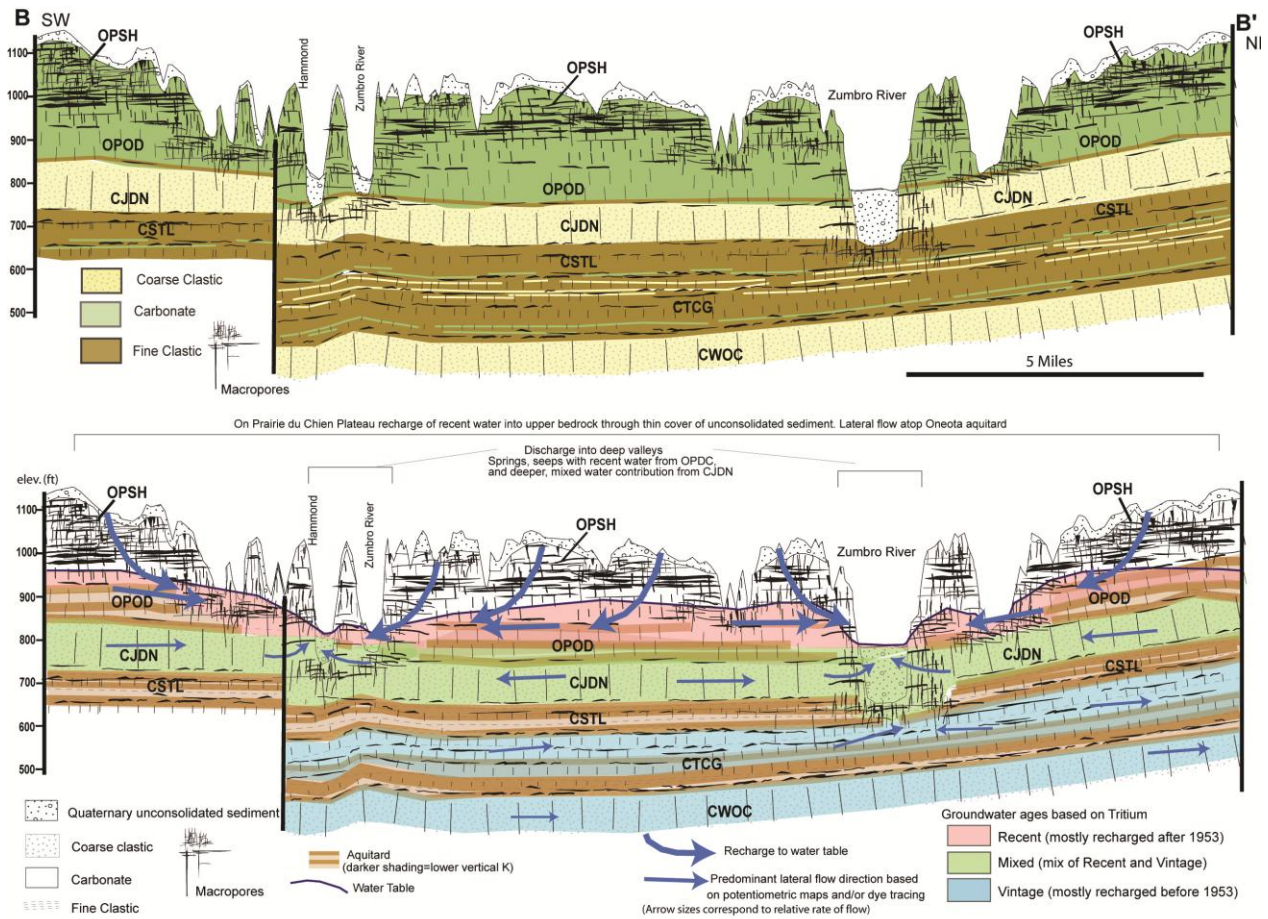
Figure 7. Cross sections, Wabasha County

Cross sections from Wabasha County highlighting hydrostratigraphic components of Paleozoic bedrock (upper section) and groundwater age as determined by tritium concentration, and showing dominant, bulk flow directions. (lower section). Note age stratification where 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. The source of water to springs that emerge from deep in the incised valleys is a mix of water dominated by recent recharge from uppermost bedrock groundwater, and deeper, more regionally derived water. 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 2 for location of cross section. Stratigraphic codes are shown in Figure 3. Modified from Runkel and others (2013).
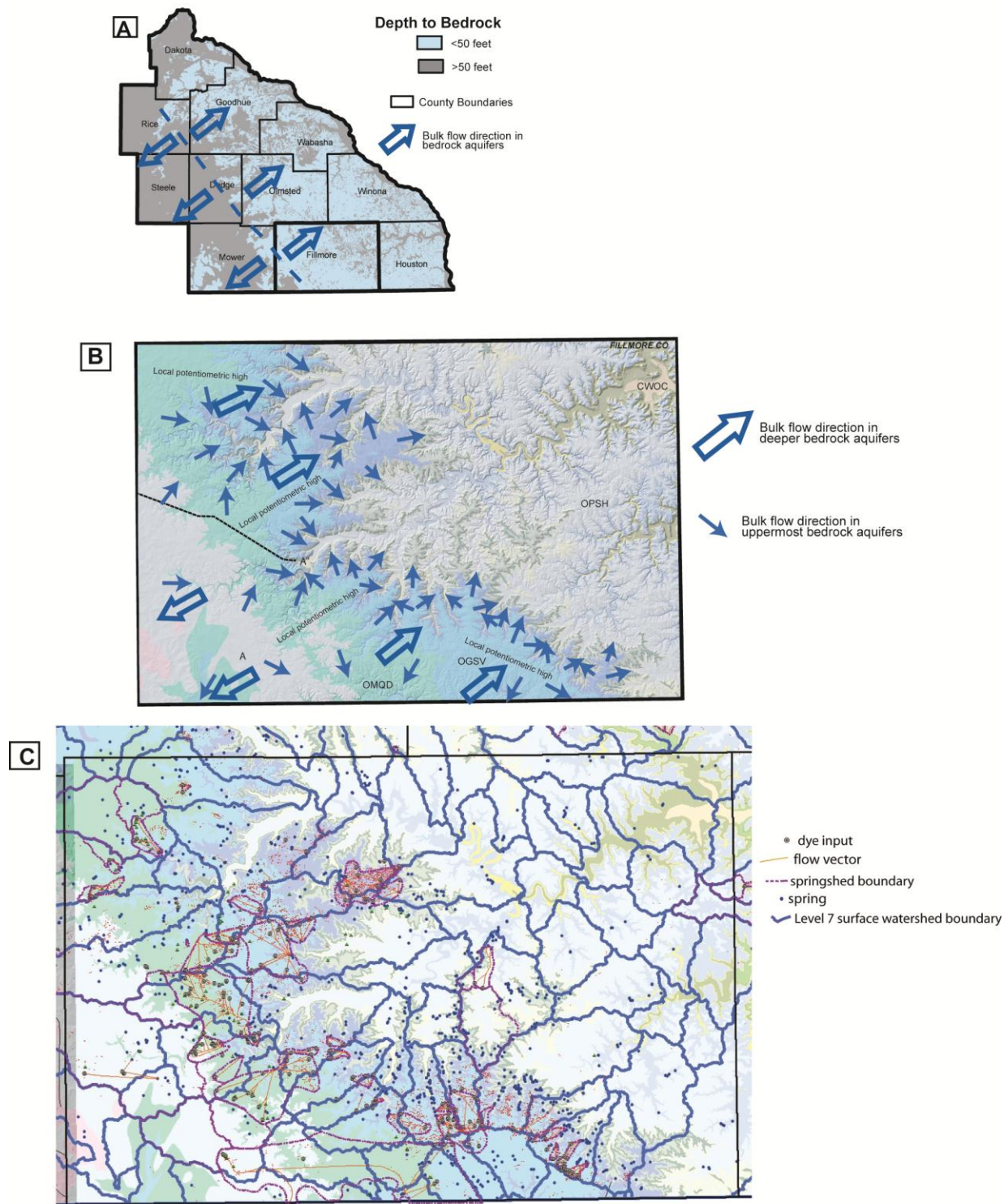
Figure 8. Groundwater flow directions

Map views of groundwater-flow directions in southeastern Minnesota: (A) bulk, dominant direction of groundwater flow in the bedrock at regional scale; (B) dominant direction of flow at more detailed scale, in Fillmore County, contrasting bulk flow directions of deeper bedrock aquifers with more highly resolved and variable directions in uppermost bedrock, and (C) comparison of DNR Level 7 surface watershed boundaries to springsheds defined by flow vectors from dye tracing in Fillmore County. Based on information from Delin and Woodward (1984), Kanivetsky (1988), Zhang and Kanivetsky (1996), Alexander and others (1996), Berg and Bradt (2003), and Campion (1997, 2002). See Figure 2 for the legend to the bedrock map. From Runkel and others (2013).

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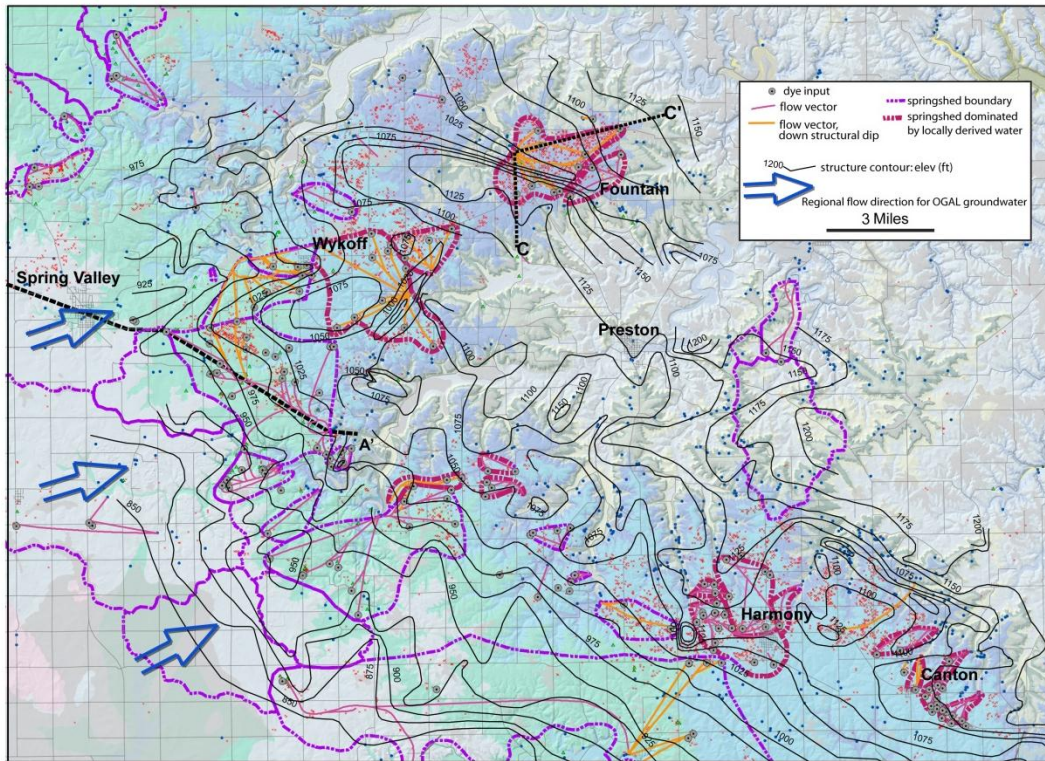
Figure 9. Springshed boundaries

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. Also highlighted are springsheds likely to be dominated by locally derived water from shallowest bedrock aquifers. See text for discussion. Springshed boundaries, flow vectors, and dye input locations modified from Alexander and others (1996). See Figure 2 for legend to bedrock map. Modified from Runkel and others (2013).
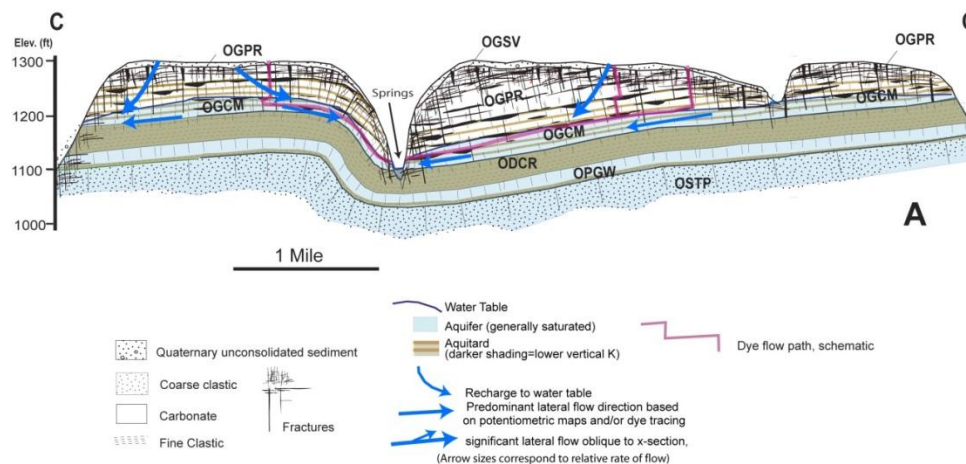
Figure 10. Cross sections showing flow down structural dip

Cross sections from western Fillmore County showing representative example of springshed where flow in uppermost bedrock is preferentially down the slope of folds in the bedrock (structural dip). The springshed at this location is also one in which the source of groundwater is likely to be dominated by locally derived, relatively young water in the shallowest bedrock. See Figure 9 for cross section location. Modified from Runkel and others (2013).
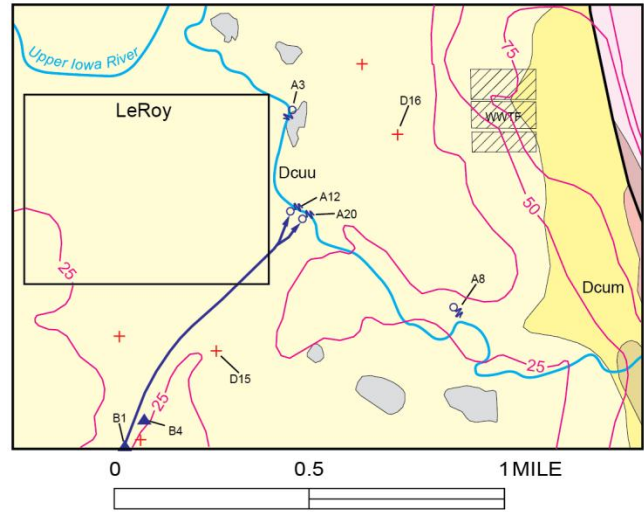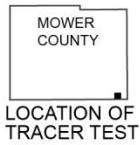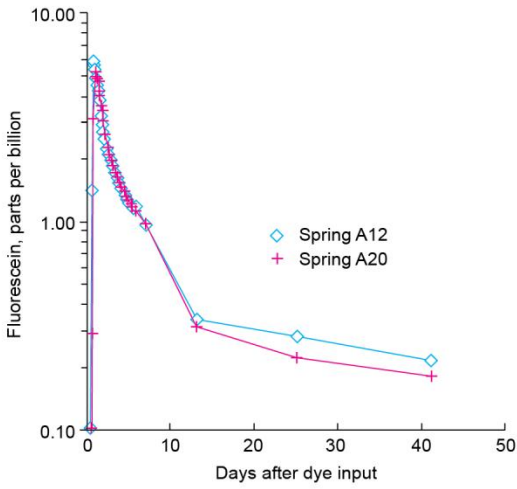
Figure 11. Dye trace result in the Lithograph City Formation.

Results of a dye trace performed in November 1997 in the Lithograph City Formation (DCUU) from Stateline Sink (MN50:B1) to Liftstation Spring (MN50:A12) and Gihon spring (MN50:A20). This dye breakthrough curve illustrates the karst-conduit-flow characteristics of this bedrock unit. The dye traveled 0.8 miles in less than 24 hours. The peak was followed by a rapid drop in dye concentration which is typical of conduit flow in a karst aquifer. Modified from Campion and Green (2002).
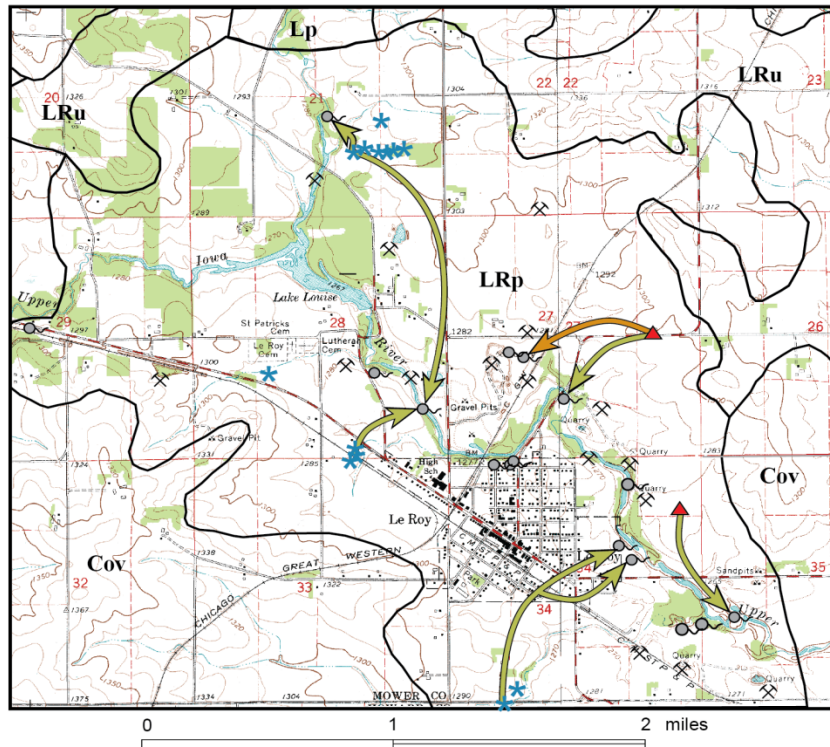
Karst Hydrogeomorphic Units

LRp **Le Roy plain.** Gently rolling plain bounded by higher elevation uplands. Surface runoff from these uplands flows onto this unit and disappears into stream sinks and sinkholes. In some areas of this unit, sinkholes are the dominant topographic feature. The western and northern boundaries of this unit are the points where the Upper Iowa and Little Iowa rivers begin to entrench into the bedrock. Ground water in this unit discharges from springs in the Upper Iowa and Little Iowa rivers. Dye traces from stream sinks and sinkholes to springs have shown both rapid ground-water flow (miles/day) and a slower (miles/month) component.

LRu **Le Roy upland.** Rolling upland bisected by the Little Iowa River. This unit is topographically higher than the Le Roy plain and discharges surface runoff onto it.

Lp **Limestone plain.** Gently rolling plains underlain by limestone or dolostone. The streams crossing this unit are not entrenched into the bedrock. As a result, water may rapidly infiltrate through the soil, but the hydraulic gradient is not steep enough to form many sinkholes.

Cov **Covered.** Rolling plains and uplands. This unit has depths of unconsolidated material that are greater than 50 feet.

Map Symbols

⚒ Quarry

✳ Stream sink

☊ Spring

▲ Verified sinkhole, field checked by one or more authors of Plate 10 of the Mower County Geologic Atlas.

Dye Trace*

— Natural gradient

— Forced—Quarry pumping-induced gradient

*This line displays the connection from a sinkhole or stream sink to a spring; the arrows indicate the direction of the groundwater flow.

Figure 12. **Dye trace results in the area of LeRoy, Minn.**
Traces were run from sinkhole sand stream sinks; the dyes were detected at springs in the Upper Iowa River. The LeRoy area contains a number of karst hydrogeomorphic units. Modified from Green and others (2002).

A.

B.

C.

Figure 13 A-C. Photographs of karst features in the Lithograph City bedrock unit
A) Small sinkhole with a cap for scale. The sinkhole is roughly two feet in diameter and three feet deep.
B) Large spring discharging from bedrock rubble on the bank of the Upper Iowa River. The spring emerges from beneath the rocks on the left side of the photo.
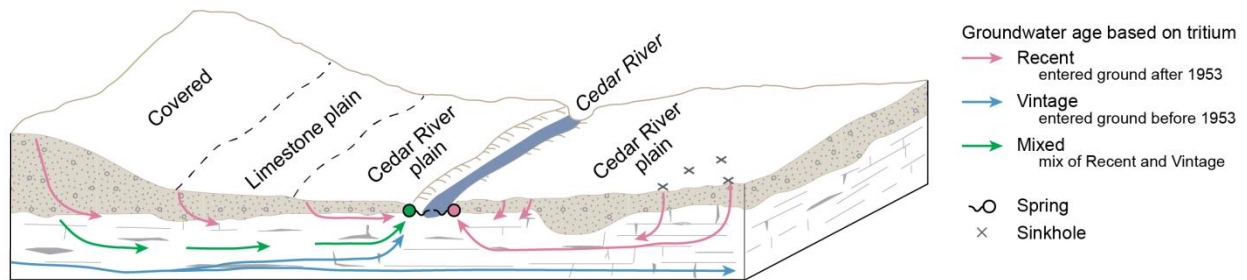C) Surface runoff flowing into a stream sink. The shovel length is three feet.

Figure 14. Groundwater age
Recent water is shown as pink, vintage (pre-1950) water, blue, and water that is a mixture, green. On the east side of the Cedar River, water moves from the land surface through sinkholes to ultimately discharge at springs. On the west side of the Cedar River, water moves through the sediment cover (and through sinkholes though they are not shown in this diagram) in the Cedar River plain and flows to springs. Regional flow is also illustrated on the west side of the Cedar River. Water infiltrates through the thick (greater than 100 feet) surficial material in the "covered" area. Those flow rates are much slower than in the Cedar River plain. As a result, the water that reaches the carbonate rock is much older. That old water flows through the fractures and conduits to mix with the young water entering the system in the Cedar River plain resulting in a mixed age signal for the spring.
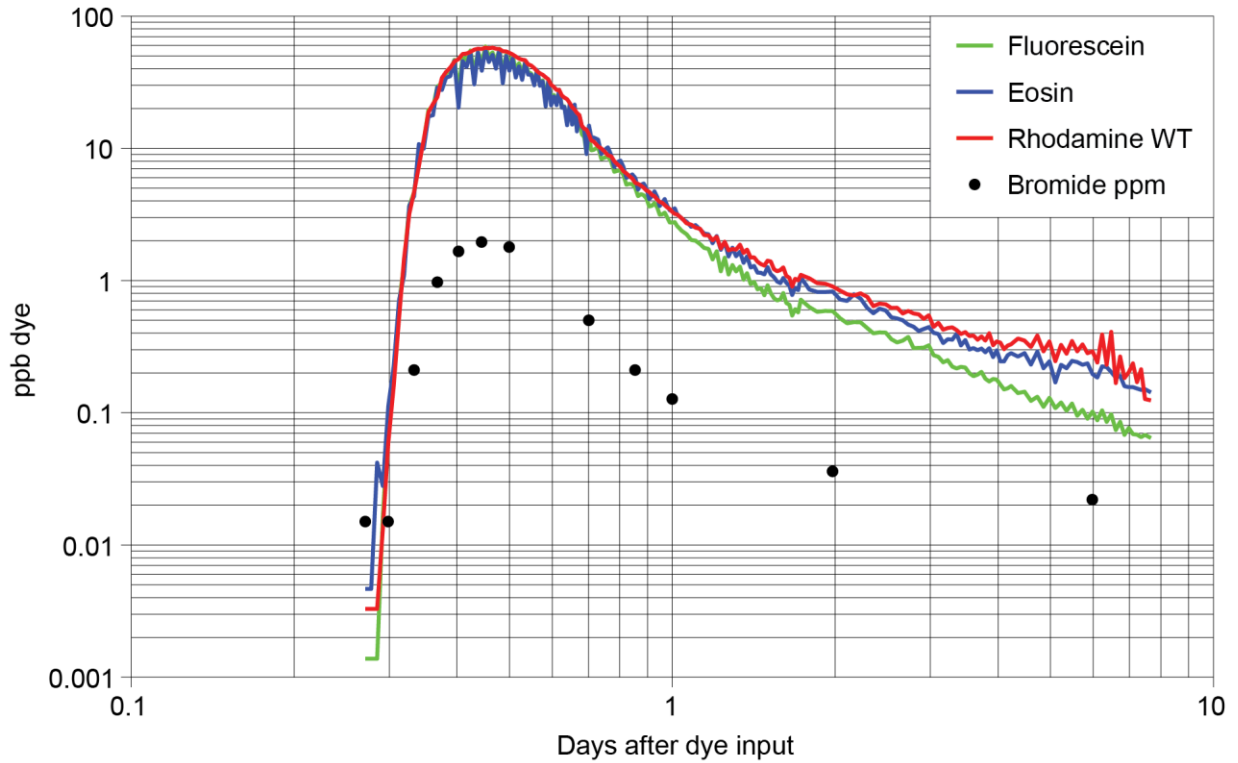
Figure 15. Dye-breakthrough curve for the Meyers springshed in the Galena limestone
This curve is typical of the response seen in Galena limestone groundwater springsheds. The breakthrough time, when dye is first detected is after six hours indicating a very direct conduit connection from the sinkhole to the spring. The peak was followed by a rapid drop in dye concentration which is typical of conduit flow in a karst aquifer.
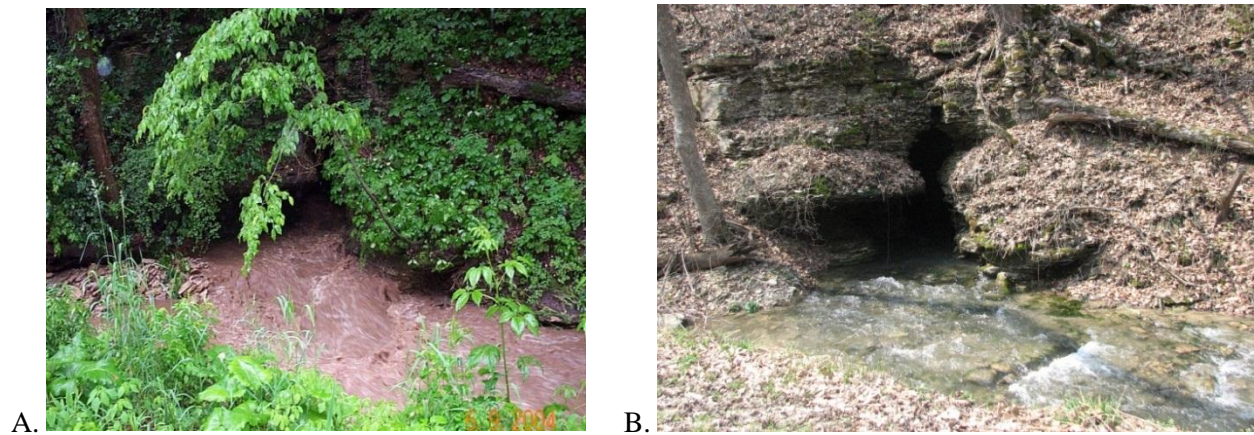

Figure 16. Photographs of Fountain Big Spring in Fillmore County
Photos contrast the conditions after a rain event (A) and during baseflow conditions (B). Water level, temperature, conductivity, and nitrate levels change dramatically at the Fountain Big Spring following precipitation and snowmelt events.

Figure 17. Bedrock voids
Large bedrock voids (person in lower left for scale) indicating the bedding-plane-parallel conduit system at the Shakopee-Oneota contact in a quarry in southern Wabasha County (MGS photo).
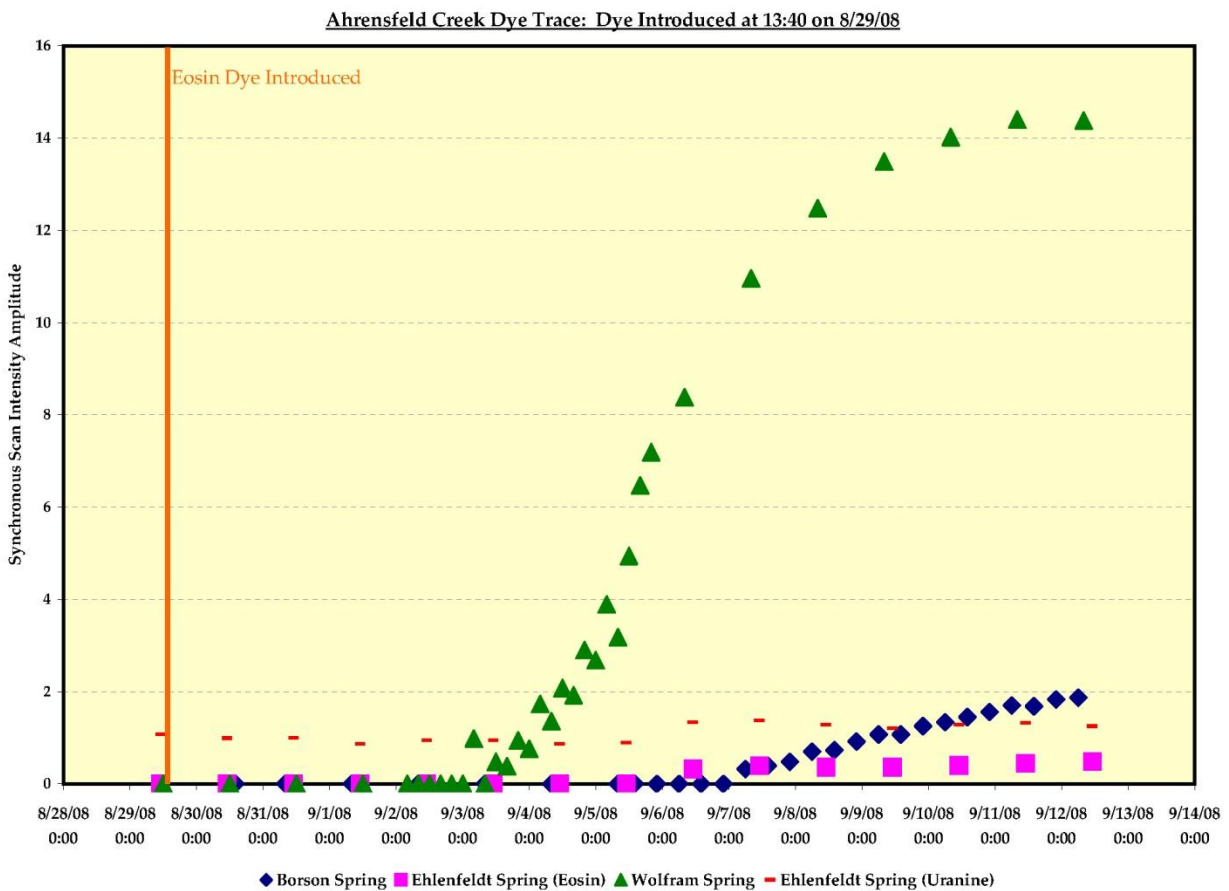

Figure 18. St. Lawrence dye-trace and dye-recovery curves
The dye breakthrough was in 6.5 days over a distance of 11,000 feet yielding a breakthrough velocity of over 1600 feet per day. This indicates that the leading-edge of the dye is moving through a well-developed conduit system.
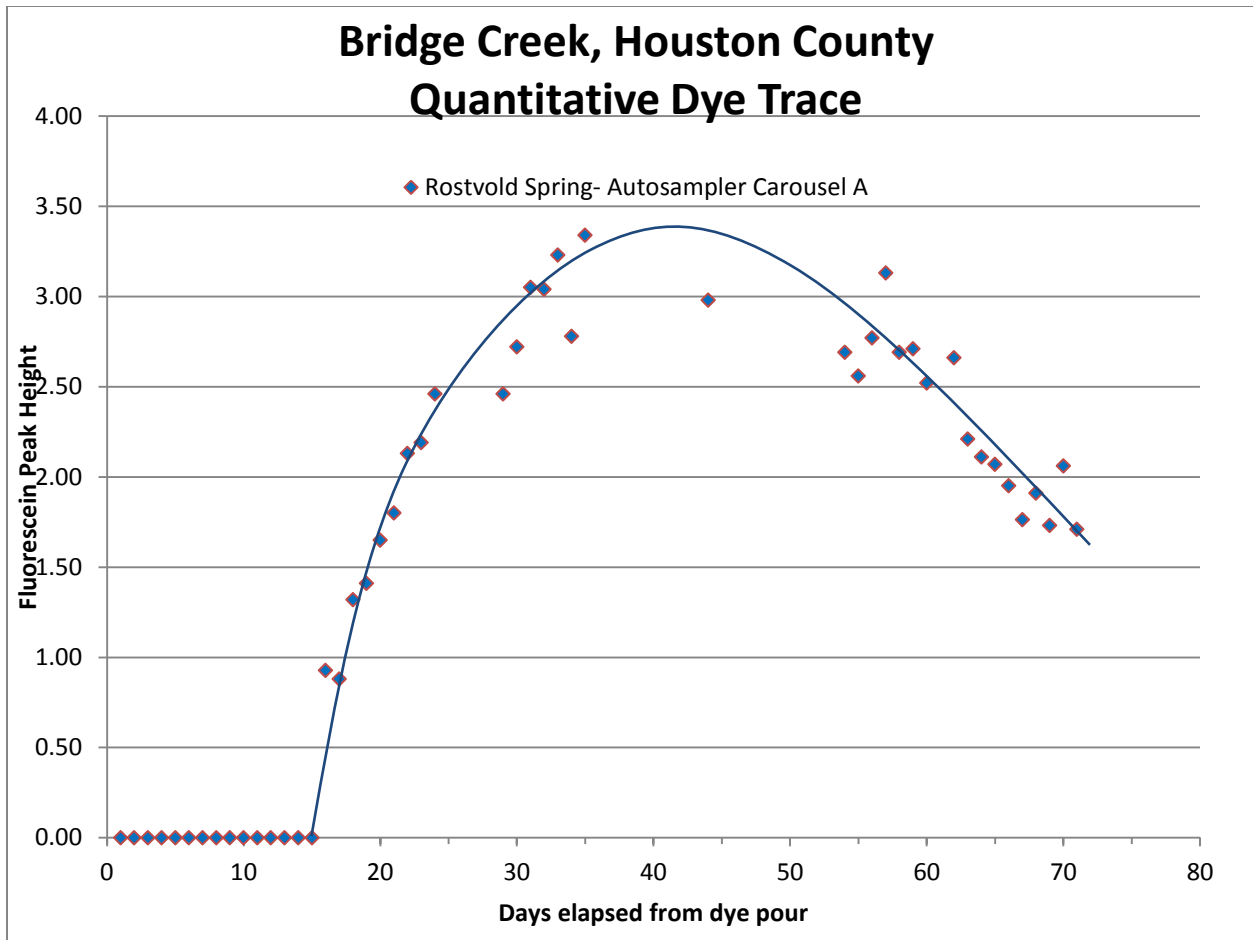
Figure 19. Tunnel City dye-trace and dye-recovery curve

The dye was introduced into a stream sink at the top of the St. Lawrence Formation. The breakthrough was in 16 days over a distance of 16,000 feet yielding a horizontal breakthrough velocity of 1000 feet per day. This indicates that the dye was moving through a well-developed network of both vertical and horizontal conduits.
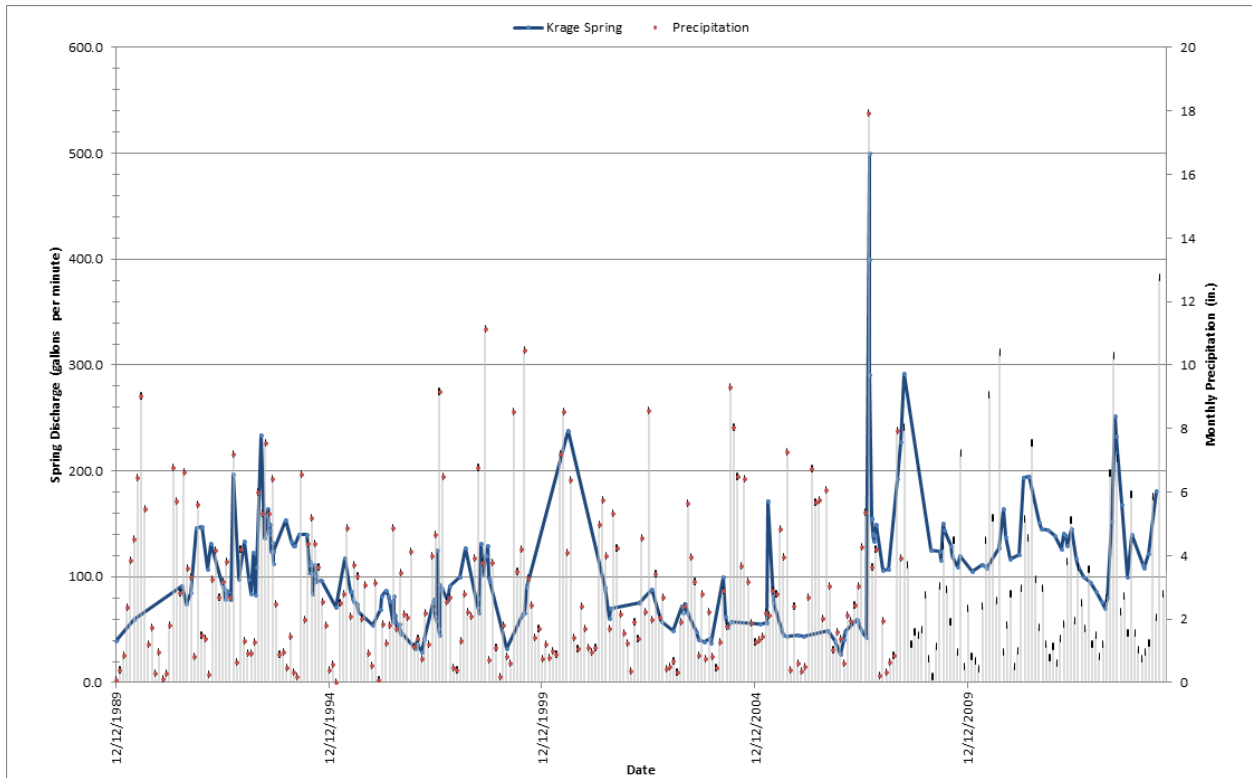
Figure 20. Krage spring discharge measurements

This spring emanates from the lower part of the Tunnel City Group. Discharge varies greatly in response to precipitation events that do not produce changes in temperature or in visible turbidity. Spring flow measurements have been taken at varying intervals (multiple times per month to four-to-six times per year). The flow is calculated by measuring the amount of time it takes to fill a 5-gallon bucket. The precipitation measurements are monthly averages from a National Weather Service observer at South Rushford, Minnesota which is 10.5 miles southwest of the spring. The flow measurement dates and monthly-average precipitation do not necessarily correspond indicating that there is not a one-to-one correlation between precipitation and spring flow.
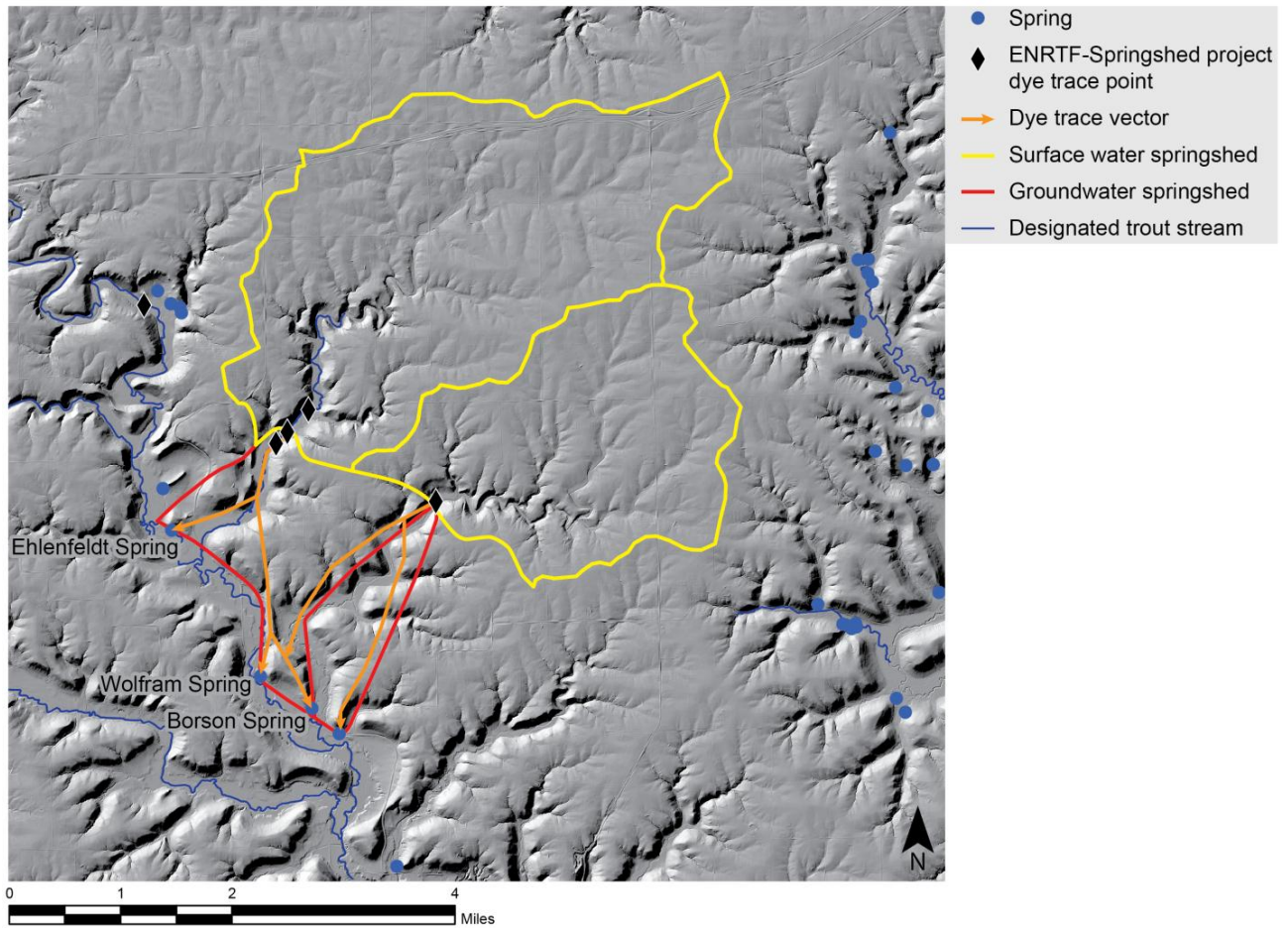
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Figure 21. St. Lawrence springsheds in the Borson spring area
The surface water springsheds total over 8000 acres. Surface water flows into stream sinks that recharge the St.
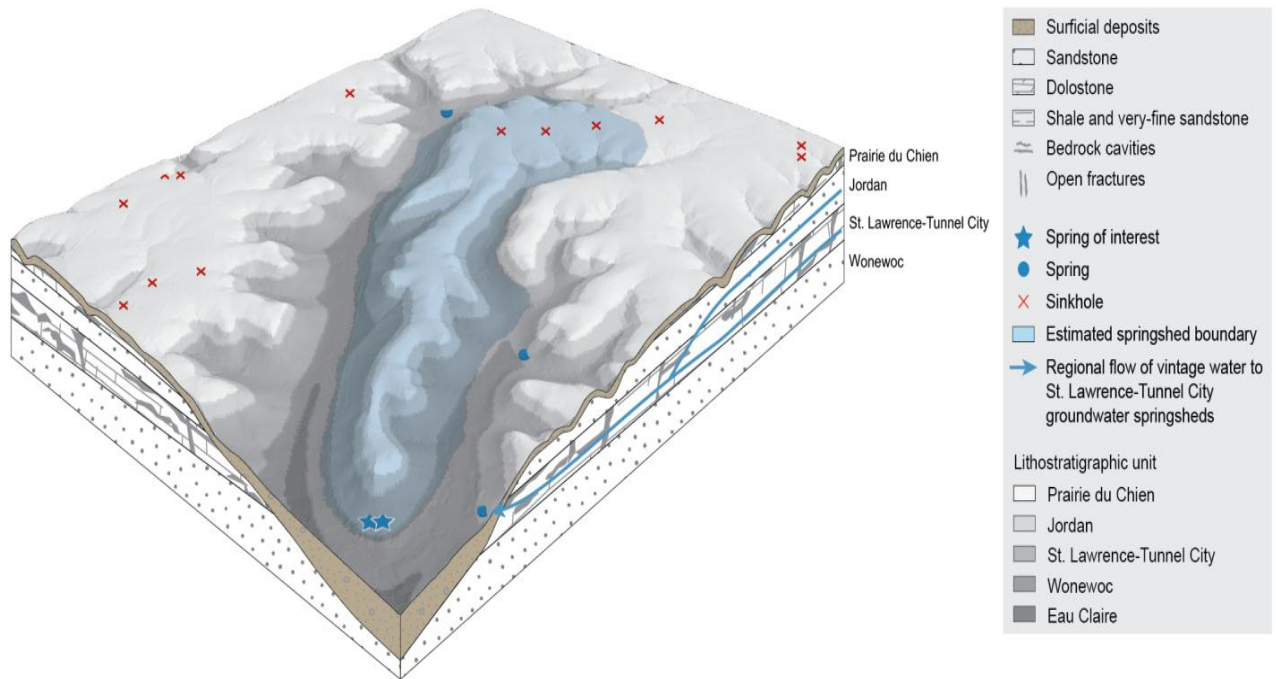Lawrence Formation and its springs.

Figure 22. St. Lawrence/Tunnel City springshed estimation example

This is a diagrammatic depiction of the estimated springshed contribution area for a St. Lawrence or Tunnel City spring. Dye tracing in these formations has demonstrated that springs may receive groundwater that begins as surface water that sinks in valleys adjacent to these springs. The sideslopes and upland of the spring's bedrock interfluve are included in the estimated springshed area because water can move down the hillslopes into the formations. The blue arrow in the geology cross-section indicates that regional vintage water from the formations flows to these springs.