Springshed Assessment Methods for Paleozoic Bedrock Springs of Southeastern Minnesota

Jeffrey A. Green[1], John D. Barry[1], and E. Calvin Alexander, Jr.[2]

[1]Minnesota Department of Natural Resources
[2]Department of Earth Sciences, University of Minnesota

Acknowledgements

Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR).

This project would not have been possible without the work of many people. Tony Runkel of the Minnesota Geological Survey provided relevant background geology and interpretation. Scott Alexander of the University of Minnesota provided oversight and analysis of the dye trace samples. Donna Rasmussen of Fillmore County provided staff to assist in dye tracing and obtained property access for many traces. Others who contributed much to this project include Betty Wheeler and Kelsi Ustipak of the University of Minnesota, Mark White (DNR), Andrew Luhmann, the Harmony and Chatfield Fire Departments, and the many landowners who allowed access to their springs, sinking streams and sinkholes. Without their cooperation, and many others not named here, much of this work would not have been possible.

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 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). Siliclastic 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.

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	Disharge 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.

Cambrian St. Lawrence Formation and Cambrian Reno Member–Tunnel City Group

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.

References

Alexander, E.C., Jr., Book, P.R., 1984, Altura Minnesota lagoon collapses, *in* Beck, B., ed., Sinkholes–their geology, engineering and environmental impact: A.A. Balkema, Rotterdam, The Netherlands, p. 311-318.

Alexander, E.C., Green, J.A., Alexander, S.C., and Spong, R.C., 1996, Springsheds, pl. 9 *of* Lively, R.S., and Balaban, N.H., eds., Geological atlas of Fillmore County, Minnesota: Minnesota Department of Natural Resources, Division of Waters, County Atlas Series C-8, Part B, scale 1:100,000.

Alexander, E.C., Jr., Broberg, J.S., Kehren, A.R., Graziai, M.M., and Turri, W.L., 1993, Bellechester Minnesota lagoon collapses: Environ. Geol., v. 22, no. 4, p. 353-361.

Alexander, E.C., Jr, Green, J.A., Runkel, A.C., and Logan, K.J., 2011, Southeastern Minnesota karst hydrogeology–new insights from data loggers, tracing, LiDAR and hydrophysics: Geological Society of America Field Guides 24, p. 243-257.

Alexander, E.C., Jr., and Lively, R.S., 1995, Karst-aquifers, caves and sinkholes, *in* Lively, R.S., and Balaban, N.H., eds., Text supplement to the geologic atlas, Fillmore County, Minnesota: Minnesota Geological Survey, County Atlas Series C-8, Part C, p. 10-18.

Alexander, S.C., 2005, Spectral deconvolution and quantification of natural organic material and fluorescent tracer dyes, *in* Beck, B.F., Sinkholes and the Engineering and Environmental Impacts of Karst: Proceedings of the 10th Multidisciplinary Conference, ASCE/GI Geotechnical Special Publication No. 144, Amer. Soc. Civil Eng., Reston, VA, p. 441-448.

Alexander, S. C., Luhmann, A.J., Alexander, E.C., Jr., Green, J.A., and Peters, A.J., 2008, Spring characterization methods and springshed mapping *in* Yuhr, Lynn B., Alexander, E. Calvin, Jr,. and Beck, Barry F., eds., Sinkholes and the engineering and environmental impacts of karst: Proceedings of the 11th Multidisciplinary Conference, ASCE/GI Geotechnical Special no. 183, Amer. Soc. Civil Eng., Reston, VA, p. 485-494.

Anderson, J.R., Runkel, A.C., Tipping, R.G., Barr, K., and Alexander, E.C., Jr., 2011, Hydrostratigraphy of a fractured urban aquitard: Geological Society of America Field Guides 24, p. 457-475.

Barry J.D., Green, J., 2014, Dye tracing high velocity flow through a regional confining layer: Driftless Area Symposium Abstract, Wisconsin Trout Unlimited, February 4-5, 2014, La Crosse, Wisconsin.

Berg, J.A., 2003, Hydrogeologic cross sections, pl. 8 *of* Falteisek, J., ed., Geologic atlas of Goodhue County, Minnesota: Minnesota Department of Natural Resources, Division of Waters, County Atlas Series C-12, Part B, scale 1:100,000.

Berg, J.A., and Bradt, R., 2003, Bedrock and water-table hydrogeology, pl. 7 *of* Falteisek, J., ed., Geologic atlas of Goodhue County, Minnesota: Minnesota Department of Natural Resources, Division of Waters, County Atlas C-12, Part B, scale 1:100,000.

Campion, M., 1997, Bedrock hydrogeology, pl. 8 *of* Falteisek, J., ed., Geologic atlas of Rice County, Minnesota: Minnesota Department of Natural Resources, Division of Waters, County Atlas Series C-9, Part B, 3 pls., scale 1:100,000.

Campion, M., and Green, J.A., 2002, Ground-water flow in bedrock aquifers, pl. 8 *of* Falteisek, J., ed., Geologic atlas of Mower County, Minnesota: Minnesota Department of Natural Resources, Division of Waters, County Atlas Series C-11, Part B, scale 1:100,000.

Dalgleish, J. and Alexander, E.C., Jr., 1984, Sinkhole distribution in Winona County, Minnesota, *in* Beck, B., ed., Sinkholes –their geology, engineering and environmental impact: A.A. Balkema, Rotterdam, The Netherlands, p. 79-85.

Delin, G.N, 1991, Hydrogeology and simulation of ground-water flow in the Rochester area, southeastern Minnesota, 1987-88: United States Geological Survey, Water Resources Investigations Report 90-4081, 101pp.

Delin, G.N., and Woodward, D.G., 1984, Hydrogeologic setting and the potentiometric surfaces of regional aquifers in the Hollandale Embayment, southeastern Minnesota, 1970-80: U.S. Geological Survey Water Supply Paper 2219, 56p.

Delta Environmental Consultants, Inc., 1995, Supplemental remedial investigation report– Amoco Oil Company Spring Valley Terminal, Spring Valley, Minnesota: Delta no. A091-088: 25p., February 21, 1995. On file at the Minnesota Pollution Control Agency.

Delta Environmental Consultants, Inc., 1996, Supplemental remedial investigation report, 1995 activities– Amoco Oil Company Spring Valley Terminal, Spring Valley, Minnesota: Delta No. A091-088. April 12, 1996. On file at the Minnesota Pollution Control Agency.

Drew, D., and Hotzl, H., 1999, Karst hydrogeology and human activities: A.A. Balkema, Rotterdam, The Netherlands, 322p.

Florida Geological Survey, 2003, Florida spring classification system and spring glossary: Special Publication no. 52, 17 p.

Green, J.A., Alexander, E.C., Jr., Marken, W.G., and Alexander, S.C., 2002, Karst hydrogeomorphic units, pl. 10 *of* Falteisek, J., ed., Geologic atlas of Mower County, Minnesota: Minnesota Department of Natural Resources, Division of Waters, County Atlas Series C-11, Part B, scale 1:100,000.

Green, J., Luhmann, A, Peters, A., Runkel, A, Alexander E.C., Jr, Alexander, S. 2008, Dye tracing within the St. Lawrence confining unit in southeastern Minnesota *in* Yuhr, L., Alexander, E.C. Jr, and Beck, B., eds., Sinkholes and the engineering and environmental impacts of karst: American Society of Civil Engineers, Proceedings GSP 183, p. 477-484.

Green, J.A., Mossler, J.H., Alexander, S.C., and Alexander, E.C., Jr., 1997, Karst hydrogeology of Le Roy Township, Mower County, Minnesota: Minnesota Geological Survey Open File Report 97-2, 2 pl., Scale 1:24,000.

Green, J.A., Pavlish, J.A., Leete, J.H. and Alexander, E.C., Jr., 2003, Quarrying impacts on groundwater flow paths *in* Beck, E.F. ed., Proceedings of the ninth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, Sept. 6-10, 2003: Huntsville, Alabama, American Society of Civil Engineers, Geotechnical Special Publication no. 122, p. 216-222.

Green, J.A., Alexander, S.C., and Alexander, E.C., Jr., 2005, Springshed mapping in support of watershed management *in* Beck, B.F. ed., Proceedings of the tenth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst, San Antonio, Texas, September 24-28, 2005: ASCE Geotechnical publication 144, Amer. Soc. Civil Engr., Reston, Virginia, p. 403-409.

Green, J.A., and Alexander, E.C., Jr., 2011, Dye tracing observations from the Prairie du Chien Group in Minnesota: 2011 Geological Society of America meeting, abstracts with programs, Abstract 60-11, v. 43, no.5, p. 167.

Green, J.A., Runkel, A.C., Alexander, E.C., Jr., 2012, Karst conduit flow in the Cambrian St. Lawrence Formation, southeast Minnesota, USA: Carbonates and Evaporites, v. 27, no. 2, p.167-172.

Hallberg, Libra, G.R., R.D., Bettis, E.A., III, and Hoyer, B.E., 1984, Hydrogeologic and water quality investigations in the Big Spring Basin, Clayton Co., IA, 1983 water year: Iowa Geological Survey Open-File Report 84-4, G. R. Hallberg, Hoyer, 1984: 231 p., 43 figs., 20 tables, 3 appendices.

Jannik, N.O., Alexander, E. C., Jr., and Landherr, L.J., 1992, Sinkhole collapse of the Lewiston, Minnesota, WWTF lagoon *in* Quinlan, J. and Stanley, A. eds.,Third Conference on Hydrogeology, Ecology, Monitoring and Management of Ground Water in Karst Terranes, December 4-6, 1991: Nashville, Tenn.,, NGWA, Dublin, Ohio, p. 715-724.

Kanivetsky, R., 1988, Bedrock hydrogeology, pl. 5 *in* Balaban, N.H., ed., Geologic atlas of Olmsted County, Minnesota: Minnesota Geological Survey County Atlas Series C-3, scale 1:100,000.

Kanivetsky, R., 1984, Bedrock Hydrogeology, pl. 4, in Balaban, N.H., and Olsen, B.M., eds., Geologic atlas of Winona County: Minnesota Geological Survey, County Atlas Series C-2, scale 1:100,000.

Luhmann, A.J., 2011. Water temperature as a tracer in karst aquifers: PhD thesis, University of Minnesota, Minneapolis, , 169 p. + supporting files, accessed at http://purl.umn.edu/113204.

Luhmann, A.J., Covington, M.D., Peters, A.J., Alexander, S., Anger, C., Green, J.A., Runkel, A.C., Alexander, E.C., Jr, 2011, Classification of thermal patterns at karst springs and cave streams: Groundwater, v. 49, no. 3, p. 324-335.

Meyer, J.R., Parker, B.L., and Cherry, J.A., 2008, Detailed hydraulic head profiles as essential data for defining hydrogeologic units in layered fractured sedimentary rock: Environmental Geology, v. 56, p. 27–44.

Meyer, J.R., Parker, B.L., and Cherry, J.A. 2014, Characteristics of high resolution hydraulic head profiles and vertical gradients in fractured sedimentary rocks: Journal of Hydrology,v. 517, p. 493-507.

Minnesota Department of Health, 2010, County Well Index Online: last accessed 2010, at http://www.health.state.mn.us/divs/eh/cwi.

Minnesota Department of Natural Resources, 2005-2014, Management Resources - MIS Unit , Minnesota LiDAR Based DEM - 3 Meter Resolution: last accessed August, 2014 at file:///V:/gdrs/data/org/us_mn_state_dnr/elev_03m_digital_elevation_model/metadata/metadata.html.

Minnesota Department of Natural Resources, 2014a, National Hydrography Dataset (NHD) - High-Resolution – Minnesota: last accessed August, 2014 at file:///V:/gdrs/data/pub/us_mn_state_mngeo/water_national_hydrography_data/metadata/metadata.html.

Minnesota Department of Natural Resources, 2014b, State Designated Trout Streams, Minnesota: last accessed August, 2014 at file:///V:/gdrs/data/pub/us_mn_state_dnr/env_trout_stream_designations/metadata/metadata.html.

Minnesota Department of Natural Resources, 2011, Forestry/Resource Assessment 2011, DNR Forestry Color Infrared Digital OrthoPhoto Quadrangles - WMS Source: last accessed August, 2014 at file:///V:/gdrs/data/org/us_mn_state_dnr/base_dnr_forestry_cir_wms/metadata/metadata.html.

Mossler, J.H., 1995, Bedrock geology, pl. 2 *of* Mossler, J.H., project manager, Geologic atlas of Fillmore County, Minnesota: Minnesota Geological Survey, County Atlas Series C-8, Part A, scale 1:100,000.

Mossler, J.H., and Book, P. R., 1984, Bedrock Geology, *in* Balaban, N.H., and Olsen, B.M., eds, Geologic atlas of Winona County, Minnesota Geological Survey, County Atlas Series C-2, scale 1:100,000.

Mossler, J.H., 2008, Paleozoic stratigraphic nomenclature for Minnesota: Minnesota Geological Survey, Report of Investigations 65, 76 p., 1 pl.

Mossler, J.H., and Hobbs, H.C., 1995, Depth to Bedrock and Bedrock Topography, pl. 4 *of* Mossler, J.H., project manager, Geologic atlas of Fillmore County, Minnesota: Minnesota Geological Survey County Atlas Series C-8, Part A, scale 1:100,000.

Muldoon, M.A., Simo, J.A., and Bradbury, K.R., 2001, Correlation of hydraulic conductivity with stratigraphy in a fractured-dolomite aquifer, northeastern Wisconsin, USA: Hydrogeology, v. 9, no. 6, p.570–583.

Pfannkuch, H. O., 1971, Elsevier's dictionary of hydrogeology: American Elsevier Publishing Company Inc., New York, N.Y. 168 p.

Petersen, T.A., 2005, Hydrogeologic Cross Sections, pl. 9 *of* Falteisek, J., ed., Geologic atlas of Wabasha County, Minnesota: Minnesota Department of Natural Resources, Division of Waters, County Atlas Series C-14, Part B, scale 1:100,000.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., and Alexander, S.C., 2006a, Hydrostratigraphic characterization of intergranular and secondary porosity in part of the Cambrian sandstone aquifer systems of the cratonic interior of North America–improving predictability of hydrogeologic properties: Sedimentary Geology, v. 184, p. 281-304.

Runkel, A.C., Tipping, R.G., Mossler, J.H., and Bauer, E.J., 2006b, Hydrogeology and mapping investigation of the St. Lawrence Formation in the Twin Cities Metropolitan area: Minnesota Geological Survey, Open File Report 06-04, 20 p. and appendix.

Runkel, A.C., Tipping, R.G. , Alexander, E.C., Jr., Green, J.A., Mossler, J.H., and Alexander, S.C., 2003, Hydrogeology of the Paleozoic bedrock in southeastern Minnesota: Minnesota Geological Survey, Report of Investigations 61, 105 p., 1 map in pocket.

Runkel, A.C., Steenberg, J.R., Tipping, R.G., and Retzler, A.J., 2013, Geologic controls on groundwater and surface water flow in southeastern Minnesota and its impact on nitrate concentrations in streams: Minnesota Geological Survey, Open File Report 14-2, 70 p.

Runkel, A.C., Tipping, R.G., Green, J.A., Jones, P. M., Meyer, J.R., Parker, B.L., Steenberg, J.R., and Retzler, A.J., 2014, Hydrogeologic properties of the St. Lawrence aquitard, southeastern Minnesota: Unpublished Report of the Minnesota Geological Survey, as contract deliverable to the Legislative and Citizens Committee on Minnesota Resources, 119 p.

Runkel, A.C., Mossler, J.H., Tipping, R.G., 2007, The Lake Elmo downhole logging project–Hydrostratigraphic characterization of fractured bedrock at a perfluorochemical contamination site: Minnesota Geological Survey, Open File Report 07-5, 12 p. and appendix.

Seaber, P.R., 1988, Hydrostratigraphic units *in* Back, W., Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: Boulder, Colo., Geological Society of America, The Geology of North America, v. O-2, p. 9-14.

Swanson, S.K., Bahr, J.M., Bradbury, K.R., and Anderson, K.M., 2006, Evidence for preferential flow through sandstone aquifers in southern Wisconsin: Sedimentary Geology, v. 184, p. 331–342.

Tipping, R.G., 2002, Karst features of Wabasha County, Minnesota *in*, Runkel, A.C., project manager, Contributions to the Geology of Wabasha County: Minnesota Geological Survey, Report of Investigations 59, p 38-46.

Tipping, R.G., Green, J.A., Alexander, E.C., Jr., 2001, Karst features, pl. 5 *in* Runkel, A.C., project manager, Geologic atlas of Wabasha County, Minnesota. Minnesota Geological Survey, County Atlas C-14, Part A, 7 pls., scale 1:100,000.

Tipping, R.G., Runkel, A.C., Alexander, E.C., Jr, and Alexander, S.C, 2006, Evidence for hydraulic heterogeneity and anisotropy in the mostly carbonate Prairie du Chien Group, southeastern Minnesota, USA: Sedimentary Geology, v. 184, p. 331-342.

Tipping, R.G., Runkel, A.C., and Gonzalez, C.M., 2010, Geologic investigation for portions of the Twin Cities Metropolitan area, I. Quaternary/Bedrock Hydraulic conductivity, II. Groundwater Chemistry: Metropolitan Council Water Supply Master Plan Development: Minnesota Geological Survey, Open File Report, 62 p.

U.S. Department of Agriculture, 2010, Farm Service Agency, Aerial Photography Field Office, National Agricultural Imagery Program (NAIP) Digital Orthorectified Images (DOQ), Minnesota: last accessed August 2014 at file:///V:/gdrs/data/pub/us_mn_state_dnr/base_2010_naip_orthophotos_tc/metadata/metadata.html.

U.S. Geological Survey and Minnesota DNR, 2006, 1:24k Digital Raster Graphic - Collars Removed: last accessed August, 2014 at file:///V:/gdrs/data/pub/us_mn_state_dnr/base_usgs_scanned_topo_024k_drg/metadata/metadata.html.

Wang, L., Lyons, J., and Kanehl, P., 2003, Impacts of urban land cover on trout streams in Wisconsin and Minnesota: Transactions of the American Fisheries Society, v. 132, p. 825-839.

Zhang, H., and Kanivetsky, R., 1996, Bedrock Hydrogeology, pl. 6, *in* Lively, R.S., and Balaban, N.H., eds., Geological atlas of Fillmore County, Minnesota: Minnesota Department of Natural Resources, Division of Waters, County Atlas Series C-08, Part B, 1:100,000.

Figures

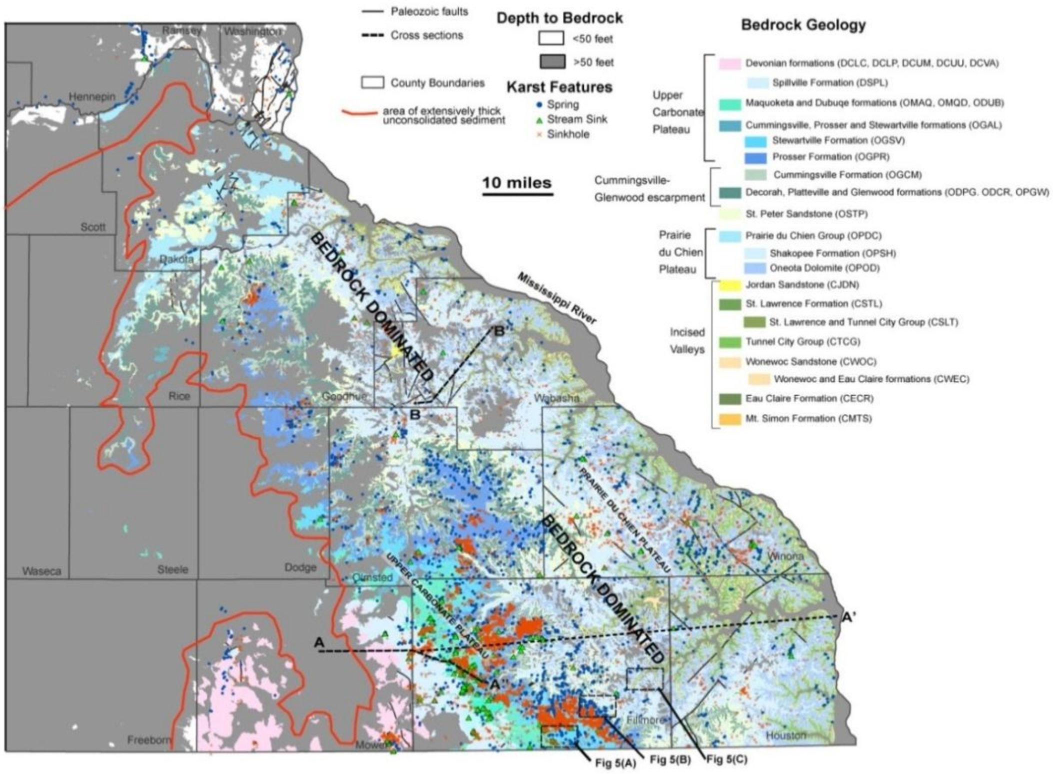


Figure 1. Generalized surfical geology of southeastern Minnesota showing first bedrock units and locations of karst features

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).

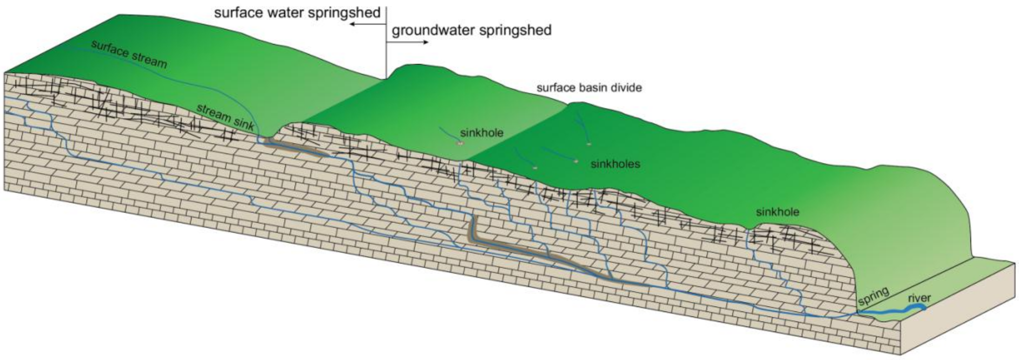


Figure 2. Springshed block diagram

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.

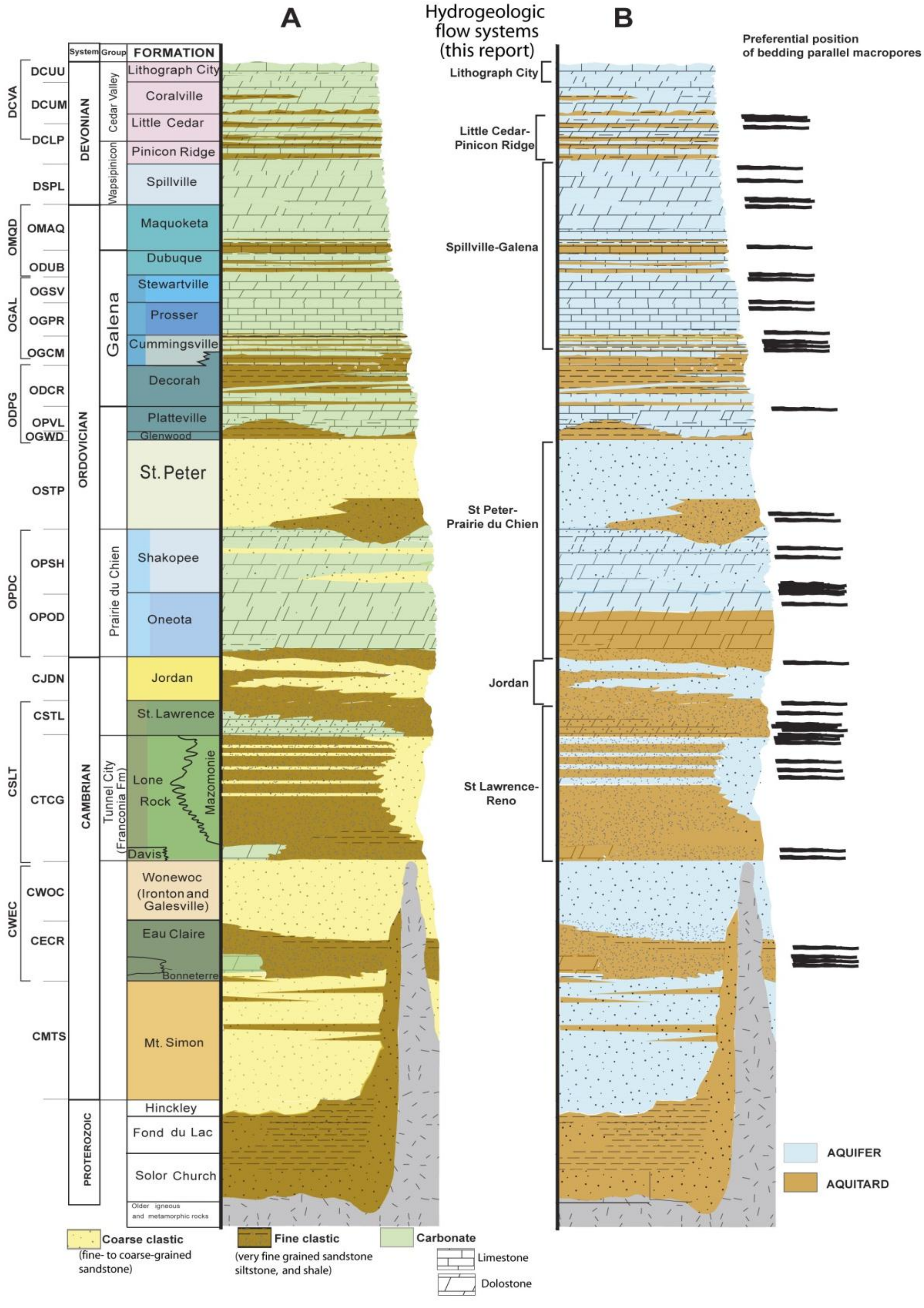


Figure 3. Stratigraphic columns for bedrock

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).

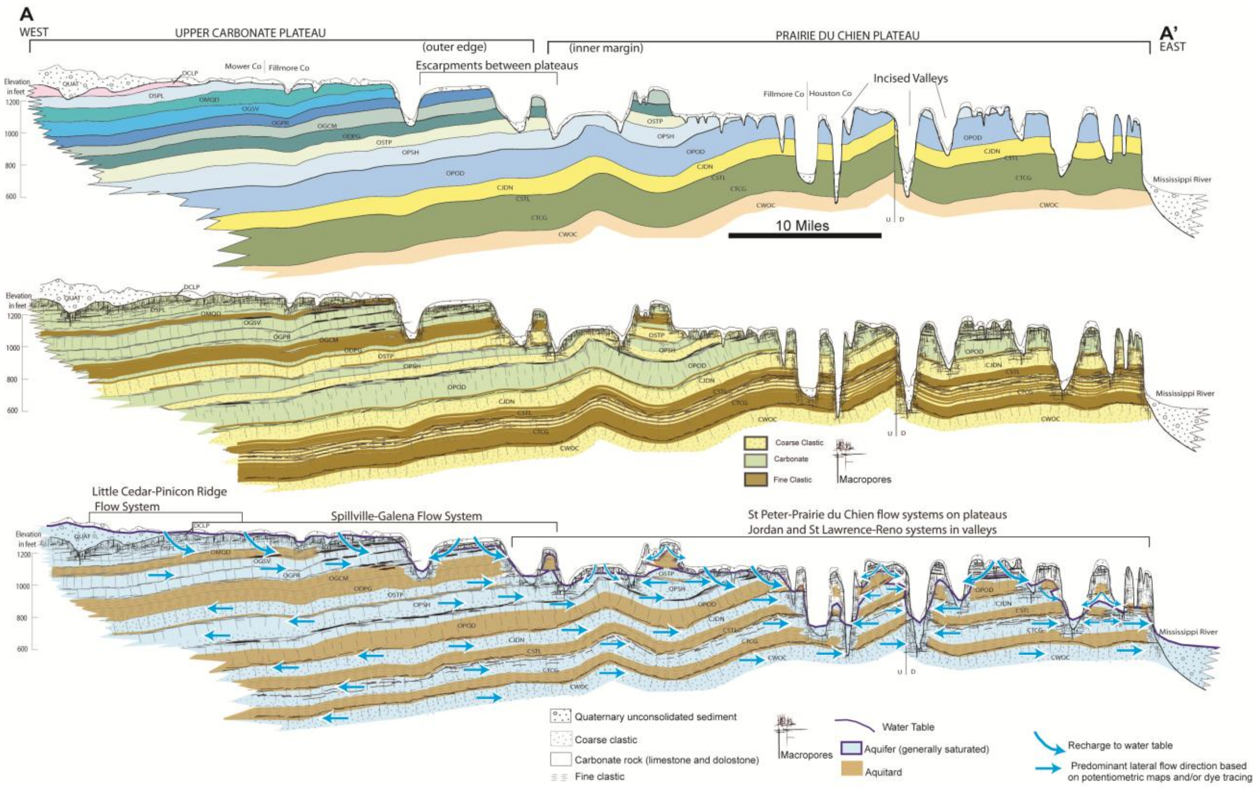


Figure 4. Regional cross sections

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).

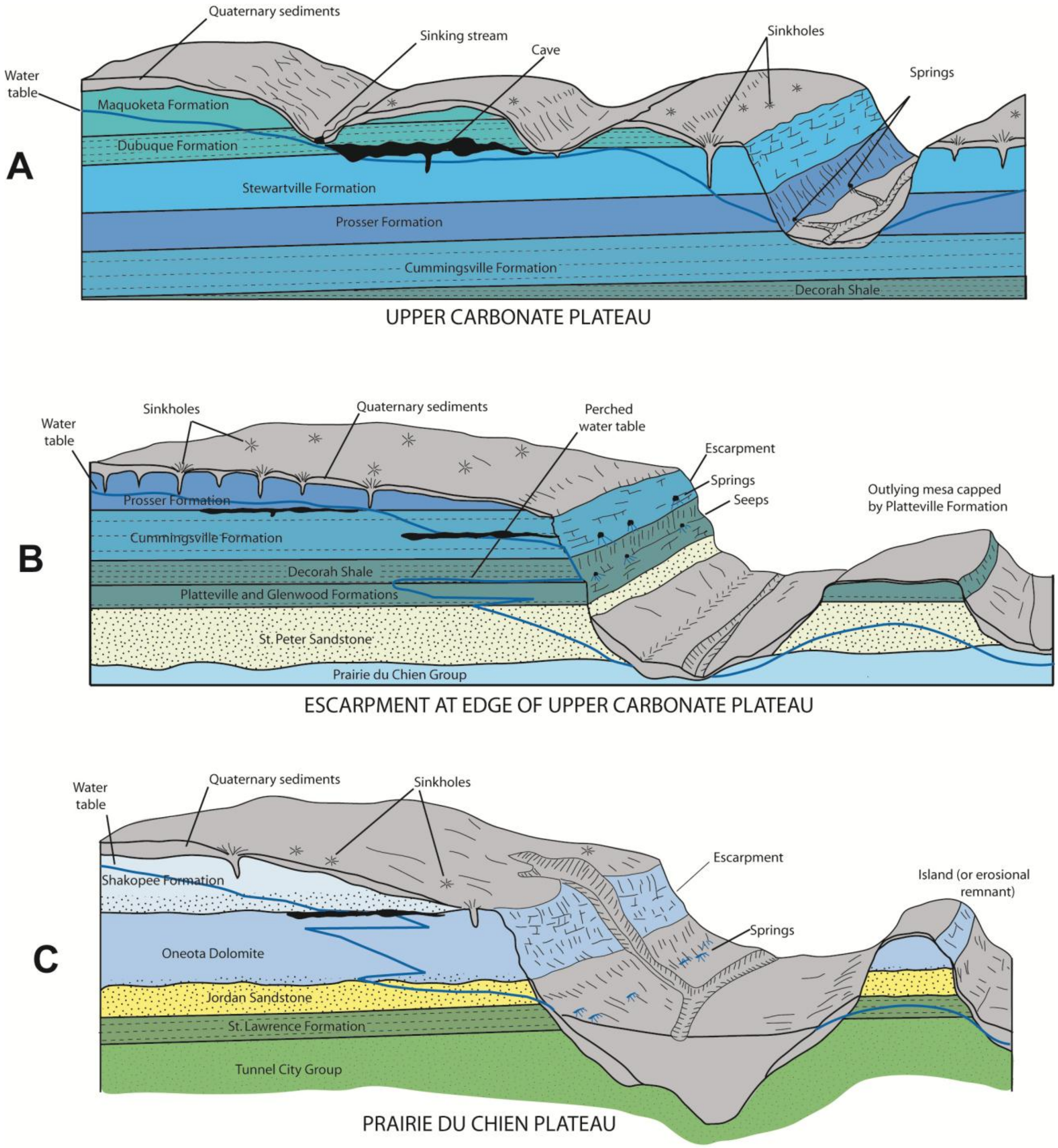


Figure 5. Block diagrams of typical landscape setting of bedrock units in southeastern Minnesota
Typical landscapes within the bedrock-dominated region of southeastern Minnesota with examples from the Upper Carbonate Plateau (A), its outer escarpment (B), and the Prairie du Chien Plateau (C). Each plateau 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).

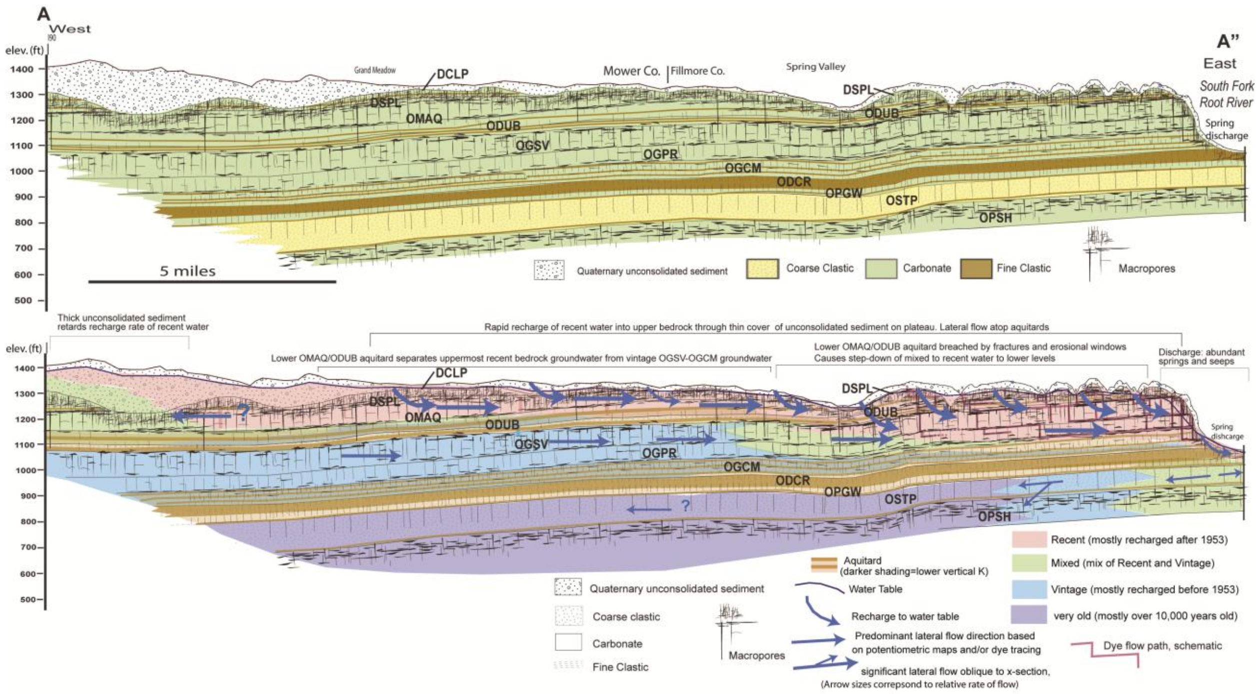


Figure 6. Cross sections, Mower to Fillmore counties

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).

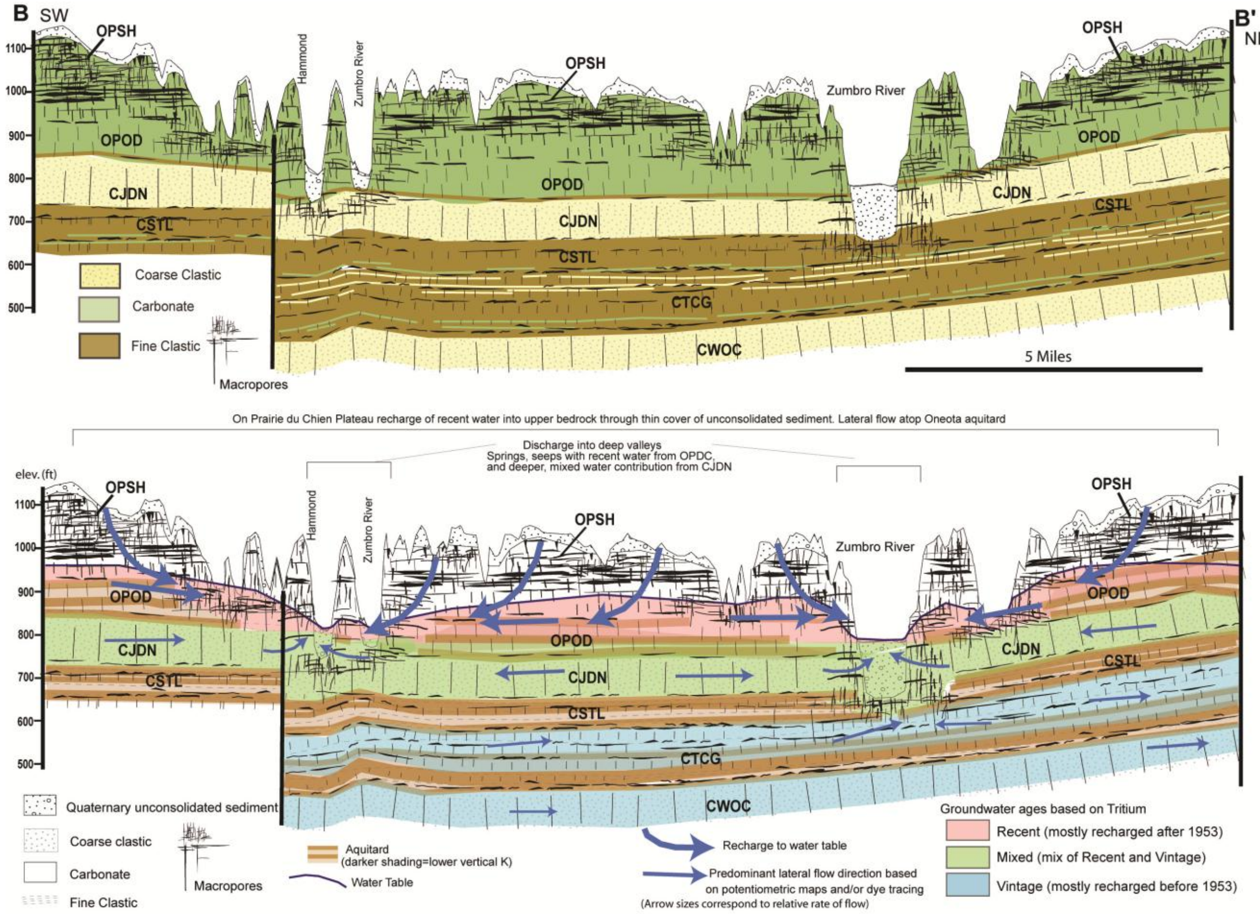


Figure 7. Cross sections, Wabasha County

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).

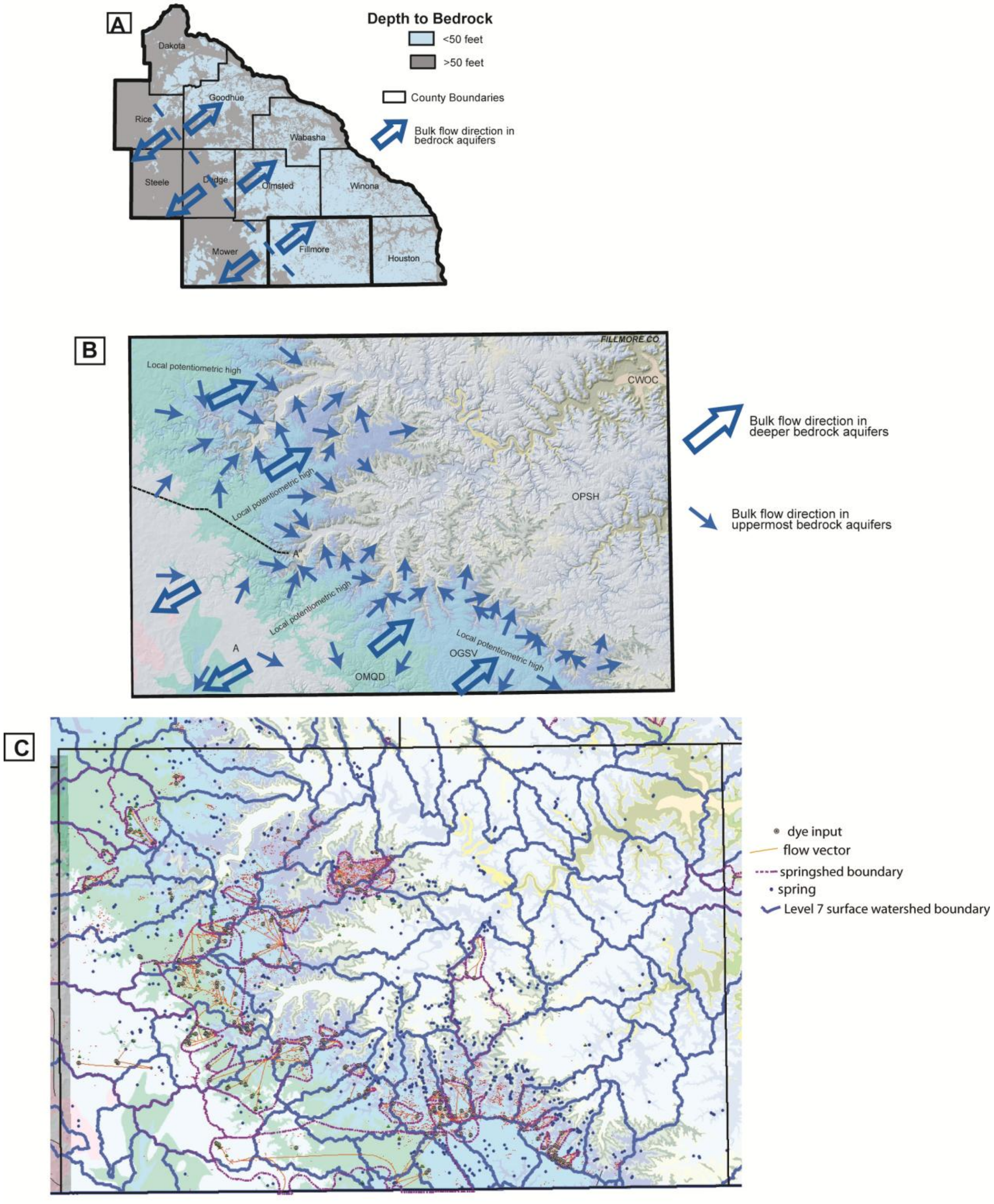


Figure 8. Groundwater flow directions

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).

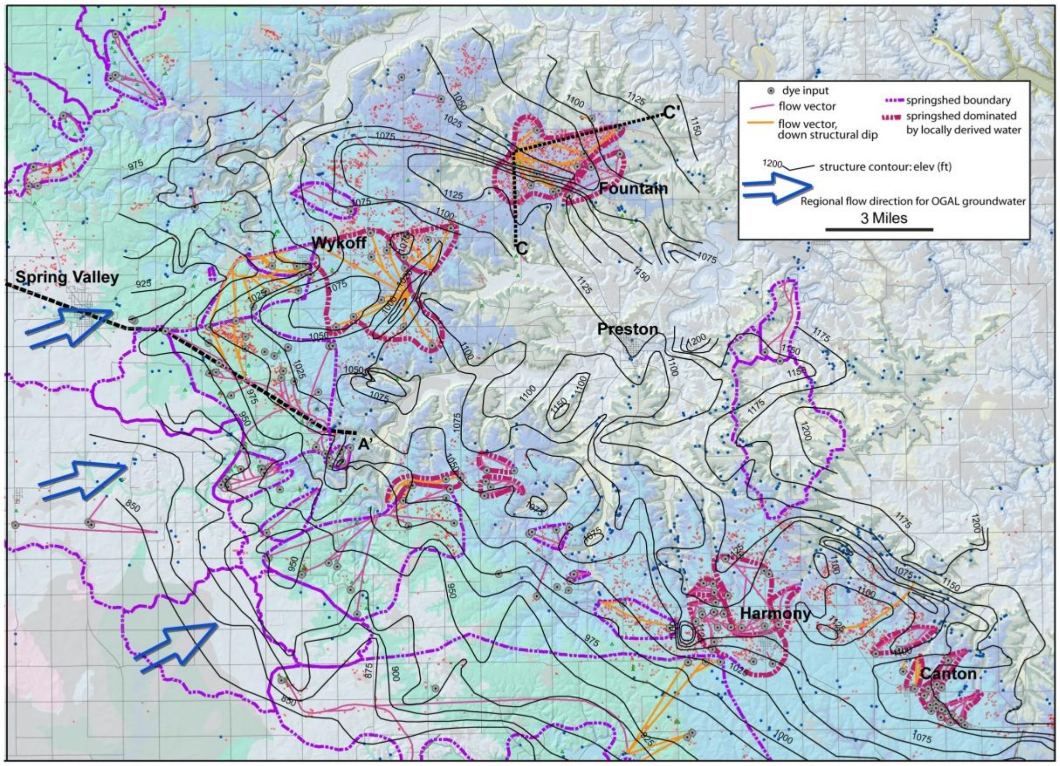


Figure 9. Springshed boundaries
Bedrock geology of part of Fillmore County highlighting a comparison of springshed boundaries, dye-trace flow vectors, and structure of the bedrock formations. The structure contours represent the elevation of the top of the St. Peter Sandstone. In some springsheds flow 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).

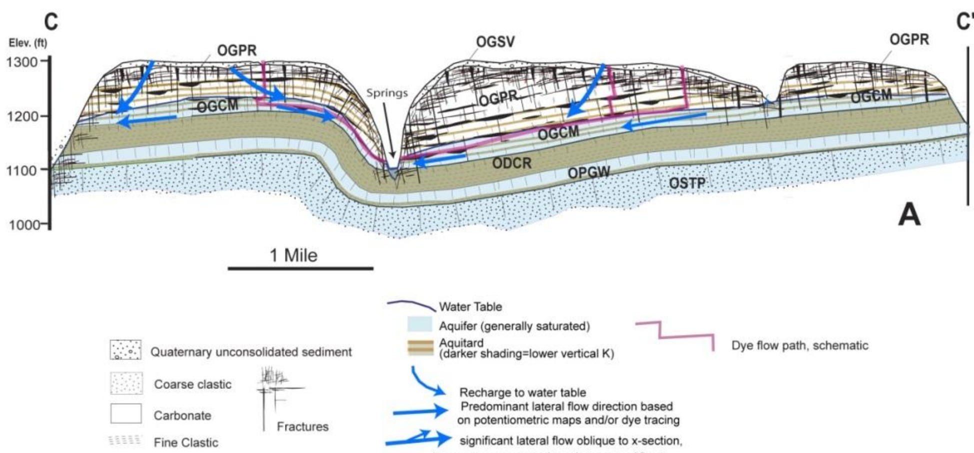


Figure 10. Cross sections showing flow down structural dip
Cross sections from western Fillmore County showing representative example of springshed where flow in uppermost bedrock is preferentially down the slope of folds in the bedrock (structural dip). The springshed at this location is also one in 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).

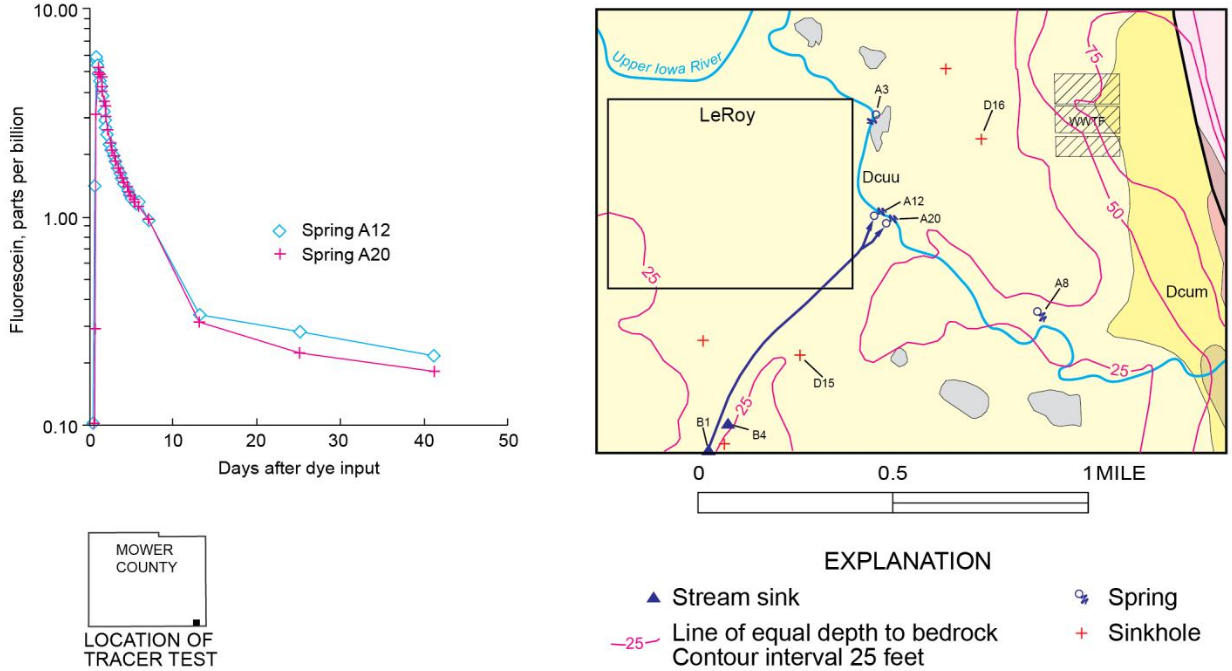
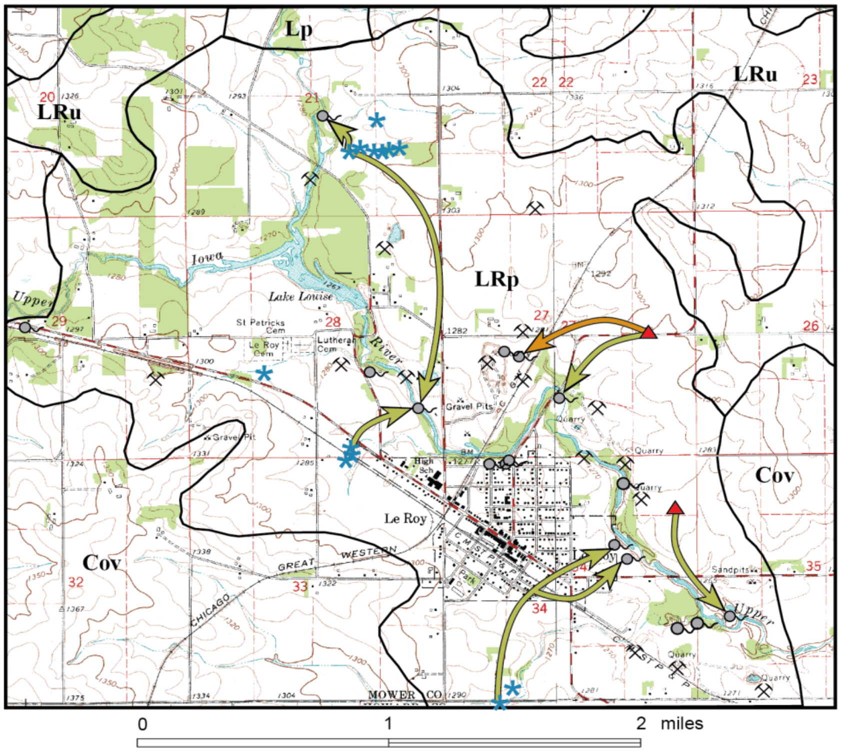


Figure 11. Dye trace result in the Lithograph City Formation.
Results of a dye trace performed in November 1997 in the Lithograph City Formation (DCUU) from Stateline Sink (MN50:B1) to Liftstation Spring (MN50:A12) and Gihon spring (MN50:A20). This dye breakthrough curve illustrates the karst-conduit-flow 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.

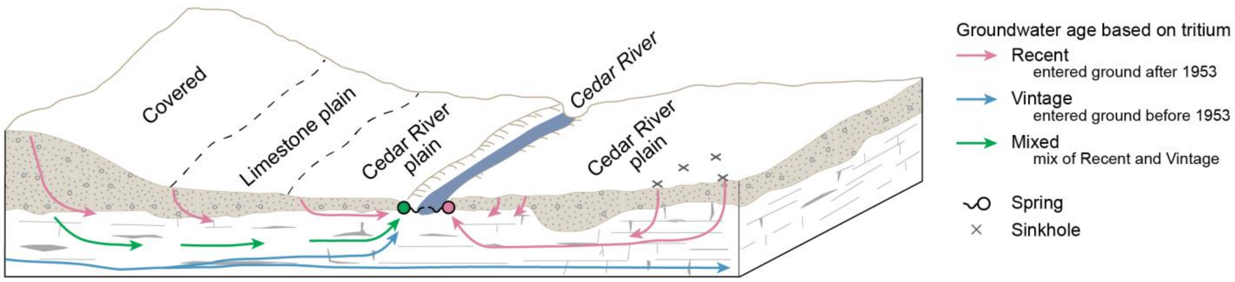


Figure 14. Groundwater age
Recent water is shown as pink, vintage (pre-1950) water, blue, and water that is a mixture, green. On the east side of the Cedar River, water moves from the land surface through sinkholes to ultimately discharge at springs. On the west side of the Cedar River, water moves through 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.

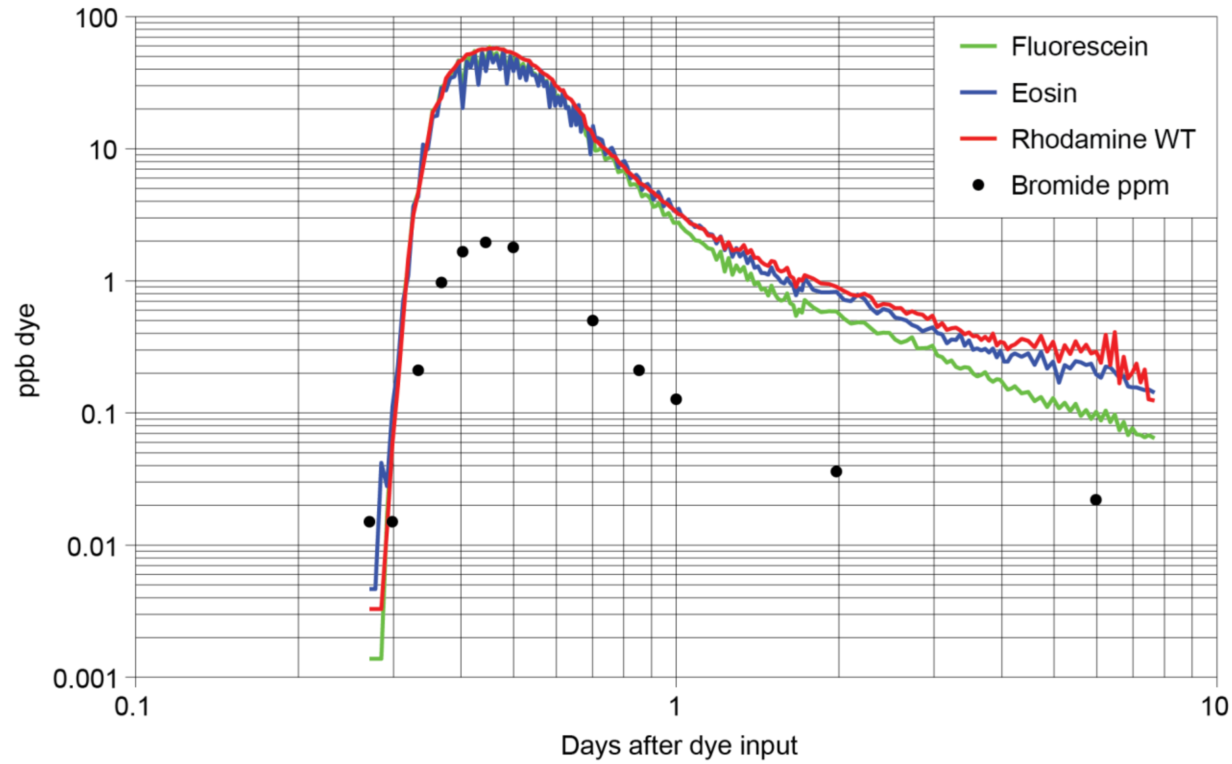


Figure 15. Dye-breakthrough curve for the Meyers springshed in the Galena limestone
This curve is typical of the response seen in Galena limestone groundwater springsheds. The breakthrough time, when dye is first detected is after six hours indicating a very direct conduit connection from the sinkhole to the spring. The peak was followed by a rapid drop in dye concentration which is typical of conduit flow in a karst aquifer.

A.  B. 

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).

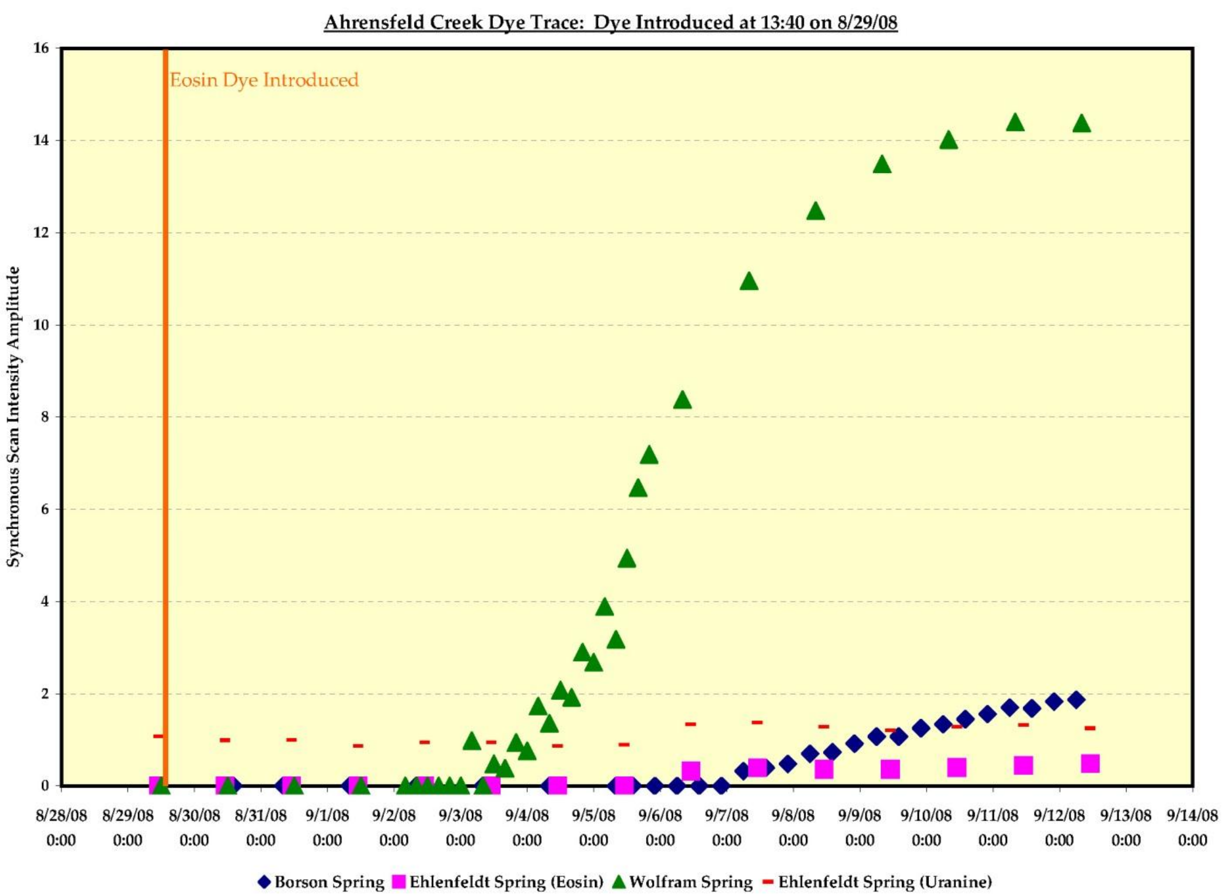


Figure 18. St. Lawrence dye-trace and dye-recovery curves
The dye breakthrough was in 6.5 days over a distance of 11,000 feet yielding a breakthrough velocity of over 1600 feet per day. This indicates that the leading-edge of the dye is moving through a well-developed conduit system.

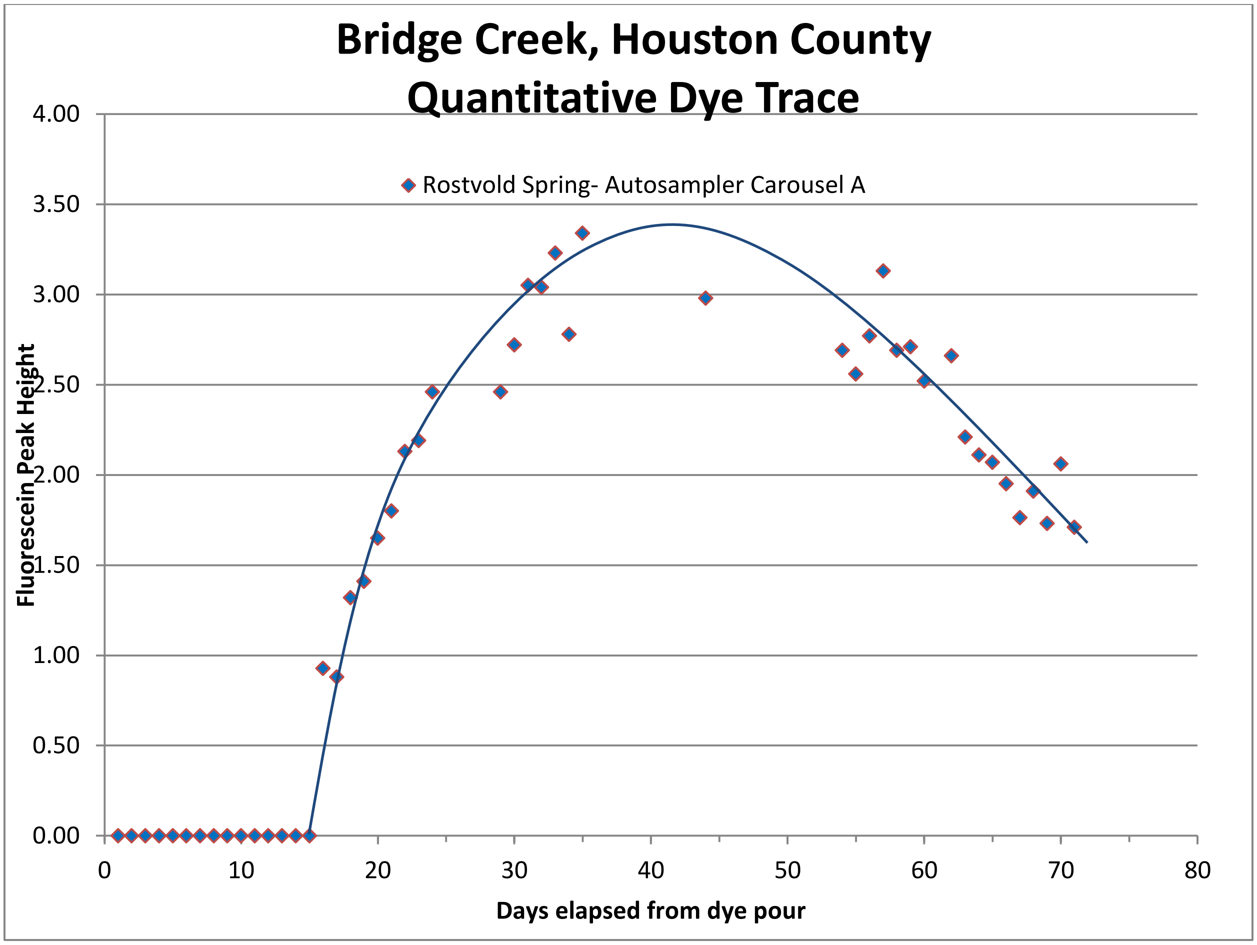


Figure 19. Tunnel City dye-trace and dye-recovery curve

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.

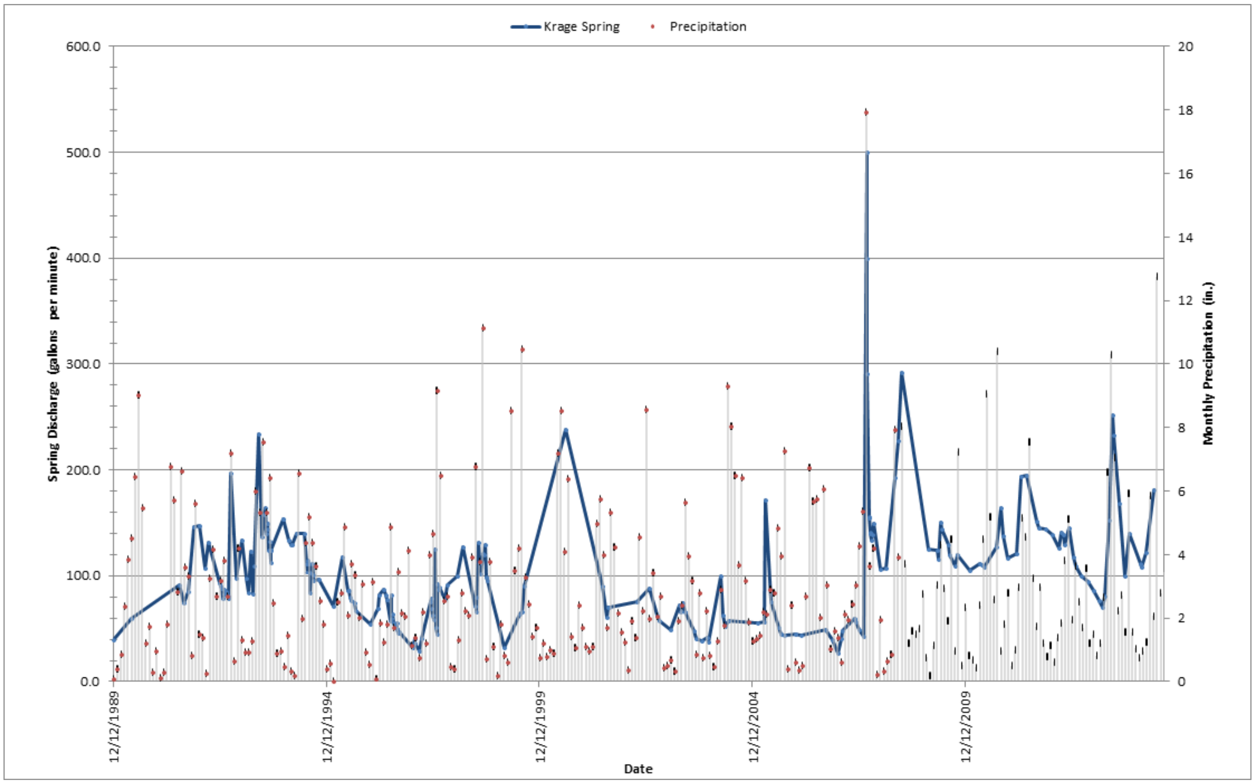


Figure 20. Krage spring discharge measurements

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.

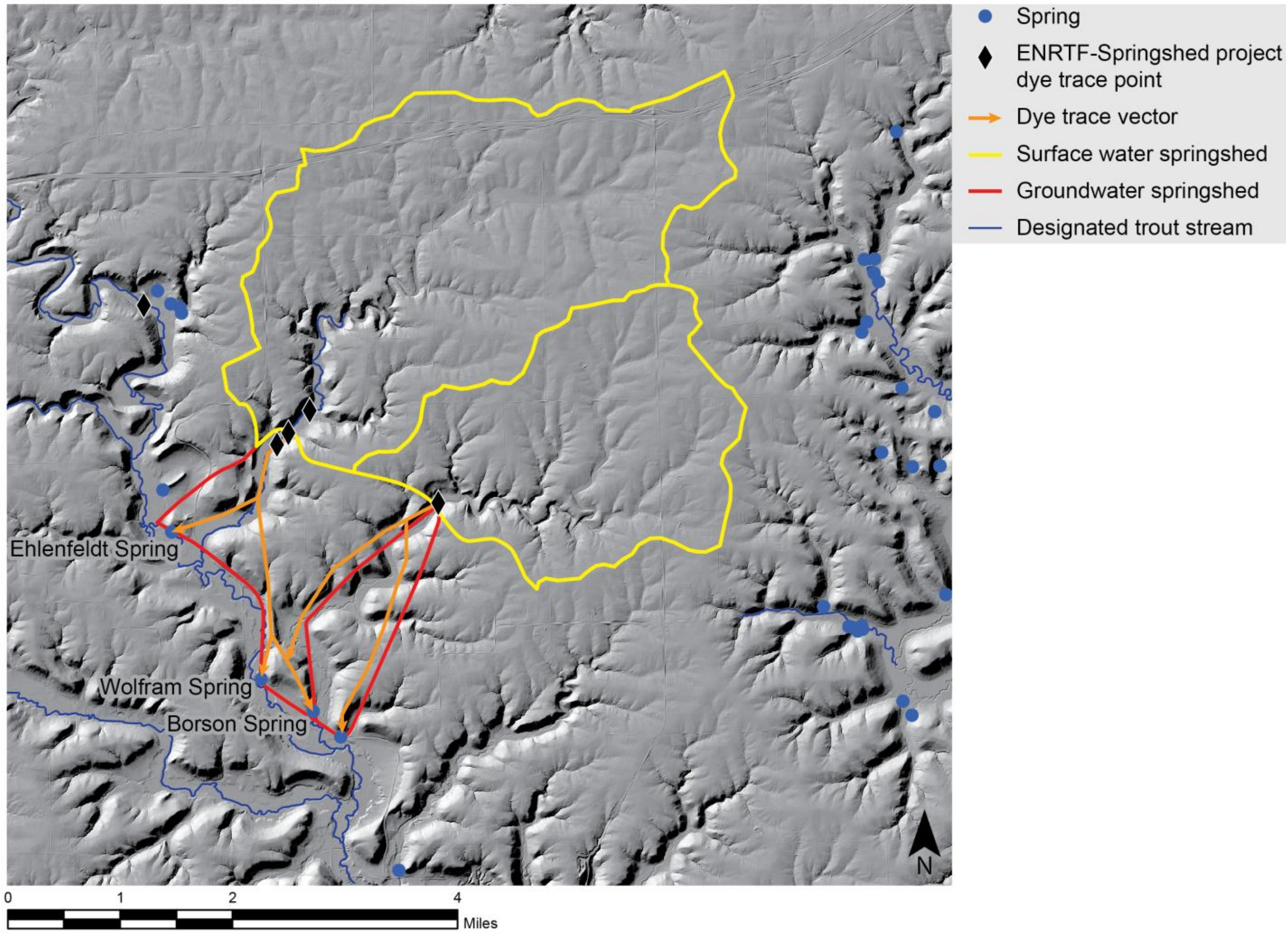


Figure 21. St. Lawrence springsheds in the Borson spring area

The surface water springsheds total over 8000 acres. Surface water flows into stream sinks that recharge the St. Lawrence Formation and its springs.

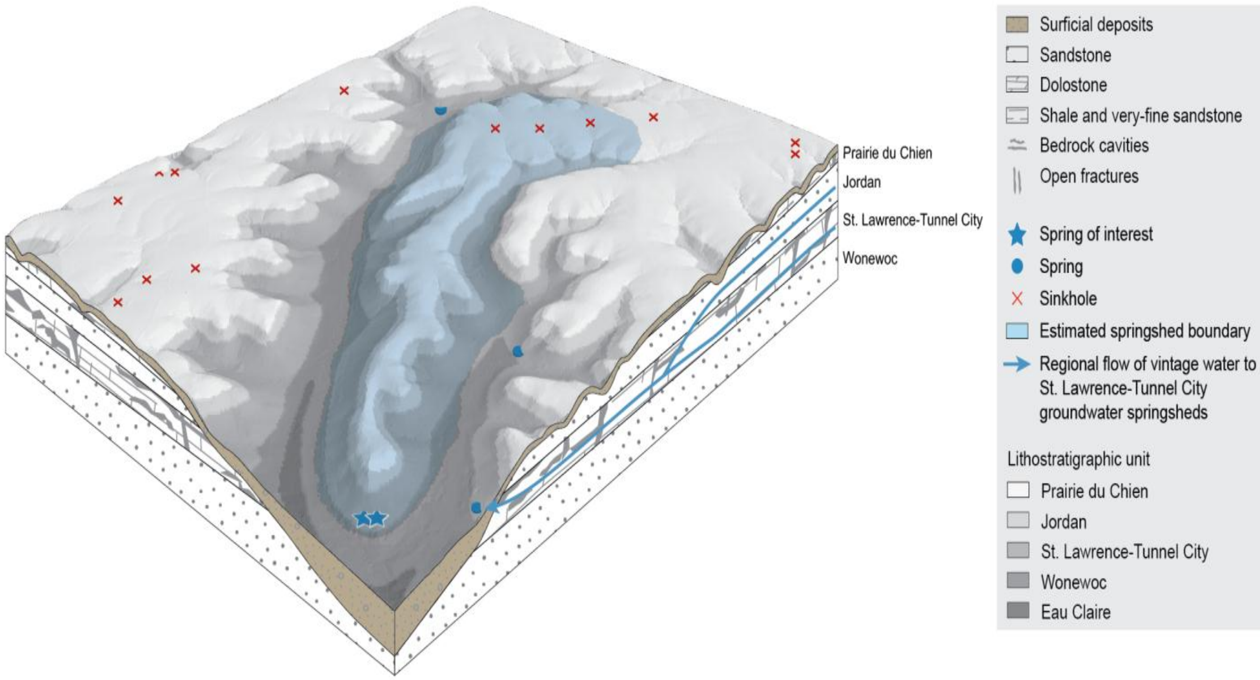


Figure 22. St. Lawrence/Tunnel City springshed estimation example
This is a diagrammatic depiction of the estimated springshed contribution area for a St. Lawrence or Tunnel City spring. Dye tracing in these formations has demonstrated that springs may receive groundwater that begins as surface water 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.

M.L. 2011 **Project Abstract**
For the Period Ending June 30, 2014

PROJECT TITLE: Trout Stream Springshed Mapping in Southeast Minnesota – Phase III
PROJECT MANAGER: Jeff Green
AFFILIATION: Minnesota Dept. of Natural Resources
MAILING ADDRESS: 3555 9th St NW, Suite 350
CITY/STATE/ZIP: Rochester, MN 55901
PHONE: 507-206-2853
E-MAIL: jeff.green@state.mn.us
WEBSITE:
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 05b1

APPROPRIATION AMOUNT: $ 220,000

Overall Project Outcome and Results

Trout streams depend on a steady supply of clean, cold water which comes from groundwater springs. These trout springs are under increasing pressure from changing land use, climate change, and groundwater withdrawals for domestic use, mining, agriculture, and energy production. Delineation of the recharge areas or springsheds of trout springs using dye tracing is a necessary first step in the conservation and protection of the trout stream coldwater supplies. This project focused on delineating groundwater springsheds both in the Galena Group limestone karst areas of Fillmore and Olmsted counties, where this work has been done for over 30 years, and in the Cambrian St. Lawrence Formation and Tunnel City Group bedrock across southeast Minnesota. Prior to this project, no springsheds had been delineated in the St. Lawrence or Tunnel City bedrock units. We demonstrated that springs discharging from these units receive surface water recharge from sinking streams and that this recharge moves hundreds of feet per day through the bedrock. This has rewritten our understanding of the hydrology of southeast Minnesota and has demonstrated that these springs, which we formerly believed to be well-protected from land surface activities, are much more vulnerable than we previously realized. Overall, during this project we mapped 41 groundwater springsheds (delineated by dye tracing) and 54 surface water springsheds (surface watersheds sending water to a point where it sinks underground into a groundwater springshed). Twelve of the groundwater springsheds and sixteen of the surface water springsheds are in the St. Lawrence Formation and Tunnel City Group. The groundwater springshed delineated areas total 50,708 acres and the surface water delineated areas total 124,447 acres. Prior to this project there was a total of 54,091 acres of both springshed types delineated. Springsheds were delineated in Dakota, Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Wabasha and Winona counties.

Project Results Use and Dissemination

Information from this project was widely disseminated. A map of the delineated springsheds and a document on Spring Assessment Protocols were produced and submitted to the LCCMR and will be published by the Minnesota Geological Survey. The springshed coverage is being used by state and local governments to target areas for conservation efforts and for Clean Water Fund project ranking. The springshed mapping will be used by the DNR for Silica Sand Mining Trout Stream Setback permitting and in Water Appropriation permit review.

Project information was presented to numerous groups including the SE MN Water Resources Board, Root River Technical Advisor Group, Fillmore County Local Water Planning committee, Southeast Minnesota County and State Feedlot officers, Midwest Federal Agency Senior Managers, and at Silica Sand mining forums in Red Wing, Lewiston, La Crescent, and Winona.

On the ground information was presented during tours of the southeast; groups that went “on tour” include Minnesota Groundwater Association, MPCA/DNR field staff, SE Minnesota water advocacy groups, Geological Society of America, Minnesota Association of Professional Soil Scientists, and state and federal agency staff from Minnesota, Iowa, and Wisconsin.

A paper on the St. Lawrence tracing work has been was published in the journal Carbonates and Evaporites. The springshed mapping work was the subject of two stories on Minnesota Public Radio. Project results were presented at numerous scientific meetings including the 11th and 12th Multidisciplinary Conference on Sinkholes and the Environmental and Engineering Aspects of Karst, the Minnesota Groundwater Association, the Midwest Groundwater Conference, the Geological Society of America, The Driftless area Symposium, and at a Winona State University Geology Department seminar.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2011 Final Report

Date of Status Update: 9/15/2014
Date of Next Status Update: Final Report
Date of Work Plan Approval: 6/23/2011
Project Completion Date: 6/30/2014 **Is this an amendment request?** Yes

Project Title: Trout Stream Springshed Mapping in Southeast Minnesota – Phase III

Project Manager: Jeff Green
Affiliation: MN DNR
Address: 3555 9th St NW
City: Rochester **State:** MN **Zipcode:** 55901

Telephone Number: (507) 206-2853
Email Address: jeff.green@state.mn.us
Web Address:

Location:

Counties Impacted: Dakota, Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Rice, Wabasha, Washington, Winona

Ecological Section Impacted: Paleozoic Plateau (222L)

Total ENRTF Project Budget:	**ENRTF Appropriation $:**	220,000
	Amount Spent $:	218,341
	Balance $:	1,659

Legal Citation: M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 05b1

Appropriation Language: $250,000 the first year and $250,000 the second year are from the trust fund to continue to identify and delineate water supply areas and springsheds for springs serving as cold water sources for trout streams and to assess the impacts from development and water appropriations. Of this appropriation, $140,000 each year is to the Board of Regents of the University of Minnesota and $110,000 each year is to the commissioner of natural resources.

I. PROJECT TITLE: Innovative Springshed Mapping for Trout Stream Management-Continuation (DNR)

II. FINAL PROJECT STATEMENT:
Trout streams depend on a steady supply of clean, cold water which comes from groundwater springs. These trout springs are under increasing pressure from changing land use, climate change, and groundwater withdrawals for domestic use, mining, agriculture, and energy production. Delineation of

the recharge areas or springsheds of trout springs using dye tracing is a necessary first step in the conservation and protection of the trout stream coldwater supplies. This project focused on delineating groundwater springsheds both in the Galena Group limestone karst areas of Fillmore and Olmsted counties, where this work has been done for over 30 years, and in the Cambrian St. Lawrence Formation and Tunnel City Group bedrock across southeast Minnesota. Prior to this project, no springsheds had been delineated in the St. Lawrence or Tunnel City bedrock units. We demonstrated that springs discharging from these units receive surface water recharge from sinking streams and that this recharge moves hundreds of feet per day through the bedrock. This has rewritten our understanding of the hydrology of southeast Minnesota and has demonstrated that these springs, which we formerly believed to be well-protected from land surface activities, are much more vulnerable than we previously realized. Overall, during this project we mapped 41 groundwater springsheds (delineated by dye tracing) and 54 surface water springsheds (surface watersheds sending water to a point where it sinks underground into a groundwater springshed). Twelve of the groundwater springsheds and sixteen of the surface water springsheds are in the St. Lawrence Formation and Tunnel City Group. The groundwater springshed delineated areas total 50,708 acres and the surface water delineated areas total 124,447 acres. Prior to this project there was a total of 54,091 acres of both springshed types delineated. Springsheds were delineated in Dakota, Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Wabasha and Winona counties.

III. PROJECT STATUS UPDATES:

Project Status as of 15 January 2012
Work began in July after the end of the government shutdown. GIS and field reconnaissance has identified numerous locations that are potential dye trace targets. Landowners are being contacted and there are several areas where traces are being planned. Six dye traces were run in three different springsheds. These traces have resulted in expanded boundaries of one springshed and the identification of a previously unmapped springshed. The spring-temperature/conductivity effort is being reviewed & adjusted to use sites with better access. This will allow us to check the sites more frequently to verify that the equipment is working adequately.

Project Status as of 15 July 2012
During the winter months, work was started on producing 1:100000 scale springshed maps to be published by the Minnesota Geological Survey. This would allow for wider dissemination of the project's mapping efforts. Numerous requests came in from counties for information and assistance on frac sand mining issues. This was an opportunity to apply the work from the ENRTF- Hydraulic Impacts of Quarries and Pits project report and discuss the impacts of frac sand mining on springs and springsheds. The lack of snow precluded snowmelt dye tracing in the spring. This was a serious setback as we normally do 4-6 snowmelt traces in several different springsheds. The snowmelt traces also can be run from sinkholes that are inaccessible to water tanker trucks. GIS and field reconnaissance has identified numerous locations that are potential dye trace targets. A triple trace was run to refine springshed boundaries and identify a new springshed. Temperature/conductivity sensors were deployed in eleven springs.

Amendment Request 9/20/2012
This is a request to move funds from fleet expenses into the equipment category. We need to purchase equipment for measuring spring temperature, conductivity, and discharge. This equipment is needed to characterize springs. The equipment will be used going forward in this project and in our future springshed mapping and spring assessment work. Funds are available in the fleet budget since the drought has cut down on our field work.

Amendment Approved 10/8/2012

Project Status as of 15 January 2013

The project moved forward with significant time spent on field work and data management. The on-going drought is having a very negative impact on our ability to do dye tracing. The low flows in springs and lack of recharge events made it difficult to run traces and it kept background dye levels elevated in springsheds where we had planned to do additional traces. In spite of these obstacles, one dual and four single dye traces were run to identify new springsheds. GIS and field recon identified additional sites for dye traces in the St. Lawrence formation. The temperature and conductivity spring monitoring network was maintained and several springs were also measured for flow volume. The St. Lawrence dye tracing work was presented at the Midwest Groundwater Conference in Minneapolis in October.

Amendment Request 4/15/2013:
To extend the project completion date one year, from June 30, 2013 to June 30, 2014, to coincide with the availability of the appropriation under M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 11 and to extend outcome completion dates accordingly. Extension of deadlines is needed, as project activities have not been completed and project funds have not been expended at the rate anticipated in the original work program due to the state shutdown. The extensions will not change any of the project outcomes.

Amendment Approved 4/30/2013

Project Status as of 15 July 2013
Field, office and GIS work continued on the project. Seven dye traces (two triple traces and one single trace) were run to refine or expand springshed boundaries and identify new springsheds. The single trace was our first attempt at dye introduction into the Cambrian Tunnel City Group. Sampling for these traces and traces started in November and December 2012 was a high priority. GIS and field recon identified additional sites for dye traces in the St. Lawrence and Tunnel City. The temperature and conductivity spring monitoring network was maintained and several springs were also measured for flow volume. The first draft of the Spring Assessment Protocols (project deliverable) was completed and is in the editing/revision phase. A method to delineate surface springsheds (land surface areas that contribute water to sinkholes and stream sinks) was developed with support from DNR GIS staff. This methodology was used to delineate surface springsheds across southeast Minnesota.

Amendment Request 10 Sept. 2013
In order to continue doing field work, this is a request to move funds from Equipment into Supplies to purchase dyes and sampling materials and to move funds from Vehicle Costs into Meals and Lodging.

Amendment Approved 9/9/2013

Project Status as of 15 January 2014
Field, office and GIS work continued on the project. A major focus was a dual dye trace that was run to delineate new springshed boundaries and focus in on characterizing flow in the Cambrian St. Lawrence Formation and Cambrian Tunnel City Group. This trace was conducted with automatic water samplers to provide greater detail on groundwater travel times. GIS and field recon identified additional sites for dye traces in the St. Lawrence and Tunnel City. The temperature and conductivity spring monitoring network was maintained and flow monitoring continued at our long-term spring flow monitoring site in southern Winona County. The editing and revising of the Spring Assessment Protocols continued with the goal of releasing them as a MGS publication.

Final Report Summary: 15 September 2014
A dual dye trace was conducted in the Galena karst of Olmsted County in cooperation with the Olmsted County SWCD. The focus of work was the production of the Spring Assessment Protocols and a springshed map of southeast Minnesota. The end-of-project final documents were prepared.

Amendment Request 15 September 2014

In order to balance final total expenditures, this is a request to move funds from Equipment into DNR Fleet Vehicle Costs and Meals & Lodging for Fieldwork.

Amendment Request Approved retroactively by the LCCMR 9-25-2014

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Innovative Trout Springshed Maps and Reports

Description: Springsheds that feed source springs of trout streams will be delineated in the Galena, Prairie du Chien, and St. Lawrence karst lands. Maps of the springsheds will be transferred to the U of M for web posting and will be linked to the DNR web site. The existing temperature-monitoring network will be maintained and expanded as equipment and sites are available. The results of our dye tracing, spring monitoring, and hydrostratigraphy investigations will be used to develop spring assessment protocols. This is a cooperative project with the U of M Geology Dept. DNR is the lead on dye tracing investigations and spring temperature and conductivity monitoring. The U of M is the lead on dye trace analysis and spring turbidity monitoring. U of M staff will be doing dye traces in selected areas and both DNR and U of M staff will be developing the spring assessment protocols.

Summary Budget Information for Activity 1:

ENRTF Budget:	**$ 220,000**
Amount Spent:	**$ 218,341**
Balance:	**$ 1,659**

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
1. Innovative Trout Springshed Maps and Reports (Conduct dye traces and field investigations for springshed map production, maps and reports of completed traces and spring parameter monitoring including spring assessment protocol development).	30 June 2014	$220,000

(See also the companion U of M project work program Activity 1)

Activity Status as of 15 January 2012

Extensive GIS and field reconnaissance work has resulted in the identification of several promising areas for dye tracing. These areas are in the counties of Fillmore, Goodhue, Houston, Wabasha and Winona. Six dye traces have been conducted in three separate springshed areas in Winona and Fillmore. A single trace was conducted near the Crystal Springs State Fish Hatchery operated by the DNR. The hatchery is supplied by two springs emanating from the Cambrian St. Lawrence formation. A stream southeast of the hatchery has been identified as a sinking stream. In August, it was sinking at or near the top of the St. Lawrence at a point ½ mile from the hatchery. A dye trace was done from this sinking point. In less than three weeks, the dye was detected at one of the hatchery springs; this is a newly identified springshed. The knowledge that one of their springs is connected to surface runoff will be used by hatchery staff for emergency planning. Five dye traces were conducted in the Galena karst of Fillmore County. A dual trace north of Wykoff expanded the boundaries of two existing springsheds. This work is supporting the watershed management efforts of local governments in the Watson Creek watershed. A triple trace was conducted in the Crystal Creek watershed west of Harmony. This work is expanding the boundaries of three springsheds. These trace results will be used by MDA as they work with farmers in the watershed to investigate runoff & tillage practices. Field recon emphasized finding St. Lawrence sites in Goodhue, Houston, Wabasha and Winona. Several sites with high potential for tracing were identified. The spring monitoring work (part of spring assessment methodology development) is continuing.

Activity Status as of 15 July 2012
A triple dye trace was run near Fountain in the Galena karst of Fillmore County. This work expanded the boundaries of two known springsheds and we identified one new springshed. Field and GIS recon work has been continuing in the Galena karst in Fillmore for the purposes of springshed boundary refinement and identification of new springsheds. A significant amount of time has been spent on GIS and field recon work to locate St. Lawrence sites in the counties of Wabasha, Winona and Houston. Five sites have been identified that are strong candidates for running dye traces. A potential site for a Prairie du Chien limestone dye trace was identified near Caledonia, MN in Houston County. Prairie du Chien traces have historically been problematic due to the chance of long (6-12 months) flow times; this site has the advantage of being quite accessible which cuts down on the time required for sampling. A St. Lawrence dye trace in the South Branch of the Whitewater River was designed and set-up; this trace is being run to determine if the South Branch is leaking into the St. Lawrence Formation and builds on two previous St. Lawrence traces conducted in tributaries to the South Branch. The temperature & conductivity loggers were deployed at springs discharging from the Prairie du Chien, St. Lawrence and Franconia formations. Six of the loggers were deployed at the three DNR Fish Hatcheries in southeast MN. The dye trace planning work and logger deployment has been coordinated with the U of M project partners. At the various frac sand meetings, detailed results from the ENRTF- Hydraulic Impacts of Quarried and Pits project were presented. The section in that report which gives guidance to local governments on information requirements for site review was highlighted as being of particular relevance to the frac sand mining debate. The potential for mines to effect springs was discussed as was the potential for mines to alter groundwater quantity and quality in springsheds.

Activity Status as of 15 January 2013
A dual dye trace was run northeast of Wykoff in the Galena karst of Fillmore County. These traces were run in the Shady Creek watershed. Shady Creek is a designated trout stream where no previous springshed mapping had been done. Both traces were recovered and two new springsheds were identified. This work will be used to design snowmelt traces this spring (assuming we receive adequate snow to provide runoff) to expand and refine the springshed boundaries. A significant amount of time has been spent on GIS and field recon work to locate St. Lawrence sites in the counties of Wabasha, Winona and Houston. As a result of that work, four dye traces were performed in the St. Lawrence during this reporting period. Three other sites that hold strong potential for St. Lawrence dye tracing were also identified. A St. Lawrence dye trace in the South Branch of the Whitewater River was run to determine if the South Branch is leaking into the St. Lawrence Formation. No dye was detected at any springs; this fits with previous work done on Rush Creek and demonstrates that the St. Lawrence is not being recharged from main-stem streams. A dye trace was run on Gilbert Creek in far northern Wabasha County. Gilbert Creek does not disappear totally into the St. Lawrence Formation but we believed it was leaking into it. Dye was detected at a spring tributary to the creek. This trace extends the geographic range of the St. Lawrence conduit flow/valley recharge phenomena significantly. A St. Lawrence trace was begun in late December at Bridge Creek in Houston County. No samples have yet been analyzed. The most significant dye trace was run at Campbell Valley Creek in southern Winona County. Dye was poured into a small pool that sinks into the top of the St. Lawrence Formation. Dye was recovered one month later at basal St. Lawrence springs and from springs discharging from the Tunnel City Formation. This is the first time we have recovered dye from the Tunnel City. This trace demonstrates that conduit flow exists in the Tunnel City and that it can be hydraulically connected to the St. Lawrence. This is highly significant as we believed the Tunnel City had some measure of separation (and protection) from surface sources. Spring monitoring and spring flow measurement is an on-going part of the project. This work will be incorporated into the spring assessment methodology which is under development. In September of 2012, the project budget was amended to provide additional money for equipment purchases. With those funds, a field-grade temperature/conductivity meter was purchased for use in spring characterization.

Activity Status as of 15 July 2013
A single dye trace was run at Bridge Creek in Houston County in late December in cooperation with the MN Dept. of Agriculture (MDA). Bridge Creek is one of their watershed study sites. The sampling for

that trace began during this reporting period. The creek was sinking into the middle part of the St. Lawrence formation. The dye was detected at several sites. The strongest dye signal (indicating the most direct connection) was at a Tunnel City spring 2.5 miles from the sinking point. This spring discharges from the upper part of the Tunnel City and is on the opposite side of a prominent ridge from the sinking point. The dye traveled the 2.5 miles in 20-40 days. Dye was also detected in a domestic well ½ mile from the sinking point. This trace is the second example of dye from a St. Lawrence stream sink moving through the St. Lawrence into the Tunnel City. At Campbell Valley in southern Winona County, the first St. Lawrence to Tunnel City trace, sampling continued. We also ran a second trace from a point upstream of where Campbell Valley creek disappears into what we believe is the Tunnel City formation. Based on this second trace, and the sampling from the St. Lawrence trace, the dye we introduced into the St. Lawrence is moving all the way through it and down through the Tunnel City to springs that discharge from the lower part of the formation. The Campbell Valley trace and the Bridge Creek trace are highly significant. They are the first traces ever done that demonstrate a connection between surface water and Tunnel City springs. We know now that these springs are much more vulnerable than previously believed and this work furthers our understanding of their hydrology.

Two triple traces were run using snowmelt runoff in the Crystal Creek watershed and the Watson/Forestville creek watershed in the Galena karst of Fillmore County. One of the traces at Crystal Creek was the first to the headwater spring of the creek so we have now begun to delineate that springshed. The other traces there and at Watson/Forestville refined known springshed boundaries. The Crystal Creek traces were run in cooperation with the MDA and the Watson/Forestville trace was run in cooperation with the Fillmore SWCD to support their watershed management activities. The spring monitoring network of Solinst level-temperature conductivity loggers captured several runoff events of significance at Crystal Spring state Fish Hatchery and at several sites in Houston and Fillmore County. These data are still being reviewed. Flow measurements at several springs were obtained to continue our work of comparing flow volumes to spring geology and springshed type and size. The first draft of the Spring and Springshed Assessment protocols (project deliverable) was completed and sent to the project partners for review and editing. A GIS method was developed using the DNR catchment tool to delineate surface (allogenic) springsheds. These springsheds contribute surface flow to stream sinks and sinkholes. The tool was used to delineate these areas that feed runoff water to the sinking points that are tied to subsurface basins that have yet to be mapped. This information will help future mapping efforts and will be useful for state and local resource managers.

Activity Status as of 15 January 2014

A dual dye trace was run at Bridge Creek and Girl Scout Camp Creek in western Houston County. The Bridge Creek trace was built upon a previous trace from a sinking point in the creek and was run in cooperation with the MN Dept. of Agriculture (MDA). Bridge Creek is one of their watershed study sites. At the time of the second Bridge Ck. trace, the stream was sinking 0.5 miles upstream from the point of our previous trace. At the first Bridge Creek trace, the dye went into the middle portion of the St. Lawrence Formation and went under a broad ridge to an upper Tunnel City Group spring. In order to learn more about groundwater flow times and the conduit system carrying the flow, the second trace was done using programmable automatic water samplers. The automatic samplers allowed us to construct a breakthrough curve and determine that the groundwater was moving at a horizontal rate of 1,024 ft. /day. This speed is consistent with flow through karst conduits and is another data point in our characterization of the St. Lawrence and Tunnel City as karst-conduit aquifers in valley settings. The dye trace on Girl Scout Camp Creek was also a St. Lawrence sinking stream investigation. Girl Scout Camp Creek has a remnant population of native brook trout and thus is of high interest to our DNR Fisheries staff. A tributary to the main stem of the creek sinks into the top of the St. Lawrence Formation; that was where we introduced dye. The dye was recovered at a St. Lawrence a spring and at an upper Tunnel City spring making this the third place where have documented the connection between Tunnel City springs and surface stream recharge. GIS and field work identified several additional St. Lawrence/Tunnel City sinking points. Those points are potential dye tracing locations. Flow measurement data continued to be collected. Considerable time and effort was spent on editing and expanding the Spring Assessment Protocols and on doing basic work for the development of dye trace reports for the many dye traces done during the life of this project.

Final Report Summary: 15 September 2014
Much significant work was accomplished during this project. The existing springshed mapping in the Galena Group limestone karst of Fillmore and Olmsted counties was expanded significantly. Dye traces were run and springsheds identified in the Prairie du Chien Group karst of Dakota and Winona counties. Fourteen dye traces were conducted in the St. Lawrence Formation and Tunnel City Group bedrock units in Houston, Winona and Wabasha counties. This work has radically altered our understanding of springs and springsheds in southeast Minnesota. Prior to this project there had been no planned dye traces in these units. While it was known that many springs emanated from them, it was assumed that they were not directly connected to the land surface by sinkholes or sinking streams. In this project we documented that springs discharging from the St. Lawrence Formation and Tunnel City Group bedrock units receive surface water recharge from sinking streams in the upper St. Lawrence Formation and that this recharge moves hundreds of feet per day through bedrock. We demonstrated that this phenomena is regional, occurring from the north edge of Wabasha county to southern Houston County, showing that the thousands of springs in southeast Minnesota that discharge from these bedrock units are far more vulnerable to human impact than previously believed. During this project we have monitored spring temperature and conductivity. That information, along with our dye tracing observations, field investigations, and GIS investigations was used to guide the development of Spring Assessment Protocols for the Paleozoic Bedrock Springs of Southeast Minnesota. This document is the first of its kind in the upper Midwest and is a compilation of the state of our knowledge on the dynamics of groundwater flow to Paleozoic bedrock springs. A map, “Mapped Paleozoic Bedrock Springsheds in Southeast Minnesota” was produced to show all of the springshed mapping that has been done in southeast Minnesota.

V. DISSEMINATION:

Description: GIS-based maps and written reports of the springsheds will be prepared and disseminated to the LCCMR, interested residents and to local, regional and state resource managers and regulators interested in specific targeted areas. Interim dye trace results will be available as GIS shape files and derived products on a dye trace by dye trace basis. Data tables of discharge and chemistry will be available as developed. Spring assessment protocols will be published and made available to local and state agency staff.

Status as of 15 January 2012
Springshed information & results were presented as part of three tours in southeast Minnesota. They were karst tours for the Geological Society of America, Minnesota Association of Professional Soil Scientists and state and federal agency staff from Minnesota, Wisconsin and Iowa. The St. Lawrence tracing work was presented at the national Geological Society of America meeting in Minneapolis in October. Springshed information and results from the ENRTF-funded “Hydraulic Impacts of Quarries and Pits” was presented at silica sand mining forums in Goodhue and Winona counties.

Status as of 15 July 2012
The St. Lawrence tracing work was presented at the Minnesota Groundwater Association spring conference. Springshed information and results from the ENRTF-funded “Hydraulic Impacts of Quarries and Pits” was presented at silica sand mining meetings in Fillmore, Houston and Olmsted counties. A coalition of southeast MN water advocacy groups and local governments sponsored a karst and hydrology tour. Springshed information & results were presented as part of that tour.

Status as of 15 January 2013
The St. Lawrence tracing work and results from the ENRTF-funded “Hydraulic Impacts of Quarries and Pits” were presented at the Midwest Groundwater Conference at the Earle Brown Center. Springshed information was discussed with NRCS/NGO and Environmental Defense Fund staff as part of a new, federally-funded Root River watershed project.

Status as of 15 July 2013

The springshed mapping work was presented at a Winona State Geology department seminar in February and at a DNR GIS users group meeting in March. Springshed mapping results, spring inventory methods and springshed assessment techniques were presented to county and state feedlot program staff at a MPCA sponsored training event in Oronoco, MN in April.

Status as of 15 January 2014
In October, the springshed mapping work was presented at a DNR groundwater training seminar for field staff, at the EcoWaters all division meeting and as part of the MGWA/AIPG fall field trip in southeast MN. An update on the work was presented at the Root River Technical Advisor Group meeting in Preston, MN November 2013.

Final Report Summary: 15 September 2014
Information from this project was widely disseminated. A map of the delineated springsheds and a document on Spring Assessment Protocols were produced and submitted to the LCCMR and will be published by the Minnesota Geological Survey. The springshed coverage is being used by state and local governments to target areas for conservation efforts and for Clean Water Fund project ranking. The springshed mapping will be used by the DNR for Silica Sand Mining Trout Stream Setback permitting and in Water Appropriation permit review.

Project information was presented to numerous groups including the SE MN Water Resources Board, Root River Technical Advisor Group, Fillmore County Local Water Planning committee, Southeast Minnesota County and State Feedlot officers, Midwest Federal Agency Senior Managers, and at Silica Sand mining forums in Red Wing, Lewiston, La Crescent, and Winona. On the ground information was presented during tours of the southeast; groups that went “on tour” include Minnesota Groundwater Association, MPCA/DNR field staff, SE Minnesota water advocacy groups, Geological Society of America, Minnesota Association of Professional Soil Scientists, and state and federal agency staff from Minnesota, Iowa, and Wisconsin.

A paper on the St. Lawrence tracing work has been was published in the journal Carbonates and Evaporites. The springshed mapping work was the subject of two stories on Minnesota Public Radio. Project results were presented at numerous scientific meetings including the 11th and 12th Multidisciplinary Conference on Sinkholes and the Environmental and Engineering Aspects of Karst, the Minnesota Groundwater Association, the Midwest Groundwater Conference, the Geological Society of America, The Driftless area Symposium, and at a Winona State University Geology Department seminar.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget:

Budget Category	$ Amount	Explanation
Personnel:	$ 201,200	Hydrologist 3
Equipment/Tools/Supplies:	$ ~~6,100~~ $3,900	Field equipment, dye, sampling supplies
Travel Expenses in MN:	~~$12,700~~ $14,900	Mileage and expenses
TOTAL ENRTF BUDGET:	**$ 220,000**	

Explanation of Use of Classified Staff- The Hydrologist 3-Southeast Minnesota Regional Groundwater Specialist has been assigned to work on the springshed project. The activities performed by this position have been assigned to other staff.

Number of Full-time Equivalent (FTE) funded with this ENRTF appropriation: 1.0

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
State			
0.05 FTE General Fund	$10,822		EcoWaters staff project support
Minnesota DNR's In-kind Contribution: $28,805 for shared services and governance	$28,805		General fund and other funds as appropriate
TOTAL OTHER FUNDS:	$ 39,627	**$**	

VII. PROJECT STRATEGY:

A. Project Partners: University of Minnesota, total from appropriation $280,000

B. Project Impact and Long-term Strategy: By delineating springsheds and making web-based maps available, this project will provide critical information for the protection and management of the springs that form the coldwater streams of southeast Minnesota. This information is critical for Total Maximum Daily Load (TMDL) implementation strategies, impaired waters remediation, ground water protection and allocation issues, and local land and water management decisions.

Karst ground water flow is the most complex hydrogeologic environment in Minnesota. Springs are the natural features that return groundwater to surface waters. Karst springs respond much faster to surface recharge than is expected from conventional hydrology theory. Karst springs exhibit a wide range of rapid responses to recharge events. Springs integrate all of the natural and anthropogenic processes that occur in their recharge areas – in their individual springsheds. Springshed mapping is critical component of karst aquifer characterization. Long-term resources are needed to gather and maintain the parameters necessary to realistically, effectively manage karst springs in Minnesota and to train staff and resource managers in the use of the available karst data. LCMR and LCCMR have played a leading role in the effort to understand and manage Minnesota's karst springs

The availability of high-resolution LiDAR maps has produced a flood of new information showing the locations of karst features. This new information is having a major impact on the springshed mapping project by identifying additional sinkholes and sinking streams as possible dye trace input points. LiDAR imagery has allowed us to identify the particular characteristics of St. Lawrence sinking streams; we are using that knowledge to identify additional sites to field check that are in remote valleys that are difficult to access.

C. Spending History:

Funding Source	M.L. 2005 or FY 2006-07	M.L. 2007	M.L. 2008 or FY 2009	M.L. 2009	M.L. 2010 or FY 2011
ENRTF via contract with U of M		125,000			
ENRTF appropriation to DNR				250,000	

VIII. ACQUISITION/RESTORATION LIST:

IX. MAP(S): Attached

X. RESEARCH ADDENDUM:

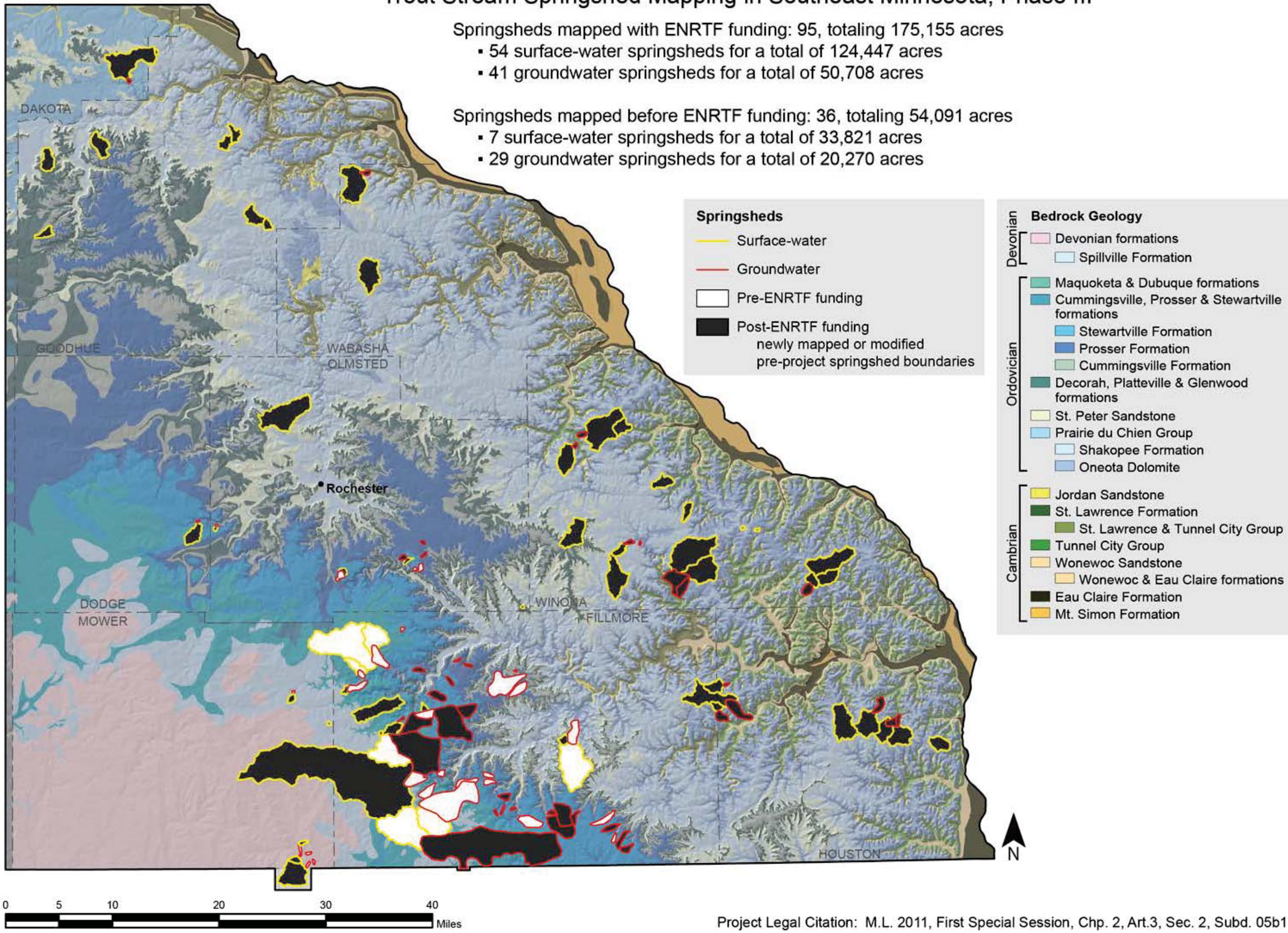
XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted not later than *15 January 2012, 15 July 2012*, *15 January 2013, 15 July 2013* **and** *15 January 2014.* **A final report and associated products will be submitted between June 30 and September 15, 2014 as requested by the LCCMR.**

Trout Stream Springshed Mapping in Southeast Minnesota, Phase III

Springsheds mapped with ENRTF funding: 95, totaling 175,155 acres
- 54 surface-water springsheds for a total of 124,447 acres
- 41 groundwater springsheds for a total of 50,708 acres

Springsheds mapped before ENRTF funding: 36, totaling 54,091 acres
- 7 surface-water springsheds for a total of 33,821 acres
- 29 groundwater springsheds for a total of 20,270 acres



Project Legal Citation: M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 05b1

Attachment A: Budget Detail

Project Title: *Trout Stream Springshed Mapping in Southeast Minnesota – Phase III*
Legal Citation: *Laws MN 2011, 1st Sp. Session, Ch. 2, Art. 3, Sect. 2, Subd. 05b1*
Project Manager: *Jeff Green*
M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 05b1 ENRTF Appropriation: $220,000
Project Length and Completion Date: *June 30, 2014*
Date of Update: *9/15/2014*

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Revised Activity 1 Budget 9/15/2014	Amount Spent	Balance
BUDGET ITEM			
Personnel (Wages and Benefits, Unemployment) *Hydrologist 3 (Jeff Green), 100%*	201,200	200,318	882
Equipment	1,800	1,474	326
Supplies	2,100	1,906	194
DNR Fleet Vehicle Costs	13,000	12,773	227
Meals & Lodging for Fieldwork	1,900	1,868	32
COLUMN TOTAL	**$220,000**	**$218,341**	**$1,659**

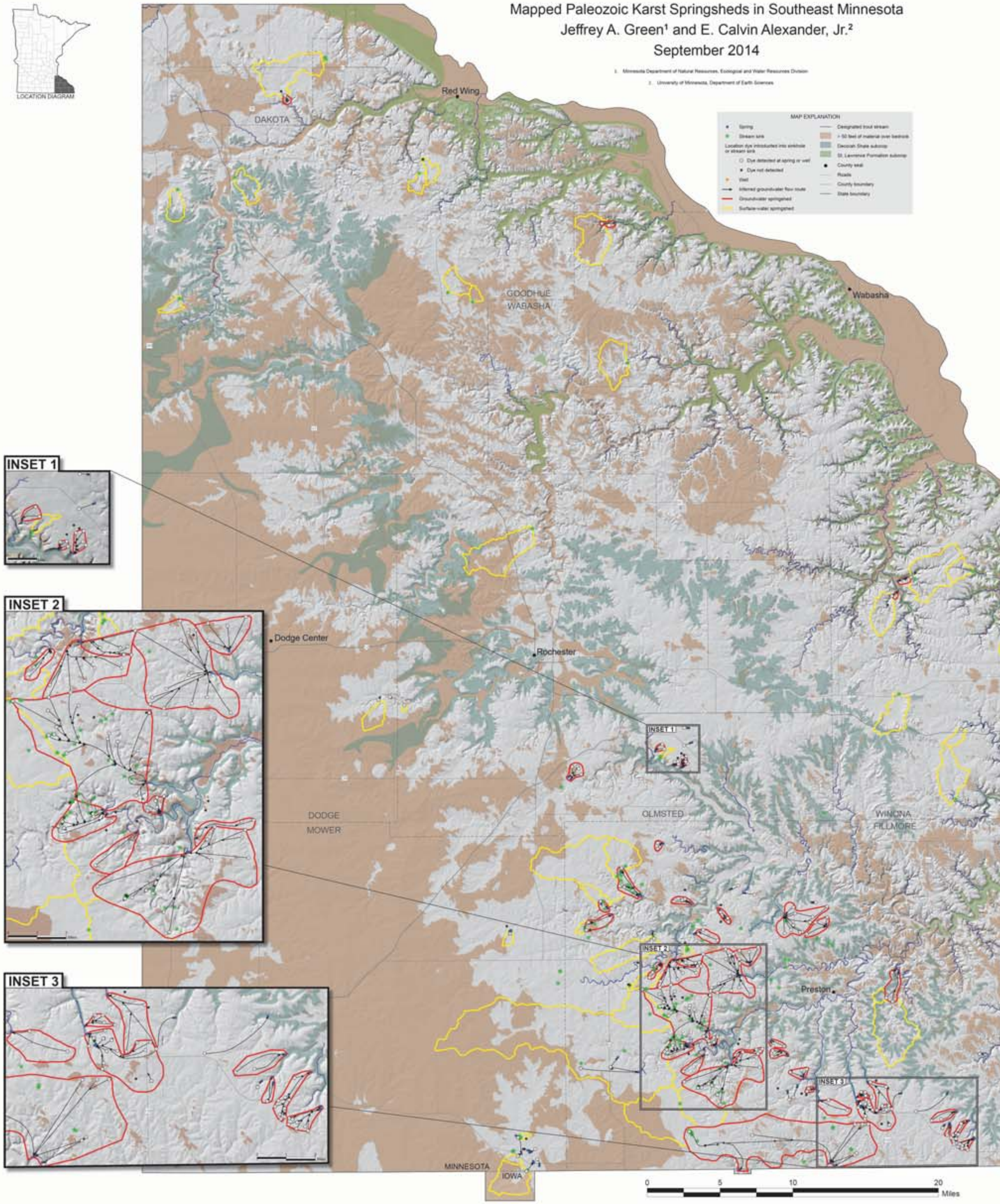
Mapped Paleozoic Karst Springsheds in Southeast Minnesota

Jeffrey A. Green[1] and E. Calvin Alexander, Jr.[2]

September 2014

1. Minnesota Department of Natural Resources, Ecological and Water Resources Division
2. University of Minnesota, Department of Earth Sciences

Map to accompany the LCCMR report:
Springshed Assessment Methods for Paleozoic Bedrock Springs of Southeastern Minnesota
Project Title: Trout Stream Springshed Mapping in Southeast Minnesota, Phase III
Legal Citation: M.L. 2011, First Special Session, Chp. 2, Art. 3, Sec. 2, Subd. 05b1



Introduction

Springs are the natural discharge points for groundwater systems. They provide baseflow for streams and are critical sources of constant-temperature water for cold water trout streams. In order to conserve and protect the source of water to a spring it is necessary to identify the springshed, the area that contributes water to the spring.

This map displays mapped springsheds as of June 2014 in the Paleozoic karst bedrock of southeast Minnesota. It also incorporates work done as part of the Fillmore County Geologic Atlas (Alexander and others, 1996, Plate 9).

Karst and Hydrogeology

Karst is a landscape-scale hydrologic system formed in soluble bedrock. Water chemically and mechanically enlarges passages resulting in integrated conduits through which it can travel rapidly, at speeds of up to several miles per day. Certain bedrock layers are more prone to karst formation (Figure 1).

The land surface may express the karst system through the presence of sinkholes and sinking streams, which are inlets or windows to the bedrock aquifer. Even areas with few or none of these features at the surface may have water moving rapidly through subsurface conduits, especially in areas where water infiltrates through thin soil.

Some of the water that has entered the subsurface emerges at the surface in springs. A groundwater springshed includes three components: 1) water that has infiltrated from the land surface into the first karst aquifer even where there are no obvious karst features present, 2) surface water that entered at a specific karst feature, and 3) regional groundwater flow.

Springsheds are dynamic and their boundaries can change as groundwater levels rise and fall. The boundaries of groundwater springsheds and the surface watersheds do not necessarily correspond.

Regional Geology and Stratigraphy

The flat-lying Paleozoic sedimentary bedrock of southeastern Minnesota is Cambrian to Devonian in age (505 to 350 million years ago) (Mossler, 2008) and was deposited as a series of shallow, fluctuating seas advanced and retreated across what is now southeastern Minnesota (Figure 2). The Cambrian-age rocks are primarily sandstone, siltstone and shale while the Ordovician and Devonian rocks are primarily carbonate (limestone and dolostone) and shale.

Rock layers that serve as the source of water for the many springs found in southeast Minnesota are highlighted on the map and stratigraphic column (Figure 2). The Decorah Shale (blue on the map) is a regional aquitard and is the boundary between the Galena limestone karst system and the Prairie du Chien karst system. Many springs discharge from the lower Galena because the water cannot move through the relatively impervious, underlying shale. The St. Lawrence Formation (green on the map) is an important regional bedrock unit from which many springs discharge and where disappearing streams (stream sinks) contribute water to springs (Green and others, 2012).

These rock units are covered by varying thicknesses of unconsolidated sediments. Areas with less than 50 feet of sediment cover have been the focus of springshed mapping efforts because sinkholes and disappearing streams are primarily found in those areas. Those features are not common where the cover is thicker than 50 feet (brown areas on the map), typically in three settings: isolated areas in the blufflands regions, along the alluvium deposits of the major rivers, and under deep glacial deposits to the west.

Methods

The surface-water springsheds were identified by analyzing LiDAR digital elevation models or topographic maps. The groundwater springsheds in southeastern Minnesota were mapped primarily through dye tracing done by the University of Minnesota, DNR, and private cavers.

The use of artificial additives (tracers) to track groundwater flow is common for karst aquifer investigations. A tracer is added to the groundwater system through a sinkhole, sinking stream, or cave stream. Then groundwater discharge locations, typically springs, are monitored for the arrival of the tracers. When input-to-discharge connections are established, the identified connection can be used to identify the area that contributes water to a spring (groundwater springshed). Frequent sampling during the tracing experiment allows the travel time of the groundwater to be calculated.

Fluorescent dyes are the preferred tracers because they are conservative (travel with water and are non-reactive), readily obtainable, non-toxic, relatively simple to analyze, detectable at very low concentrations and not naturally present in the groundwater. For this study, the dyes used were eosine (CAS 17372-87-1), Rhodamine WT (CAS 37299-86-8), and uranine C/fluorescein (CAS 518-47-8). Multiple dyes were used to trace from different sinkholes at the same time. The traces were carried out with 200–1200 grams of dye. The dyes were introduced into the groundwater systems through sinking streams, snow melt running into sinkholes, and dry sinkholes. In the latter case, the dyes were flushed with water from a tanker truck (typically 500–2000 gallons). Dye traces were conducted in the Lithograph City Formation, Spillville Formation, Galena Group, Prairie du Chien Formation, St. Lawrence Formation, and the Tunnel City Group.

Springs, streams, and wells were monitored to determine background levels both before and after dye inputs with a combination of integrating charcoal packets and direct water samples. The charcoal packets and water samples were analyzed using a scanning spectrofluorophotometer in the Earth Sciences Department of the University of Minnesota. All three dyes could be measured in parts per billion.

Results

This map displays mapped groundwater and surface-water springsheds across southeast Minnesota. The groundwater springshed boundaries are outlined in red and reflect groundwater levels in the first bedrock karst aquifer at the time that the dye traces were conducted. Surface-water springsheds are outlined in yellow. Common boundaries of neighboring springsheds represent surface-water or groundwater divides. Sinkholes or stream sinks that were used as dye-trace input points are symbolized differently depending on whether or not dye was later detected in the springs that were being monitored. The dye-trace vectors (black arrows) are the diagrammatic depiction of the groundwater flow route.

The five insets are enlargements of areas with a high density of dye trace points and vectors.

References

Alexander, E.C., Green, J.A., Alexander, S.C., and Spong, R.C., 1996, Springsheds, Plate 9, Geologic Atlas of Fillmore County, Minnesota: Part B, County Atlas Series C-8, Minnesota Department of Natural Resources, St. Paul, Minn.

Green, J.A., Runkel, A.C., Alexander, E.C., Jr., 2012, Karst conduit flow in the Cambrian St. Lawrence Formation, southeast Minnesota, USA, Carbonates and Evaporites, Volume 27, Issue 2, p. 167-172.

Mossler, J.H., 2008, Paleozoic stratigraphic nomenclature for Minnesota: Minnesota Geological Survey Report of Investigations 65, 76 p., 1 pl.

Acknowledgements

Funding for this project was provided by the Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative-Citizen Commission on Minnesota Resources (LCCMR).

This project would not have been possible without the work of many people. Scott Alexander of the University of Minnesota provided oversight and analysis of the dye trace samples. Donna Rasmussen of Fillmore County provided staff to assist in dye tracing and obtained property access for many traces. Other individuals who contributed much to this project include Tony Runkel of the Minnesota Geological Survey, Betty Wheeler, Kelsi Ustipak, and Andrew Luhmann of the University of Minnesota, Mark White (DNR), Andrew Peters (formerly DNR), the Harmony and Chatfield Fire Departments, and the many landowners who allowed access to their springs, sinking streams and sinkholes. Without their cooperation this work would not have been possible.

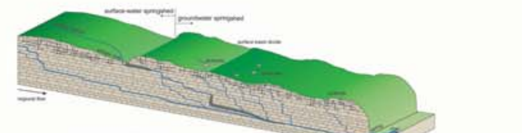


Figure 1. Springshed block diagram

Perennial and intermittent streams flowing across the land surface descend into stream sinks or sinkholes. Those sinking points mark the beginning of a groundwater springshed carrying groundwater flow to a spring. The black lines represent the general direction of groundwater flow through enlarged openings in the subsurface, such as vertical and horizontal joints and fractures. The gray-shaded linear features represent larger conduits carrying groundwater flow.

Regional groundwater flow is a component of a groundwater springshed. Water enters the groundwater system by way of continued infiltration from the surface and can come from areas far beyond the surface-water springsheds. Regional sources of water to groundwater springsheds have a significantly longer underground residence time and provide a large fraction of spring discharge from the St. Lawrence Formation and Tunnel City Group.

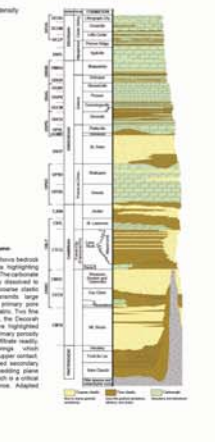
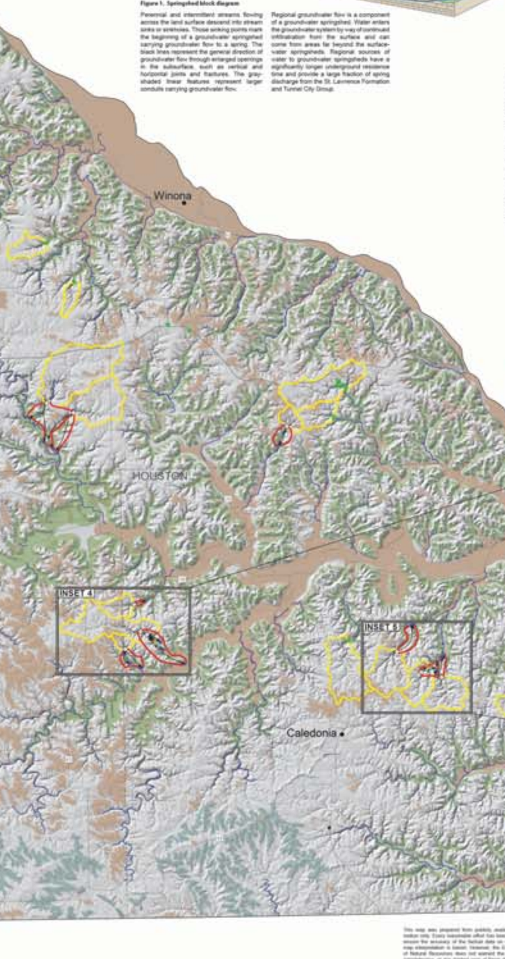
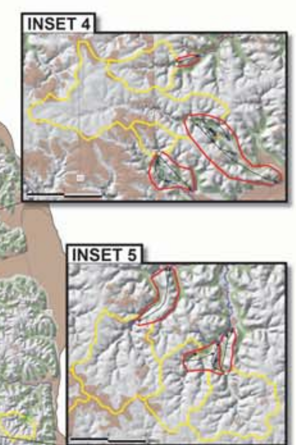


Figure 2. Stratigraphic column

This stratigraphic column shows bedrock of southeastern Minnesota highlighting lithostratigraphic attributes. The carbonate bedrock has been partially dissolved to form karst aquifers. The coarse clastic bedrock stores and transmits large volumes of water in the primary pore space in the sandstone matrix. Two fine clastic bedrock formations, the Decorah and the St. Lawrence, are highlighted on the map. Their lower primary porosity does not allow water to infiltrate readily, creating numerous springs which discharge laterally at their upper contact. These units have enhanced secondary porosity in the form of bedding plane fractures and conduits, which is a critical factor for spring occurrence. Adapted from Mossler (2008).





M.L. 2011 **Project Abstract**
For the Period Ending June 30, 2014

PROJECT TITLE: Trout Stream Springshed Mapping in Southeast Minnesota – Phase III
PROJECT MANAGER: E. Calvin Alexander, Jr.
AFFILIATION: U of MN
MAILING ADDRESS: 450 McNamara Alumni Ctr, 200 Oak St SE
CITY/STATE/ZIP: Minneapolis, MN 55455
PHONE: 612-624-3517
E-MAIL: alexa001@umn.edu
WEBSITE:
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 05b2

APPROPRIATION AMOUNT: $ 280,000

Overall Project Outcome and Results

Trout streams depend on a steady supply of clean, cold water which comes from groundwater springs. These trout springs are under increasing pressure from changing land use, climate change, and groundwater withdrawals for domestic use, mining, agriculture, and energy production. Delineation of the recharge areas or springsheds of trout springs using dye tracing is a necessary first step in the conservation and protection of the trout stream coldwater supplies. This project focused on delineating groundwater springsheds both in the Galena Group limestone karst areas of Fillmore and Olmsted counties, where this work has been done for over 30 years, and in the Cambrian St. Lawrence Formation and Tunnel City Group bedrock across southeast Minnesota. Prior to this project, no springsheds had been delineated in the St. Lawrence or Tunnel City bedrock units. We demonstrated that springs discharging from these units receive surface water recharge from sinking streams and that this recharge moves hundreds of feet per day through the bedrock. This has rewritten our understanding of the hydrology of southeast Minnesota and has demonstrated that these springs, which we formerly believed to be well-protected from land surface activities, are much more vulnerable than we previously realized. Overall, during this project we mapped 41 groundwater springsheds (delineated by dye tracing) and 54 surface water springsheds (surface watersheds sending water to a point where it sinks underground into a groundwater springshed). Twelve of the groundwater springsheds and sixteen of the surface water springsheds are in the St. Lawrence Formation and Tunnel City Group. The groundwater springshed delineated areas total 50,708 acres and the surface water delineated areas total 124,447 acres. Prior to this project there was a total of 54,091 acres of both springshed types delineated. Springsheds were delineated in Dakota, Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Wabasha and Winona counties.

Project Results Use and Dissemination

Information from this project was widely disseminated. A map of the delineated springsheds and a document on Spring Assessment Protocols were produced and submitted to the LCCMR and will be published by the Minnesota Geological Survey. The springshed coverage is being used by state and local governments to target areas for conservation efforts and for Clean Water Fund project ranking. The springshed mapping will be used by the DNR for Silica Sand Mining Trout Stream Setback permitting and in Water Appropriation permit review.

Project information was presented to numerous groups including the SE MN Water Resources Board, Root River Technical Advisor Group, Fillmore County Local Water Planning committee, Southeast Minnesota County and State Feedlot officers, Midwest Federal Agency Senior Managers, and at Silica Sand mining forums in Red Wing, Lewiston, La Crescent, and Winona.

On the ground information was presented during tours of the southeast; groups that went “on tour” include Minnesota Groundwater Association, MPCA/DNR field staff, SE Minnesota water advocacy groups, Geological Society of America, Minnesota Association of Professional Soil Scientists, and state and federal agency staff from Minnesota, Iowa, and Wisconsin.

A paper on the St. Lawrence tracing work has been was published in the journal Carbonates and Evaporites. The springshed mapping work was the subject of two stories on Minnesota Public Radio. Project results were presented at numerous scientific meetings including the 11th and 12th Multidisciplinary Conference on Sinkholes and the Environmental and Engineering Aspects of Karst, the Minnesota Groundwater Association, the Midwest Groundwater Conference, the Geological Society of America, The Driftless area Symposium, and at a Winona State University Geology Department seminar.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2011 Work Plan

Date of Status Update: **9/18/2014**
Date of Next Status Update: Final Report
Date of Work Plan Approval: 8/11/2011
Project Completion Date: 6/30/2014 **Is this an amendment request?** Yes

Project Title: Trout Stream Springshed Mapping in Southeast Minnesota - Phase III

Project Manager: E. Calvin Alexander, Jr.
Affiliation: U of MN
Address: 450 McNamara Alumni Ctr, 200 Oak St SE
City: Minneapolis **State:** MN **Zipcode:** 55455

Telephone Number: (612) 624-3517
Email Address: alexa001@umn.edu
Web Address:

Location:

Counties Impacted: Dakota, Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Rice, Wabasha, Washington, Winona

Ecological Section Impacted: Paleozoic Plateau (222L)

Total ENRTF Project Budget:	**ENRTF Appropriation $:**	280,000
	Amount Spent $:	250,159
	Balance $:	29,841

Legal Citation: M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 05b2

Appropriation Language:
$250,000 the first year and $250,000 the second year are from the trust fund to continue to identify and delineate water supply areas and springsheds for springs serving as cold water sources for trout streams and to assess the impacts from development and water appropriations. Of this appropriation, $140,000 each year is to the Board of Regents of the University of Minnesota and $110,000 each year is to the commissioner of natural resources.

I. PROJECT TITLE: Innovative Springshed Mapping for Trout Stream Management-Continuation (U of MN)

II. PROJECT SUMMARY: Trout streams depend on a steady supply of clean, cold water to exist. Minnesota's karst lands contain 173 designated trout streams each of which is sourced from springs. Those trout springs are under increasing pressure from changing land use. Additional large groundwater withdrawals for energy production and other development loom in the future. Delineation of the recharge areas or springsheds of the trout springs is a crucial first step in the protection of the trout fisheries and the restoration of those that have been degraded. This project is to develop innovative identification and delineation tools to determine the supply areas (springsheds) for springs serving as coldwater sources for modern and historic trout streams and assessing impacts on them from land and water development.

III. PROJECT STATUS UPDATES:

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Innovative Trout Springshed Maps and Reports

Description: Springsheds that feed source springs of trout streams will be delineated in the Galena, Prairie du Chien, and St. Lawrence karst lands. Maps of the springsheds will be transferred to the U of M for web posting and will be linked to the DNR web site. The existing temperature-monitoring network will be maintained and expanded as equipment and sites are available. The results of our dye tracing, spring monitoring, and hydrostratigraphy investigations will be used to develop spring assessment protocols.

Summary Budget Information for Activity 1:

ENRTF Budget:	**$ 280,000**
Amount Spent:	**$ 250,159**
Balance:	**$ 29,841**

Activity Completion Date:

Outcome	**Completion Date**	**Budget**
1. Innovative Trout Springshed Maps and Reports (Conduct dye traces and field investigations for springshed map production, maps and reports of completed traces and spring parameter monitoring including spring assessment protocol development).	30 June 2014	$280,000

(See also the companion U of M project work program Activity 1)

Activity Status as of *13 May 2013*

Thirty-one new dye traces have been conducted in the Galena, Prairie du Chien and St. Lawrence Karsts since the start of the biennium – in cooperation with Jeff Green at the MN DNR. These traces have refined and extended previously mapped springsheds and defined new springsheds. Successful traces in the Prairie du Chien Karst have been extended northward into the Trout Brook springshed south of Miesville in Dakota County. The headwaters springs of Trout Brook have some of the highest nitrate levels observed in SE MN trout streams. A pdf of Joel Groten's Trout Brook report is attached below.

The karst phenomena discovered in the previous biennium's project in the St. Lawrence Formation is now known to extend from Houston County north through Winona County into Wabasha County. Many of Minnesota's best trout streams are fed by springs emerging from the St. Lawrence. The temperature monitoring network was has emphasized long term data sets from the springs feeding the Crystal Springs, Peterson and Lanesboro State Fish Hatcheries. Shorter term temperature monitoring has been successful in two springs in Dakota County's Trout Brook.

Two Research Assistants, Betty Wheeler and Kelsi Ustipak, have been working on this project since 1 July 2012. Kelsi has been conducting field work in cooperation with the DNR setting up and running dye traces. She has been conducting fluorometric analyses of the resulting charcoal detector and water samples, analyzing the data and writing reports on the dye traces in each area. This provides the new data for the springshed maps and assessment protocols. Betty has been adding all of Kelsi's new data to a comprehensive data base of all of the historic dye traces we have been able to document. That new data base includes data from previous decades of traces sponsored by the LCMR and LCCMR and other agencies and individuals. Dye tracing in Minnesota apparently started in 1941 when the predecessor of the Minn. Dept. of Health conducted dye traces to combat water pollution problems in the karst around Harmony and Canton in Fillmore County. Betty's data base is supplying information to Jeff Green's regional scale springshed mapping efforts. This data base will be made available on a web site when it is finished and will be accessible to any interested users.

The subcontract to Tony Runkel, Bob Tipping and Julia Steenberg at the Minnesota Geological Survey has proven to be a key element in our work. The MGS staff have provided refined stratigraphic information on the dye input points and the trout springs. Their data have significantly improved our understanding of the hydrogeology of Trout Springsheds – and our dye traces have fundamentally changed the conceptual models of SE Minnesota's hydrogeology. The MGS staff is constructing new structural contour maps which are revealing how subtle structures affect ground water flow and the locations of the trout springs in SE Minn.

In addition to the close partnership with Jeff Green and the DNR and contractual relationship with the MGS, ongoing partnerships with the MPCA and MDA are making significant contributions to our efforts. The MDA is providing valuable contacts with the local agricultural community and helping significantly with field work in selected areas. MPCA ongoing monitoring programs are building on our springshed maps and MPCA staff have made significant contributions to this project's field work.

Finally, college students are making significant contributions to the effort through class dye traces, Undergraduate Research Opportunity Grants and NSF sponsored REU summer internships.

Good progress has been made on all of the Activity 1 project goals. Dye traces and field investigations are progress very well. Springshed maps and reports are being finished. The spring parameter monitoring system is accumulating interesting, informative and useful information. The spring assessment protocol are on track and emphasizing practical, direct steps to evaluate trout streams.

Amendment Request:

1. We request that the end date of this project be extended to June 30, 2014. This project started late in part due to the shutdown of the state government. An extension of the end date will allow more time to achieve better outcomes, more detailed publications, more complete reports which incorporate more of the historic data and results. It will allow time for constructive comments and suggestions on the GIS based springshed maps and data bases to be incorporated into these major products.

Approved by LCCMR on 15 May 2013.

Final Report Summary: 15 September 2014
Research Scientist Kelsy Ustipak completed her work and left the project at the end of June 2013. Betty Wheeler continued as a 75% time Research Scientist through the end of June 2014. Betty has assembled end-of-project final documents on dye tracing efforts funded by the LCCMR since 2007. Triple dye traces were conducted with NSF Summer Interns Jacob Phipps and Alexa LaQua in Forestville Mystery Cave State Park in summer 2013. Quantitative traces were conducted at Bridge Creek in Houston County in the fall of 2013. A dual dye trace was conducted in the Galena karst of Olmsted County in cooperation with the Olmsted County SWCD in the spring of 2014. Work has focused on compiling and interpreting data for the production of the Spring Assessment Protocols and Springshed Map.

In addition to supplying very important stratigraphic and structural information for the dye tracing efforts, MGS staff have reestablished a working interface to the Karst Features Data Base. Location information on about five thousand new sinkholes, springs and other karst features have been added to the KFDB in support of the dye tracing and springshed mapping efforts.

Amendment Request 15 September 2014
In order to balance final total expenditures, this is a request to move funds from Travel Expenses to Salaries.

Amendment Approved ______

V. DISSEMINATION:

Description: GIS-based maps and written reports of the springsheds will be prepared and disseminated to the LCCMR, interested residents and to local, regional and state resource managers and regulators interested in specific targeted areas. Interim dye trace results will be available as GIS shape files and derived products on a dye trace by dye trace basis. Data tables of discharge and chemistry will be available as developed. Spring assessment protocols will be published and made available to local and state agency staff.

Status as of *13 May 2013*

Results of this joint project are being disseminated to all levels of society as rapidly as they are completed. At the local level copies of reports and papers are sent directly to the private land owners involved when they are finalized. County officials are actively using our results and suggesting additional locations for work. An invited talk at the Eagle Bluff Environmental Learning Center on “The Impact of Karst on Agriculture” was presented on 6 April 2013. A similar version of that talk was presented at the Driftless Area Symposium in LaCrosse, WI in March 2012. On 16-18 April 2013 Jeff Green and I presented a Short Course on Karst Hydrogeology to the MPCA and County Feed Lot Officers and staff in Oronoco, MN.

At the state scale presentations on various aspects of the results of this project are regularly presented at Minn. Ground Water Association spring and fall meetings. At the national scale talks and posters are regularly presented at Geological Society of America, American Geophysical Union , and Sinkhole Conference Meetings.

Finally, a very strong synergistic working relationship has been established between the U of Mn, DNR, MGS, MPCA and MDA as we each build on the latest research of each other’s groups.

Final Report Summary: *1 August 2014*

Information from this project was widely disseminated. A map of the delineated springsheds and a document on Spring Assessment Protocols were produced and submitted to the LCCMR and will be published by the Minnesota Geological Survey. The springshed coverage is being used by state and local governments to target areas for conservation efforts and for Clean Water Fund project ranking. The springshed mapping will be used by the DNR for Silica Sand Mining Trout Stream Setback permitting and in Water Appropriation permit review. The 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst is scheduled to be held in Rochester, Minnesota 5-9 October 2015. This will further disseminate the Minnesota karst hydrogeology information gained by several decades of LCMR and LCCMR supported research to a local, state, national and international community of karst resource managers.

Project information was presented to numerous groups including the SE MN Water Resources Board, Root River Technical Advisor Group, Fillmore County Local Water Planning committee, Southeast Minnesota County and State Feedlot officers, Midwest Federal Agency Senior Managers, and at Silica Sand mining forums in Red Wing, Lewiston, La Crescent, and Winona. On the ground information was presented during tours of the southeast; groups that went "on tour" include Minnesota Groundwater Association, MPCA/DNR field staff, SE Minnesota water advocacy groups, Geological Society of America, Minnesota Association of Professional Soil Scientists and state and federal agency staff from Minnesota, Iowa and Wisconsin.

A paper on the St. Lawrence tracing work was published in the journal *Carbonates and Evaporites*. The springshed mapping work was the subject of two stories on Minnesota Public Radio. Project results were presented at numerous scientific meetings including the 11th and 12th Multidisciplinary Conference on Sinkholes and the Environmental and Engineering Aspects of Karst, the Minnesota Groundwater Association, the Midwest Groundwater Conference, the Geological Society of America, The Driftless area Symposium and at a Winona State University Geology Department seminar.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget:

Budget Category	$ Amount	Explanation
Personnel:	$ 193,059	1 Research Assistant (50%), 1 Research Specialist (90%), P.I. (8%), Research Scientist (12%), Under graduate lab assistant.
Equipment/Tools/Supplies/Analytical:	$ 35,900	Field equipment, dye, sampling supplies
Travel Expenses in MN:	$ 20,041	Mileage and expenses
Contract with MGS	$ 31,000	1 month/year of Tony Runkel and Bob Tipping
TOTAL ENRTF BUDGET:	**$ 280,000**	

Number of Full-time Equivalent (FTE) funded with this ENRTF appropriation: 1.75

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
U of Mn (1 m/yr for Alexander)	$20,848		P.I salary
TOTAL OTHER FUNDS:	$ 20,848	**$20,848**	

VII. PROJECT STRATEGY:

A. Project Partners: Minnesota Department of Natural Resources, total from appropriation $220,000

B. Project Impact and Long-term Strategy: By delineating springsheds and making web-based maps available, this project will provide critical information for the protection and management of the springs that form the coldwater streams of southeast Minnesota. This information is critical for Total Maximum Daily Load (TMDL) implementation strategies, impaired waters remediation, ground water protection and allocation issues, and local land and water management decisions.

Karst ground water flow is the most complex hydrogeologic environment in Minnesota. Springs are the natural features that return groundwater to surface waters. Karst springs respond much faster to surface recharge than is expected from conventional hydrology theory. Karst springs exhibit a wide range of rapid responses to recharge events. Springs integrate all of the natural and anthropogenic processes that occur in their recharge areas – in their individual springsheds. Springshed mapping is critical component of karst aquifer characterization. Long-term resources are needed to gather and maintain the parameters necessary to realistically, effectively manage karst springs in Minnesota and to train staff and resource managers in the use of the available karst data. LCMR and LCCMR have played a leading role in the effort to understand and manage Minnesota's karst springs

The availability of high-resolution LiDAR maps, scheduled for July 2009, will produce a flood of new information showing the locations of karst features. We anticipate that new information will have a major impact on the springshed mapping project.

C. Spending History:

Funding Source	**M.L. 2005 or FY 2006-07**	**M.L. 2007 or FY 2008**	**M.L. 2008 or FY 2009**	**M.L. 2009 or FY 2010**	**M.L. 2010 or FY 2011**
ENRTF appropriation to U M		250,000			
ENRTF appropriation to UM				250,000	

VIII. ACQUISITION/RESTORATION LIST:

IX. MAP(S): Attached

X. RESEARCH ADDENDUM:

Covington, Luhmann, Myre, Perne, Jones, Alexander, and Saar (2014) Relationships between conduit properties and the damping and retardation of thermal pulses in karst conduits. Abst submitted to the Fall 2014 AGU Meeting in San Francisco.

Luhmann, A.J, M.D. Covington, J.M. Myre, M. Perne, S.W. Jones, E.C. Alexander, Jr., M.O. Saar (2014) Thermal damping and retardation in karst conduits. Hydrol. Earth Syst. Sci. Discuss., 18, 1-54. www.hydrol-earth-syst-sci-discuss.net/18/2014
doi: 10.5194/hessd-18-1-2014

Phipps, Jacob D., Alexa J. LaQua and E. Calvin Alexander, Jr. (2013) Springsheds and water quality in Forestville Mystery Cave State Park, Minnesota. Poster 135-7, GSA Program with Abstracts, v. 47, n. 7, p. 353.

Alexander, E. Calvin Jr. (2013) Mystery Cave, Minnesota: A window into the paleohydrology of the Upper Mississippi Valley. Abstract 276-9, GSA Program with Abstracts, v. 47, n. 7, p. 640.

Alexander, E. Calvin Jr., Anthony C. Runkel, Robert G. Tipping and Jeffrey A. Green (2013) Deep time origins of sinkhole collapse failures in sewage lagoons in SE Minnesota. *In:* (Lewis Land, Daniel H. Doctor and J. Brad Stephenson editors) ***NCKRI Symposium 2 Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst***, Carlsbad, New Mexico, published on-line by NCKRI, Carlsbad, NM, p. 285-292. ISBN 978-0-9795422-7-5

Rahimi, Mina and E. Calvin Alexander Jr. (2013) Locating sinkholes in LiDAR coverage of a glacio-fluval karst, Winona County, MN. *In:* (Lewis Land, Daniel H. Doctor and J. Brad Stephenson editors) ***NCKRI Symposium 2 Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst***, Carlsbad, New Mexico, published on-line by NCKRI, Carlsbad, NM, p. 469-480. ISBN 978-0-9795422-7-5

Alexander, Scott C., Mina Rahimi, Erik Larson, Cody Bomberger, Brittany Greenwaldt and E. Calvin Alexander, Jr. (2013) Combining LiDAR, aerial photography and pictometric tools for karst features database management. *In:* (Lewis Land, Daniel H. Doctor and J. Brad Stephenson editors) ***NCKRI Symposium 2 Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst***, Carlsbad, New Mexico, published on-line by NCKRI, Carlsbad, NM, p. 441-448. ISBN 978-0-9795422-7-5

Luhmann, Andrew J., Matthew D. Covington, Scott C. Alexander, Su Yi Chai, Benjamin F. Schwartz, Joel T. Groten and E. Calvin Alexander, Jr. (2013) Comparison of discharge, chloride, temperature, uranine, δD, and suspended sediment responses from a multiple tracer test in Karst. Carbonates and Evaporites, v. 28, p. 191-199. Published online 13 Feb 2013, DOI 10.1007/s13146-013-0127-8.

Anger, Cale T. and E. Calvin Alexander, Jr., (2012) Bench-scale models of dye breakthrough curves. Carbonates and Evaporates, Published online 10 Oct 2012, DOI 10.1007/s13146-012-0092-7.

Luhmann, Andrew J., Matthew D. Covington, Scott C. Alexander, Su Yi Chai, Benjamin F. Schwartz, Joel T. Groten and E. Calvin Alexander, Jr. (2012) Comparing Conservative and Nonconservative Tracers in Karst and Using Them to Estimate Flow Path Geometry. Journal of Hydrology, Vol. 448-449, p. 201-211.

Alexander, E. Calvin, Jr., Jeffrey A. Green, Anthony Runkel and Katherine J. Logan (2011) Southeastern Minnesota karst hydrogeology: New insights from data loggers, tracing, LiDAR and hydrophysics. *in* Miller, J.D., Jr., Hudak, G.J., Wittkop, C. and McLoughlin, P.I. eds., Archean to Anthropocene: Field Guides to the Geology of the MidContinent of North America: Geological Society of America Field Guide 24, p. 243-257.

Brick, Greg and E. Calvin Alexander, Jr. (2011) Early Graphic Representations of Groundwater Nitrate Concentrations, Ground Water, first published online Dec., 2011 at: DOI: 10.1111/j.1745-6584.2011.00896.x; then in Ground Water, v. 50, no 2, Mar-Apr. 2012, p 319-322.

Luhmann, Andrew J., Matthew D. Covington, Andrew J. Peters, Scott C. Alexander, Cale T. Anger, Jeffrey A. Green, Anthony C. Runkel and E. Calvin Alexander, Jr. (2011) Classification of Thermal Patterns at Karst Springs and Cave Streams, Ground Water, Vol 49, no.3, p 324-334. (Published on line: 16 Jul 2010, DOI: 10.1111/j.1745-6584.2010.00737.x)

Runkel, Anthony C., Robert R. Tipping, Perry M. Jones, Jessica R. Meyer, Beth L. Parker, E.C. Alexander, Jr., Julia R. Steenberg (2013) A Multilevel Monitoring System Provides New Insights into a Bedrock Aquitard in Southeastern Minnesota. Hydrogeology and Public Health: Connecting Science, Education and Poilicy. Minn. Ground Water Association Spring Conference, St. Paul, MN, 24 Apr 2013.

Alexander, E. Calvin, Jr. Jeffrey Green (2013) Introduction to Karst, MN Karst–Nature and Occurrence, Karst Aquifer Characterization (three invited talks). Minnesota Karst Landscape's Interactions with Feedlots, Minn. Pollution Control Agencey, Oronoco, MN, 16-18 April, 2013.

Alexander, E. Calvin, Jr. (2013) Impact of Karst on Agriculture (invited talk). Dinner on the Bluff, Eagle Bluff Environmental Learning Center, Lanesboro, MN, 6 Apr 2013.

Garmon, William Travis, Peters, Joseph Paul, Ustipak, Kelsi R. and Alexander, E. Calvin, Jr. (2012) Mapping karst springsheds in Fillmore County, Minnesota: Increasingly nuanced interpretations (poster 163-7). Abstracts with Programs, 4-7 November 2012 GSA Annual Meeting & Exposition, Charlotte, NC, p. 413.

Wheeler, Betty J., Alexander, Scott C., Green, Jeffrey, A., and Alexander, E. Calvin, Jr. (2012) Ground water tracing information database for Minnesota. (poster) *The 57th Annual Midwest Ground Water Conference: Groundwater Opportunities and Conflicts in the 21st Century: Economy to Ecology, Program with Abstracts.* 1-2 Oct. 2012, Earle Brown Heritage Center, Brooklyn Park, MN. Hosted by the Minnesota Ground Water Association.

Alexander, Scott C., Rahimi Kazerooni, Mina, Larson, Erik, Bomberger, Cody, Greenwaldt, Brittany, and Alexander, E. Calvin, Jr. (2012) The combined application of LiDAR, aerial photography and pictometric tools for sinkhole delineation. (poster) *The 57th Annual Midwest Ground Water Conference: Groundwater Opportunities and Conflicts in the 21st Century: Economy to Ecology, Program with Abstracts.* 1-2 Oct. 2012, Earle Brown Heritage Center, Brooklyn Park, MN. Hosted by the Minnesota Ground Water Association.

Ustipak, Kelsi R., Green, Jeffrey A., and Alexander, E. Calvin, Jr. (2012) Integration of water tracing and structural geology for the delineation of springsheds. (poster) *The 57th Annual Midwest Ground Water Conference: Groundwater Opportunities and Conflicts in the 21st Century: Economy to Ecology, Program with Abstracts.* 1-2 Oct. 2012, Earle Heritage Center, Brooklyn Park, MN. Hosted by the Minnesota Ground Water Association.

Green, Jeffrey A., Runkel, Anthony, and Alexander, E. Calvin, Jr. (2012) Karst hydrogeology investigations in the Cambian St. Lawrence Aquitard. (talk) *The 57th Annual Midwest Ground Water Conference: Groundwater Opportunities and*

Conflicts in the 21st Century: Economy to Ecology, 1-2 Oct. 2012, Earle Brown Heritage Center, Brooklyn Park, MN. Hosted by the Minnesota Ground Water Association.

Alexander, E. Calvin, Jr., Runkel, Anthony Green, Jeffrey A. (2012) Deep time in the Upper Mississippi Valley Karst. (talk) *The 57th Annual Midwest Ground Water Conference: Groundwater Opportunities and Conflicts in the 21st Century: Economy to Ecology*, 1-2 Oct. 2012, Earle Brown Heritage Center, Brooklyn Park, MN. Hosted by the Minnesota Ground Water Association.

Barr, Kelton D. L. and Alexander, E. Calvin, Jr. (2012) Examples of hypogenic karst collapse structures in the Twin Cities Metropolitan Area, Minnesota. (talk) *The 57th Annual Midwest Ground Water Conference: Groundwater Opportunities and Conflicts in the 21st Century: Economy to Ecology*, 1-2 Oct. 2012, Earle Brown Heritage Center, Brooklyn Park, MN. Hosted by the Minnesota Ground Water Association.

Talbot, Michael T. and Alexander, E. Calvin, Jr. (2012) The impact of karst on agriculture. (invited talk). Minn. Ground Water Association Meeting, 19 April 2012, Earle Brown Center, St. Paul, MN.

Alexander, E. Calvin, Jr. (2012) The impact of karst on agriculture (invited, keynote address). 5th Driftless Area Symposium, 27-28 March, 2012, La Crosse, WI.

Anderson, Julia, Runkel, Anthony, Tipping, Robert G., Barr, Kelton D., and Alexander, E. Calvin, Jr. (2011) Hydrostratigraphy of a fractured, urban aquitard. Abstract 110-4, 2011 Geological Society of America Meeting & Exposition, *Abstracts with Programs*, Vol. 43, No. 5, p. 289.

Brick, Greg, Alexander, E. Calvin, Jr., Watkins, Justin and Lundy, James R. (2011) Surface and groundwater nitrate databases for southeastern Minnesota, USA. Poster 108-3, 2011 Geological Society of America Meeting & Exposition, *Abstracts with Programs*, Vol. 43, No. 5, p. 285-286.

Ladd, Bethany S., and Alexander, E. Calvin, Jr. (2011) Dye tracing in the Jordan Sandstone near the Crystal Springs State Fish Hatchery, Winona County, Minnesota. Poster 108-4, 2011 Geological Society of America Meeting & Exposition, *Abstracts with Programs*, Vol. 43, No. 5, p. 286.

Luhmann, Andrew J., Covington, Matthew D., and Alexander, E. Calvin, Jr. (2011) Using a multi-tracer experiment to estimate flow path geometry. Abstract 135-7, 2011 Geological Society of America Meeting & Exposition, *Abstracts with Programs*, Vol. 43, No. 5, p. 342.

Green, Jeffrey A., and Alexander, E. Calvin, Jr. (2011) Dye tracing observations from the Prairie du Chien Group in Minnesota, Abstract 60-11, 2011 Geological Society of America Meeting & Exposition, *Abstracts with Programs*, Vol. 43, No. 5, p. 167.

Talbot, Michael T. and Alexander, E. Calvin, Jr. (2011) The impact of karst on agriculture.

a. (abstract) (*eds.: Engel, Annette Summers, Engel, Scott, Moore, Paul J., DuChene, Harvey)* Carbonate Geochemistry: Reactions and Processes in Aquifers and Reservoirs, Billing, MT, 6-9 August 2011, Karst Waters Institute Special Publication 16, KWI, P.O. Box 1442, Leesburg, VA 20177, p. 69.

b. 1 November, Soft Rock Seminar, Geology and Geophysics Dept. Seminar, Univ. of Minn.

c. 9 November, Minn. Speleological Survey, Bloomington, Minn.

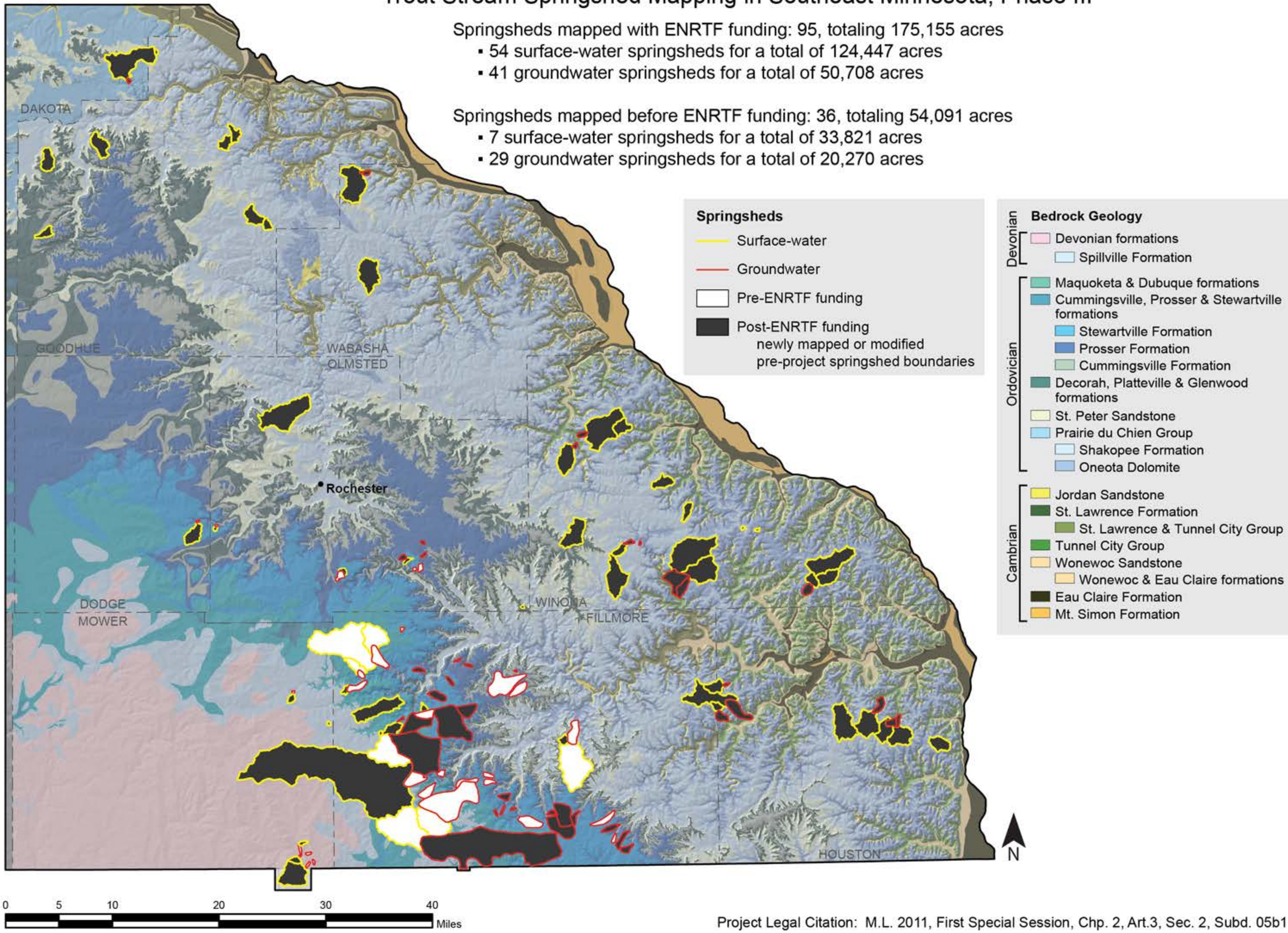
XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted not later than *15 January 2012, 15 July 2012*, *15 January 2013*, and *1 August 2014*. A final report and associated products will be submitted between June 30 and August 1, 2014 as requested by the LCCMR.

Trout Stream Springshed Mapping in Southeast Minnesota, Phase III

Springsheds mapped with ENRTF funding: 95, totaling 175,155 acres
- 54 surface-water springsheds for a total of 124,447 acres
- 41 groundwater springsheds for a total of 50,708 acres

Springsheds mapped before ENRTF funding: 36, totaling 54,091 acres
- 7 surface-water springsheds for a total of 33,821 acres
- 29 groundwater springsheds for a total of 20,270 acres



Project Legal Citation: M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 05b1

Attachment A: Budget Detail for M.L. 2011 (FY 2012-13) Environment and Natural Resources Trust Fund Projects

Project Title: *Innovative Springshed ampping for Trout Stream Management*

Legal Citation: *M.L. 2011, First Special Session, Chp. 2, Art.3, Sec. 2, Subd. 05b2,*

Project Manager: E. Calvin Alexander, Jr.

M.L. 2011 (FY 2012-13) ENRTF Appropriation: $ *280,000*

Project Length and Completion Date: 30 June 2014

Final Report 18 September 2014

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	Activity 1 budget Revised 9/25/2014	Amount Spent	Balance
	Innovative Trout Springshed maps and Reports			
Personnel: Research Assistant: 2 years (50% 12 months per year) = $77,781 Research Specialist: 2 year (90% 12 months per year) = $56,716 Dr. E. Calvin Alexander, Jr.: 1 month per year salary & benefits for 2 years = $20,848 Scott Alexander: 1.5 months per year salary & benefits for 2 years = $16,805 undergraduate lab assistant: 2 years = $20,909	$193,059	$193,412	$193,412	$0
Equipment/Tools /Supplies : Equipment: nitrate data loggers; temperature, conductivity, stage data loggers = $20,000 Supplies: dye, charcoal, bottles, lab and field chemicals, lab and field expendable supplies = $7,500	$27,500	$27,500	$10,513	$16,987
Analytical Expenses: Cation/anion analyses - Geology Lab at U of M approximately $40 per sample, ~162 samples - $6,500 Isotope analyses - Texas State, San Marcos, TX, approximately $15 per sample, ~100 samples - $1,500 (The Texas State lab has been used for previous phase of the proejct and continues to have the best capability available for this work at a reasonable price.	$8,000	$8,000	$6,349	$1,651
Travel & Subsistence In-state: mileage and expenses = $20,041 (per amounts in University plan for employee expenses reimbursement)	$20,441	$20,088	$8,885	$11,556
Contracts: MGS Tony Runkel: 1 month per year and benefits for 2 years (8% time, 1 month per year) = $16,000 Bob Tipping: 1 month per year and benefits for 2 years (8% time, 1 month/year) = $15,000	$31,000	$31,000	$31,000	$0
COLUMN TOTAL	**$280,000**	**$280,000**	**$250,159**	**$30,194**