



## Karst Feature Inventory & Management Plan



Cave within O'Conner's Creek Subwatershed

Outcrop exposed north of  
Highway 10 and west of St. Croix Trail S.



June 13, 2007

# Karst Feature Inventory and Management Plan

Final Report

Prepared for the Lower St. Croix Watershed Management Organization



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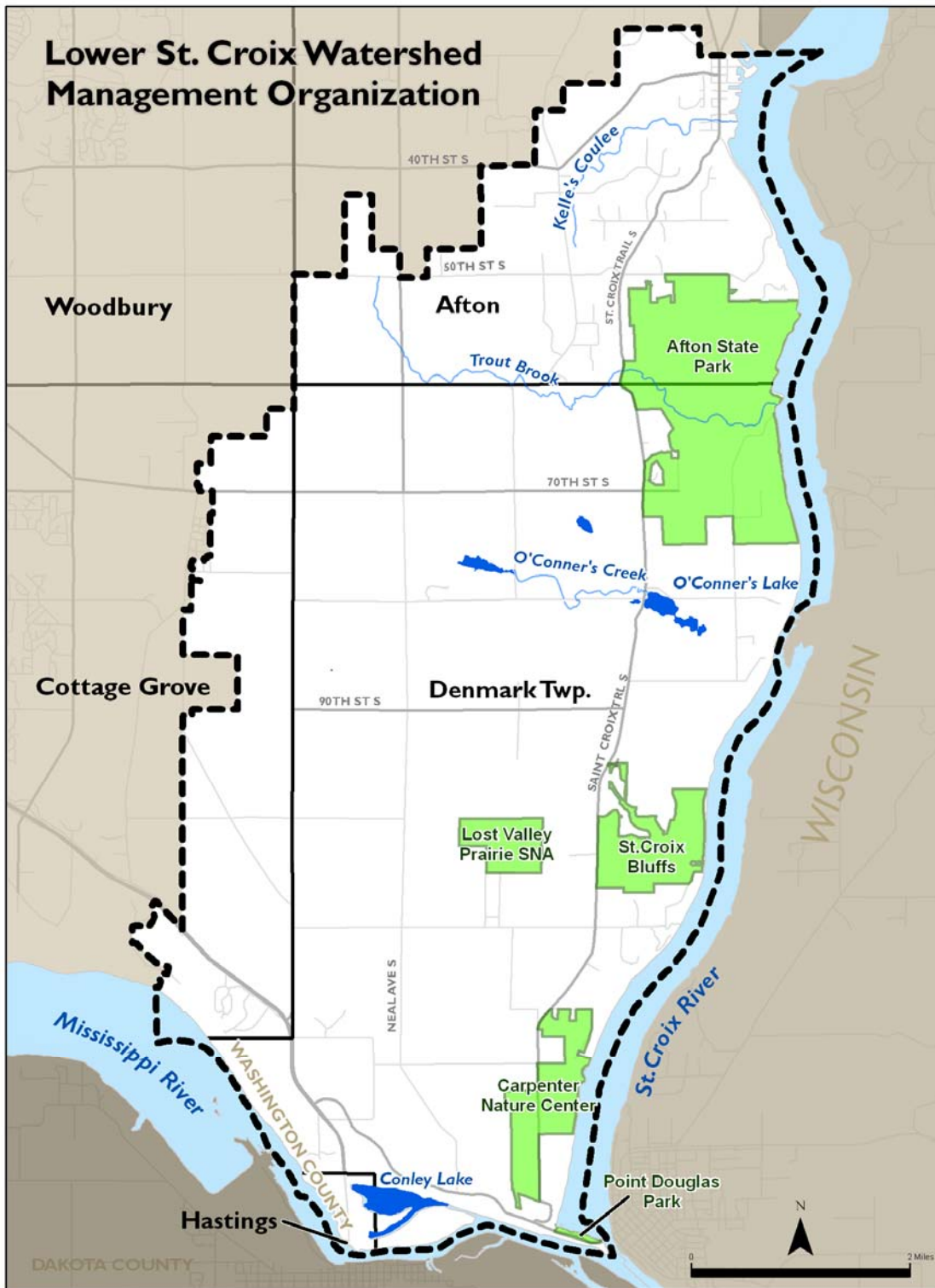
## A. Plan Development

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The Lower St. Croix Watershed Management Organization (LSCWMO) is located in southeastern Washington County, Minnesota (Figure 1). In order to effectively manage LSCWMO resources, the Karst Inventory and Management Plan was developed with the purpose of identifying karst features and applying appropriate management guidelines in the presence of these features. The need to develop this plan was identified in the LSCWMO's Watershed Management Plan (2005).

Karst often refers to a specific type of terrain, typically formed in carbonate rocks such as dolostone and limestone where groundwater has solutionally enlarged openings to form subsurface drainage systems. Although carbonates make up the majority of karst landscapes, karst can also form in silicate lithologies such as sandstone and quartzite. However, karst systems are more than a specific type of landform. The predominate control that defines an area karstic is heterogeneity of flow. Karst systems are dominated by heterogeneous flow that ranges from porous media flow to turbulent flow. Karst areas are well connected to groundwater and have the propensity to allow surface water contaminants to rapidly reach the water table and drinking water supplies. Karstic regions are often characterized by a lack of surface drainage, and frequently have associated sinkholes and caves. Sinkhole collapse is another documented problem associated with karstic regions. Water that is rapidly introduced to aquifers is more likely to be polluted as contaminants have not had the time to be naturally attenuated by the soil column.

Figure 1. Location Map



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## B. Watershed Geology

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LSCWMO geology consists of both bedrock and surficial deposits. Both bedrock and surficial deposits are present at the surface within the watershed, although surficial deposits are thin to non-existent in a large area of the watershed.

### **Surficial Geology**

Surficial geologic units in the LSCWMO contain sediments deposited during glacial and post glacial times. Figure 2 illustrates the surficial deposits of the watershed. The majority of the LSCWMO was un-glaciated during the last glacial episode, referred to as the Wisconsin Glaciation, which is unique in Washington County. Deposits primarily consist of glacial outwash, till and terrace deposits. Other less prominent surficial geologic deposits include organic deposits associated with wetland areas and floodplain alluvium on the banks of Trout Brook. Glacial outwash material in the LSCWMO consists of sand, silt, and gravel. Glacial till in the watershed is characterized by clay.

Terrace deposits are prevalent along the St. Croix River valley, while outwash deposits are found along the Mississippi River and adjacent to each of the perennial streams in the watershed. The Pre-Wisconsin Keweenaw Till (also referred to as “Old Grey Till”) is present throughout the watershed and is remnant of pre-Wisconsin Glaciations. The most prevalent feature visible in the surficial geology figure is the large area where bedrock is near the surface.

### **Bedrock Geology**

Bedrock geologic units in the LSCWMO are of early Paleozoic age (525 – 400 million years old) and were originally deposited as marine sedimentary rocks (Mossler and Bloomgren, 1990). The five bedrock groups of the LSCWMO which outcrop (are exposed directly at the surface) or subcrop (are exposed in the subsurface directly below surficial sediments) are from youngest to oldest, the Platteville Glenwood Formation, St. Peter Sandstone, Shakopee and Oneota Formations of the Prairie du Chien Group, Jordan Sandstone, and the St. Lawrence Formation. The extent of these units is illustrated in Figure 3. The lithology (geologic make up) of the different bedrock units varies dependent upon the depositional setting of the formations. Sandstone units such as the St. Peter and Jordan Sandstones were deposited in high energy environments such as beaches, sand bars, and sand dunes. Shale units such as the St. Lawrence formation were formed in low energy environments when silt and mud was deposited as mud flats in quiet waters. Carbonate layers such as the Prairie du Chien group and Platteville consist of limestone and dolostone derived from algae and marine invertebrate shells that accumulated on the sea floors. Figure 4 illustrates the near surface bedrock units found in the LSCWMO and their relative positions.

Figure 2: LSCWMO Surficial Geology

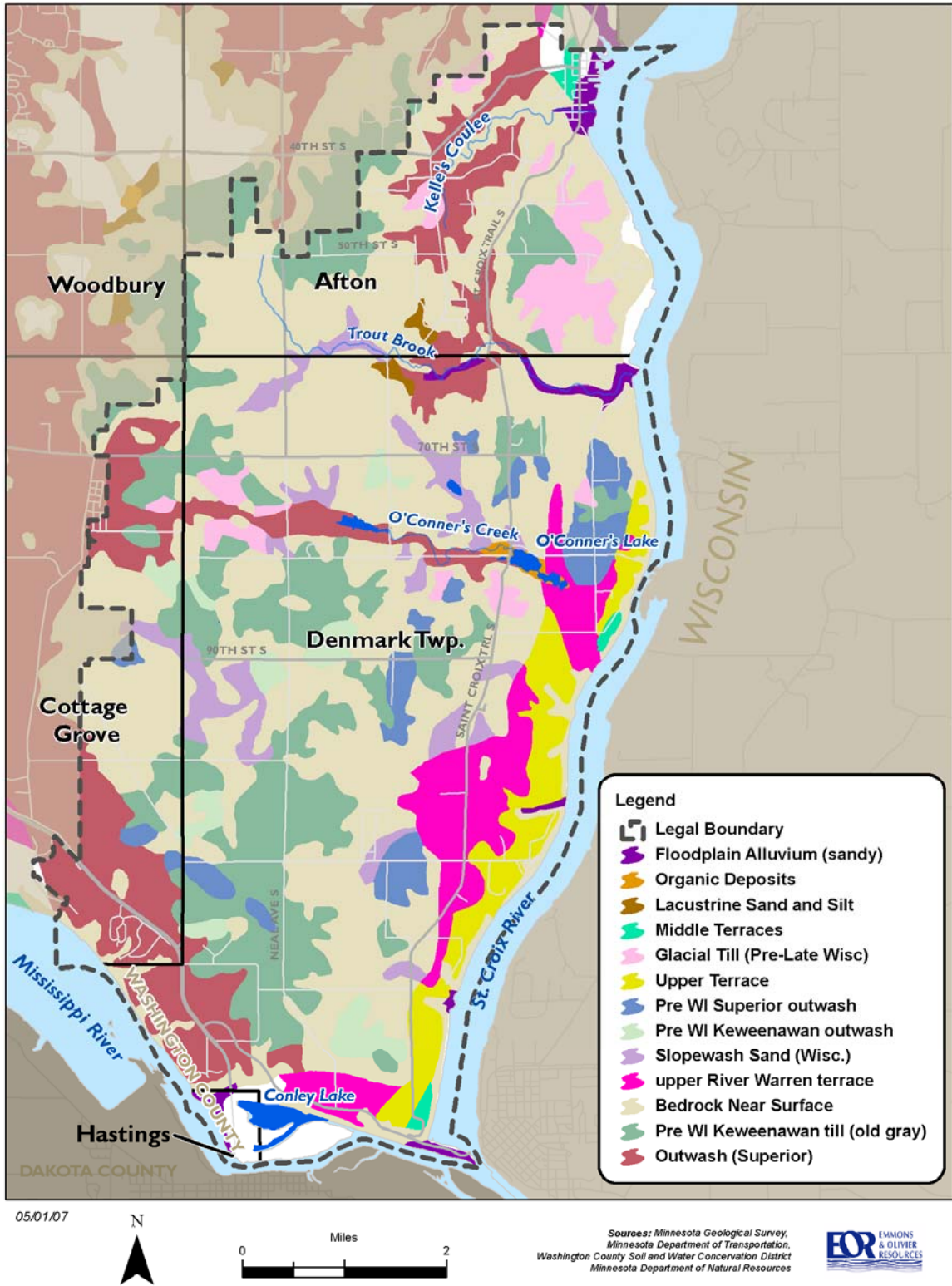
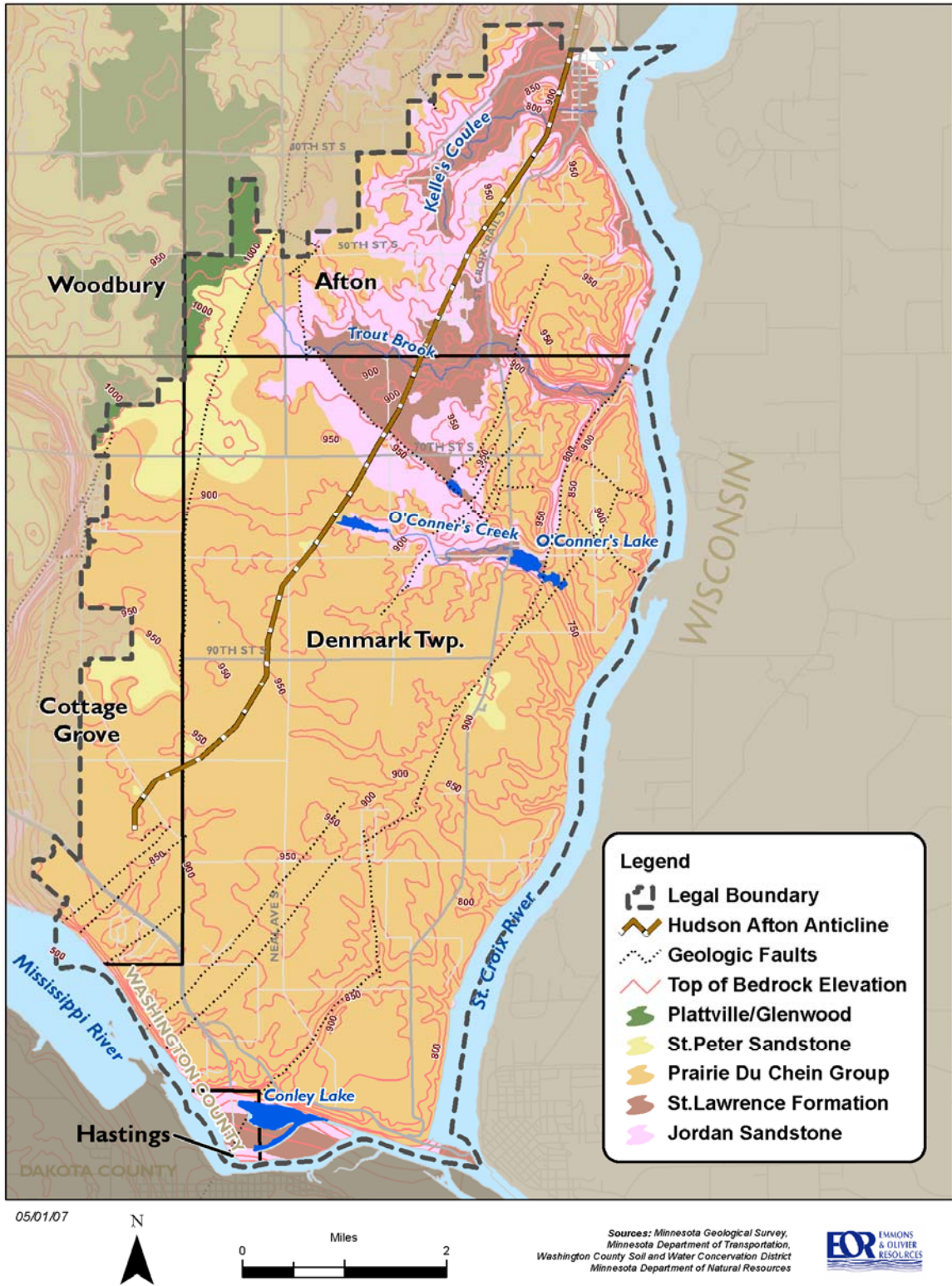
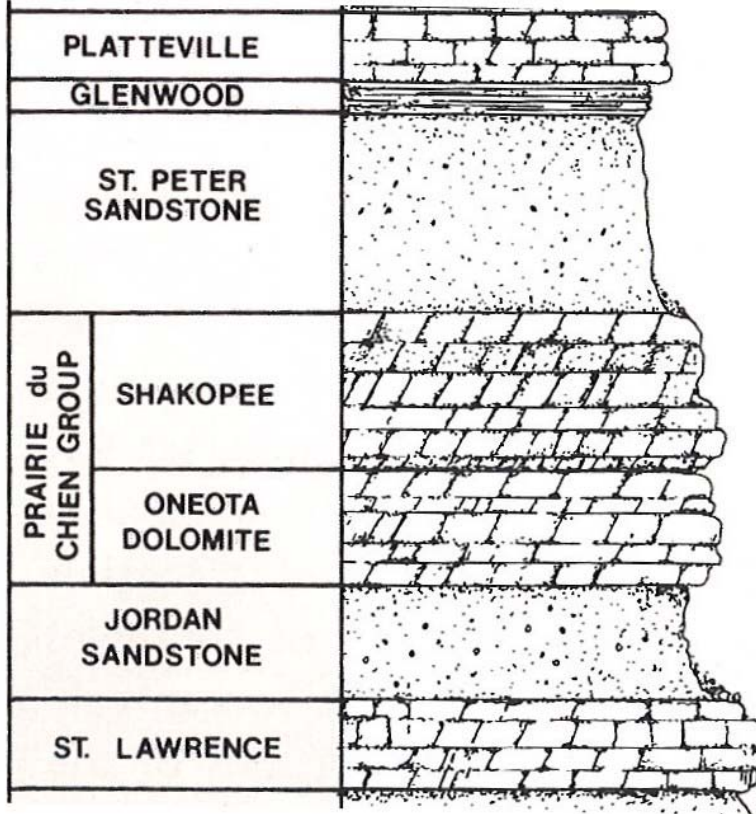


Figure 3: LSCWMO Bedrock and Structural Geology



**Figure 4. General Stratigraphic Column of Upper Geologic Units of the LSCWMO**



(Source: *Minnesota's Geology*)

The LSCWMO is located on the eastern side of a structural geologic feature known as the Twin Cities Basin. The Twin Cities basin is the result of numerous faults and folds that created a depressional feature in the center, near St. Paul, and positive features at the margins (Mossler and Bloomgren, 1990). The LSCWMO is also intersected by a large scale geologic fold known as the Hudson-Afton anticline (Figure 3). Associated with the anticline are numerous smaller folds and faults (Mossler and Bloomgren, 1990). Geologic faults are evident in areas where bedrock unit contacts are not at equal elevations. Bedrock unit contacts occur where two separate geologic units meet. Since all of the bedrock units of interest in the LSCWMO were originally laid down as a function of marine sedimentary processes, the units were initially parallel to each other in a layer cake fashion. These sedimentary processes create units that are younger on top (near the surface) and older with depth. Faulting displaces the geologic contacts so that units are no longer parallel to each other on each side of a fault, but rather offset by a distance. Some of these geologic features are visible at outcrop in the southern areas of the watershed, others in the Tiller-Davies Quarry in Denmark Township. Folding, faulting, and differential erosion is responsible for the range of first encountered bedrock units in the LSCWMO visible in Figure 3. Folding is visible in Figure 5, as bedrock bedding planes which were initially deposited horizontally, now having convex and concave orientations.

**Figure 5. Folded Bedding Contacts of the Prairie Du Chien Group exposed at the Tiller/Davies Quarry**



### **Hydrogeology**

The Prairie du Chien Group is the first bedrock unit and aquifer used for domestic water supply in the majority of the LSCWMO (Figure 3). This geologic unit is divided into two major sections that are comprised predominately of dolostone. The upper unit, the Shakopee Formation, is predominately dolostone with minor sandstone and chert layers. The lower unit, the Oneota Formation, is predominately massive dolostone (Mossler and Bloomgren, 1990). The Prairie du Chien Group is known as a dual porosity aquifer due to the presence of the matrix rock itself (dolostone), and bedding plane conduits and vertical fractures. Porosity is the void space in a rock unit in which through water flows. The presence of vertical fractures and bedding plane conduits in the Prairie du Chien Group make the unit susceptible to pollution and are partially responsible for karstic features within the watershed. A 2003 study of the Hydrogeology of the Paleozoic Bedrock in southeastern Minnesota conducted by the Minnesota Geological Survey (MGS) noted that the Prairie du Chien is “ubiquitously fractured” in shallow bedrock conditions similar to much of the LSCWMO. The study notes that the Prairie du Chien Group occurs as the uppermost bedrock across much of Southeastern Minnesota and states that the densities of springs and sinkholes correspond to “major bedding-plane parallel conduit systems.” These systems tend to occur at the geologic contact of the Shakopee and Oneota Dolomite and the St. Peter Sandstone and Shakopee Dolomite where they lie directly beneath the land surface (Dalglish and Alexander, 1984; Tipping and others, 2001). Figure 6 illustrates fractures and dissolution conduits of the Shakopee Formation of the Prairie du Chien Group exposed in the Tiller/Davies Quarry.

**Figure 6. Bedding Plane Conduits and Vertical Fractures exposed at the Tiller/Davies Quarry**

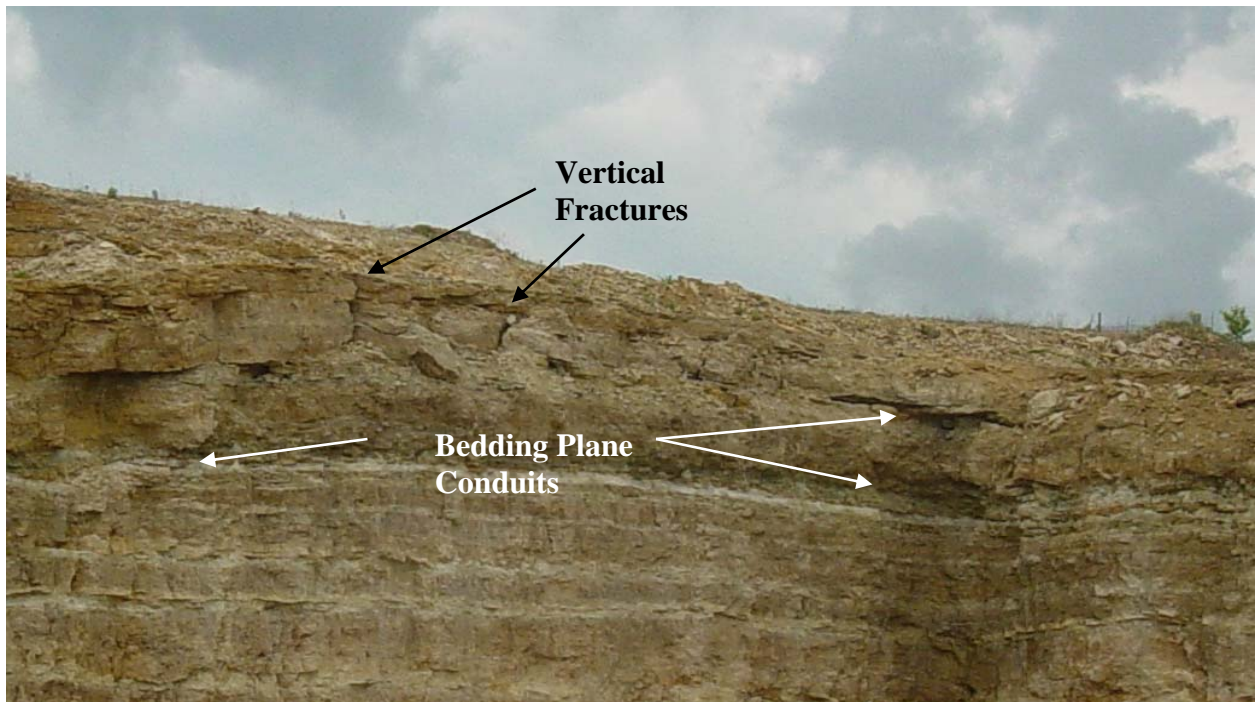


Figure 7 is an example of a solutionally enlarged conduits and bedrock fractures visible at a bluff in the O’Conner’s Creek subwatershed west of County Road 21.

**Figure 7. Large conduits exposed in Prairie du Chien Outcrop.**



Borehole geophysical studies of wells by the MGS have identified solution cavities and/or fractures in the Shakopee Formation of the Prairie du Chien Group in nearby test wells in Woodbury. The solution cavities and fractures were identified using an expandable caliper that identifies intervals greater than the diameter of the well drilled. Currently there are no wells in the LSCWMO that have borehole geophysics data that include caliper testing. The presence of visible fractures and joints at Shakopee Formation outcrops and in quarries within the watershed coupled with the Woodbury geophysical data illustrates the likely presence of these features over a large area in the LSCWMO region.

### **Geologic Cross Sections**

The MGS and the Minnesota Department of Health (MDH) have developed a database of wells in the state that allows users to search for geologic and construction information of wells in the state. This database is known as the County Well Index (CWI). Attributes listed in the CWI include basic information such as well location, well depth, and the well's static water level. More specific information included in the database includes casing size and depth, well elevation and groundwater elevation, subsurface lithology, and depth to bedrock.

A public version of the CWI is available at the MDH website located at <http://www.health.state.mn.us/divs/eh/cwi/>. The CWI was accessed to identify geologic units within the watershed and as an input to develop geologic cross sections.

CWI data were also accessed using a cross-section tool developed by the MDH. Four cross sections were developed to analyze general depth to bedrock values and aid in the identification of the first bedrock unit. Surficial topography along each cross section was developed using the MetroGIS 30-meter digital elevation model. Cross section locations and interpretation are shown on Figures 8 through 12.

Geological cross sections developed using data collected at wells in the watershed (Figures 8-12) illustrate a thin veneer of soil overlying carbonate and sandstone bedrock throughout the majority of the LSCWMO. Soils overlying bedrock vary throughout the watershed from clay to sand and gravel. Several bedrock valleys are within the LSCWMO. In these locations, one or more bedrock units were eroded away in ancient times and have since been filled or partially filled with glacial outwash material and alluvium.

Figure 8: Cross Section Layout Map

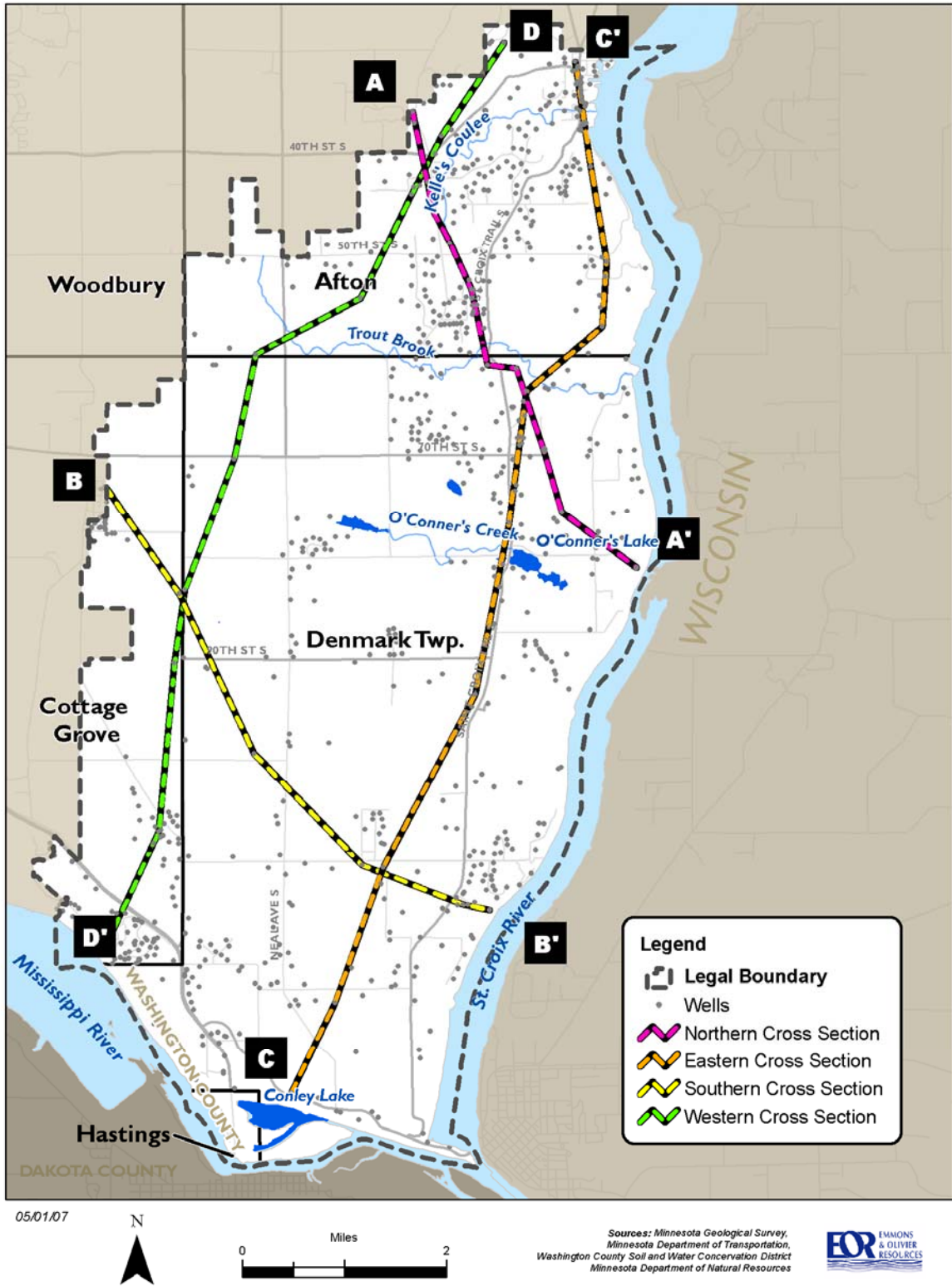
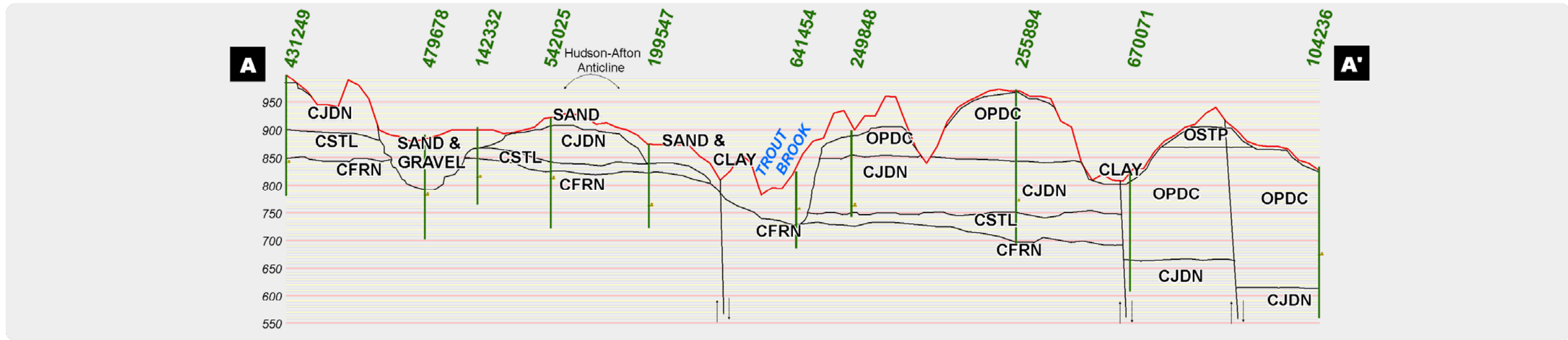


Figure 9: Northern Cross Section

Vertical Exaggeration 15X

Source: Minnesota Geological Survey



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999999 - Minnesota Unique Well Number

- Geologic Fault

OSTP	- St. Peter Sandstone	CSTL	- St. Lawrence Formation
OPDC	- Prairie du Chien Unit	CFRN	- Franconia Formation
CJDN	- Jordan Sandstone	CIGL	- Ironton-Galesville Sandstone

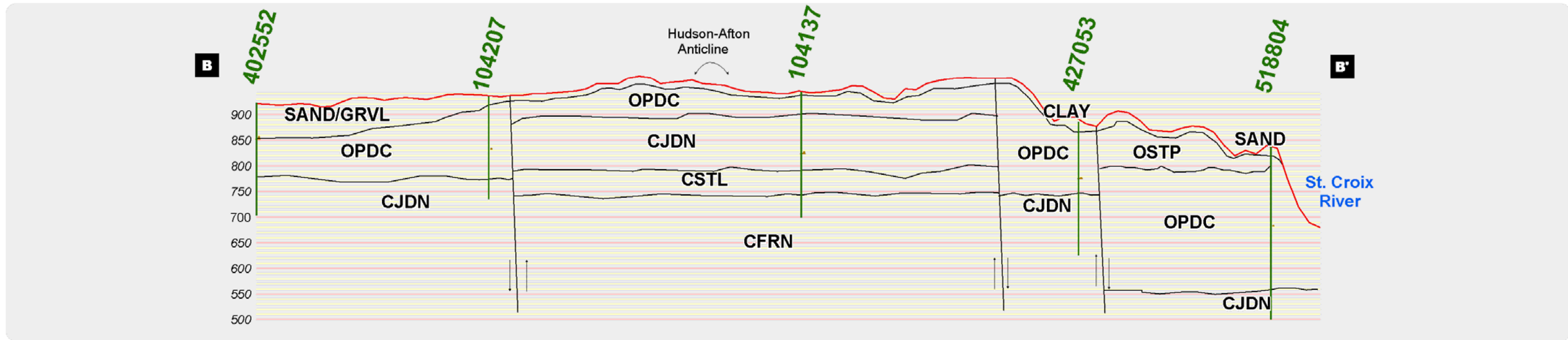
### Northern Cross Section



Figure 10: Southern Cross Section

Vertical Exaggeration 15X

Source: Minnesota Geological Survey



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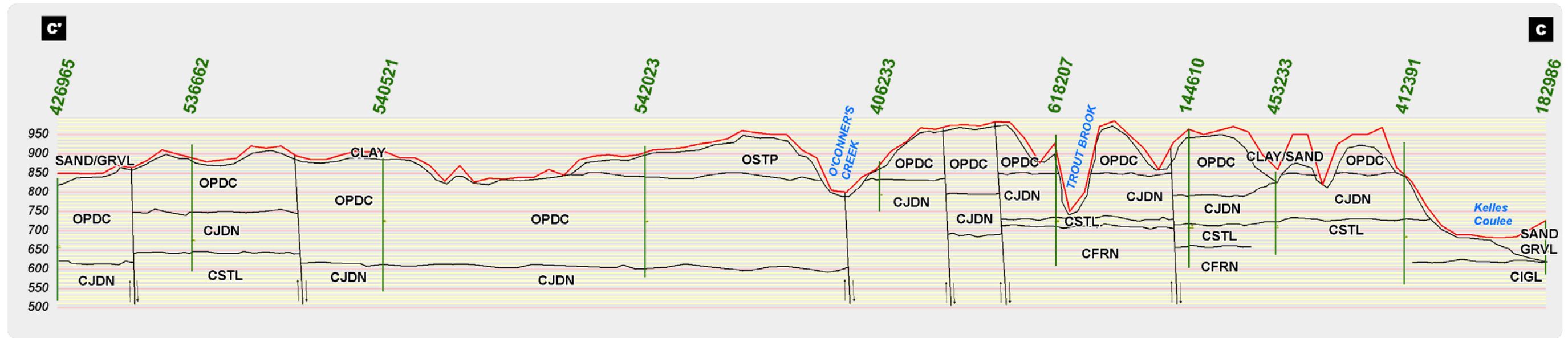
### Southern Cross Section



Figure 11: Eastern Cross Section

Vertical Exaggeration 15X

Source: Minnesota Geological Survey



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999999 - Minnesota Unique Well Number

- Geologic Fault

OSTP	- St. Peter Sandstone	CSTL	- St. Lawrence Formation
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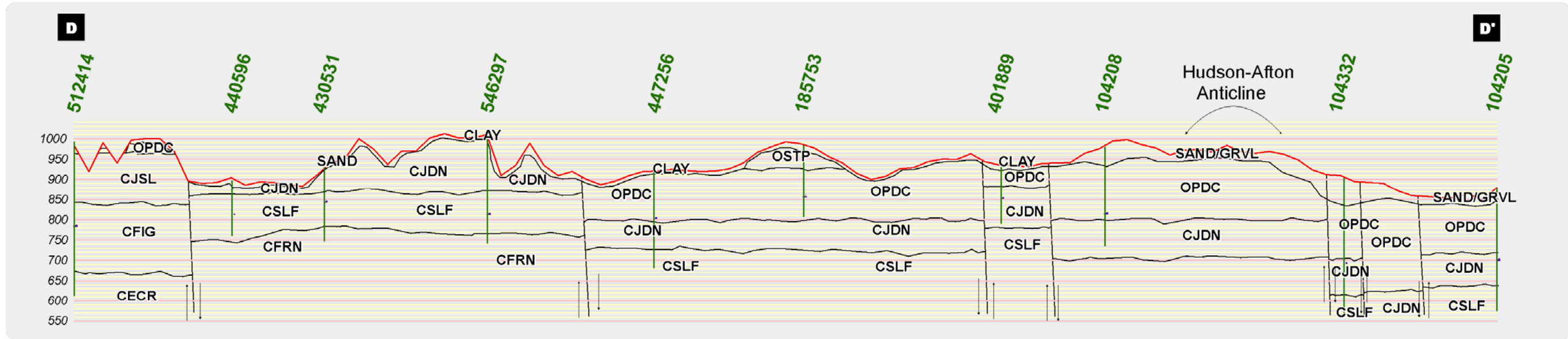
### Eastern Cross Section



Figure 12: Western Cross Section

Vertical Exaggeration 15X

Source: Minnesota Geological Survey



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## Western Cross Section



## **Sensitivity to Pollution**

The presence of fractured soluble bedrock, geologic faulting, and thin soil cover makes the LSCWMO susceptible to groundwater pollution. Recognition of this sensitivity was published in the 1990 Washington County Geologic Atlas (Atlas). Plate 6 of the Atlas assesses the risk of the Water Table Aquifer and the Prairie du Chien Aquifer to pollution (Meyer, 1990). The risk assessment determined that the vast majority of the LSCWMO has a very high sensitivity rating for the Prairie du Chien Aquifer, and much of the Water Table Aquifer has a high to very high sensitivity rating. A very high sensitivity rating states that “contaminates will almost certainly reach the groundwater aquifer in hours to months.” The sensitivity rating was based on the ability of geologic materials of the area to attenuate contaminants, the rate at which contaminated water can flow to or through aquifers, and the travel time it would take a contaminant released on the surface to reach the Prairie du Chien Aquifer. Thin soil horizons increase the chance of pollution reaching upper aquifers because soils are the first line of defense for attenuating contaminants. Nearly a third of the wells in the LSCWMO use the Prairie du Chien and Jordan aquifers. These aquifers are the first bedrock aquifers in the majority of the LSCWMO and are vulnerable to contamination due to the geologic setting. Continued identification of karst features in the LSCWMO and the careful siting of future stormwater ponds and septic treatment systems are necessary to prevent degradation of groundwater resources through anthropogenic means.

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## C. Karst Resource Inventory and Data Collection

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Karst features including sinkholes, springs, and sinking streams have been noted in the LSCWMO by MGS personnel and personnel from the University of Minnesota's Hydrogeology Group. Sinkholes are surface manifestations of subsidence caused by collapse of subsurface conduits and fractures. Springs are points where subsurface groundwater flow is concentrated and act as foci for discharge from karst aquifers. Sinking streams are locations on the surface where a perennial or ephemeral stream disappears underground through a sinkhole or by gradual downward percolation through porous streambed material.

Numerous geological faults have been noted in the LSCWMO region. One of the key findings of the Cottage Grove Nitrate Study is that fault zones in southern Washington County appear to act as high zones of hydraulic conductivity allowing for rapid transmission of surface water through the Prairie du Chien Group to the Jordan Sandstone (Barr, 2003).

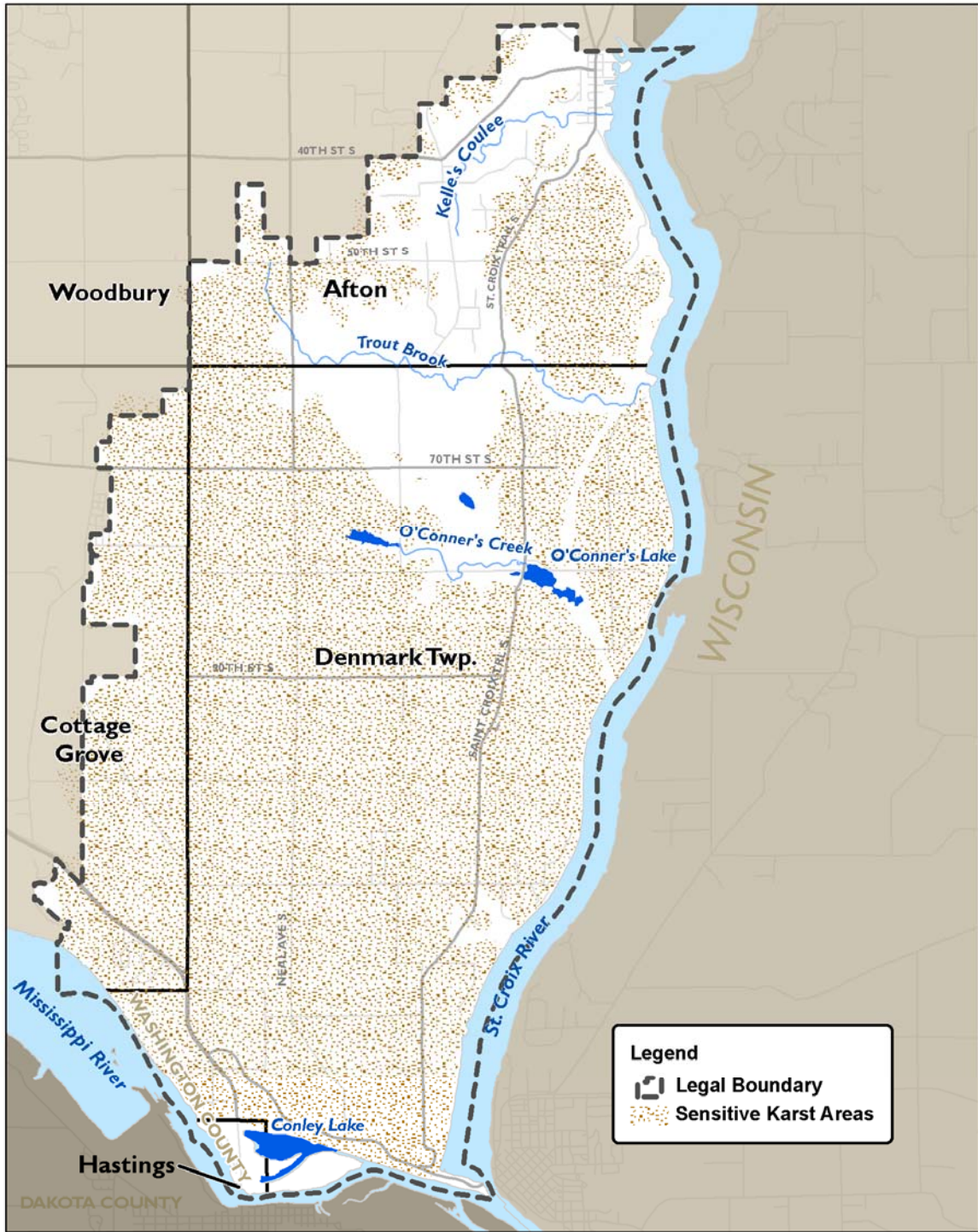
Karst sensitive areas are defined as those areas with less than 50 feet of surficial materials overlying unconsolidated St. Peter Sandstone or the soluble dolomitic Prairie du Chien Group (Gao and others, 2002; Alexander, 2006). The designation of less than 50 feet to soluble bedrock as a factor of active karst terrain has been developed for southeast Minnesota by researchers at the University of Minnesota's Department of Geology and Geophysics Hydrogeology Working Group. This group has extensively studied karst and karst features of Southeast Minnesota for several decades and has determined that most sinkholes statistically occur in less than 50 feet to soluble bedrock depth range. Both the St. Peter Sandstone and the Prairie du Chien Group are recommended by the Minnesota Pollution Control Agency (MPCA) to be treated as karst aquifers (MPCA, 2005). Figure 13 illustrates the areas within the LSCWMO that are identified as karst sensitive, which includes the majority of the watershed.

In addition to mapping karst sensitive areas, karst features were identified through mapping and field methods. Potential karst investigation areas were located and mapped to identify areas where additional information will be needed at the time of development.

EOR staff met with agency personnel to discuss karst features and issues related to stormwater and sinkhole collapse. Staff from the DNR, University of Minnesota's Hydrogeology Working Group, Washington County Department of Environment and Public Health, and the Minnesota Geological Survey was present at a meeting in Woodbury, Minnesota held to discuss issues related to sinkhole formation/collapse and stormwater management. The meeting was scheduled after the dramatic sinkhole formation and pond draining of a stormwater pond at the Dancing Waters Development in Woodbury.

The MPCA, MDH, MGS, Wisconsin DNR, and several cities in karstic areas of Minnesota and Wisconsin were also contacted to discuss karst related issues and guidance related to stormwater, feedlots and spills. Dialog from the Woodbury meeting, discussion with the University of Minnesota's Hydrogeology Working Group, and exchanges with city engineers were incorporated into this document

Figure 13: Karst Sensitive Areas



05/01/07



Sources: Minnesota Geological Survey,  
Minnesota Department of Transportation,  
Washington County Soil and Water Conservation District  
Minnesota Department of Natural Resources



## **Karst Features Database and Existing Data**

Karst features were identified through review of existing databases including the Karst feature database, the Geologic Atlas for Washington County, and mapped springs that were identified during previous studies. Figure 14 includes all of the identified karst features.

An existing database of karst features of Southeastern Minnesota has been developed by the MGS, the Department of Geology and Geophysics at the University of Minnesota, and the Minnesota Department of Natural Resources (DNR). Karst features are stored in Microsoft ACCESS 2000 DBMS and are linked to corresponding Arc View shape files. Inventory points and the karst database are updated regularly as new field information is acquired and are available at the MGS website <http://mgsnt4.mngs.umn.edu/karst/>. These points are illustrated on Figure 14.

The Geologic Atlas for Washington County (Atlas) contains information on sinkhole location, spring location, and bedrock exposure. These data are available on Plate 1 of the Atlas and are attributed to both field sightings by MGS geologists and locations offered by landowners. All sinkholes and springs from the Atlas are identified in the karst data base, in addition to points added since the printing of the Atlas in 1990.

Plate 1 of the Atlas was rectified in a GIS environment to create a map of bedrock outcrop features. This map was then used to verify and analyze areas of thin soil cover. Figure 14 identifies mapped bedrock outcrops in the LSCWMO. Bedrock outcrop locations identified through fieldwork were added to the map.

Spring locations have been field identified and mapped as part of the Afton and Denmark Natural Resource Inventories and Water Resource Inventories (EOR, 2001; WCD, 2001; Barr and WCD, 2002). These spring locations vary in size and may not be present on a permanent basis.

## **Aerial Photographic Interpretation**

Historical and current modern aerial photographs were analyzed to locate karst and potential karst features in the LSCWMO. The review of historical aerial photographs in conjunction with modern aeriels was initiated to locate features that may have been eliminated over time. Sinkholes located in agricultural regions are often filled with rock, refuse, and soil to allow these sites to be farmed. Historic photos from 1947 were retrieved from the Minnesota Department of Natural Resources and rectified to spatially locate features. Use of historical aerial photographs provided indistinct results due to the resolution of the photographs. No additional features were added using historic aerial photographic interpretation.

2003 aerial photographs obtained from the US Department of Agriculture (USDA, 2003) were utilized to examine landscape features within the watershed and potential karst features. Karst features, specifically sinkholes, may be identified using aerial photographs in conjunction with landform contours to identify points on the landscape where depressional lows or terminating swales are possible karst features. Features such as tree clusters in open active agricultural land

and areas that appear to have terminated swales identified through GIS analysis were assigned karst investigation areas. These locations are identified on Figure 15. In addition, several existing points from the karst features database were shifted to more representative locations using aerial photography.

### **Topographic Contours**

Landform topographic contours were analyzed for the presence of depressional contours within the watershed. Depressional contours can be surface manifestations of sinkholes and paleo-sinkholes. In Minnesota, depressional contours are also sometimes the by product of ice block depressions created from glacial activity. Ten foot contours of the LSCWMO (USGS and Metropolitan Council, 1999) were analyzed in a GIS setting to spatially observe the occurrence of depressional features. Depressional contours were compared to known sinkhole locations to identify potential trends in sinkhole location. Since the LSCWMO is a known karstic region, these areas were investigated using field observations where possible and modern aerial photographic interpretation. Depressional areas should be thoroughly field investigated before using these areas as potential stormwater storage areas in the future. Depressional contour sites are included with the Investigation Areas illustrated in Figure 15.

### **Field Work**

The LSCWMO was traversed to investigate regions with depressional landform contours. Select landowners were contacted following aerial photographic interpretation, depressional contour identification, and field work. In cases where contact with landowners was not obtained, landowners were left a solicitation letter requesting information pertinent to karst and karst features. No landowners responded to our solicitation letters. Property was only accessed after acquiring permission from landowners. Photos documenting the thin soil conditions of several areas of the watershed were taken to document the shallow depth to bedrock. Discussion with landowners led to the “discovery” of two sinkholes located south of 80th Street and east of Manning that had been filled with overburden. Discussion and field work also led to the removal of one incorrectly identified sinkhole.

**Figure 14: Karst Feature Database and Bedrock Outcrops**

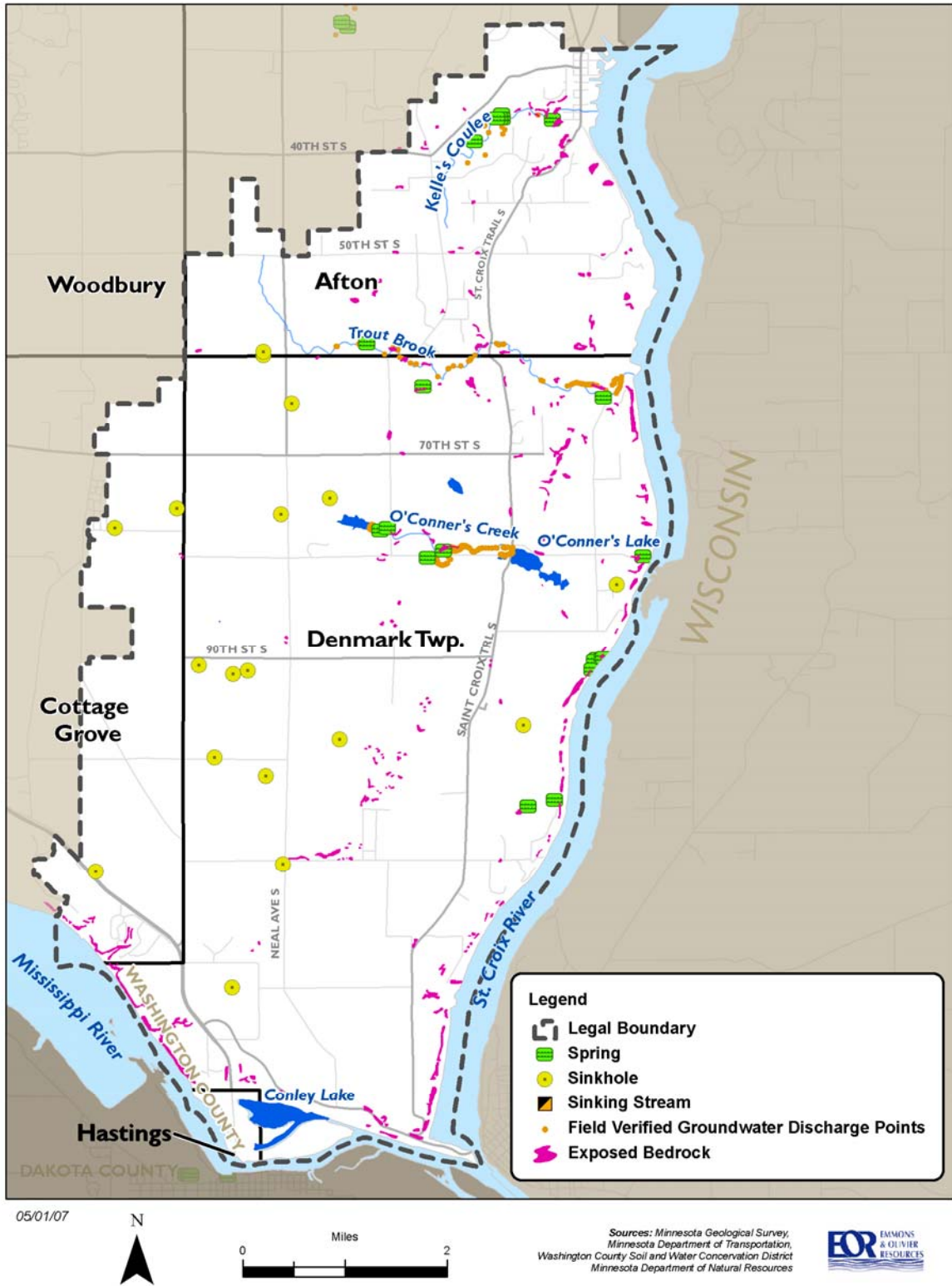
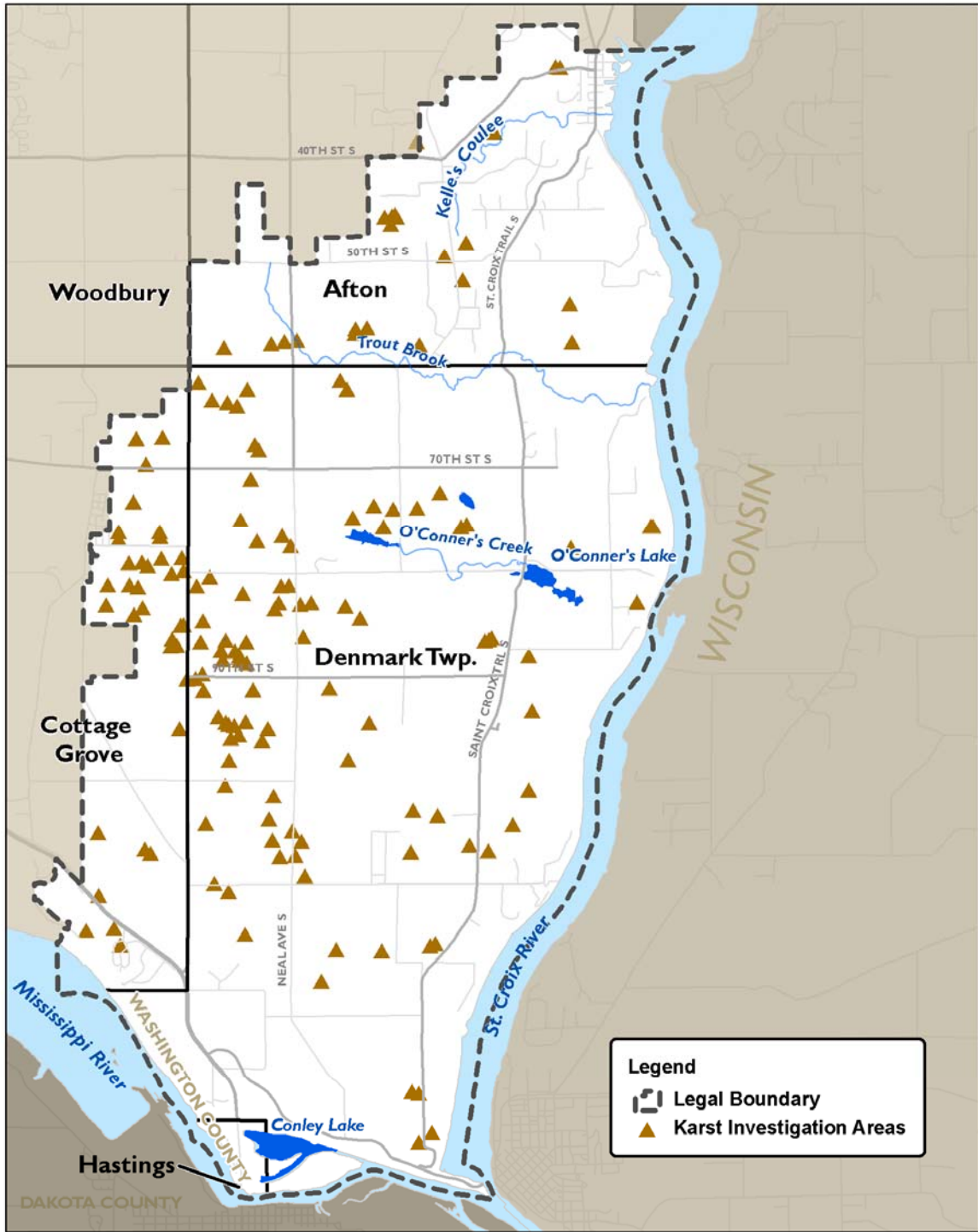


Figure 15. Karst Investigation Areas



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## D. Karst Guidelines and Management

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Due to the presence of shallow bedrock conditions, karst features, and geologic fractures and faults in the LSCWMO, the typical installation of excavated stormwater detention basins may not be prudent in some cases. Concentrating increased runoff due to development into the relatively small space of a stormwater detention basin may create hydraulic heads that cause sinkhole development or sinkhole collapse.

Small scale, on-site best management practices (BMP) are more applicable in karstic regions than typical large ponds and regional stormwater detention facilities. The October 2005 catastrophic sinkhole development and failure of the Dancing Waters stormwater pond in nearby Woodbury is believed to have taken place due to hydrostatic pressure of water in the stormwater pond flushing fill and liner material into existing fractures in the St. Peter Sandstone. It is estimated that roughly 70 acre feet of stormwater drained in 48 hours or less during this event. This failure a dramatic example of hazards associated with regional stormwater basins in karstic terrain. In lieu of this, smaller on-site BMPs and large open area diffuse infiltration practices are recommended.

There are already a number of existing standards and guidelines to apply in the LSCWMO. There is a need to further explore and provide guidance on specific requirements for development and stormwater management in karst areas of the LSCWMO. This section includes a summary of existing standards and guidelines, and provides documentation in support of LSCWMO Rules.

### Existing Standards and Guidelines

#### *Minnesota Pollution Control Agency - Stormwater*

Minnesota Rules Chapter 7090 regulates stormwater discharges in the State. A General Construction Permit has been issued by the MPCA, which permits stormwater discharges to surface and groundwater resources. The General Construction Permit includes a provision which states that the construction plans and associated documents must provide additional measures as necessary to assure compliance with surface and ground water standards in Minnesota Rules 7050 and 7060 in karst areas.

Minnesota Rules Chapter 7050, which regulates Waters of the State, includes groundwater as part of the waters of the State, and sets water quality standards based on the EPA's primary and secondary drinking water standards for groundwater used for domestic consumption. These standards are not for stormwater discharges, but are for the overall groundwater. Minnesota Rules Chapter 7060 regulates the protection and preservation of groundwater. This Rule includes a nondegradation policy for groundwater which states:

*It is the policy of the agency that the disposal of sewage, industrial waste, and other wastes shall be controlled as may be necessary to ensure that to the maximum practicable extent the underground waters of the state are maintained at their natural quality unless a determination is*

*made by the agency that a change is justifiable by reason of necessary economic or social development and will not preclude appropriate beneficial present and future uses of the waters.*

Minnesota Rules Chapter 7050 and 7060 do not specifically set standards for groundwater quality protection in karst areas, but are overall Rules addressing groundwater protection throughout the State.

#### *Minnesota Pollution Control Agency - Feedlots, Manure Spreading and Storage*

Existing rules and guidance regarding feedlots, manure spreading, and manure storage in karstic and shallow bedrock settings have been issued by the MPCA and are available at <http://www.pca.state.mn.us/publications/wq-f8-13.pdf> and <http://www.pca.state.mn.us/publications/feedlots-manureapplication.pdf>. These documents contain state siting requirements and guidance for manure storage areas and manure application in karstic areas of the State of Minnesota. State requirements for siting manure storage areas in karst settings vary dependent upon the number of animals using the storage facility, soil type, depth to bedrock, and topographic slope.

#### *Minnesota Pollution Control Agency – Groundwater Investigations in Karst Areas for Petroleum Remediation Areas*

The Petroleum Remediation Program of the MPCA developed a guidance document for Groundwater Investigations in Karst Areas. The document, Guidance Document 4-09 (<http://www.pca.state.mn.us/publications/c-prp4-09.pdf>), provides guidance on appropriate procedures and techniques for conducting accurate, reliable, and cost effective groundwater investigation in areas of karst terrain to be applied in the event of a petroleum spill or leaking tank.

#### *Washington County - Stormwater Management*

There are existing local ordinances and standards that may be in direct opposition with standards necessary to protect karst areas. Specifically, Washington County Ordinance 131 section 10.3, number 10 specifies stormwater rules for subdivisions. Specifically, rules A through D state the storm water detention facility shall, at a minimum, have the following design characteristics:

- A.) A permanent pond surface area equal to 2% of the impervious area draining to the pond or 1% of the entire area draining to the pond, which ever amount is greater.
- B.) An average permanent pool depth of 4 to 10 feet.
- C.) As an alternative to A and B above, the Washington County Plat Commission may require that the volume of the permanent pool be equal to or greater than the runoff from a 2 inch rainfall for the fully developed site.
- D.) A permanent pool length to width ratio of 3:1 or greater.

This ordinance could require ponding scenarios that would be inappropriate in karst regions and threaten groundwater quality. Further discussion with Washington County is needed to resolve this issue.

## *Washington County - Individual Septic Treatments Systems*

Improperly operating Individual Septic Treatments Systems (ISTS) may introduce nitrate, phosphorous, pathogens, chemicals and viruses into aquifers. In karst settings, the possibility of aquifer contamination via ISTS may be heightened. Septic care and maintenance is similar in karst settings as it is in non karstic regions. Washington County Ordinance 128 specifies in Section 17.2 that “The owner of an individual sewage treatment system or the owner’s agent shall regularly, but in no case less frequently than every three years, have the tank or tanks pumped. As an alternative, the owner may inspect and measure the accumulations of scum, which includes grease and other floating materials at the top of each septic tank and compartment along with the sludge, which includes the solids denser than water.” Due to the sensitivity of karst environments, ISTS systems should be in compliance with Section 17.2.

### **LSCWMO Guidelines and Management**

Communities in karst settings throughout the country are developing karst area design specifications and soil investigation procedures for siting and designing stormwater BMPs. The Minnesota Stormwater Manual, 2005, compiled guidance related to stormwater treatment in karst settings. The guidance was based on the experience of communities that deal with karst issues and concerns. Communities with experience in karst and stormwater management that contributed to the Manual include Carroll County, MD [1996a and b]; St. Johns River Water Management District, FL [2001]; and Jefferson County, WV [Laughland 2003]).

LSCWMO guidelines and processes for a karst sensitivity analysis and karst investigation areas are developed in support of the LSCWMO Rules. Guidance on sinkhole remediation and monitoring of best management practices (BMPs) in karst areas is also presented. The majority of this information was derived from the Minnesota Stormwater Manual, 2005.

#### *Guidelines*

The following guidelines have been included as a first level of groundwater protection for the karst sensitive areas within the LSCWMO. The guidelines are meant to address concerns related to karst regions, but do not contain substantial prescriptive information because of the variability inherent to karst geology in Minnesota. These guidelines should be followed for all proposed stormwater management facilities in the LSCWMO.

1. Developers, communities, public works agents and others managing stormwater should conduct thorough geotechnical investigations prior to proceeding with projects or building in active karst areas. The level of geotechnical investigation will depend on the likelihood of active karst being present. Karst features should be identified and reported to the appropriate state (such as DNR and MGS) and local agencies (such as the city, township or county). Any known occurrences should be surveyed for specific location and permanently recorded on the property deed. For transition karst areas, local discretion and the likelihood of karstic features should be used to determine the amount of geotechnical investigation.

2. Knowledge of or the presence of sinkholes is an absolute indication of active karst. In these cases, an easement or reserve area should be identified on the development plats for the project so that all future landowners know of the presence of active karst on their property.
3. In many cases, identified sinkholes can and should be remediated and stormwater directed away. In other cases, remediation is not possible and the normal regional hydrologic patterns must be maintained. In this case, however, precautions should be taken to extensively pretreat any water that drains into a known sinkhole area. If at all possible, runoff should be routed away from active karst features.
4. Discharges from stormwater management facilities or directly from impervious surfaces should not be routed directly to a sinkhole.
5. Sinkholes developing within stormwater management facilities should be reported to the MGS and MDH as soon as possible after the first observation of occurrence. They should then be repaired, abandoned, adapted, managed and/or observed for future changes, whichever of these are appropriate.
6. Sinkhole formation is less likely when water is allowed to soak diffusely into the soil and when stormwater is managed for smaller, more diffuse quantities that limit the volume and rates of flow handled by each BMP. Adequate precautions should be taken to assure that all potential contaminants are removed from infiltrating stormwater.
7. Where ponds and wetlands are deemed necessary, they should be designed and constructed with a properly engineered synthetic liner. A minimum of three feet of unconsolidated soil material should exist between the bottom of the pond or wetland and the surface of the bedrock layer. Pond and wetland depths should be fairly uniform and limited to no more than ten feet in depth.

Table 1 provides an overview of karst related design considerations for five BMP structural groups as included in the Minnesota Stormwater Manual, 2005.

**Table 1. Structural BMP Use in Karst Settings (MPCA, 2005)**

<b>BMP</b>		<b>Karst Considerations</b>
<b>Bioretention</b>		<ul style="list-style-type: none"> <li>• If contaminant levels remain high after treatment or if water inflow presents a threat, an underdrain and/or use of a synthetic or other impermeable membrane liner should be considered to seal the bottom of the system</li> </ul>
<b>Filtration</b>	<b>Media</b>	<ul style="list-style-type: none"> <li>• See the note above</li> </ul>
	<b>Vegetative</b>	<ul style="list-style-type: none"> <li>• Avoid water ponding</li> <li>• Should be engineered to avoid channel erosion and optimize pollutant removal</li> </ul>
<b>Infiltration</b>	<b>Infiltration Trench</b>	<ul style="list-style-type: none"> <li>• Not typically recommended in active karst areas due to sinkhole formation and inadequate treatment by a scarcity of underlying soils</li> <li>• If used, should have supporting geotechnical investigations and calculations</li> </ul>
	<b>Infiltration Basin</b>	<ul style="list-style-type: none"> <li>• Pretreatment should be extensive to limit risk of groundwater contamination</li> <li>• Local review authority should be consulted for approval</li> </ul>
<b>Stormwater Ponds</b>		<ul style="list-style-type: none"> <li>• Should be constructed with a synthetic or clay liner in sensitive karst areas</li> <li>• Should have supporting geotechnical investigations and calculations</li> <li>• Should be limited to a maximum ponding depth (e.g., &lt; 10 feet)</li> </ul>

*Karst Sensitive Areas*

A Karst Sensitivity Analysis should be conducted during the development process or as needed on all sites that are included in the karst sensitive area of the LSCWMO.

Due to the complex nature of karst and fractured bedrock settings, geotechnical investigations cannot follow a template guideline, but rather will be tailored upon the setting and specific circumstances and findings. These guidelines may represent more than what is needed for some site studies. The following sections outline processes that should be used to investigate the karst nature of the site. The majority of this information is taken directly from the Minnesota Stormwater Manual, 2005.

Karst investigations are recommended for all stormwater facilities that are located in an active karst area with known karstic features (sinkholes, solution cavities, direct hydraulic connection between surface water and groundwater). The purpose of a karst investigation is to identify subsurface voids, cavities, fractures, or other discontinuities which could pose an environmental concern or a construction hazard to an existing or proposed stormwater management facility. Of special concern is preventing the possibility that an unimpeded route will be provided to move polluted runoff into the regional groundwater system. The guidelines outlined below should not be interpreted as all-inclusive. The design of any geotechnical investigation should reflect the

size and complexity of the proposed project, as well as local knowledge of the threat posed by the karstic geology.

Because of the complexity inherent to active karst areas, there is no single set of investigatory guidelines that works for every location. Typically, however, the sequence involves some visual observation for the presence of sinkhole features (the single easiest evidence that active karst is present), followed by an assessment of the subsurface heterogeneity (variability) of the site through geophysical investigation and/or excavation. With this information in-hand, borings or observation wells can then be accurately installed to obtain vertical data surrounding or within a karst feature. The following sections describe general guidance that may or may not be used depending upon the local situation and information deemed as needed.

The Karst Sensitivity Analysis should contain the following at a minimum:

1. Site review to identify any active karst features including sinkholes, springs, caves, or sinking streams and
2. Subsurface exploration.

If the site exhibits characteristics of active karst, at least one subsurface cross section should be provided for all stormwater facilities proposed on the site, showing confining layers, depth to bedrock, and water table (if encountered). It should extend through a central portion of the proposed installation, using the actual geophysical and boring data. A sketch map or formal construction plan indicating the location and dimension of the proposed practice and line of cross section should be included for reference, or as a base map for presentation of subsurface data.

### Site Review and Subsurface Exploration

A site review should be conducted to identify any existing or historical karst features on the site and downstream of the site. In addition, surface water drainage characteristics should be documented. The subsurface investigation should determine the nature and thickness of subsurface materials, including depth to bedrock and the water table. Subsurface data may be acquired by backhoe excavation and/or soil boring. These field data should be supplemented by geophysical investigation techniques deemed appropriate by a qualified professional, which will show the location of karst formations under the surface. This is an iterative process that might need to be repeated until the desired detailed knowledge of the site is obtained and fully understood. The data listed below should be acquired under the direct supervision of a qualified and experienced karst scientist.

Pertinent site information to collect includes the following:

1. Bedrock characteristics (ex. type, geologic contacts, faults, geologic structure, rock surface configuration).
2. Soil characteristics (ex. type, thickness, mapped unit, geologic source/history).
3. Photo-geologic fracture trace map.
4. Bedrock outcrop areas.
5. Sinkholes and/or other closed depressions.

6. Perennial and/or intermittent streams, and their flow behavior (ex. a stream in a karst area that loses volume could be a good indication of sinkhole infiltration).

The following guidance should be used to aid in the subsurface exploration.

### 1. Location of Borings

The local variability typical of karst areas could mean that a very different subsurface could exist a very small distance away, perhaps as little as six-inches. To accommodate this variability, the number and type of borings must be carefully assessed. If the goal is to locate a boring down the center of a sinkhole, geophysical tests or excavation results can show the likely single location to achieve that goal. If the goal is to “characterize” the entire site, then an evaluation needs to occur to determine the number and depth needed to adequately represent the site. Again, the analyst must acknowledge the extreme variability and recognize that details can easily be missed. Some general guidance for locating borings includes:

1. Getting at least one boring in each geologic unit present, as mapped by the MGS and U.S. Geological Surveys (USGS) and local county records;
2. Placing an adequate number as determined by a site investigation near on-site geologic or geomorphic indications of the presence of sinkholes or related karst features;
3. Locating along photo-geologic fracture traces;
4. Locating adjacent to bedrock outcrop areas;
5. Locating a sufficient number to adequately represent the area under any proposed stormwater facility; and
6. Documenting any areas identified as anomalies from any existing geophysical or other subsurface studies.

### 2. Number and Depth of Borings

The number and depth of borings will depend entirely upon the results of the subsurface evaluation obtained from the observational, geophysical, and excavation studies, and other borings. There are no prescriptive guidelines to determine the number and depth of borings. These will have to be determined by the qualified staff conducting the BMP management evaluation based upon the data needs of the installation. The borings must extend well below the bottom elevation of the designed BMP, however, to make sure that there are no karst features that will be encountered or impacted as a result of the installation.

### 3. Identification of Material

All material identified by the excavation and geophysical studies and penetrated by the boring should be identified, as follows:

1. Description, logging, and sampling for the entire depth of the boring.

2. Any stains, odors, or other indications of environmental degradation.
3. A minimum laboratory analysis of two soil samples, representative of the material penetrated including potential limiting horizons, with the results compared to the field descriptions.
4. Identified characteristics should include, as a minimum: color; mineral composition; grain size, shape, sorting and degree of saturation.
5. Any indications of water saturation should be carefully logged, to include both perched and groundwater table levels, and descriptions of soils that are mottled or gleyed\* should be provided. Be aware that groundwater levels in karst can change dramatically in short periods of time and will not necessarily leave mottled or gleyed evidence.
6. Water levels in all borings should be recorded over a time-period reflective of anticipated water level fluctuation. That is, water levels in karst geology can vary dramatically and rapidly. The boring should remain fully open to a total depth reflective of these variations and over a time that will accurately show the variation. Be advised that to get a complete picture, this could be a long-term period. Measurements could of course be collected during a period of operation of a BMP, which could be adjusted based on the findings of the data collection.
7. When conducting a standard penetration test (SPT), estimation of soil engineering characteristics, including “N” or estimated unconfined compressive strength, should be reported.

\* Mottled – Soil marked with irregular brown and gray/black colors indicative of poor drainage and routine saturation cycles

Gleyed - A blue-gray, sticky, compacted soil, usually indicative of saturated conditions

#### 4. Geophysical and Dye Techniques

There are many different techniques available to “view” the nature of the subsurface in karst areas. These techniques can be used to detect the presence of karst features or to collect additional data on the character of a known feature. Stormwater managers in need of subsurface geophysical surveys are encouraged to obtain the services of a qualified geophysicist experienced in karst geology. Some of the geophysical techniques available for use in karst terrain include: seismic refraction, ground-penetrating radar, electric resistivity.

The surest way to determine the flow path of water in karst geology is to inject dye into the karst feature (sinkhole or fracture) and watch to see where it emerges, usually from a spring. The emergence of a known dye from a spring grants certainty to a suspicion that groundwater moves in a particular pattern. Dye tracing can vary substantially in cost depending upon the local karst complexity, but it can be a reasonably priced alternative, especially when the certainty is needed.

### *Karst Investigation Areas*

Karst Investigation Areas have been identified throughout the LSCWMO. These areas should be further investigated to determine if the point is a karst feature following the guidance above within the Karst Sensitivity Analysis and should specifically focus on the identified feature.

### *Sinkhole Remediation*

There are several approaches to sinkhole remediation if it is found that such an approach is desirable. Sinkhole sealing involves investigation, stabilization, filling and final grading. In the investigation phase, the areal extent and depth of the sinkhole(s) should be determined. The investigation may consist of excavation to bedrock, soil borings, and/or geophysical studies. Sealing small-sized sinkholes is normally achieved by digging out the sinkhole to bedrock, plugging the hole with concrete, installing several impermeable soil layers interspersed with plastic or geotextile, and crowning with an impermeable layer and topsoil. For moderate sinkholes, an engineered subsurface structure is usually required.

It is often not feasible to seal large sinkholes so other remediation options must be pursued. These could include construction of a low-head berm around the sinkhole, clean-out of the sinkhole to make sure all potentially contaminating materials are removed, landscaping and conversion of land use in the sinkhole to open space or recreation, provided it can be done in a manner that provides adequate safety. In any of these cases, pre-treatment of any stormwater entering the sinkhole is imperative. Final grading of sinkholes in open space settings should include the placement of low permeability topsoil or clay and a vegetative cover, with a positive grade maintained away from the sinkhole location to avoid ponding or infiltration, if feasible.

### *Monitoring of BMPs in Karst Regions*

A water quality monitoring system installed, operated and maintained by the owner/operator may be desirable or even required under some circumstances, particularly where drinking water supplies are derived from groundwater or in association with known sources of contamination. The location of monitoring wells or BMP performance monitoring will again depend upon the nature of the BMP and surrounding karst characteristics. As with all nonpoint source related monitoring, the capture of runoff events is the key goal. In karst areas, this could mean the installation of a monitoring system designed to reflect variable water behavior typical of karst water flow. Attempting to monitor this behavior without a thorough understanding of the local geology will be difficult and could lead to a wasted effort.

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## **E. Education and Information**

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An informational flyer was developed to distribute to LSCWMO residents, emergency responders, and local units of government. The flyer includes a map of karst sensitive regions of the LSCWMO, basic karst information facts, karst concerns, and a list of numbers to call in the case of an accidental spill of environmentally damaging materials. The informational flyer developed as part of this plan is included as Appendix A.

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## **F. Implementation Plan**

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Appropriate management of natural resources in the LSCWMO watershed due to its karst setting is the primary goal of activities proposed under the implementation plan. The following implementation activities are proposed to increase understanding of hydrology and groundwater systems within the unique geological setting of the LSCWMO. The proposed activities are not intended to improve the conditions of the groundwater resources, but rather monitor or increase the ability to characterize the watershed more fully.

The following Implementation Programs and Projects were identified during this Study.

### ***1.) Groundwater Monitoring Program***

A groundwater monitoring program will provide the LSCWMO with data on the quality and quantity of groundwater resources. There is currently little monitoring of groundwater resources in the LSCWMO. Monitoring groundwater chemistry over time may show trends in the quality of groundwater in the watershed and allow the LSCWMO to identify any threats to drinking water supplies and groundwater dependent resources.

The WMO will install or acquire the use of existing groundwater monitoring wells within the primarily used aquifers of the watershed. The WMO will actively monitor groundwater chemistry and level to assess changes in groundwater quality and hydrology. Groundwater analysis could include pesticides, volatile organic compounds, gasoline range organics, lead, cadmium, manganese, nickel, copper, zinc, nitrate, nitrite, and chloride. The WMO will determine the scope of this program in terms of the number of wells monitored and the frequency of monitoring during program initiation. Final number and siting of wells will be determined based on distribution of existing wells, funding, and access.

Project Timeline – 2007-ongoing

Cost Range – Monitoring Program – \$5,000 - \$20,000/year

Cost Range – Well Installation – To be determined as needed

Considerations: Cost will vary depending on the number of sampling points. Analytical cost is estimated at \$350/sample, other costs include coordination with labs, sample bottles and equipment preparation, field work time/expenses, dedicated line sets for each well, sample delivery, and result analysis/reporting.

### ***2.) Work with Washington County to Amend their Ordinances to Reference Karst Regions***

Currently Washington County stormwater ordinances do not address the potential for karst landscapes and features. The LSCWMO will work with Washington County to amend the County ordinances to include karst specific protection strategies and groundwater quality protection.

Project Timeline – 2007-2008

Cost Range –\$1,000 - \$4,000

### ***3.) Purchase digital 2-foot contour data***

The availability and use of two-foot contour data will allow the LSCWMO to further identify potential karst investigation areas. Specifically, two-foot data will assist the LSCWMO and member communities with identifying downstream drainage paths during the development review process, if a site drains to an off-site existing sinkhole, or potential sinkhole, additional analysis will be required. Two-foot contour data are available from Washington County for purchase. Contour data will also be available for use in future and ongoing studies and will strengthen the accuracy of future modeling output. These data are available in digital format (GIS/CADD) and in hard copy format. These data can be purchased as needed, by section or half-section.

Project Timeline – 2007-on-going

Cost – Hard Copy Maps - \$2,000

Cost – Digital Data – To be determined as needed

### ***4.) Spring Inventory***

Springs are the natural discharge points of aquifers and as such represent prime locations to monitor the integrated, regional condition of groundwater resources. Most springs are not shown on maps, and must be found via fieldwork. A search for springs along the eastern and southern perimeter of the LSCWMO along the banks of the St. Croix and Mississippi Rivers is proposed to complete an initial spring search started in 2004. The 2004 search covered the region between Afton State Park and St. Croix Bluffs Park along the banks of the St. Croix River. The spring search should be conducted in winter time when temperatures are below freezing, it is under this condition that spring and seep resurgence of groundwater is the only unfrozen features on the landscape and provides clear unambiguous locations of these features.

Project Timeline - 2011-2012

Cost Range - \$2,000-\$6,000

Considerations – Cost range is assuming a student from the University of Minnesota is doing the fieldwork as part of a thesis project.

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## Glossary

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The definitions provided in this glossary have been included to provide assistance in reading the Karst Inventory and Management Plan.

**Anticline** A convex fold in rock, the central part of which contains the oldest section of rock.

**Aquifer** Rock or sediment in a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield economical quantities of water to wells and springs.

**Aquifer, confined** A formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations. Confined groundwater is generally subject to pressure greater than atmosphere.

**Aquifer, unconfined** An aquifer whose upper boundary consists of relatively porous natural material which transmits water readily and does not confine water. The water level in the aquifer is the water table and is exposed to the atmosphere through openings in the overlying materials.

**Aquitard (or confining layer)** A geologic formation of low permeability that greatly inhibits the movement of groundwater.

**Basin** A syncline-like depression of strata created from the folding of the earth's crust.

**Bedding Plane** A planar surface separating different compositions or grain sizes of rock. Bedding planes represent successive depositional surfaces and energy environments that existed at the time of sedimentation.

**Bedrock** A general term for the rock, usually solid, that underlies soil or other unconsolidated material.

**Bedrock aquifer** An aquifer composed of bedrock formations.

**Bedrock valley** A valley consisting primarily of a carbonate mineral such as calcite or dolomite, the chief minerals in limestone and dolostone, respectively.

**Block-fault** A section of rock separated from other rock by one or more faults.

**Cave** A naturally formed opening beneath the surface of the Earth, typically formed by dissolution of carbonate bedrock. Caves may also form by erosion of coastal bedrock, partial melting of glaciers, or solidification of lava into hollow tubes.

**Confining unit** An aquitard over an aquifer, with potentiometric head at higher elevation than the confining unit. A confining unit prevents groundwater from flowing upward.

**Contact** A planar surface separating different geological units. Contacts may be sharp or tenuous.

**Contact spring** A spring located at the interface of an aquitard or confining layer and aquifer.

**Contaminant** In a broad sense, any physical, chemical, biological, or radiological substance or matter in water. In more restricted usage, a substance in water of public health or welfare concern. Also, an undesirable substance not normally present or an unusually high concentration of a naturally occurring substance, in water, soil, or other environmental medium.

**Contour map** A map displaying lines that connect points of equal value and separate points of higher value from points of lower value. Often used to show land or groundwater level surfaces.

**Depositional Setting** The environment in which the accumulation of sediments by either physical or chemical sedimentation originally took place.

**Dissolution Conduit** A high permeability pathway formed by the dissolution of the parent rock.

**Development** Generally defined to include land-disturbing activities; structural development, including construction, installation, or expansion of a building or other structure; creation of impervious surfaces.

**Dolostone** A carbonate rock (e.g. limestone) made up predominately of the mineral calcium magnesium carbonate.

**Erosion** Any process that wears away the surface of the land by the action of water, wind, ice, or gravity including weathering, solution, corrosion, and transportation. Erosion can be accelerated by the activities of people and nature.

**Fault** A fracture in rock along which movement can be demonstrated. A fracture in the earth's crust forming a boundary between rock masses that have shifted.

**Flow** The rate of water discharged from a source given in volume with respect to time.

**Fold** A planar feature, such as a bedding plane, that has been deformed into a geometry that is no longer parallel.

**Glacial deposits** Material deposited as a result of glacial activity. See also Quaternary deposits.

**Glacial lake deposits** Flat-topped hills composed of silt, sand, and gravel deposited at the bottom of lakes that developed in potholes in glaciers. When the surrounding ice melted, the lakes drained and the lakebed deposits were left as hills on the surrounding landscape.

**Glacial till** Glacial deposits composed of mostly unsorted sand, silt, clay, and boulders deposited directly by the glacial ice.

**Gradient** Steepness or angle of a slope. Also the rate of change in hydraulic head over distance.

**Groundwater** Water located in inter-connected pores found beneath the water table.

**Groundwater discharge** The process of groundwater leaving an aquifer.

**Groundwater discharge area** The point or region where groundwater leaves an aquifer. Groundwater discharge areas include the land surface, streams, lakes, wetlands, springs, and seeps. Groundwater also discharges to wells.

**Groundwater recharge** The process whereby surface water infiltrates into groundwater. Also the transfer of groundwater from any one aquifer into another aquifer.

**Groundwater recharge area** The region or area in which groundwater recharge occurs.

**Groundwatershed** The hydrologic boundary within the groundwater system within which all groundwater flow to a certain point.

**Hydraulic conductivity** A coefficient of proportionality describing the rate at which water can move through an aquifer or other permeable medium.

**Hydraulic head** The top elevation of a water body under normal atmospheric pressure.

**Hydrogeology** The science of water use, quality, occurrence, movement, and transport beneath the earth's surface.

**Hydrology** The study of water, especially its natural occurrence, characteristics, control, and conservation.

**Hydrologic soil groups** The classification of soils by their reference to the intake rate of infiltration of water, which is influenced by texture, organic matter content, stability of the soil aggregates, and soil horizon development.

**Ice contact deposits** Sediment deposited beneath or adjacent to the glacier margin. Ice contact deposits are typically rich in sand and gravel.

**Individual Sewage Treatment System (ISTS)** (also known as septic system) A sewage treatment system connected to a single dwelling or establishment, consisting of sewage tanks and a soil treatment area (usually a drain field or mound).

**Infiltration** The movement of water into soil or porous rock. Infiltration occurs as water flows through the larger pores of rock or between soil particles under the influence of gravity, or as a gradual wetting of small particles by capillary action.

**Karst** A topography developed largely by the dissolution of bedrock. Karst topography is often characterized by springs, sinkholes, solution valleys, caves, and disappearing streams. Karst features create conditions of rapid groundwater infiltration and flow.

**Landlocked basins** Depressions which have no available surface outlet for rainfall and snowmelt events up to and including the 100-year storm event.

**Limestone** A sedimentary rock composed mostly of the carbonate mineral calcium carbonate.

**Lithology** The systematic description of rocks, in terms of mineral composition and texture.

**Nitrate** An organic chemical compound composed of one nitrogen and three oxygen molecules (NO<sub>3</sub>). Sources of nitrate include fertilizers, pesticides, animal and human waste. Nitrate easily dissolves in water and readily moves through soil and into regional aquifers.

**Non-point source pollution** Pollution originating from diffuse areas (land surface or atmosphere) having no defined source. Examples include field agricultural chemicals and urban runoff pollutants.

**Nutrient** Element essential for plant or animal growth. Major nutrients include nitrogen, phosphorus, carbon, oxygen, sulfur, and potassium.

**Outwash deposits** Sediment deposited by the glacier meltwater away from the glacier margin. Outwash is usually composed of sand, sand and gravel, or fine sand and silt.

**Paleozoic** An era of geologic time lasting from 570 to 245 million years ago.

**Perched (Lake or Wetland)** A surface water body that is underlain by a fine grained geologic unit or aquitard that restricts the downward movement of surface water. Perched lakes and wetlands are less connected to groundwater systems.

**Perennial stream** A stream that flows from source to mouth during all seasons of the year.

**Permeability** The ability of a substance, such as rock or soil, to allow a liquid to pass or soak through it.

**Phosphorus** An element that is essential to plant life but contributes to an increased trophic level (eutrophication) of water bodies.

**Point source pollution** Pollution originating from a single identifiable source. Examples include waste disposal sites, leaking storage tanks, chemical spills, ruptured pipelines, and individual sewage treatment systems.

**Pollutant** Any solute or cause of change in physical properties that renders water unfit for a given use.

**Porosity** The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

**Primary porosity** Created by a high degree of porosity in geologic materials such as sand and gravel.

**Quaternary period** Geologic time beginning about 1.5 million years ago to present.

**Quaternary deposits** Unconsolidated soils deposited during the Quaternary (most recent) geologic period.

**Sandstone** A sedimentary rock composed of abundant rounded or angular fragments of sand set in a fine-grained cemented matrix of silt or clay.

**Secondary porosity** Alteration of geologic materials creating highly fractured and broken materials.

**Sedimentary rock** Any rock composed of sediment. The sediment may be particles of various sizes such as gravel or sand, the remains of animals or plants as in coal and some limestones or chemicals in solution that are extracted by organic or inorganic processes. Sandstone, shale, siltstone, and limestone are common sedimentary rocks.

**Sedimentation** The process or action of depositing sediment caused by erosion.

**Seeps** Groundwater/surface water connections caused by river or stream erosion into a near-surface aquifer.

**Setback** The minimum horizontal distance between a structure, sewage treatment system, or other facility and a street right-of-way, ordinary high water level mark, sewage treatment system, bluffline, road, highway, property line or other facility.

**Sinkholes** A depression in the earth's surface caused by dissolving of underlying limestone, salt, or gypsum. Drainage is provided through underground channels which may be enlarged by dissolution or the collapse of a cavern roof.

**Sinking stream** A point on the surface where a perennial or ephemeral stream disappears underground through a sinkhole or by gradual downward percolation through porous streambed material.

**Spring** A concentrated discharge of groundwater coming out at the surface as flowing water; a place where the water table crops out at the surface of the ground and where water flows out more or less continuously. Its occurrence depends on the nature and relationship of rocks, especially permeable and impermeable strata, on the position of the water table, and on the topography.

**Stratigraphy** The study of rock strata distribution, deposition, and age.

**Stormwater runoff** Water falling as rain during a storm and entering a surface water body by flowing over the land.

**Subcrop** The first bedrock unit encountered beneath surficial or Quaternary deposits.

**Surface water runoff** Precipitation, snowmelt, or irrigation in excess of what can infiltrate or be stored in small surface depressions.

**Surficial deposit** Sediments, typically unconsolidated, deposited above bedrock units. Examples include loess, Quaternary deposits, and sand dunes. Also see Quaternary deposits.

**Terrace deposits** Sand and gravel deposited by vastly large post-glacial rivers that ran through the St. Croix and Mississippi River valleys.

**Till** Un-stratified and unsorted material deposited directly by a glacier. Till consists of clay, sand, gravel, or boulders mixed in any proportion.

**Unconsolidated** Sediment that has no mineral cement or matrix binding its grains together.

**Unsaturated zone (or zone of aeration)** The part of the soil profile in which the voids are not completely filled with water. The zone between the land surface and the water table.

**Water table** The point beneath the unsaturated zone where aquifer materials are fully saturated and the water levels are directly responsive to changes in atmospheric pressure. The water table level may also be reflected in lakes, streams, and wetlands.

**Water table aquifer** The uppermost unconfined aquifer in any given area. Water table aquifers are commonly found in surface or glacial sediment but can be formed in bedrock aquifers.

**Watershed** The geographic region within which water drains into a particular river, stream, or body of water.

**Well** An artificial excavation put down by any method for the purposes of withdrawing water from the underground aquifers.

**Wellhead protection plan** Plan intended to protect and preserve the quality of groundwater used as a source of drinking water. A typical wellhead protection plan will have a number of critical elements to include: (1) delineating the roles and responsibilities of state agencies, local governments, and water purveyors; (2) delineation of wellhead protection areas; (3) contaminant source inventories; (4) management options; (5) siting of new wells; (6) contingency and emergency planning; and (7) public participation.

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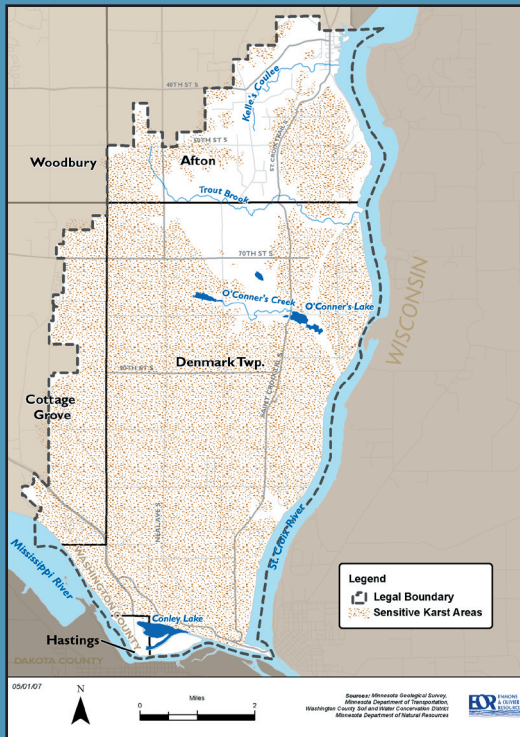
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**APPENDIX A – LSCWMO KARST EDUCATION PAMPHLET**

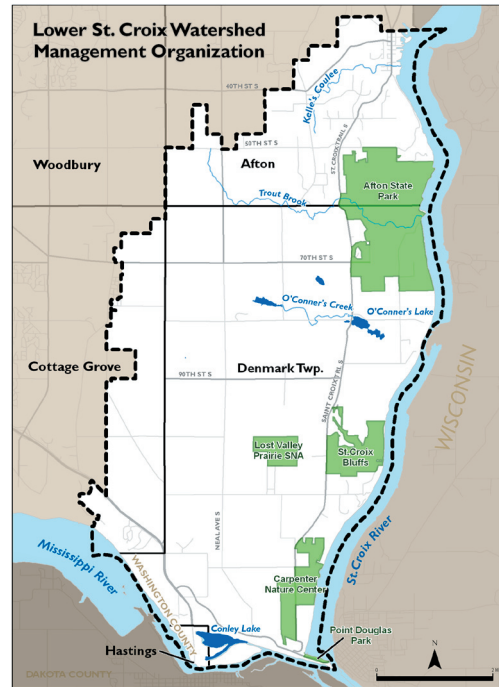
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# KARST SENSITIVE AREAS IN THE LSCWMO



## KARST FEATURES

- **Sinkhole** depression in the land's surface caused by subsidence of underlying material
- **Spring** point where focused groundwater discharge creates overland flow
- **Sinking Stream** point where surface water rapidly infiltrates into the ground
- **Cave** naturally formed opening in the earth's surface caused by dissolution of bedrock



## LSCWMO CONTACT INFORMATION

Lower St. Croix Watershed Management Organization  
 Jennifer Olson, LSCWMO Administrator  
 c/o Emmons & Olivier Resources, Inc.  
 651 Hale Avenue North  
 Oakdale, MN 55128  
 (651) 770-8448

Visit the LSCWMO web page at:  
[www.denmarktownship.org](http://www.denmarktownship.org)



LSCWMO



Protecting Groundwater  
in a Unique Setting



# KARST LANDSCAPES

The LSCWMO is responsible for protecting surface and ground water resources in Denmark Township and portions of Afton, Cottage Grove and Hastings.

The LSCWMO has completed an inventory and study that describes the unique geologic setting of the watershed. The majority of the LSCWMO is located in an active karst region.

Karst is a distinctive type of landscape characterized by complex drainage patterns. Most karst landscapes are formed on soluble bedrock.

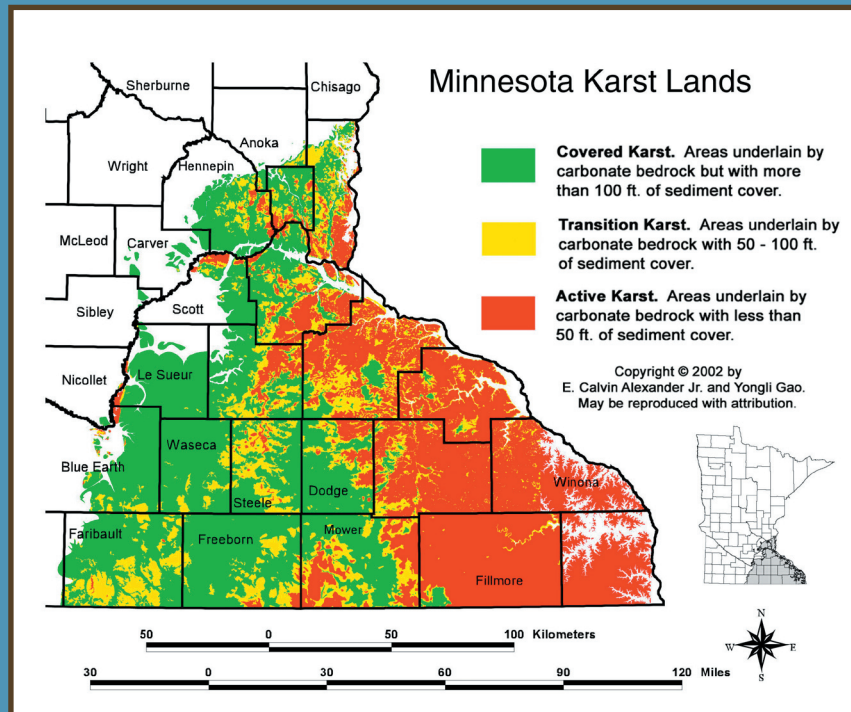
## Karst Concerns

Karst landscapes are sensitive to pollution and land use. Extra care must be taken to ensure that human activities don't negatively effect groundwater through the introduction of pollution into the karst aquifer. Nearly one third of all drinking water wells in the LSCWMO obtain their water from a karst aquifer.

Proper application of fertilizer, disposal of liquid waste and chemicals, and routine maintenance of septic systems is imperative within the watershed to protect groundwater resources.

## Karst Features

- Karst landscapes have thin soils and are underlain by soluble bedrock such as limestone and dolostone
- Karst landscape features include sinkholes, sinking streams, caves and springs
- Karst landscapes are characterized by relatively little surface drainage
- Groundwater is susceptible in karst areas to land use activities



## Who to Contact:

Drinking water aquifers in the LSCWMO are very susceptible to contamination. It is important to report any type of activity or spill that may cause environmental damage to the appropriate parties.

Spills of environmentally damaging materials, such as toxic, corrosive, flammable, petroleum products, and industrial chemicals are mandated by law to be reported to the Minnesota Duty Officer. In addition, Washington County and the local government should be contacted. In cases where a spill is a threat to life or property, call 9-1-1 first.

Minnesota Duty Officer  
1-800-422-0798

Washington County Department of Public Health and Environment  
651-430-6655

City of Afton  
651-436-5090

City of Cottage Grove  
651-458-2807

City of Hastings  
651-480-6150

Denmark Township  
651-436-1704