Karst Landscape Units of Houston and Winona Counties

Groundwater Atlas Program: GW-06

Report

Accompanies two map plates:

Plate 1, Karst Landscape Units of Houston County

Plate 2, Karst Landscape Units of Winona County

DEPARTMENT OF NATURAL RESOURCES

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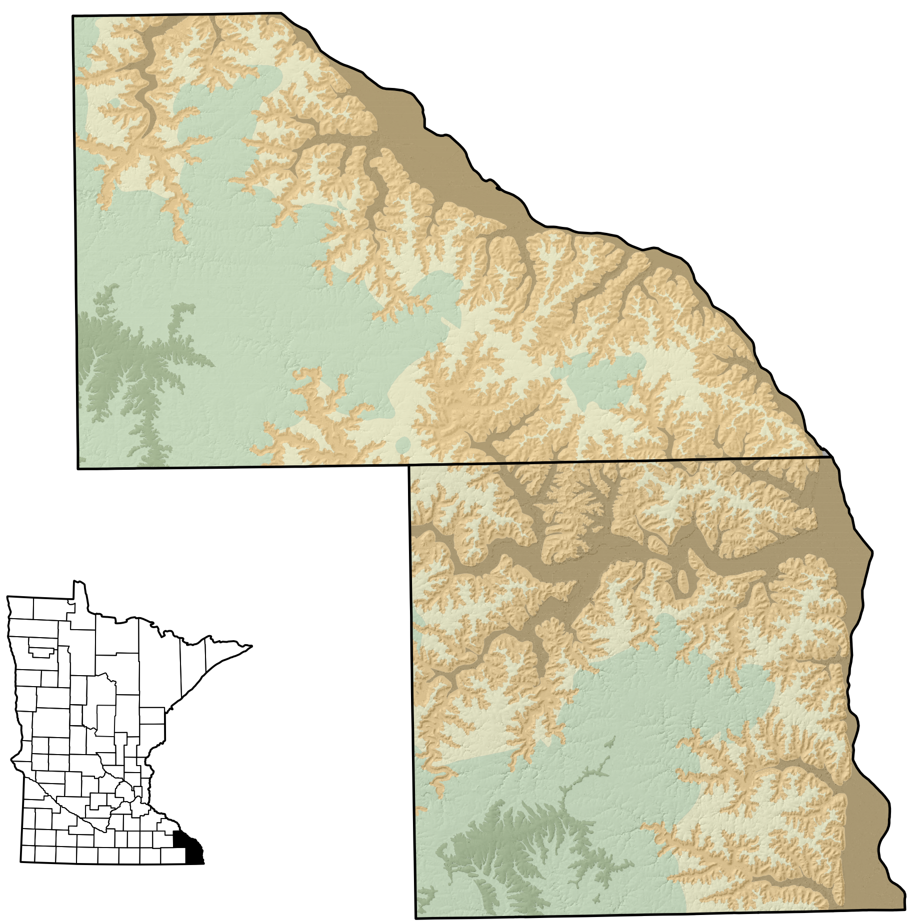

This report, karst features, dye tracing, and springs can be found at the following link.

mndnr.gov/groundwatermapping > Springs, Springsheds, and Karst

Citation

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Most importantly, we would like to thank the many Houston and Winona county landowners who allowed access to their property to inventory sinkholes, stream sinks, and springs and to conduct fluorescent dye tracing and spring monitoring. Without their cooperation, this effort would not have been possible.

Technical reference

Maps were compiled and generated in a geographic information system. Digital data products are available from the Minnesota Department of Natural Resources (DNR) Groundwater Atlas Program.

Maps were prepared from DNR and other publicly available information. Every reasonable effort has been made to ensure the accuracy of the data on which the report and map interpretations were based. However, the DNR does not warrant the accuracy, completeness, or any implied uses of these data. Users may wish to verify critical information; sources include both the references here and information on file in the offices of the Minnesota Geological Survey and the DNR. Every effort has been made to ensure the interpretations conform to sound geologic and cartographic principles. These maps should not be used to establish legal title, boundaries, or locations of improvements.

Base maps were modified from the Minnesota Geological Survey, Geologic Atlases of Houston and Winona counties (Part A), Minnesota, 2014. Universal Transverse Mercator projection, Zone 15N, North American Datum of 1983. North American Vertical Datum of 1988.

Report contents

Accompanying map inserts

Karst Landscape Units of Houston and Winona Counties

By Jeffrey A. Green and John D. Barry

Introduction

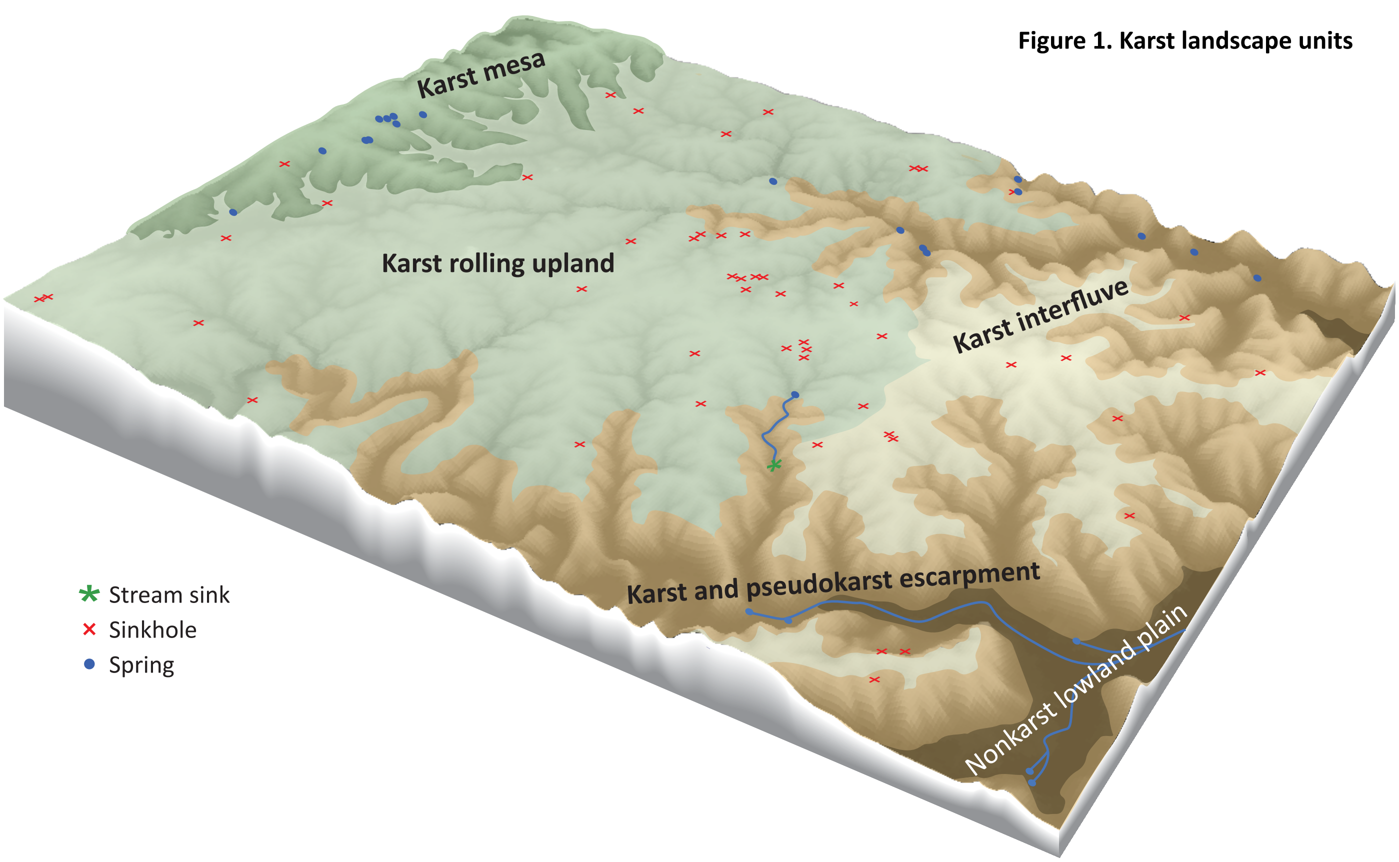
This report and the accompanying maps (Plates 1 and 2) describe the ***karst***, ***pseudokarst***, and ***nonkarst*** landscape types of Houston and Winona counties. Located in southeastern Minnesota, these counties were untouched by the last Pleistocene glaciations, which preserved their rugged and varied surface topography. Landscape form is dominated by pronounced surface erosion that creates the many coulees and deep valleys and by dissolution of the underlying Paleozoic bedrock. Dissolution of the bedrock creates distinct hydrology and surface and subsurface features that are karst. In karst, there are close connections between the land surface and the underlying bedrock. Fractures and enlarged pathways allow for rapid transport of water, creating unpredictable groundwater travel times and flow directions. Karst makes groundwater vulnerable to activities on the land surface and complicates its protection and remediation.

The mapping approach applied to this project builds upon methods used to create the Karst Hydrogeomorphic Units for the Mower County Geologic Atlas (Green and others, 2002a, Green and others, 2002b).

The landscape types are subdivided in to five ***landscape units*** typical of southeastern Minnesota and are classified based on their hydrology, landscape form, and geology (Figure 1). Each includes the land surface and its connections to underlying aquifers. Classifying landscapes into units helps to identify the groundwater characteristics beneath, because classic signs of karst (sinkholes, stream sinks, and springs) are not always present at the land surface.

The ***karst mesa*** is the highest in elevation and is found in the southwestern corner of each county. From its gently sloping top it drops steeply to the ***karst rolling upland***, an extensive plateau that makes up the largest landscape unit of each county. Narrow ridges of the plateau extend into deeply dissected valleys as ***karst interfluve.*** From the interfluve and rolling upland, the ***karst and pseudokarst escarpment*** drops off steeply to the ***nonkarst lowland plain*** of the stream and river valleys.

Figure 1. Karst landscape units



Landscape types

Karst

Karst surface features and sensitive groundwater resources are likely to occur in areas where there is less than fifty feet of unconsolidated material above carbonate bedrock. Carbonate rock is the first bedrock encountered in over half of Houston and Winona counties, particularly in the upland areas (Steenberg, 2014a, 2014b, 2014c, 2014d).

Shallow carbonate aquifers of southeastern Minnesota are dominated by turbulent flow where groundwater moves rapidly through subsurface conduits and fractures, making these aquifers vulnerable to human activities (Green and others, 2014). Nitrate, pathogens, and other contaminants can move into shallow groundwater through open conduits or by diffuse flow through thin soil cover (Libra and others, 1984; Runkel and others, 2014a, Barry and others, 2020).

Karst features occur in the Cummingsville, Platteville, and Shakopee formations, the Oneota Dolomite, and the St. Peter Sandstone (Witthuhn and Alexander, 1995). Although not carbonate, the St. Peter sandstone is fractured in many locations throughout southeastern Minnesota and has numerous sinkholes that are interpreted to have formed by dissolution of the underlying dolostone of the Shakopee Formation (Dalgleish and Alexander, 1984a). It is therefore grouped within karst landscape units.

Pseudokarst

Pseudokarst exhibits properties similar to karst but is produced by processes other than dissolution, such as fracturing (Halliday, 2007). Pseudokarst in Houston and Winona counties occurs in fine-grained siliciclastic bedrock such as sandstone, siltstone, and shale.

In southeastern Minnesota pseudokarst, fractures primarily develop mechanically and are much smaller than those in traditional carbonate karst (Runkel and others, 2003). These fractures can transmit groundwater rapidly from stream sinks in the lowermost Jordan Sandstone, and the St. Lawrence and Lone Rock formations (Green and others, 2008, 2012; Barry and others 2015, 2018; Runkel and others, 2014b, 2018).

Nonkarst

Nonkarst is found in major valleys, where unconsolidated sediment generally greater than 50 feet thick overlies siliciclastic geologic units, resulting in no sinkholes or stream sinks. Underlying the valleys are the Wonewoc Sandstone, Eau Claire Formation, and Mt. Simon Sandstone. Although mapped as nonkarst lowland plain on the accompanying plates, groundwater fracture flow has been documented in these formations elsewhere in Minnesota and in Wisconsin (Runkel and others, 2003). In local areas these units may function similar to St. Lawrence and Lone Rock formation pseudokarst. In different landscape settings where not covered in unconsolidated sediment or shallowly buried, they would be classified as pseudokarst.

Mapping

Landscape units were identified using field observation, surface karst feature mapping, karst feature distribution and density, geologic properties, land-surface slope gradient, landscape form, hydrologic characteristics as determined by fluorescent dye tracing and spring monitoring, springshed mapping, hydrogeologic reports, and geochemistry.

Data elements were combined in a geographic information system (GIS) and compared to the landscape during field verification. Descriptions of how each landscape unit was delineated follow in the Landscape Units section of this report.

Bedrock geologic units from Part A, Plate 2 of the geologic atlases of each county formed the foundation (Steenberg, 2014a, 2014c). An aggregated range of slope gradients (representative slope) was acquired from the Soil Survey Geographic Database (SSURGO) (USDA-NRCS, 2019 and 2020) to determine prominent changes in the land surface that are associated with the erodibility of the underlying bedrock. Slope class was coupled with karst features and overlain on bedrock geology projected onto a one-meter LiDAR hillshade base to determine boundaries of landscape units. Boundary modifications were made using varying buffer distances, representative slope groups, and geologic contact starting points.

A conceptual hydrogeologic model was developed from several data sources. Sinkholes and streams from the Karst Features Database were used to identify geologic and landscape units with high densities (UMN, 2020; Tipping and others, 2015). Spring locations were accessed from the Minnesota Spring Inventory (DNR, 2019a). Well locations, aquifer designations, and groundwater elevation data were accessed from the County Well Index (MGS and MDH, 2019). Inferred groundwater flow paths and hydrologic characteristics were determined from fluorescent dye trace results from the Minnesota Groundwater Tracing Database (DNR, 2019b).

Additional sources came from the results of spring flow monitoring (Green and others, 2014), spring temperature monitoring (Luhman, 2011), previous investigations (Tipping, 1994; Tipping and others, 2006; Runkel and others, 2003, 2006, 2014a, 2014b, 2018), and geochemical results from a comprehensive set of well and spring samples collected in each county (Barry, 2021; in preparation).

Vertical distribution of karst features within each geologic unit was determined in GIS by assigning elevations to features using digital elevation models from Steenberg 2014b and 2014d. Histograms were generated using the number of karst features in each geologic unit.

Not all karst features could be field verified because of time, property access, and staffing limitations. Karst features can change over time; sinkholes routinely develop or are filled by property owners, and stream sinks may change location or fill with sediment. The maps only display the inventoried karst features at the time of mapping and represent lower limits because mapping is incomplete.

Surface features

The formation of surface karst features (sinkholes, stream sinks, and springs) is controlled by the composition, mechanical properties, previous erosion and chemical weathering, and structure of the underlying bedrock units. Sinkholes are primarily formed in the carbonate rock of the Prairie du Chien Group. Stream sinks are most common in the fine-grained siliciclastic rocks of the lower Jordan and St. Lawrence formations (Figure 2).

Sinkholes

In Houston and Winona counties, sinkholes are closed depressions developed over soluble carbonate bedrock and the St. Peter sandstone. Nearly 300 sinkholes have been mapped in Houston County and nearly 1,400 in Winona County, ranging in size from a few feet in diameter to half an acre. Depths are variable, but generally range from 1–30 feet. Most form as cover-collapse sinkholes, where unconsolidated soil and sediment is carried away by conduits and fractures in the underlying bedrock. When loss occurs slowly, shallow bowl-shaped depressions form; when loss is rapid, steep sided sinkholes form. A small number of these are vertical shafts, most commonly found where the soils are less than 5 feet thick.

In southwestern Winona County, a high concentration of ponded sinkholes are found in southeastern St. Charles Township and southwestern Utica Township. Over 50 have been identified using LiDAR and aerial photography. While some have been drained for agricultural production, others still exist as relatively permanent surface-water features. It is unclear why water ponds in these sinkholes. It is possible that their underlying conduits are plugged with till. Glacial till is not commonly found in Winona County, but remnants exist in the western portions (Lusardi and others, 2014). Windblown silt, called loess, is also common in southwestern Winona County and may contribute to ponding in this area.

Stream sinks

Stream sinks are locations where surface water in streams disappears into the subsurface. Their locations may shift over a range of surface-water flow conditions. Stream sinks occur in two forms: 1) discrete locations where water disappears into the ground and 2) stream reaches where water disappears over tens to hundreds of feet. Stream sinks most commonly form in the pseudokarst of the lower Jordan Sandstone and the St. Lawrence Formation; they are less common in the St. Peter Sandstone, Shakopee Formation, Oneota Dolomite, and Lone Rock Formation.

Springs and Seeps

Springs and seeps are where groundwater emerges from the land surface. They provide an important ecological function supplying cool isothermal water essential to trout streams. The term spring commonly refers to locations where focused groundwater emerges; seeps occur over larger areas than springs. Many springs emanate from specific hydrostratigraphic positions, with a large number emanating from the St. Lawrence and Lone Rock formations. Groundwater from springs may be a mixture of at least two sources: 1) young locally-sourced and anthropogenically impacted groundwater and 2) older regionally-sourced unimpacted groundwater (Runkel and others, 2014a; Barry and others, 2018; Barry, 2021; in preparation).

Springsheds

Springsheds are defined as the surface-water and groundwater basins that contribute discharge to a spring (Florida Geological Survey, 2003). Surface-water springsheds contribute to groundwater through direct infiltration or by surface-water loss into stream sinks or sinkholes. Activities on the land surface can rapidly impact groundwater emerging from a spring. Delineation is necessary to determine groundwater flow direction of potential spills or accidental chemical releases and to guide land use activities.

Surface-water basins are land areas that contribute the young locally-sourced groundwater component of a spring. The groundwater basins that contribute older regionally-sourced groundwater to these same springs were not delineated, but typically extend well beyond the surface-water delineations.

Surface-water springsheds were delineated using the Minnesota DNR AutoCatchment Dataset (DNR, 2018). Surface watersheds were combined with a 1-meter digital elevation model created from LiDAR data to modify their areas so they terminate at stream sinks.

Fluorescent dye tracing is used to determine groundwater flow direction and rate, and to establish connections between recharge points (sinkholes or stream sinks) and discharge points (springs, streams, or wells). Although groundwater emerging from springs is a mixture of both young local and older regionally-sourced water, the inferred groundwater flow paths only describe travel in the uppermost aquifers and aquitards. Springsheds, inferred groundwater flow paths, and associated data from the results of dye trace investigations are available online through the Minnesota Groundwater Tracing Database application (DNR, 2019b).

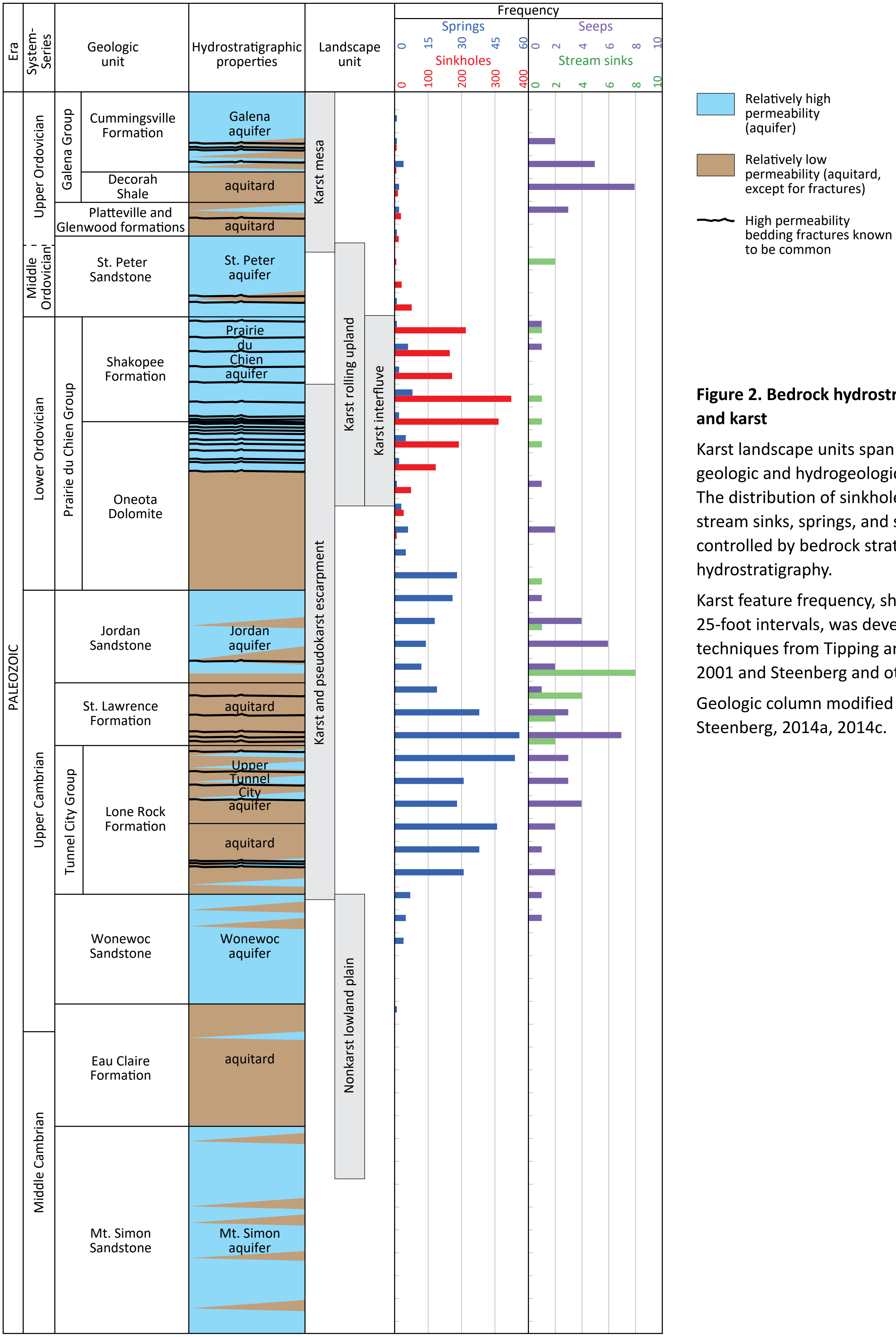


Figure 2. Bedrock hydrostratigraphy and karst

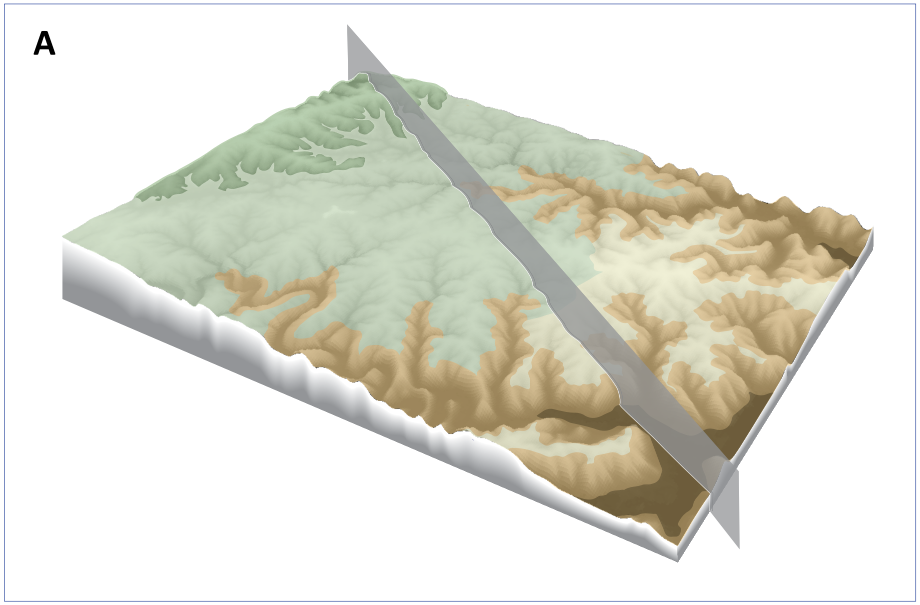
Karst landscape units span multiple geologic and hydrogeologic units. The distribution of sinkholes, stream sinks, springs, and seeps is controlled by bedrock stratigraphy and hydrostratigraphy.

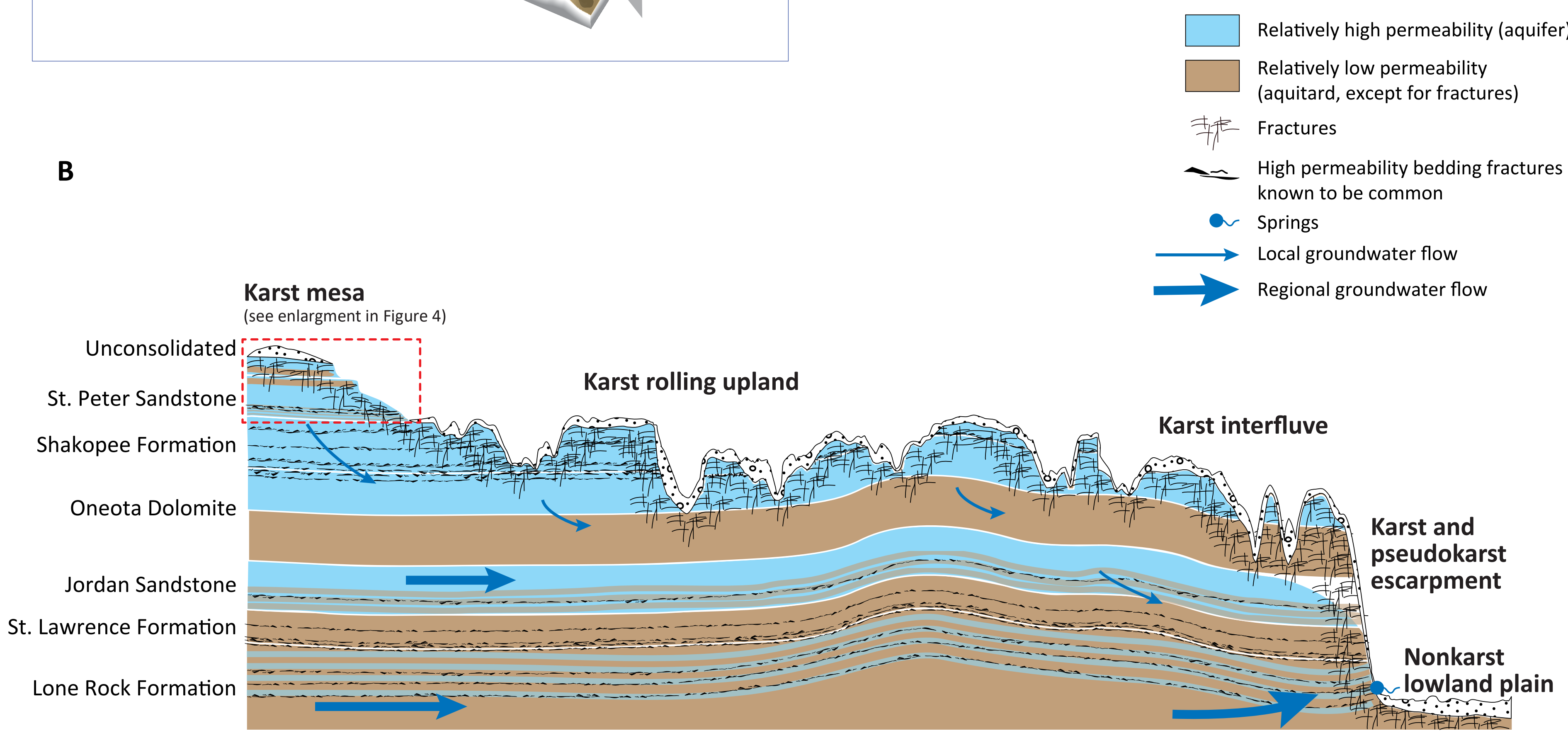
Karst feature frequency, shown in 25-foot intervals, was developed using techniques from Tipping and others, 2001 and Steenberg and others, 2014.

Geologic column modified from Steenberg, 2014a, 2014c.

Figure 3. Cross section of karst landscape units

The gray slice in diagram A is depicted as the hypothetical cross section below (B). The cross section links the landscape units, hydrogeology, and local and regional groundwater flow.

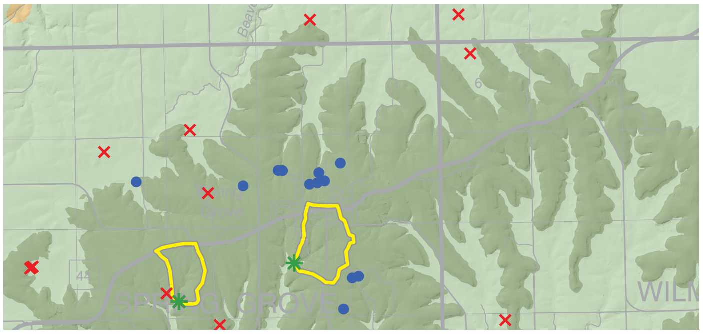




Landscape units

Five landscape units are found in Houston and Winona counties. Four units are karst; the lowland plain is nonkarst. Landscape units include the land surface and its connections to underlying aquifers.

Karst mesa



Landscape unit delineation

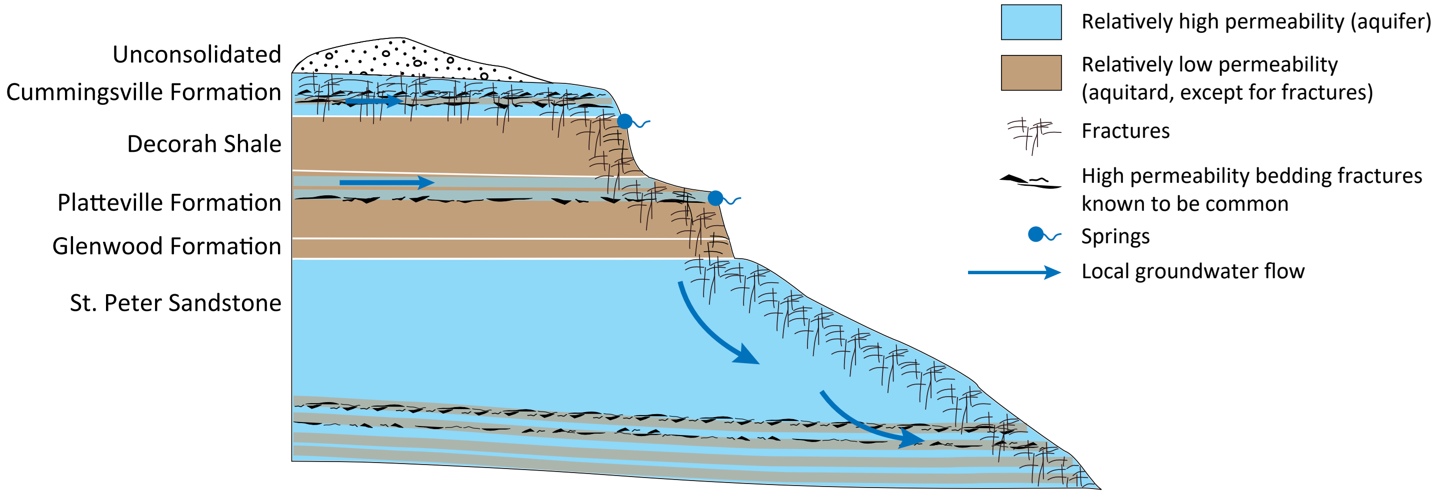
The karst mesa unit is highest in elevation and is found in the southwestern corner of each county. The gently sloping top of the mesa drops off steeply to the karst rolling upland. The landscape unit was created in GIS by querying all Cummingsville, Platteville, and Decorah formation polygons and joining them with areas of the St. Peter Sandstone with a slope equal to or greater than 8 percent.

Landscape unit characteristics

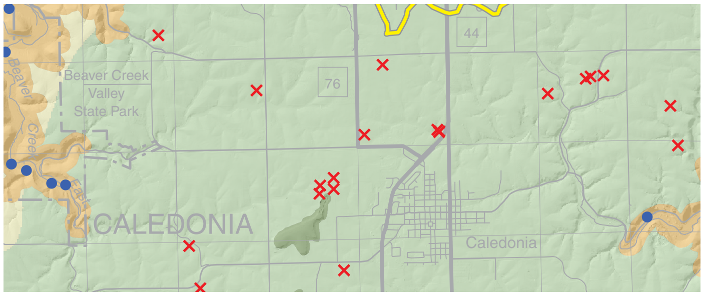
- The karst mesa landform rises above the surrounding upland plateau with slopes of 0–8 percent on the summits and 8–40 percent on the side slopes.
- Depth of unconsolidated material over bedrock is less than 50 feet. The summits are underlain by limestone and shale of the Cummingsville Formation, the Decorah Shale, or limestone and shale of the Platteville and Glenwood formations. Side slopes are predominately underlain by the St. Peter Sandstone.
- Sinkholes typically occur individually, are less than 30 feet wide, and are primarily found on the crest or base of the mesa. Spring flow and surface runoff can disappear into sinkholes, stream sinks, or fractures in the St. Peter Sandstone at the base of the mesa where it transitions to the adjoining karst rolling upland unit.
- Groundwater recharge and flow in the Cummingsville and Platteville formations is primarily through fractures and conduits. The lowermost part of the Cummingsville is interbedded limestone and shale and functions with the Decorah Shale as a local and regional aquitard (Delin, 1990). Water moves vertically through the karsted limestone top of the mesa until it reaches the interbedded shale and limestone of the lower Cummingsville and the Decorah shale. Water then primarily moves laterally to hillside edges, emerging as springs and seeps (Lindgren, 2000).
- Karst mesas rise above the regional Prairie du Chien plateau; recharge from precipitation is the sole source of groundwater in the mesa.

Figure 4. Enlarged inset from Figure 3

Mesa cross section depicting landform, high permeability fractures, spring hydrostratigraphy, groundwater flow, and aquifers and aquitards.



Karst rolling upland



Landscape unit delineation

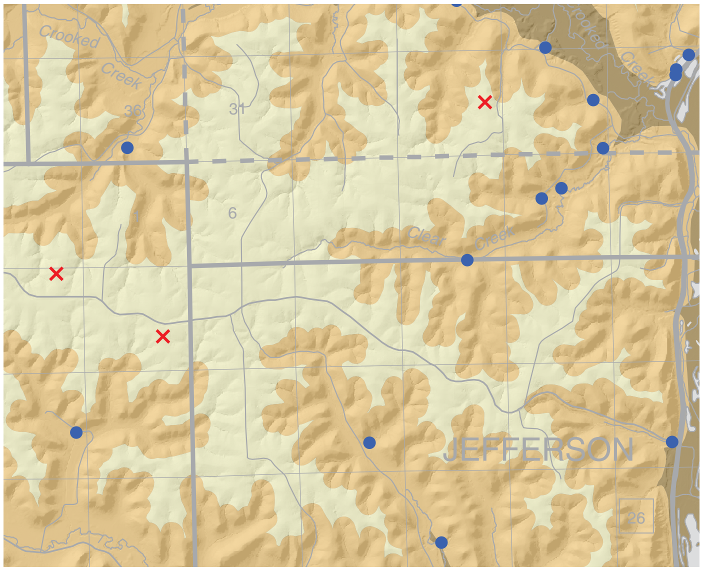
The karst rolling upland is an extensive plateau that makes up the largest landscape unit of each county. The landscape unit was created in GIS by identifying areas of the Paleozoic plateau that are not karst mesa, karst and pseudokarst escarpment, or karst interfluve.

Landscape unit characteristics

- Karst rolling upland is the largest karst unit in the counties. It consists of dissected plains with slopes primarily from 0–18 percent, but can range up to 60 percent.
- It represents areas of the Paleozoic plateau with generally less than 50 feet of unconsolidated material over the St. Peter Sandstone, Shakopee Formation, or Oneota Dolomite (Runkel and others, 2014a).
- Sinkholes are the primary surface karst feature, occurring both individually and in clusters. They range in width from 1–300 feet and in depth from 1–30 feet.
- Preferential sinkhole and stream sink formation occurs in the karst rolling upland due to paleokarst developed at the Shakopee-Oneota boundary. Paleokarst features are visible as small caves and sediment-filled zones in quarries and outcrops (Alexander and others, 2013). This stratigraphic position was a factor in sinkhole development and failure of three municipal wastewater lagoons in southeast Minnesota (Alexander and Book, 1984; Jannick, 1991; Alexander and others, 1993). These incidents demonstrate that leakage from surface impoundments can reactivate relict sinkholes. The Shakopee-Oneota boundary paleokarst serves as a regional zone of rapid groundwater flow (Tipping and others, 2006) and has the highest number of sinkholes associated with it (Figure 2).
- Dye tracing completed in neighboring Fillmore County from a stream sink in this high transmissivity zone determined groundwater time of travel of multiple miles per day (Green, 1994).
- Four fluorescent dye traces have been completed in the Prairie du Chien Group of the karst rolling upland. The Lewiston Interchange dye trace in Winona County was a dual dye trace with one dye poured into a sinkhole and the other into a stream sink. Dye from the sinkhole traveled ½ mile in less than a week, emerging at visible levels in a spring. Dye from the stream sink traveled at a slower rate, roughly ½ mile in 6 months (DNR, 2019b). These travel times are consistent with previous tracing in the Prairie du Chien Group (Wheeler, 1993; Green and Alexander, 2011, 2015). Dyes were not detected from a sinkhole south of Caledonia in Houston County or from an Altura wastewater lagoon in Winona County.
- Surface-water springsheds contribute surface flow to stream sinks within this unit and in the adjoining karst and pseudokarst escarpment unit.
- Depth to groundwater is typically greater than 50 feet, however portions of the Prairie du Chien are saturated and can provide adequate yield to wells (Barry, 2021, in preparation). Springs are not abundant, but those that exist can have significant flow.
- Groundwater in the karst rolling upland is a mixture of both local and regional sources. Precipitation that is not lost to evapotranspiration rapidly infiltrates through thin soils into conduits and fractures, or becomes overland runoff that disappears into sinkholes and stream sinks. This local groundwater flow component is commonly impacted by activities at the land surface (Runkel and others, 2014a).

  Regional groundwater flow in the karst rolling upland has a longer time of travel than the local component. It consists of groundwater that recharged to the west, in Olmsted and Fillmore counties and beyond. Regionally-sourced groundwater has moved eastward underneath the overlying Upper Carbonate plateau and generally shows less anthropogenic contamination than younger locally-sourced water. Minimally impacted regionally sourced groundwater frequently dilutes nitrogen-enriched locally-sourced groundwater (Runkel and others, 2014a; Barry, 2021 in preparation).

Karst interfluve



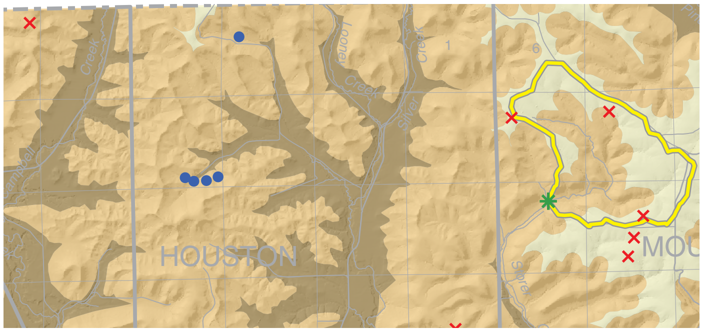
Landscape unit delineation

Karst interfluves are narrow ridges of the rolling upland that extend into deeply dissected valleys. The valleys lower the water table within the Prairie du Chien, resulting in minimal saturation. Karst interfluve was mapped in GIS by identifying areas where the groundwater elevation of the Prairie du Chien is lower than the base of the Oneota.

Landscape unit characteristics

- Karst interfluves have slopes primarily from 0–18 percent, but can range up to 60 percent. They divide deeply incised stream valleys and are hydrologically complex.
- Interfluves generally have less than 50 feet of unconsolidated material over the Shakopee Formation and Oneota Dolomite.
- Sinkholes are the primary surface karst feature, ranging from 1–100 feet wide and 1–20 feet deep. Most occur individually; some interfluves have dense clusters.
- Preferential sinkhole development occurs in paleokarst at the contact between the Shakopee and Oneota (Figure 2).
- The relatively small surface area of interfluves limits the amount of local recharge they receive. Recharge from precipitation is the sole source of groundwater.
- Prairie du Chien springs and wells are rare in interfluves, indicating inadequate saturated thickness for groundwater supply (Green and Barry, 2020). The absence of wells and springs in the karst interfluve suggests that the Prairie du Chien drains vertically by gravity into the underlying Jordan Sandstone. Dewatered Prairie du Chien and partially saturated Jordan have been described in a similar geologic setting elsewhere in southeastern Minnesota (Tipping and others, 2019).
- Valleys relieve stress on the rock and promote the development of vertical fractures which can provide enhanced pathways for recharge to move into underlying formations (Runkel and others, 2018).
- The karst interfluve landscape can pose a challenge for land and water management. A suitability assessment for a landfill expansion in Winona County found groundwater migration to each side of the interfluve (Dahlgleish and Alexander, 1984b). Dye injected into a lower Oneota well was detected in adjacent valleys at three wells in the Lone Rock and Wonewoc formations and two springs emanating from the Lone Rock Formation. Dye was not detected in other Lone Rock and Wonewoc wells and springs in these same valleys, illustrating the difficulty of remediation in this landscape unit.

Karst and pseudokarst escarpment



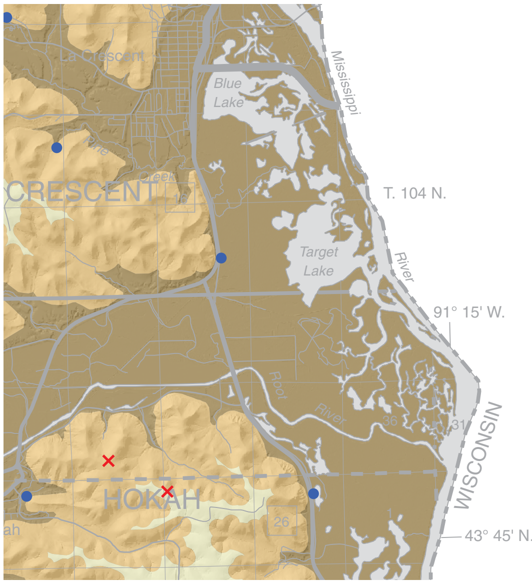
Landscape unit delineation

The karst interfluve and karst rolling upland drop off steeply into the karst and pseudokarst escarpment. The landscape unit was created in GIS by applying a 150-meter buffer upslope from the top of the Jordan Sandstone and a 15-meter buffer downslope from the base of the Lone Rock Formation. It includes all of the Jordan Sandstone, the St. Lawrence Formation, Lone Rock Formation and small areas of the Wonewoc Sandstone at the foot of the escarpment.

Landscape unit characteristics

- Karst and pseudokarst escarpment consists of dissected bluffs, has slopes from 0 to greater than 68 percent, and is hydrologically complex.
- Bedrock varies with ridgetops and hill shoulders underlain by Shakopee Formation and Oneota Dolomite, upper side slopes underlain by Jordan Sandstone, lower side slopes and footslopes underlain by St. Lawrence Formation, and toe slopes underlain by Lone Rock Formation or Wonewoc Sandstone.
- The St. Lawrence and Lone Rock formations are mainly fine- to very fine-grained sandstone, siltstone and shale with some dolostone (Steenberg, 2014a, 2014c) and lack evidence of bedrock dissolution that would classify them as karst (Barry and others, 2015).
- Sinkholes are found in the ridgetops and hill shoulders underlain by the Shakopee Formation and Oneota Dolomite. They do not form in the Jordan Sandstone or the St. Lawrence and Lone Rock formations.
- Surface-water springsheds that begin in the karst rolling upland terminate at lower Jordan, St. Lawrence or Lone Rock formation stream sinks where surface flow becomes groundwater.
- In tributary valleys streams commonly sink into the lower Jordan Sandstone and the upper St. Lawrence Formation. Some lose flow but do not totally disappear as they cross the St. Lawrence Formation (Green and others, 2012). Stream sink locations are ephemeral, often moving up and down the valley depending on stream flow. Flood events can close or reopen stream sinks and change the flow regime of streams and springs. For example, in 1920 the upper reach of Indian Springs Creek in Houston County disappeared into the streambed (Surber, 1920), but is currently perennial.
- Springs are numerous, primarily discharging from the St. Lawrence and Lone Rock formations (Figure 2). Springs are often found at the base of ridge points and steep hillsides, where younger local recharge mixes with older regionally-sourced groundwater. Regional groundwater is lower in nitrate and other anthropogenic chemicals and dilutes locally-sourced groundwater. In general, regional flow comes from areas to the west and from underneath the Prairie du Chien plateau (Runkel and others, 2014a).
- Fluorescent dye tracing has shown groundwater time of travel can approach that of classic karst aquifers, with values from hundreds to over a thousand feet per day (Green and others, 2008, 2012; Barry and others, 2015, 2018). Dye breakthrough to springs is often rapid, however the tails of dye recovery curves are very long. Dye has been detected over 2 years after input, demonstrating that potential negative effects on water quality may persist in the St. Lawrence and Lone Rock formations.

Nonkarst lowland plain



Landscape unit delineation

Nonkarst lowland plain is present in major stream and river valleys. The landscape unit was created in GIS by identifying areas where the Wonewoc Sandstone is adjacent to the karst and pseudokarst escarpment and includes all areas where the Eau Claire Formation or Mt. Simon Sandstone is first bedrock.

Landscape unit characteristics

- Slopes are primarily from 0–6 percent. However, steeper areas along major streams and at the boundary with the karst and pseudokarst escarpment range up to 60 percent.
- Depth of unconsolidated sediment above bedrock ranges from less than 50 feet to over 200 feet, with the shallower depths primarily over the Wonewoc Sandstone.
- The lowland plain is underlain by the Wonewoc Sandstone, the siltstone and shale of the Eau Claire Formation, or the Mt. Simon Sandstone.
- Bedding plane fractures are common in these formations and are similar to those found in the pseudokarst of the St. Lawrence and Lone Rock formations (Gellash and others, 2013). However, thick unconsolidated sediment prevents surface expression of pseudokarst features. Sinkholes do not form in this landscape unit.
- Springs are less common than in the karst and pseudokarst escarpment and primarily emanate from the upper portions of the Wonewoc Sandstone.
- Water chemistry collected in support of the Houston and Winona atlases indicates that springs in this landscape unit are primarily fed by deep regional groundwater. Anthropogenic influences can affect even the deepest valleys where locally-sourced anthropogenically impacted groundwater mixes with older regionally-sourced groundwater.
- Wells completed in the Eau Claire and Mt. Simon are often under artesian conditions in river valleys.

References

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

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

Alexander, E.C., Jr., Runkel, A.C., Tipping, R.G., and Green, J.A., 2013, Deep time origins of sinkhole collapse failures in sewage lagoons in southeast Minnesota: Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, p. 285–292.

Barry, J.D., 2021, Groundwater atlas of Winona County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-34, Part B, report, 2 pls.

Barry, J.D., Green, J.A., Rutelonis, J.W., Steenberg, J.R., and Alexander, E.C., Jr., 2018, Coupling dye tracing, water chemistry, and passive geophysics to characterize a siliciclastic pseudokarst aquifer, southeast Minnesota, USA: Proceedings of the 15th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, p. 5–16.

Barry, J.D., Green, J.A., and Steenberg, J.R., 2015, Conduit flow in the Cambrian Lone Rock Formation, southeast Minnesota: Proceedings of the 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, p. 31–42.

Barry, J.D., in preparation, Groundwater atlas of Houston County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-33, Part B.

Barry, J.D., Miller, T.P., Steenberg, J.R., Runkel, A.C., Kuehner, K.J., and Alexander, E.C., Jr., 2020, Combining high resolution spring monitoring, dye tracing, watershed analysis, and outcrop and borehole observations to characterize the Galena Karst, southeast Minnesota, U.S.A: Proceedings of the 16th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, p. 3–17.

Dalgleish, J.B., and Alexander, E.C., Jr., 1984a, Sinkholes and sinkhole probability *in* Geologic atlas of Winona County, Minnesota: Minnesota Geological Survey, County Atlas Series C-2, Part A, Plate 5.

Dalgleish, J.B., and Alexander, E.C., Jr., 1984b, Hydrogeologic investigation of the proposed expansion site of the Winona County (Murphy) landfill: Department of Geology and Geophysics, University of Minnesota, prepared under a grant from Winona County, final report. Available from the University of Minnesota Digital Conservancy.

Delin, G.N., 1990, Hydrogeology and simulation of ground-water flow in the Rochester area, southeastern Minnesota, 1987–88: U.S. Geological Survey, Water Resources Investigations Report 90-4081, 102 p.

DNR, 2019a, Minnesota spring inventory: Minnesota Department of Natural Resources, Groundwater Atlas Program, statewide dataset of springs, accessed July 2019.

DNR, 2019b, Minnesota groundwater tracing database: Minnesota Department of Natural Resources, Groundwater Atlas Program, accessed July 2019.

DNR, 2018, MNDNR level 09 - DNR autocatchments: Minnesota Department of Natural Resources, Groundwater Atlas Program. Available from the Minnesota Geospatial Commons website, MNDNR Watershed Suite, accessed May 2019.

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

Gellasch, C.A., Bradbury, K.R., Hart, D.J., and Bahr, J.M., 2013, Characterization of fracture connectivity in a siliciclastic bedrock aquifer near a public supply well (Wisconsin, USA): Hydrogeology Journal, v. 21, p. 383–399.

Green, J.A., 1994, Karst aquifer investigation-Lanesboro State Fish Hatchery: Minnesota Department of Natural Resources, Division of Waters. Available from the University of Minnesota Digital Conservancy.

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., and Alexander, E.C., Jr, 2015, Creation of a map of Paleozoic bedrock springsheds in southeast Minnesota: Proceedings of the 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, p. 211–222.

Green, J.A., Alexander, E.C., Jr., Marken, W.J., and Alexander, S.C., 2002a, Karst hydrogeomorphic units of Mower County, Minnesota *in* Geologic atlas of Mower County: Minnesota Department of Natural Resources, County Atlas Series C-11, Part B, Plate 10.

Green, J.A., and Barry, J.D., 2020, Development of karst landscape unit maps for Houston County, Minnesota, USA: Proceedings of the 16th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, p. 344–353.

Green, J.A., Barry, J.D., and Alexander, E.C., Jr., 2014, Springshed assessment methods for Paleozoic bedrock springs of southeastern Minnesota: Minnesota Department of Natural Resources, Report to the Legislative-Citizen Commission on Minnesota Resources, 48 p.

Green, J.A., Luhmann, A.J., Peters, A.J., Runkel, A.C., Alexander, E.C., Jr., and Alexander, S.C., 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: Proceedings of the American Society of Civil Engineers, GSP 183, p. 477–484.

Green, J.A., Marken, W.J., Alexander, E.C., Jr., and Alexander, S.C., 2002b, Karst unit mapping using geographic information system technology, Mower County, Minnesota, USA: Environmental Geology, v. 42, no. 5, August 2002, p. 457–461.

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

Halliday, W.R., 2007, Pseudokarst in the 21st century: Journal of Cave and Karst Studies, v. 69, no. 1, p. 103–113.

Jannik, N.O., Alexander, E.C., Jr., and Landherr, L.J., 1991, The sinkhole collapse of the Lewiston, Minnesota waste water treatment facility lagoon: Proceedings of the 3rd Conference on Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terranes, p. 715–724. Available through the National Service Center for Environmental Publications.

Libra, R.D., Hallberg, G.R., Ressmeyer, G.G., and Hoyer, B.E., 1984, Groundwater quality and hydrogeology of Devonian carbonate aquifers in Floyd and Mitchell counties, Iowa: Iowa Geological Survey, Open File Report 84-2.

Lindgren, R.J., 2000, Ground-water recharge and flowpaths near the edge of the Decorah-Platteville-Glenwood confining unit, Rochester, Minnesota: U.S. Geological Survey, Water Resources Investigations Report 00-4215.

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

Lusardi, B.A., Adams, R.S., and Hobbs, H.C., 2014, Surficial geology *in* Setterholm, D., Geologic atlas of Winona County, Minnesota: Minnesota Geological Survey, County Atlas Series C-34, Part A, Plate 3.

MGS and MDH, 2019, County well index: Minnesota Geological Survey, with the assistance of the Minnesota Department of Health. Online database accessible through the Minnesota Department of Health, Minnesota Well Index mapping application.

Runkel, A.C., Steenberg, J.R., Tipping, R.G., and Retzler, A.J., 2014a, 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 14-02, 154 p.

Runkel, A.C., Tipping, R.G., Alexander, E.C., Jr., and Alexander, S.C., 2006, Hydrostratigraphic characterization of intergranular and secondary porosity in part of the Cambrian sandstone aquifer system 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., 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 Investigation 61, 105 p., 2 pls.

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., 2014b, Hydrogeologic properties of the St. Lawrence aquitard, southeastern Minnesota: Minnesota Geological Survey, Open-File Report 14-04, 119 p.

Runkel, A.C., Tipping, R.G., Meyer, J.R., Steenberg, J.R., Retzler, A.J., Parker, B.L., Green, J.A., Barry, J.D., and Jones, P.M., 2018, A multidisciplinary-based conceptual model of a fractured sedimentary bedrock aquitard–improved prediction of aquitard integrity: Hydrogeology Journal, November 2018, v. 26, issue 7, p. 2133–2159.

Steenberg, J.R., 2014a, Bedrock geology *in* Setterholm, D., Geologic atlas of Houston County, Minnesota: Minnesota Geological Survey, County Atlas Series C-33, Part A, Plate 2.

Steenberg, J.R., 2014b, Bedrock topography and depth to bedrock *in* Setterholm, D., Geologic atlas of Houston County, Minnesota: Minnesota Geological Survey, County Atlas Series C-33, Part A, Plate 4.

Steenberg, J.R., 2014c, Bedrock geology *in* Setterholm, D., Geologic atlas of Winona County, Minnesota: Minnesota Geological Survey, County Atlas Series C-34, Part A, Plate 2.

Steenberg, J.R., 2014d, Bedrock topography and depth to bedrock *in* Setterholm, D., Geologic atlas of Winona County, Minnesota: Minnesota Geological Survey, County Atlas Series C-34, Part A, Plate 4.

Steenberg, J.R., Tipping, R.G., and Runkel, A.C., 2014, 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 14-03, 33 p.

Surber, T., 1920, Streams of southeastern Minnesota: Minnesota Game & Fish Department, Surveys and Investigations.

Tipping, R.G., 1994, Southeastern Minnesota regional ground-water monitoring study–a report to the Southeast Minnesota Water Resources Board: Minnesota Geological Survey, Open-File Report 94-01, 122 p.

Tipping, R.G., Runkel, A.C., Alexander, E.C., Jr., Alexander, S.C., and Green, J.A., 2006, Evidence for hydraulic heterogeneity and anisotropy in the mostly carbonate Prairie du Chien Group, southeastern Minnesota, USA: Sedimentary Geology, v. 184, p. 305–330.

Tipping, R.G., Green, J.A., and Alexander, E.C., Jr., 2001, Karst features *in* Geologic atlas of Wabasha County, Minnesota: Minnesota Geological Survey, County Atlas Series C-14, Part A, Plate 5.

Tipping, R.G., Rantala, M., Alexander, E.C., Jr., Gao, Y., and Green, J.A., 2015, History and future of the Minnesota karst feature database: Proceedings of the 14th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, p. 263–270.

Tipping, R.G., Runkel, A.C., Steenberg, J.R., Retzler, A.J., and Hoxmeir, J., 2019, Evaluation of temperature, stream flow, and hydrogeology impact on brook trout habitat. Report to the Legislative-Citizen Commission on Minnesota Resources, p. 12-13.

University of Minnesota, 2020, Karst feature inventory points: University of Minnesota Department of Earth and Environmental Sciences and the Minnesota Department of Natural Resources, accessed June 2020. Available on the Minnesota Geospatial Commons website.

USDA-NRCS, 2019 and 2020, Soil Survey Geographic Database (SSURGO): U.S. Department of Agriculture–Natural Resources Conservation Service. Data for Houston County, Minnesota and Winona County, Minnesota, accessed July 2019 and June 2020.

Wheeler, B.J., 1993, Groundwater tracing in the Duschee Creek Karst Basin in southeast Minnesota: University of Minnesota, Master's thesis. Available through the University of Minnesota Digital Conservancy.

Witthuhn, K., and Alexander, E.C., Jr., 1995, Sinkholes and sinkhole probability *in* Geologic atlas of Fillmore County, Minnesota: Minnesota Department of Natural Resources, County Atlas Series C-8, Part B, Plate 8.

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