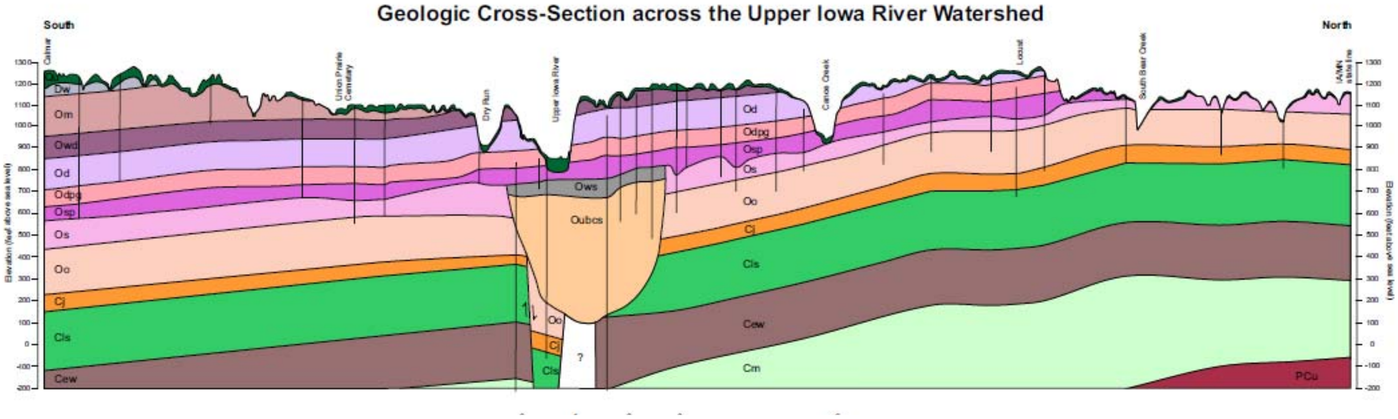
GEOLOGIC MAPPING FOR WATER QUALITY PROJECTS IN THE UPPER IOWA RIVER WATERSHED

Technical Information Series No. 54



Iowa Geological and Water Survey
Robert D. Libra, State Geologist

Iowa Department of Natural Resources
Roger L. Lande, Director
September 2011

Geologic Mapping for Water Quality Projects in the Upper Iowa River Watershed

Iowa Geological and Water Survey
Technical Information Series 54

C. F. Wolter, R. M. McKay, H. Liu, M. J. Bounk, R. D. Libra

Supported in part by the U.S. Geological Survey - National Cooperative Geologic Mapping Program and the Iowa Department of Natural Resources – Watershed Improvement Program through the US EPA Nonpoint Source Pollution Program

September 2011

Iowa Geological and Water Survey
Robert D. Libra, State Geologist

Iowa Department of Natural Resources
Roger L. Lande, Director

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Geologic mapping provides information on the subsurface part of watersheds, which is necessary for evaluating the vulnerability of groundwater to nonpoint-source contamination, the groundwater contributions to surface water contamination, and for targeting best management practices for water quality improvements. Detailed mapping of bedrock geologic units, key subsurface horizons, and surficial karst features was carried out in the Upper Iowa River watershed (UIRW) in northeast Iowa. The mapping identifies the three-dimensional distribution of aquifers and aquitards, and therefore the most likely pathways for significant groundwater transport. The addition of karst features identifies areas of concentrated groundwater recharge and discharge, as well as likely subsurface zones that allow more rapid movement of recharge water to wells and streams.

This report summarizes the methods and results of this mapping. Key resulting products are Geographic Information System layers that can be combined with other mapped data, such as land use, livestock concentration, or slopes, to assess best management approaches.

Rocks of the Ordovician-age Galena Group and the Devonian-age Cedar Valley Group are the most transmissive bedrock units in the eastern and central parts of the watershed, and are prone to the development of karst. Land surface activities can readily result in groundwater contamination of these aquifers. These strata are separated by the intervening Maquoketa Formation, which acts as an aquitard. Groundwater discharge to the surface as springs and seeps often occurs where the contact between the Cedar Valley and the Maquoketa Formation are at the land surface. The Maquoketa also limits the movement of groundwater between the two aquifers vertically and constrains the horizontal extent of concentrated groundwater flow.

The Galena Group rocks are underlain by a sequence of shales and shaley carbonate rocks that act as an aquitard, resulting in many large springs and seeps issuing from near the base of the Galena strata, and limiting flow downward into the underlying units. The underlying units in the eastern part of the watershed, the Ordovician-age St. Peter Sandstone and Prairie du Chien Group, the Cambrian-age Jordan Sandstone are productive aquifers. As a result of the slope of the bedrock units they also form the bedrock surface in the central to eastern limits of the watershed. This thick rock sequence contains no extensive confining beds to restrict groundwater vertically but they are not very susceptible to karst and concentrated groundwater recharge, flow, and discharge.

Information and concepts developed as part of this work have been extended to larger parts of the shallow rock and karst regions of eastern Iowa. Two examples of applications of the detailed mapping to watershed planning efforts within the Upper Iowa watershed are included in this report.

INTRODUCTION – GROUNDWATER AND WATERSHEDS

A watershed is typically defined and mapped as the topographic area contributing runoff to a stream above some point of interest. A more complete delineation incorporates the subsurface zone that contributes actively circulating groundwater to the stream and requires considering a watershed as a three-dimensional hydrologic package.

Groundwater in any Iowa watershed is fed by recharge from precipitation and snowmelt, moves laterally and horizontally through the subsurface, and discharges back to the surface into the watershed's stream and its tributaries. This groundwater contribution is commonly referred to as baseflow. The depth from which actively circulating groundwater contributes to stream flow is dependent on watershed relief and the permeability of the underlying geologic materials. Low-relief watersheds underlain by slowly permeable materials typically have relatively shallow depths of actively circulating groundwater and relatively small groundwater-derived baseflow contributions. In contrast, in high relief watersheds underlain by highly permeable materials, groundwater may circulate to considerably greater depths and provide significant baseflow contributions to the receiving stream. Between these conceptual relief and permeability "end members" lay watersheds with a gradation of circulation depths and baseflow contribution volumes.

When addressing nonpoint source contributions to surface water bodies, an understanding of watershed hydrology is required to identify critical areas where water interacts with and mobilizes contaminants, such as nutrients, sediment, bacteria, or pesticides; and to identify the pathways by which mobilized contaminants reach the surface water of interest. This allows for targeting best management practices to locations where the greatest water quality benefits will accrue. A similar understanding of the subsurface hydrology, or hydrogeology, allows better identification of sources, pathways, and delivery points for groundwater and contaminants transported through the watershed's subsurface geological "plumbing system."

In this report we provide a hydrogeological assessment of the Upper Iowa River watershed in northeast Iowa. This assessment includes the three-dimensional mapping of the bedrock and unconsolidated materials that underlie the watershed, including their thickness, distribution, and top and bottom elevations. It provides a classification of the relevant geologic units into their hydrologic roles as aquifers which readily transmit groundwater, or aquitards which restrict and divert groundwater flow. In addition it provides mapping of concentrated groundwater recharge and discharge points from karst features such as losing streams, sinkholes, and springs. All relevant mapping products are in the form of geographic information system (GIS) coverages, or electronic map layers. This allows the mapping to be readily used in watershed assessments and targeting of best management practices, and to be updated as needed. These coverages are available online via the Iowa Department of Natural Resources (IDNR) – Natural Resources GIS Library (http://www.igsb.uiowa.edu/nrgislibx/).

The mapping products created for this work, and the concepts behind them, have been applied to several watersheds in Iowa, including two located within the Upper Iowa River watershed. The two Upper Iowa watersheds are included as case studies in Appendices A and B.

UPPER IOWA RIVER WATERSHED

The Upper Iowa River watershed (UIRW) encompasses about 1,005 square miles in northeast Iowa and southeast Minnesota (Fig. 1). This report focuses on the Iowa portion of the watershed, which covers parts of Howard, Winneshiek, and Allamakee counties. The Upper Iowa is a tributary to the Mississippi River. Kiel (2005) supplies a summary of watershed characteristics. Watershed elevations range from about 1,440 feet in the headwaters to about 610 feet at the junction with the Mississippi River, giving the watershed about 830 feet of total relief. Land use is primarily agricultural. About 41% of the watershed is row-cropped for corn and soybeans, while about 35% is grassland, pasture, or land enrolled in the Conservation Reserve Program. Nineteen percent of the watershed is forested and residential and commercial uses account for about 3 percent. Estimated watershed population was about 27,300 as of the 2000 U.S. Census, with 45% of the population residing outside of incorporated areas. The watershed contains about 1,900 farms with an average size of about 280 acres. The watershed supports a significant livestock population, including about 97 thousand cattle and calves, 180 thousand hogs, and 200 thousand chickens.

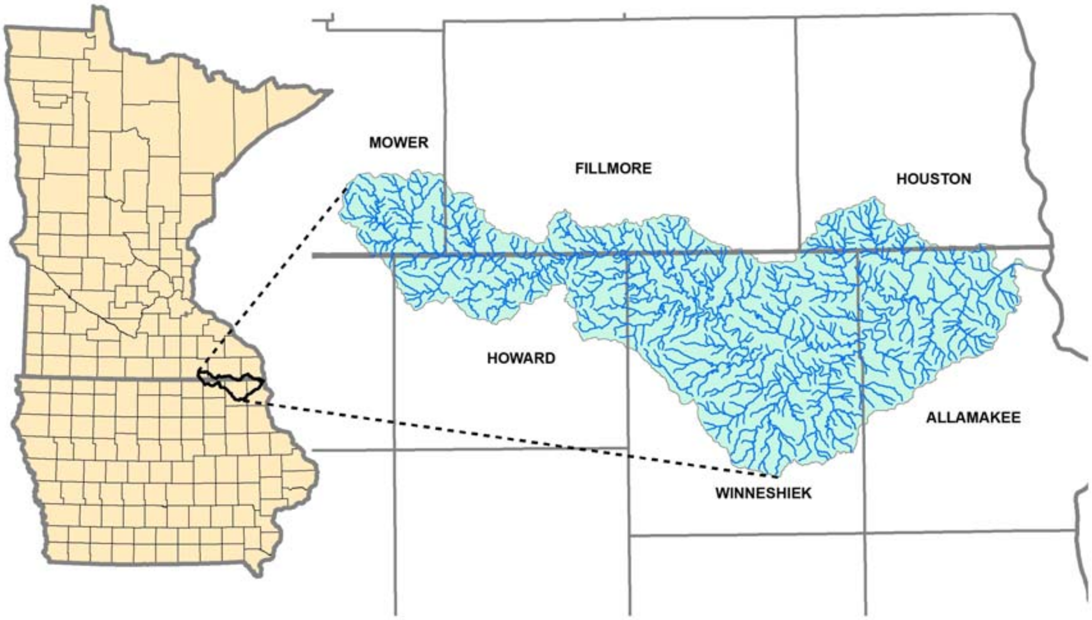


Figure 1. Location of the Upper Iowa River watershed.

Annual precipitation in the watershed averages about 33 inches, and average snowfall is about 40 inches per year. The growing season is about 150 days long. The U.S. Geological Survey maintains a gaging station about 18 miles upstream of the junction with the Mississippi; the drainage area above the gage is 770 square miles. Average and median discharges for the 1939-2008 period of record were 626 and 368 cubic feet per second, respectively. This amounts to about 11 inches of runoff annually, equivalent to about one third of the average precipitation.

Compared to other similarly sized Iowa watersheds, the UIRW exhibits relatively low row-crop intensity and a relatively high water yield (Libra et al., 2004). Documented water quality problems exist. Reaches of the UIR were placed on the state’s 303(d) list of impaired waters beginning in 2004, with primarily bacterial and biological impairments cited. Mean concentrations of nitrate-nitrogen (NO3-N) for water-years 1987-1996, estimated as the mean of monthly analyses, was 4.1 mg/L with an average annual water yield of 11.2 inches (Schilling and Libra, 2000; Libra et al., 2001). Libra and others (2004) estimated average total nitrogen concentrations of 7 mg/L for water years 2000-2002, based on flow-weighted estimates of monthly samples. Average annual water yield for this period was 10.6 inches.

The UIRW is underlain mainly by a series of Paleozoic-age bedrock units consisting of limestones and dolomites (collectively referred to as carbonates), sandstones, and shales. The sandstone and carbonate strata typically act as aquifers, and the shales as aquitards. Overlying the bedrock is a variable thickness of unconsolidated materials, which are typically thicker in the western part of the watershed and thinner to the east. Much of the eastern part of the watershed lies in what is commonly referred to as the "Driftless Area" of the upper Mississippi River Basin, which was once believed to be non-glaciated and hence free of glacial drift. Prior (1976) more properly termed the Iowa portion of the region the "Paleozoic Plateau," as glacial deposits, while largely removed by erosion, do exist in northeast Iowa. The thin nature of the glacial deposits and loess result in a shallow, rock controlled landscape and near-surface, vulnerable aquifers. Where carbonate rocks are near the surface, karst features are prominent. The shallow, fractured rock and high-relief nature of the watershed make the area one of Iowa's most scenic, and supplies large quantities of groundwater to the area's coldwater trout streams. The following sections describe the mapping methods and resulting distribution of the geologic deposits and karst features that control the subsurface hydrology of the UIRW.

BEDROCK GEOLOGY

Previous Geologic Mapping and Data Sources

The area encompassed by the Upper Iowa River watershed was last mapped geologically in 1998 by Iowa Geological and Water Survey (IGWS) staff. This mapping was carried out with support of the U.S. Geological Survey-National Cooperative Geologic Mapping Program (NCGMP), and mapped the bedrock geology of a 17-county region of northeast Iowa (Witzke et al., 1998). Although that mapping effort incorporated significant amounts of new data that had been obtained since the previous 1969 bedrock geologic map of the area (Hershey, 1969), the large scale compilation nature of the 1998 map precluded it from being as accurate as needed for the current study.

The current geologic mapping was supported in part by the NCGMP and the IDNR-Nonpoint Source Program. This effort derived information concerning bedrock unit distribution and bedrock elevations from the following data sources: 1) new field inventory and investigation of quarries and outcrops along all roads, public lands, and some private lands; 2) existing outcrop, quarry and well log records in IGWS files; 3) 224 new well logs produced from previously unstudied well sample sets, and review of driller logs from unstudied wells; 4) areas of shallow rock as defined by U.S.. Department of Agriculture-Natural Resources Conservation Service digital soils maps; 5) a limited number of new site specific drillholes and coreholes; 6) quadrangle geologic mapping within the UIRW (Tassier-Surine et al., 2005; 2006; McKay et al., 2006; 2007; 2008; Liu et al., 2007; 2008; and Witzke and Anderson, 2006); and 7) bedrock geologic maps from adjacent counties in Minnesota (Mossler, 1995; and Runkel, 1996).

Bedrock Topography (Elevation of the Bedrock Surface)

Figure 2 is a topographic map showing the elevation of the bedrock surface. Across the eastern three quarters of the UIRW the topography of the bedrock surface closely resembles the topography of the land surface. In this eastern region the ridge tops are typically capped by less than 50 feet of Quaternary sediment, the valley walls are mantled by thin sediment, and the valley floors usually are underlain by 10 to 70 feet of alluvium. The lowest elevation of the bedrock surface, slightly less than 550 feet above sea level, is at the confluence of the Upper Iowa River

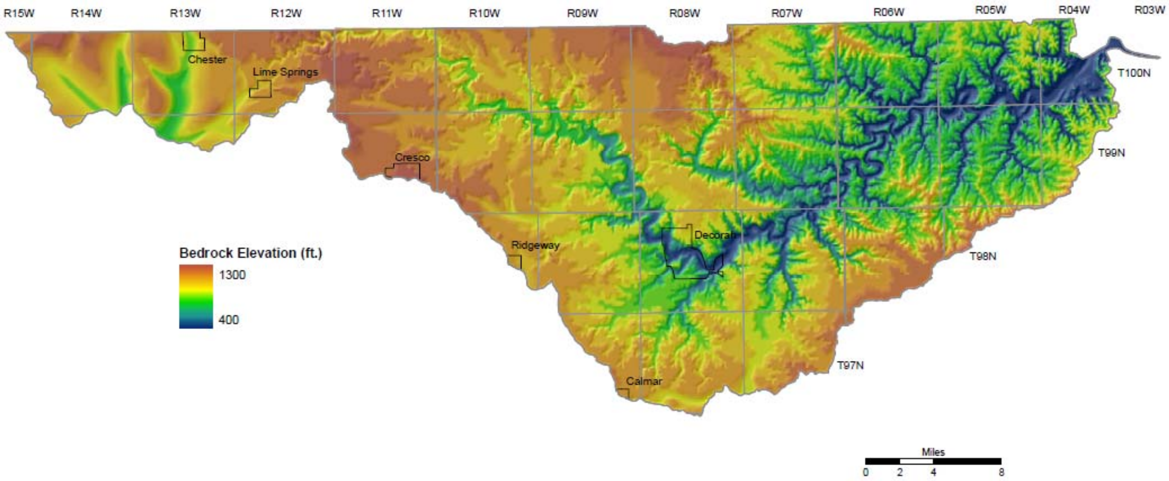


Figure 2. Bedrock topography, Upper Iowa River watershed.

and the Mississippi River. The highest elevations of the bedrock surface, in excess of 1,300 feet above sea level, occur along several uplands in the central and western parts of the watershed.

The configuration of the bedrock surface in the far western region departs significantly from surface topography. In this area bedrock valleys incised to elevations of 1,000 feet above sea level trend to the south and southwest, while surface drainage trends northeast towards the Upper Iowa River. These bedrock valleys, such as the one beneath Hayden Prairie State Preserve, contain as much as 300 feet of Quaternary sediment.

Bedrock Stratigraphy, Aquifers & Aquitards, and Map Units

One of the primary goals of the study was to gain a more thorough understanding of relationships between bedrock geology and karst features within the watershed. Since karst features within the watershed are all developed within bedrock aquifers, bedrock formations were grouped into mapping units that represented either entire aquifer systems, subdivisions of aquifer systems, or aquifer-separating aquitards within the watershed. Figure 3 illustrates the entire stratigraphic column within the area of the watershed and the division of bedrock units into aquifers, aquitards, map units, and their component geologic formations. Major rock types, distinctive accessory lithologies, and distinguishing rock fabric features, as well as major spring, seep, and unconformity horizons are graphically summarized.

Bedrock is exposed at numerous outcrops throughout the UIRW. Our study inventoried 1,028 outcrops and quarries on readily accessible land and rights-of-way, but there are probably at least twice that many outcrops situated on private land that we did not visit. As expected, rock exposure is common along steep valley walls where it sporadically outcrops as small to large rock cliffs. Outcrops are significantly fewer within upland and valley floor areas that are widely covered by mantles of glacial and alluvial sediments, respectively. Man-made road cuts and quarries are common throughout the watershed and are excellent sites to observe and investigate bedrock geology.

There is approximately 1,600 feet of total bedrock thickness variably exposed throughout the watershed (Figure 3). The oldest exposed rock in the watershed is Cambrian sandstone of the Wonewoc Formation; it outcrops low in the valley wall of the Upper Iowa River Valley near the confluence with Irish Hollow in Allamakee County. The youngest rock exposed in the watershed is Cretaceous ironstone and sandstone of the Windrow Formation. It outcrops in two places; northeast of Waukon at Iron Hill in Allamakee County where it overlies the Ordovician Dunleith Formation, and on a private farmstead along the Minnesota border northeast of Lime Springs, Howard County where it rests on Devonian Cedar Valley Group.

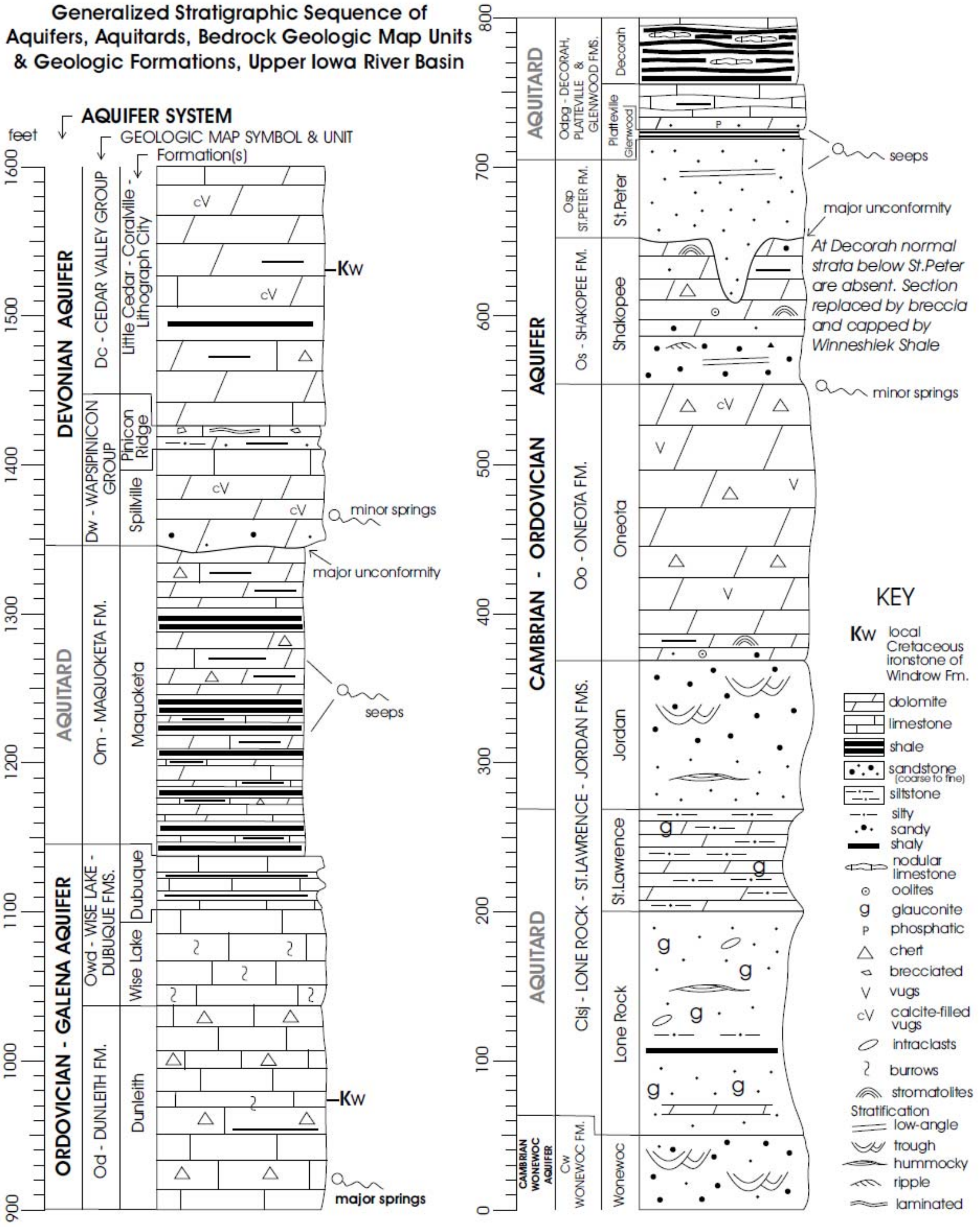


Figure 3. Stratigraphic sequence within the Upper Iowa River watershed.

Structure of the Bedrock Formations

The generalized structural configuration of strata across the watershed is best portrayed by a structure contour map illustrating the elevation above sea level of the top of the St. Peter Sandstone Formation (Figure 4). The St. Peter Sandstone is a readily recognized rock stratum that can be confidently picked from both well samples and driller logs, thus making it the most reliable datum from which structure can be determined. Although the St. Peter is not present across much of the eastern third of the watershed, the structure on the top of the St. Peter throughout the remainder of the study area illustrates the gradual dip to the southwest of all the rock formations in the watershed.

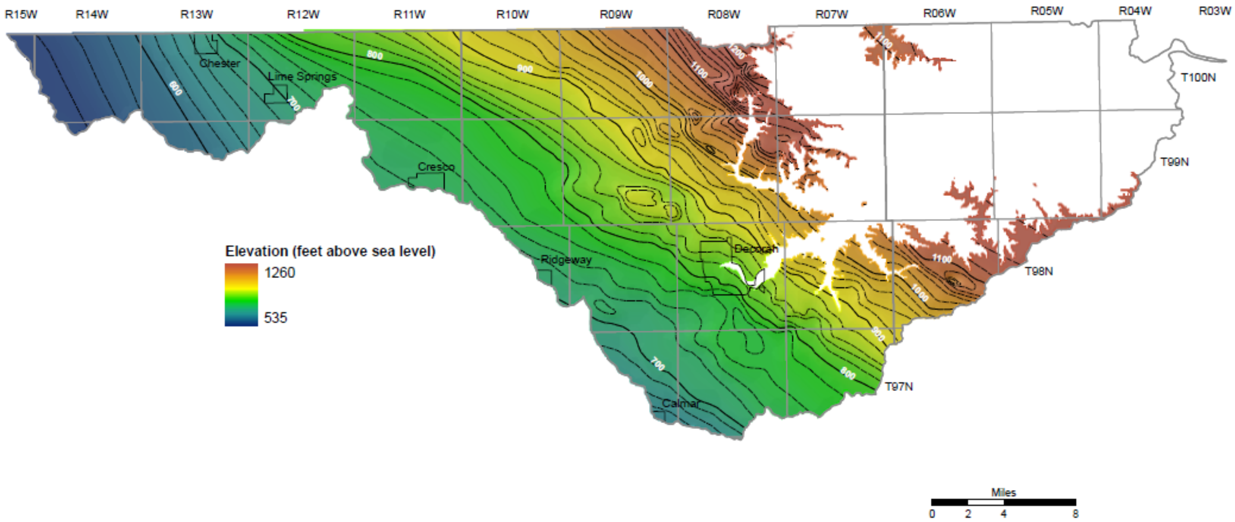


Figure 4. Elevation of the St. Peter Sandstone surface in the Upper Iowa River watershed.

This dip to the southwest ranges between 18 to 40 feet per mile with the steepest dips being present north of Decorah in the north-central portion of the watershed. This structural configuration combined with the depth of incision of stream courses, and the presence of major unconformities controls the distribution of bedrock formations at the bedrock surface throughout the watershed (Figure 5). This results in the oldest Cambrian strata comprising the bedrock surface in the northeast part of the watershed, and the younger Devonian strata being preserved in the southern and western portion of the watershed. Small crustal flexures in the eastern part of the watershed have been mapped by McKay (1993) utilizing the top of the Jordan Sandstone as a datum.

Another method of illustrating geologic structure is by geologic cross sections across the watershed. Figure 6 is a geologic cross section that transects the watershed parallel to the general southwest dip of watershed strata from the Minnesota border on the northeast to Calmar in the south. The cross section illustrates the thickness of mapped units, their dip to the southwest, and areas of incision by stream and river courses along the line of section. The central area of the cross section, partially beneath the City of Decorah, documents an unusual structural feature of stratigraphic disruption where normal geologic strata are truncated by a significant region of anomalous sedimentary strata that are composed of shale, breccia, conglomerate, and sandstone.

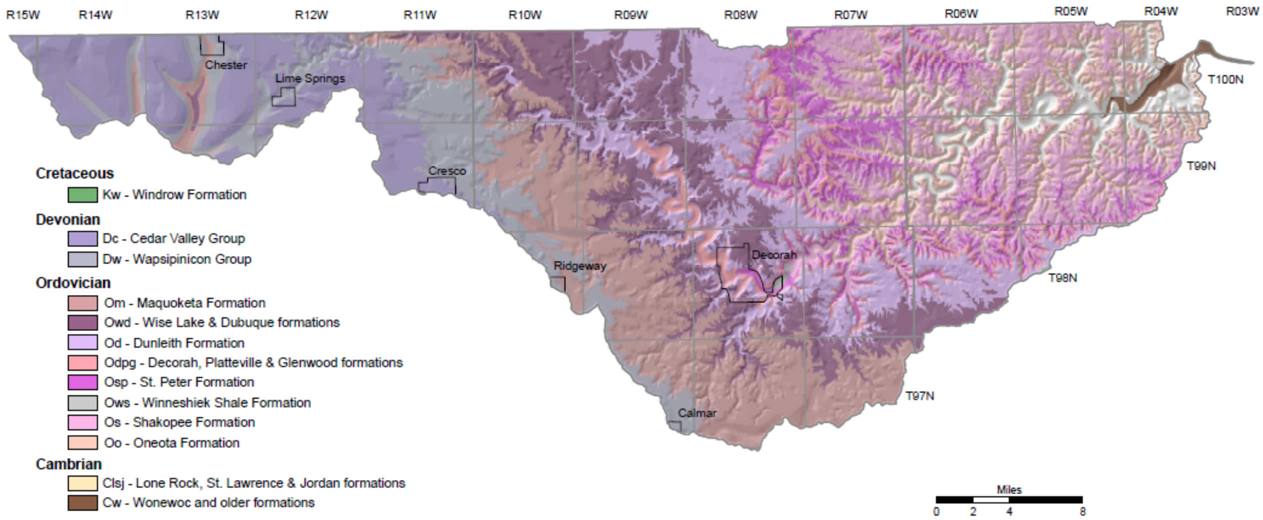


Figure 5. Bedrock geologic map of the Upper Iowa River watershed.

This feature, presently referred to as the "Decorah Structure," is suspected of being a buried Middle Ordovician meteorite impact crater (Liu et al., 2009; McKay et al., 2010, 2011). The subsurface structure is circular in plain view, over 600 ft deep, and is filled by breccia and conglomerate that is capped by the fossiliferous 60 to 90 ft thick Winneshiek Shale (Liu et al., 2006). The previously reported Decorah Fault (Lorenz et al., 1961) appears to be related to normal faulting along the basin/crater margin. Young and others (2005) recognized the anomalous stratigraphy, but did not relate it to an extraterrestrial impact origin. The structure is almost entirely buried and concealed by St. Peter Sandstone and younger bedrock strata, and Quaternary river alluvium. It is known primarily from the study of water well samples, two shallow cores, and one exposure. Investigation of this unusual structural and stratigraphic feature is continuing at IGWS through support from an award from the National Science Foundation (Liu, et al., 2010).

Description of Map Units

Figure 5, the bedrock geologic map, illustrates the distribution of bedrock formations at the bedrock surface throughout the watershed. The geologic cross section (Figure 6) shows the majority of the bedrock map units exposed in the watershed, but also shows several formations and groupings of formations that are deeply buried and do not outcrop in the watershed. This discussion will entail only those units that outcrop in the watershed and were used as designated map units on the geologic map.

Wonewoc Sandstone and older formations. The Wonewoc Sandstone, also referred to as the Ironton-Galesville Sandstone in the older literature, is a porous, fine to coarse grained, quartz sandstone. It is the oldest Paleozoic age rock formation exposed in the state and it outcrops at one known location in the lower reach of the Upper Iowa River Valley near Irish Hollow (Anderson et al., 1979). The formation has a full thickness of approximately 100 feet but only the upper 10 feet is exposed at the Irish Hollow outcrop. The formation serves as an aquifer, particularly for domestic use in the eastern part of the watershed. Karst does not occur within this map unit. Part of the eastern extent of this map unit include older shale and sandstone units, the Eau Claire and Mt. Simon formations, that do not outcrop in the watershed, and are only present in the subsurface.

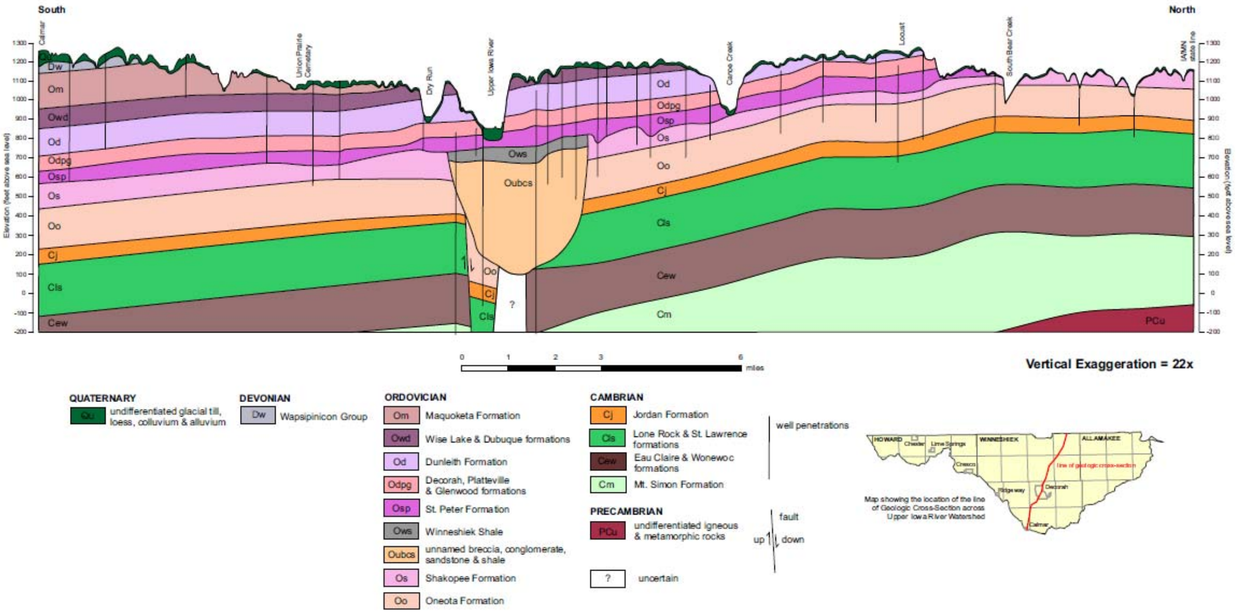


Figure 6. Geologic cross-section of the Upper Iowa watershed.

Lone Rock – St. Lawrence – Jordan formations. These three formations were grouped into one mapping unit because the contact of the lower Jordan with the St. Lawrence is usually poorly exposed and difficult to pick from driller logs. The Lone Rock is a very-fine to fine grained, glauconitic and feldspathic sandstone with minor beds of dolomite and green-gray shale. It has a gradational contact with the overlying dolomites and siltstones of the St. Lawrence Formation and the two units attain an average thickness of about 180 to 200 feet. Several outcrops of these strata are described in Anderson and others (1979), and McKay (1993).

The Jordan Formation is a porous, fine to coarse grained, feldspathic and quartzose sandstone that has an average thickness of 100 feet. It comprises the lower portion of the well known Cambro-Ordovician or "Jordan" aquifer system from which numerous public and private water systems throughout central and eastern Iowa draw groundwater (Horick and Steinhilber, 1978). The communities of Calmar and Cresco have Jordan wells, as do private well owners in the eastern part of the watershed. Readily accessible outcrops occur at Quandahl and Dorchester, and at numerous points down valley. Descriptions of Jordan outcrops in and near the UIRW are contained in Anderson and others (1979), Witzke and McKay (1987), and McKay (1993). Karst does not occur within this map unit.

Oneota Formation. The Oneota Formation, the lower division of the Prairie du Chien Group, is named after the former name applied to the Upper Iowa River. It forms the middle portion of the Cambro-Ordovician Aquifer. It averages 180 feet in thickness and is composed of relatively pure dolomite and cherty dolomite with lesser sandstone and shale in its lower 30 feet; it often contains vugs or large pores that may be partially to totally filled with calcite crystals. The formation outcrops in many places downstream of the "upper dam" on the Upper Iowa River, and forms prominent scenic cliffs and bluffs capping the Jordan Sandstone in the eastern part of the watershed. Davis (1970a and 1970b), and Witzke and McKay (1987) described a series of readily accessible road cuts through the Oneota along State Highway 76 south of the Upper Iowa River, and along State Highway 9 west of Lansing. Numerous Cambro-Ordovician wells are completed open to the Oneota because its fractured dolomite strata hosts significant groundwater resources. The Oneota contains a limited number of caves and karst features, and is considered to be only slightly karst-susceptible.

Shakopee Formation. The Shakopee Formation is the upper division of the Prairie du Chien Group. It consists of 20-25 foot thick basal sandstone overlain by dolomite, often sandy, and minor green shales and thin sandstones. A major unconformity or surface of erosion separates the Shakopee from the overlying St. Peter Sandstone, and total thickness of the Shakopee varies depending upon the extent of truncation at that unconformity surface; the formation averages between 50 to 100 feet thick. Oolites, chert, and stromatolites are distinctive components of the formation. The unit is typically poorly exposed except at quarries and road cuts. Small springs have been noted near its contact with the underlying Oneota Formation, and caves are known to be present within the unit in Allamakee County. Water wells are commonly completed in or through the Shakopee. The formation is considered to be only slightly karst-susceptible.

Winneshiek Shale Formation. The Winneshiek Shale is a new name for a recently recognized shale that is only known to exist in the Decorah area (Young et al., 2005; Liu et al., 2006). The shale is well laminated, medium to dark gray, slightly sandy and contains an unusual invertebrate and early vertebrate fossil fauna. Its thickness varies from 60 to 90 feet and its distribution is limited to a circular area 3.5 miles in diameter. It occurs with a sharp contact beneath the St. Peter Sandstone except for a small area east of Decorah where it is present at the bedrock surface and overlain by alluvium of the Upper Iowa River. Only one small exposure of the shale is known to exist. The shale is thought to occupy the upper portion of the sedimentary fill of a buried Middle Ordovician meteorite impact crater (Liu et al., 2009; McKay et al., 2010, 2011). Crater-fill strata beneath the shale are incompletely known, but are partially composed of breccia and subordinate conglomerate and sandstone. The shale is considered a local aquitard that separates the St. Peter Sandstone from the breccia/conglomerate interval. A number of domestic water wells derive their water supply from the as yet unnamed breccia interval beneath the Winneshiek shale.

St. Peter Sandstone Formation. The St. Peter Sandstone is a porous, fine to medium grained quartz sandstone that averages 50-100 feet thick across the watershed. To the north of Decorah it forms the sides and/or tops of distinctive elongate ridges such as Sattre Ridge and Waterloo Ridge. Typical exposures of the St. Peter occur along Canoe Valley and Middle Hesper roads. Local residents commonly refer to the St. Peter as bluff sand. The formation serves as a major source of groundwater for domestic wells. Karst does not occur within this map unit.

Decorah – Platteville - Glenwood formations. These three formations were grouped into one mapping unit because individually they are thin, and in aggregate they act as an aquitard between the overlying Galena Aquifer and the underlying Cambro-Ordovician Aquifer. The map unit averages 80-90 feet thick. The lower formation, the Glenwood Shale, is a 7-8 foot thick green shale and siltstone that contains some quartz sand and phosphate pellets; it was named by Calvin (1906) for exposures in Glenwood Township. The middle formation, the Platteville, is a 25-30 feet thick fossiliferous limestone that is widely quarried in parts of the watershed. The upper formation, the Decorah Shale, named by Calvin (1906) for numerous exposures at Decorah is composed of shale in its lower part and thinly interbedded shale and fossiliferous nodular limestone in the upper part. It is exposed at the Bruening Rock Products quarry along State Highway 9 where 43 feet of the formation is well exposed (Emerson et al., 2005) and along Dug

Road and Ice Cave Road. Witzke and others (2005) provide a recent description of the Glenwood and Platteville at a new road cut along Locust Road.

This map unit acts as a major aquitard throughout the watershed and forms an impermeable stratal unit below the Galena Aquifer. Figure 7 illustrates the elevation of the top of the Decorah Formation. Its presence restricts the downward vertical migration of water from the overlying Galena and forces Galena Aquifer groundwater to discharge laterally at major springs and seeps where valley incision is below or near the base of the Galena. All the major springs in the Decorah area, Twin Springs, Dunnings Spring, Siewers Springs, Malanaphy Springs, Falcon Springs, and numerous other springs, are present due to this aquifer/aquitard pairing along the deeply incised tributaries and valley of the Upper Iowa River. Karst does not occur within this map unit. Figure 8 utilizes the elevation of this unit and surface topography to show the depth to the Decorah within the watershed.

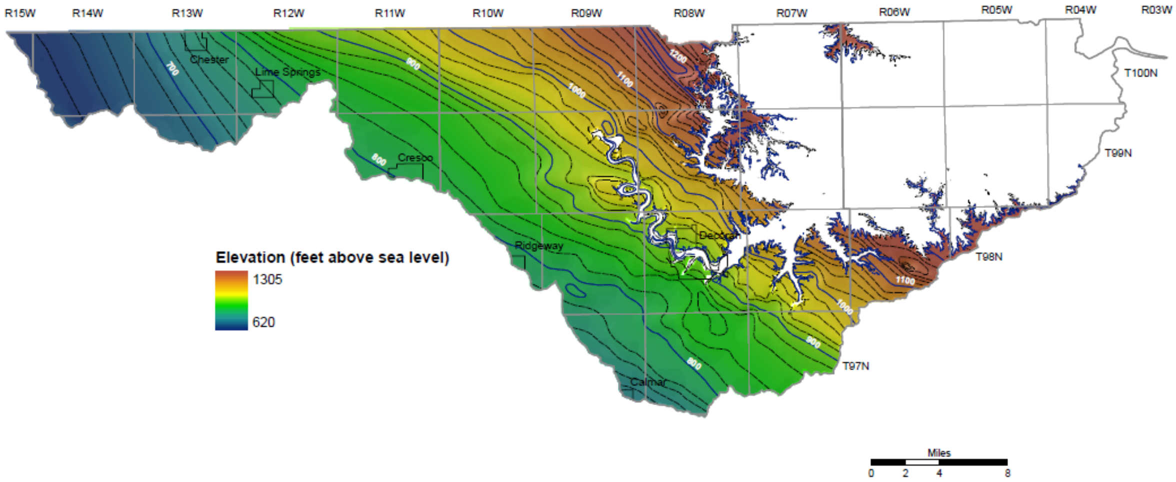


Figure 7. Elevation of the Decorah Shale in the Upper Iowa River watershed.

Dunleith Formation. The Dunleith Formation, the lower division of the Galena Aquifer, is composed of 135 feet of fractured, variably fossiliferous and cherty limestone. Detailed descriptions of the formation can be found in Levorson and Gerk (1972a; 1972b; 1975; 1983) and Levorson and others (1987). Witzke and Ludvigson (2005) provide a recent description of the unit at a new road cut along Pole Line Road. This formation outcrops extensively at Decorah and upstream on the Upper Iowa River and its tributaries; quarries mine stone from this unit. All the major springs in the Decorah area, Twin Springs, Dunnings Spring, Siewers Springs, Malanaphy Springs, Falcon Springs, and numerous other springs, issue from this unit and many domestic wells are completed in this formation. The formation comprises the lower portion of the Galena Aquifer and hosts an abundance of karst, sinkholes, and caves. The formation is considered to be highly karst-susceptible.

Wise Lake and Dubuque formations. The Wise Lake and Dubuque formations, here grouped to form the upper division of the Galena Aquifer, are composed of 100-105 feet of variably fossiliferous limestone with minor shale in the upper 30 feet. The Wise Lake is distinct from the underlying Dunleith by nature of its thick bedded, extensively bioturbated fabric (burrows) and lack of chert. The Dubuque Formation is less bioturbated, and contains echinoderm grainstone beds and distinctive thin shale beds. Both formations are described in detail in Levorson and Gerk (1972a; 1972b; 1975; and 1983), and Levorson and others (1979 and 1987). Witzke and others (2005) provide a recent description of a portion of the unit at a new road cut along Pole Line

Road. The Wise Lake outcrops extensively south and west of Decorah on the Upper Iowa River and its tributaries; numerous quarries mine stone from the Wise Lake, and some domestic wells are completed within the unit. The map unit comprises the upper portion of the Galena Aquifer and hosts an abundance of karst, sinkholes, and caves. The map unit is considered to be highly karst-susceptible.

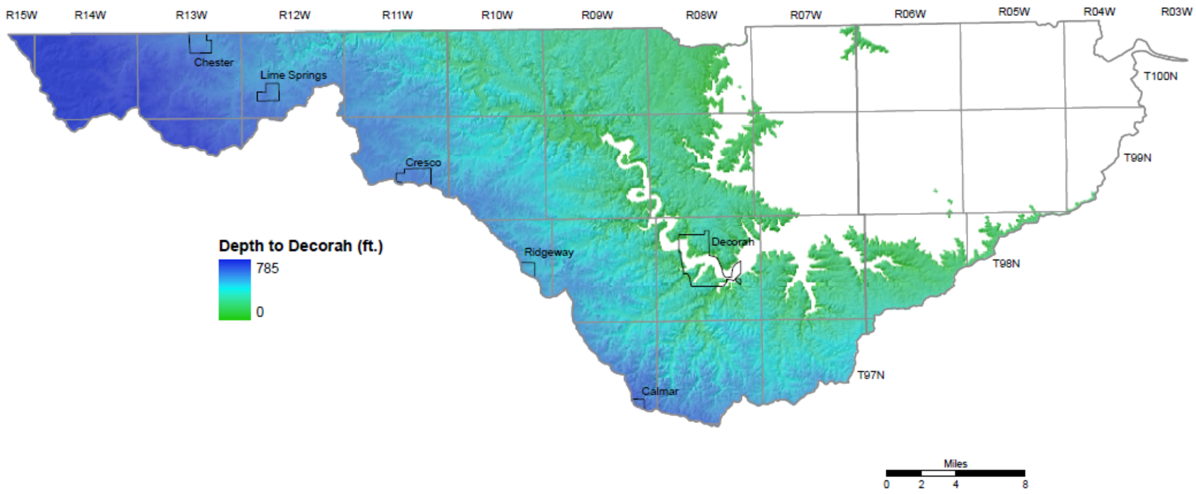


Figure 8. Depth to the top of the Decorah Shale, Upper Iowa River watershed.

Maquoketa Formation. The Maquoketa Formation forms an imperfect aquitard between the underlying Galena Aquifer and the overlying Devonian Aquifer. It consists of up to 190 feet of variably fossiliferous, and cherty, limestone and dolomite with subordinate shale interbeds. Significant amounts of the limestone and dolomite are argillaceous or shaly, but portions of the formation contain enough sound carbonate rock to be quarried for road stone. Levorson and others (1987) give a general description of the Maquoketa in northeast Iowa. Excellent road cuts of the Maquoketa are located in Madison Township along Madison Road, north of Ridgeway (Section 18, T98N R9W), and along 265th Avenue southeast of Ridgeway (Section 33, T98N R9W). A major unconformity separates the Maquoketa from the overlying Devonian strata and relief of several meters locally and tens of meters regionally is developed along that surface of erosion. Some sinkholes are noted in areas that are mapped as Maquoketa, typically from the lower part of the formation. Although inadequately or poorly documented, sinkholes and karst may form in the limestone portion of the lower Maquoketa. Figure 8 illustrates the elevation of the top of the Maquoketa, and Figure 9 shows the depth to the Maquoketa.

Wapsipinicon Group. The Wapsipinicon Group forms the lower portion of the Devonian aquifer. It averages 90-100 feet thick and consists of two formations, the Spillville Formation, 60-75 feet thick, overlain by the Pinicon Ridge Formation, 15-20 feet thick. The Spillville, named after quarry exposures at Spillville (Klapper and Barrick, 1983), consists of medium to thick bedded porous dolomite that often has abundant calcite crystal vug fillings. Locally, a distinctive limestone stromatolite facies forms the upper 10 feet. Springs and seeps, made possible by the porous and fractured dolomite, occur both near the base and top of the Spillville. The overlying Pinicon Ridge consists of shale and dolomite in its lower few feet overlain by laminated to brecciated limestone. The basal shaly zone probably acts as thin and relatively imperfect aquitard where present. The Wapsipinicon, while partially exposed in numerous road cuts, is best exposed at several quarries in the Cresco area and to the west. Witzke and others (1988) contains a more extensive discussion of the group. The map unit is considered to be karst-susceptible, and where near the land surface, rainfall has been observed to infiltrate rapidly into this unit.

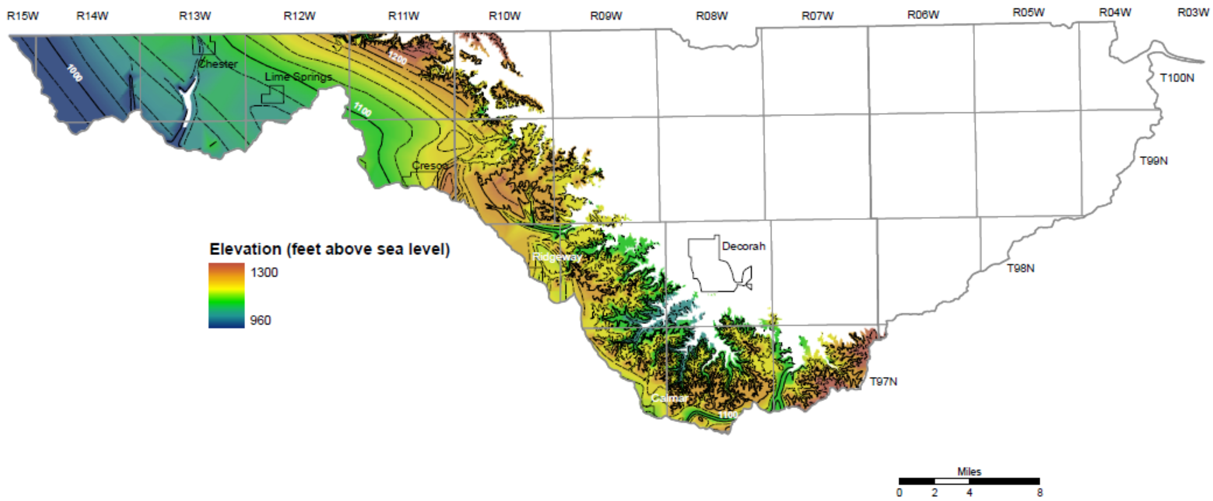


Figure 9. Elevation of the top of the Maquoketa Formation, Upper Iowa River watershed.

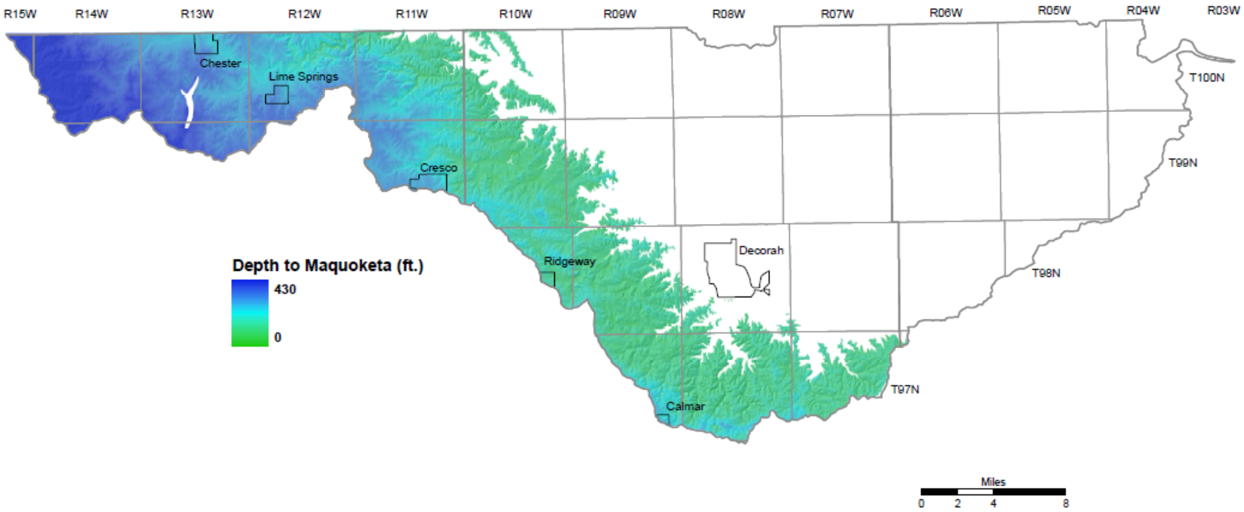


Figure 10. Depth to the top of the Maquoketa Formation, Upper Iowa River watershed.

Cedar Valley Group. The Cedar Valley Group forms the upper division of the Devonian Aquifer throughout the southwest and west portions of the UIRW. It is composed of variably fossiliferous fractured dolomite and limestone that is slightly argillaceous and cherty in some horizons. Maximum thickness reaches 150 feet in the western end of the watershed. The group's component formations, the Little Cedar, Coralville, and Lithograph City, are discussed fully in Witzke and others (1988). The map unit hosts an abundance of karst and sinkholes, and is considered to be highly karst-susceptible.

Windrow Formation. The Cretaceous age Windrow Formation, the youngest bedrock unit in the watershed, occurs as isolated outliers of iron cemented sand and gravel and ironstone at two localities, Iron Hill, north of Waukon, Allamakee County, and a farmstead in north-central Howard County. The Windrow is the coarse grained eastern facies of the Dakota Formation of western Iowa, and has been mined for iron at Iron Hill and at numerous pits in southeast Minnesota (Anonymous, 1943; Andrews, 1958; and Witzke and Ludvigson, 1996). It rests unconformably on the Dunleith Formation in Allamakee County, and the Cedar Valley Group in Howard County. It is not considered an aquifer within the UIRW and does not host karst.

KARST MAPPING

Karst and Water Quality

Sinkholes represent direct pathways for surface runoff water to enter aquifers without the benefit of filtration through the soil. Sinkholes are formed when the underlying soluble carbonate bedrock has been dissolved through time by percolating groundwater, creating voids in the subsurface. When the overlying materials can no longer bridge the void(s), collapse occurs. Sinkholes are often connected to enhanced zones of fractures and conduits which allow the relatively rapid movement of water and contaminants from sinkholes through the subsurface. Conduits may be relatively minor pipe-like features, or enlarged into caverns. In either event they represent highly preferred pathways for groundwater.

While sinkholes represent direct points of groundwater recharge, springs and seeps represent direct points of groundwater discharge back to the land surface. Springs and seeps occur where the water table intersects the land surface, typically in stream valleys. Where a karst aquifer is underlain by an aquitard, groundwater moves laterally above the aquitard, and springs and seeps typically are concentrated where the contact between the units intersects the land surface.

Sinkholes connected to springs via transmissive conduit zones are termed the "conduit-flow" part of a karst aquifer (White, 1969). While conditions vary widely, in many karst-fractured rock aquifers permeable pathways within the bulk of the aquifer are formed by fractures and bedding plane partings that have only been modestly enlarged by dissolution. Recharge occurs by infiltration (as is does in non-karst aquifers) "between the sinkholes." The fracture-bedding plane zones of these aquifers were referred to by White (1969) as the "diffuse-flow" parts of the aquifer. Groundwater in the diffuse-flow parts of the aquifer tends to move towards and discharge to the more transmissive conduits, which functions as drains that feed springs.

Losing streams occur where the local water table has dropped below the level of a stream bed, allowing water to flow downward. Karst areas are commonly typified by losing streams, as the development of conduit-flow systems tends to lower the water table in the aquifer, and the fractured and dissolved nature of the aquifer allows for ready downward leakage of surface water. In areas of karst development, some losing streams end in clearly visible sinkholes, while others tend to lose water more diffusely into the stream bed. Under relatively low flow conditions in many karst settings, total loss of stream flow occurs.

The varying ways water enters and travels through karst groundwater systems has a profound effect on the quality of the recharge water, and hence on the quality of groundwater discharging back to the surface. Following rainfall or snowmelt, runoff to sinkholes and losing streams deliver recharge water with relatively high concentrations of sediment, sediment-attached nutrients such as phosphorus and ammonia-nitrogen, herbicides, organic matter, and bacteria. In contrast, infiltration recharge to the aquifer, passing through the relatively thin cover of soil and surficial materials, delivers relatively high concentrations of soluble, non-adsorbing contaminants, in particular nitrate. These differing recharge waters have distinct chemical signatures, as documented by extensive studies in the Big Spring groundwater basin, located to the south of the

UIRW but in a similar geologic terrain (Hallberg et al., 1983, 1984; Rowden et. al, 2001). Figure 11 schematically shows relationships between land-use, karst, and water quality.

Sinkhole and Spring Mapping Methods

Previous knowledge of sinkholes in the Upper Iowa River watershed comes from Natural Resources Conservation Service (NRCS) county soil surveys for Howard, Winneshiek, and Allamakee counties. These soil surveys were performed from 1956-1960 (Winneshiek), 1962-1967 (Howard), and 1984-1987 (Allamakee). Therefore, some of these surveys were mapped over 40 years ago, which, although short in geological terms, is plenty of time for new sinkholes to develop and old ones to be filled in naturally or with human assistance. The soil surveys also did not focus as much on forested areas as on crop production areas and therefore may have missed sinkholes in the forested areas.

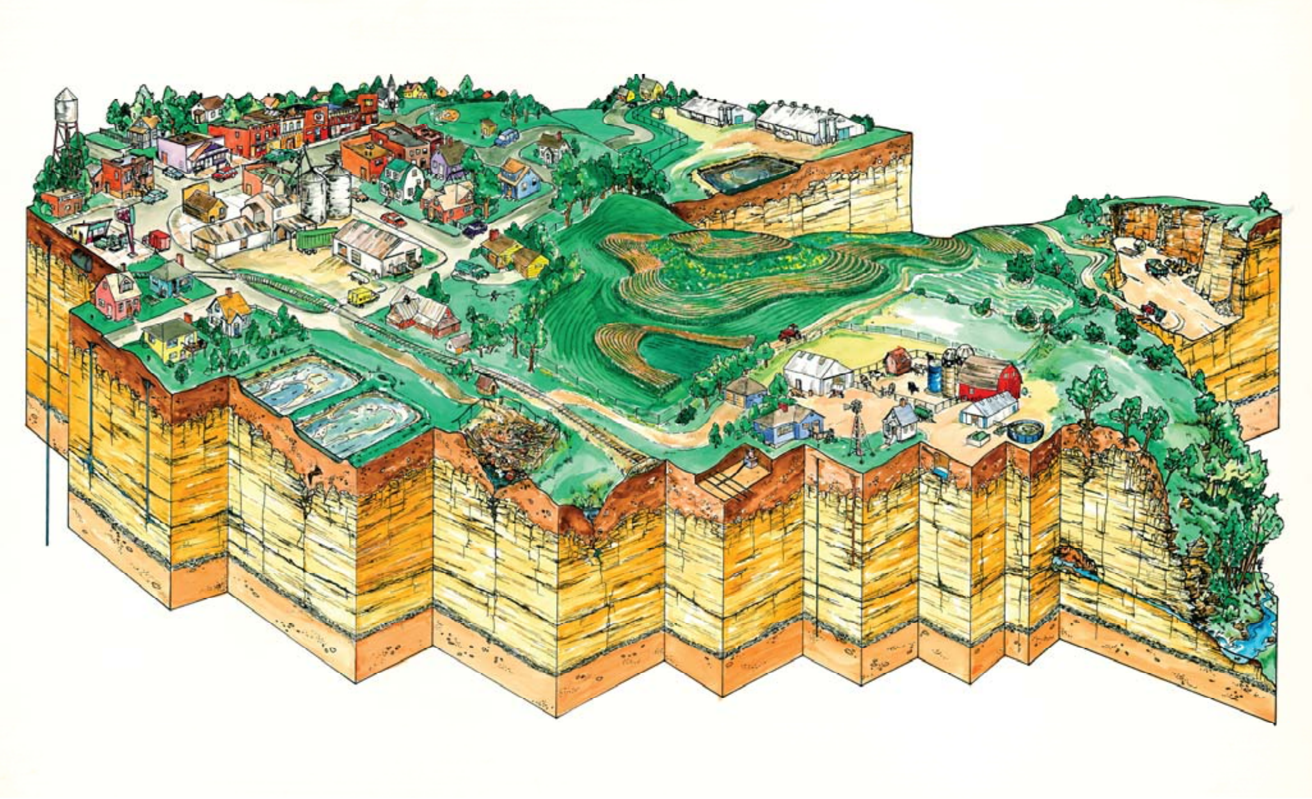


Figure 11. Land-use, karst, and water quality relationships (illustration courtesy of the Southeast Minnesota Water Resources Board).

For this report, we attempted to verify the existence of the NRCS mapped sinkholes and search for any new sinkholes that may have formed since the surveys were completed or were missed by the original surveys. This was accomplished using a two-step procedure. First, 2002 color infra-red (CIR) aerial photography was used to verify the NRCS mapped sinkholes were still present and to locate any new sinkholes that were visible on the photographs. The second step was to utilize field surveys using GPS receivers to search for sinkholes in wooded areas where verification from aerial photography is difficult.

ArcView 3.3 software was used to compare the 2002 CIR photography with the NRCS sinkhole coverage to verify the NRCS sinkholes as well as search for new sinkholes. Staff also performed drive-by field surveys using a laptop and ArcView 3.3 software to verify sinkholes near roadways located using the 2002 CIR photography. All roads in the Upper Iowa River watershed were surveyed this way.

In addition, student-interns under the direction on the Northeast Iowa Resource Conservation and Development office contacted landowners for permission to access their property, and where obtained, surveyed the woodlands for sinkholes and springs using a Garmin 76 or Garmin 12 XLS GPS receiver. The students were able to survey 112,000 acres of the Upper Iowa River watershed, which is about 22 percent of the watershed. The intern field crews worked in the areas of the watershed where existing sinkhole and geologic mapping suggested most sinkholes are likely to occur.

Sinkhole and Spring Mapping Results

Within the area surveyed by the students there were 1,031 sinkholes mapped by the NRCS as part of the county soil surveys. The student surveys, 2002 CIR photography review, and drive-by surveys identified 2,331, an addition of 1,300 sinkholes, or 126 percent, relative to the soil survey mapping. For the rest of the watershed 1,887 sinkholes were mapped versus 1,258 originally mapped by the NRCS, an addition of 629, or 50 percent. This comparison shows that being able to walk through forested areas of the watershed adds considerably to the number of sinkholes located. The students also mapped 838 springs and seeps in the survey area which were essentially all new. Mapped sinkholes and springs are shown on Figures 12 and 13, respectively, along with the bedrock geology.

Some new products that are helping to locate sinkholes in Iowa are LiDAR (Light Detection And Ranging) derived DEMs (Digital Elevation Models) and geo-rectified historical photography. LiDAR derived DEMs have a spatial resolution of 1 meter and are therefore able to show sinkholes as small as a few meters in diameter, even in forested areas. Not only can the sinkholes be plotted as a point, but their size and depth can also be determined from the DEM and represented spatially. The Iowa DNR is in the process of obtaining LiDAR for the whole state. The Iowa DNR also recently finished geo-rectifying aerial photography from the 1930s for the whole state and is currently repeating the process with 1950s photography.

Using these two additional tools, a much more complete picture of the history of sinkholes in Iowa can be obtained. In a comparison done on a small area where the three methods of identifying sinkholes were available, the number obtained from the NRCS was 335, from student and drive-by surveys was 648, and from LiDAR and historical photography was 933 (Fig. 14). The LiDAR and historical photography almost doubles the additional sinkholes found as compared to the student and drive-by surveys. If this holds true for the whole state, the number of known sinkholes will increase from approximately 12,000 to about 36,000.

Losing Stream Mapping

Losing streams segments were also mapped during this project. While staff were doing drive-by surveys looking for sinkholes they also noted if water was flowing at any stream crossings.

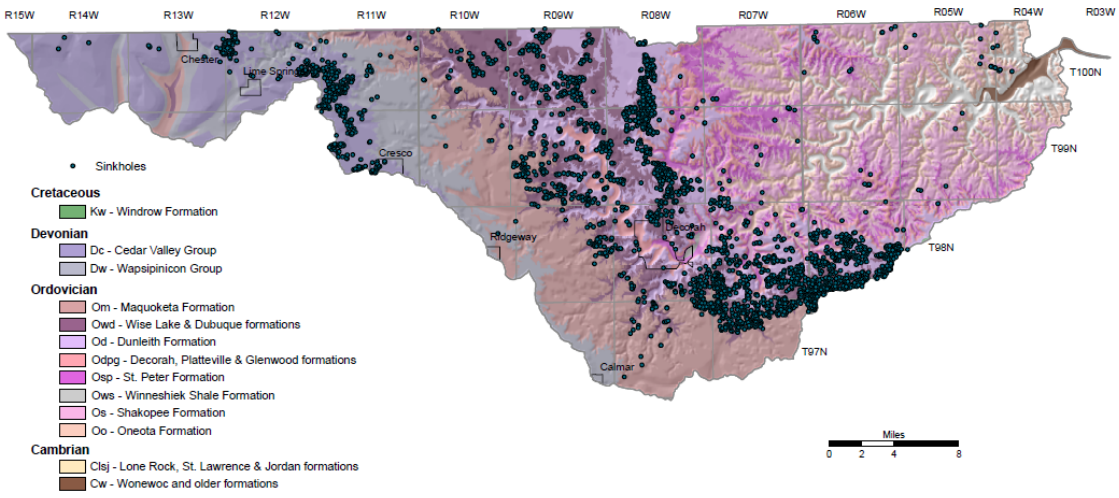


Figure 12. Locations of sinkholes in the Upper Iowa River watershed.

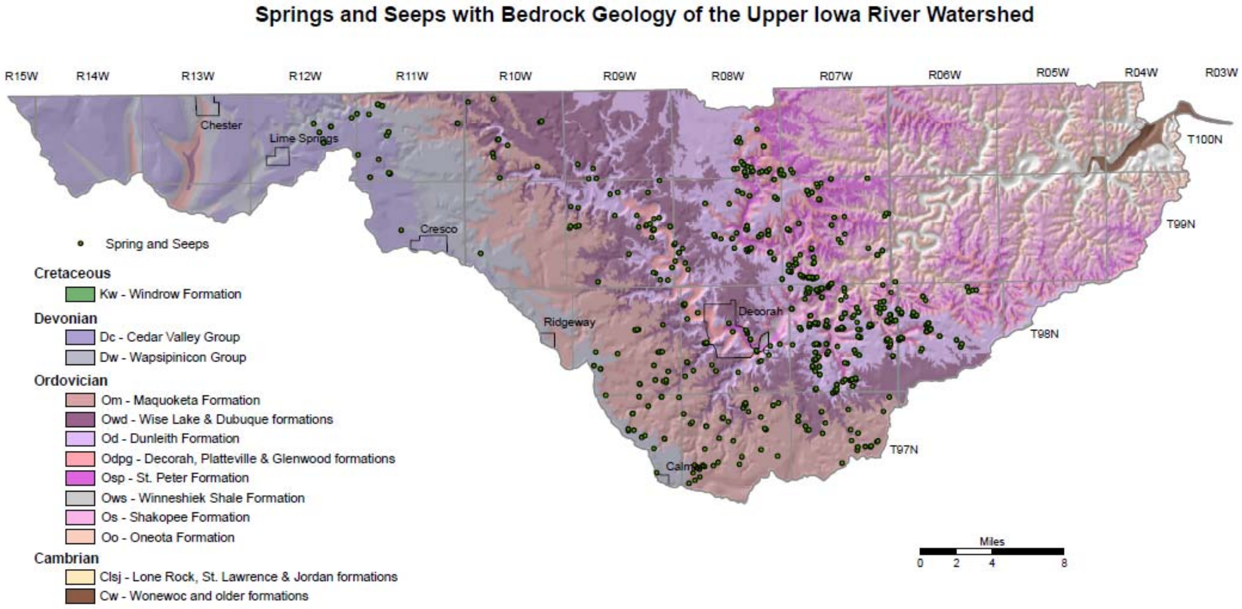

Springs and Seeps with Bedrock Geology of the Upper Iowa River Watershed

Figure 13. Location of springs and seeps in the Upper Iowa River watershed.

This was done in early spring before any large rain events so that any streams that lose flow might actually be dry. This information was plotted on the stream network. Any stream segments that went from having flow to not having flow downstream were then identified as losing stream segments. This information was added to other known losing stream segments, including those that have been identified by the IDNR Fisheries Bureau. Sixty-one losing stream segments were identified this way (Fig. 15).

Geologic Associations

The sinkhole, springs and seeps, and losing stream segment mapping were compared with the bedrock mapping to examine relationships between the occurrences of the various karst features and different bedrock units. Table 1 shows the number of sinkholes, springs/seeps, and losing stream segments that occur in each of the bedrock units. The occurrence per square mile of bedrock unit is also calculated for sinkholes and springs/seeps.

Almost 78 percent of the sinkholes occur in the Wise Lake/Dubuque and Dunleith formations, which comprise the Galena Group. These two formations also have the highest occurrence of sinkholes per square mile with 19.6 and 13, respectively. Another 16 percent of the sinkholes occur in the Cedar Valley Group, with an occurrence of 8 per square mile. The Galena and Cedar Valley strata are carbonate rocks that are known from regional analysis to be highly susceptible to solutional processes and karst development in Iowa and adjacent states, so the results of this relationship are consistent with the regional picture. The greatest occurrences of springs and seeps are in the Decorah/Platteville/Glenwood, Maquoketa, and Dunleith formations. A total of 660 springs and seeps are in these three formations, constituting 79 percent of the springs located in

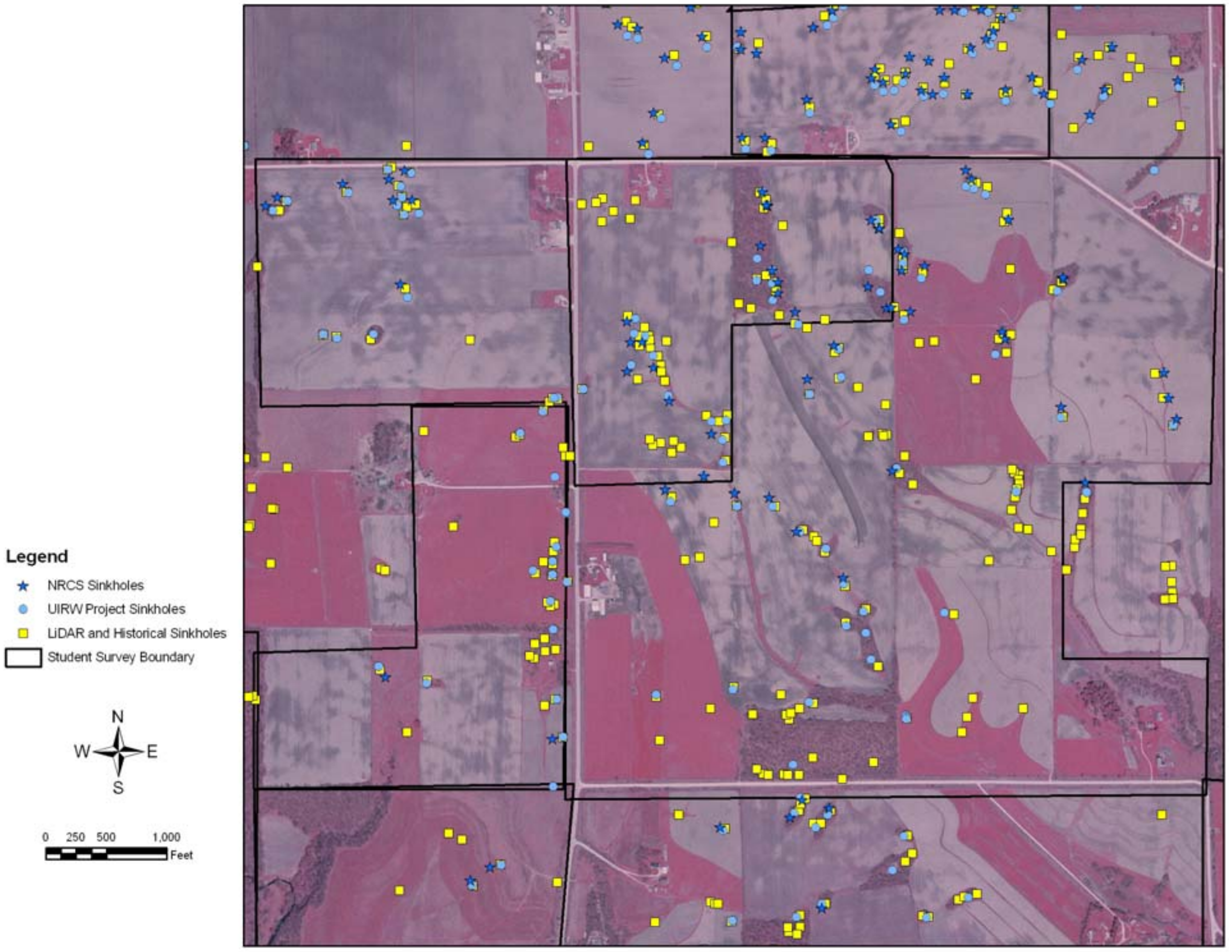


Figure 14. Comparison of NRCS, LiDAR/historical photography, and field-mapped sinkholes.

the watershed. The Decorah/Platteville/Glenwood formations have the highest density with almost 10 per square mile, while the Dunleith, Maquoketa, and St. Peter formations are the next highest, around 1 per square mile. Springs tend to occur most commonly near the contacts between an aquifer and an underlying low permeability confining bed, where groundwater flow is directed laterally and towards stream valleys.

Of the 61 losing streams identified in the watershed, 43, or 70 percent of the total, flow over the Dunleith and Wise Lake/Dubuque formations. These two formations are also associated with the highest number and density of sinkholes. The remainder of the losing streams are mainly distributed amongst the Maquoketa, St. Peter, and Shakopee formations.

APPLICATION TO WATERSHED PLANNING

The maps and GIS coverages developed for this project can be used when planning watershed-based water quality improvements. They identify areas where aquifers used for drinking water are susceptible to contamination, and where practices that promote infiltration are likely to contribute to groundwater quality degradation. They identify sinkholes and losing stream reaches, where groundwater recharge is concentrated, and springs and seeps, where groundwater discharge is concentrated. Subsurface groundwater flow in karst areas can be concentrated in conduit-like zones, and pass directly under surface streams and watershed topographic divides. The mapping places limits on the areas where subsurface groundwater flow in karst conduits travel underground and resurface. Karst features are concentrated in two separate rock sequences, the Cedar Valley formation, and the Wise Lake through Dunleith formations (Fig. 12). As these units are separated by the non-karstic Maquoketa Formation (Fig. 6), recharge water and contaminants (carried by percolation, runoff to sinkholes, or via losing streams) are not transferred between these two karst-prone geologic units. This concept, in combination with the areal distribution of

Table 1. Number and density of karst features by geologic unit.

Bedrock Unit	**Area (sq mi)**	**Sinkholes**		**Springs**		**Losing Streams**
		(Number)	**(Per sq mi)**	**(Number)**	**(Per sq mi)**	
Cedar Valley	**83**	**663**	**7.98**	**16**	**0.19**	**0**
Wapsipinicon	**72**	**23**	**0.32**	**23**	**0.32**	**2**
Maquoketa	**131**	**114**	**0.87**	**137**	**1.05**	**6**
Dubuque / Wise Lake	**101**	**1974**	**19.64**	**36**	**0.36**	**20**
Dunlieth	**100**	**1303**	**13.01**	**127**	**1.27**	**23**
Decorah/ Platteville	**40**	**47**	**1.17**	**396**	**9.84**	**2**
St. Peter	**48**	**37**	**0.78**	**57**	**1.20**	**4**
Shakopee	**100**	**37**	**0.37**	**29**	**0.29**	**3**
Oneota	**67**	**19**	**0.28**	**15**	**0.22**	**1**
Jordan	**30**	**1**	**0.03**	**2**	**0.07**	**0**

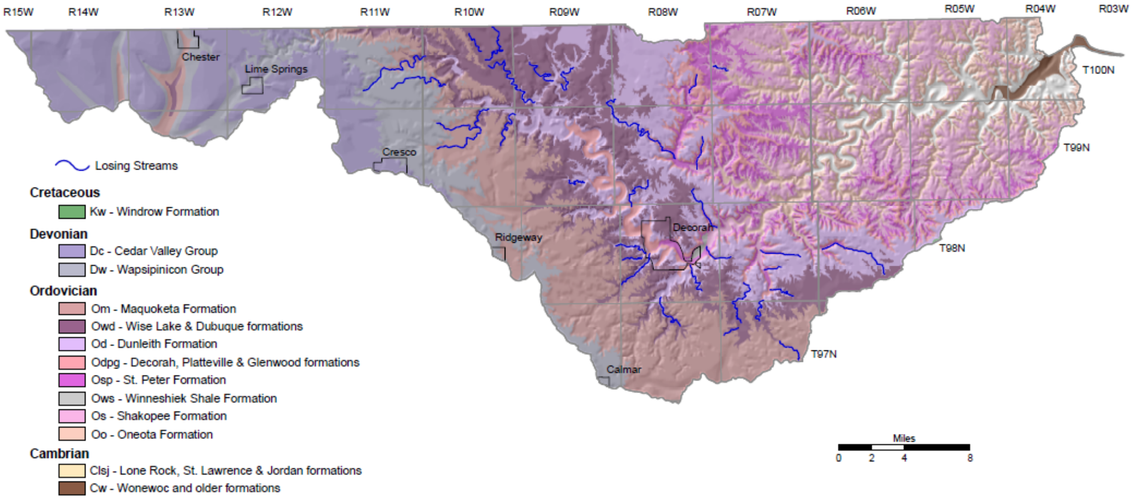


Figure 15. Location of losing stream reaches in the Upper Iowa River watershed.

the units and watershed topography, constrains the distance groundwater will travel in the subsurface and where it will discharge to streams. Geologic evaluations of two watersheds using the mapping tools discussed in this report are presented as examples in Appendices A and B.

ACKOWLEDGEMENTS

Geologic and karst mapping in the watershed involved many IGWS Staff, including Brian Witzke, Andy Asell, Stephanie Surine, Chris Kahle, Deb Quade, Bill Bunker, James Giglierano, Robert Rowden, and Amy Sabin. Mary Pat Heitman, Rick Langel and Lynette Seigley provided editorial review. In addition we acknowledge the contributions of Luther College staff Jean Young and Birgitta Mead, and their students Gabriel Demuth, Steffan Merten, Will Viner, Meghan Miner, Jared Bendel, and Carl Haakenstad.

Significant logging of well samples was done by University of Iowa students, including Ryan Clark, Ben Belgarde, Darice Roberts, Amber Koch, Gregory Stark, Thomas Marshall, Kelly Wilhelm, Kristy Hanley, and Sarah Byram. Drilling for the mapping was provided by Aquadrill Inc. of Swisher, IA.

Northeast Iowa RC&D staff Lora Friest, Adam Kiel, Paul Berland, and Nels Rasmussen were instrumental in planning the project and overseeing a crew of student karst feature mappers including Nick Steffens, Amanda Rolling, Justin Rilling, Kelly Crouthamel, Rachel Amantis, Richard Kittelson, Jeremy Bril, Justin Steffens, Ross Evelsizer, April Hutchinson, Sammy Jo Massman, Hannah Hagen-Atwell, Justin Landsgaard, Jo Zwack, Ruth Rolling, and Amy Kristapovich.

Many landowners allowed access to their property for mapping and drilling, and we thank Rose Kittleson, Tom Jewel, Bob Jewel Jr., Duane Kuehner, Corbin and Lucy Schempp, Cloyd Dolley, Jim Stevens, Lorado Adelmann, Ted & Pine Wilson, the late Gordon MacMasters, Steven and Jane Hildebrand, Darrell Henning, Lloyd Gossman, Robert Snell, John Ryan, Delores Gerber, Mike Miller, Elton Thorson, Jim and Shirley Casterton, Harold Jammes, James Craw, Anne Dykstra, John Schnitzler, Jim Horihan, Don Sacquitne, Joel and Patty Kruse, Laurie Ollendieck, Randy Greenslade, John Smith, Ray Ferrie, Roger and Kari Ferrie, and Kent and Lynne Sootheran.

Logistical support and access to records was provided by Dave Stanley (Bear Creek Archaeology), Joe Artz (Office of the State Archaeologist), Dave Ohlert (Winneshiek County Engineers Office), Mike Root (Bruening Rock Products), the Allamakee County Engineers Office, Rick Edwards (Decorah Parks & Recreation Dept.), and Dave Pahlas and Rick Bohr (Decorah Water Dept.). Finally we acknowledge the administrative support of past and current Iowa Department of Natural Resources - Nonpoint program staff Ubbo Agena, Steve Hopkins, and Allen Bonini.

REFERENCES

Anderson, R.A., McKay, R.M., and Witzke, B.J., 1979, Fieldtrip Guidebook to the Cambrian Stratigraphy of Allamakee County: Geological Society of Iowa Guidebook 32, 11 p.

Andrews, G.W., 1958, Windrow Formation of Upper Mississippi Valley region, a sedimentary and stratigraphic study: Journal of Geology, v. 66, p. 597-624.

Anonymous, 1943, Waukon Iron Ore Deposit - Allamakee County, Iowa: United States Department of the Interior, Bureau of Mines, War Minerals Report 148, 7 p.

Buckner, R.L., and Highland, J.D.. 1974. Soil Survey of Howard County, Iowa: U.S. Department of Agriculture, Soil Conservation Service, 131 p.

Calvin, S., 1906, Geology of Winneshiek County: Iowa Geological Survey, Annual Report, v. 16, p. 37-146.

Davis, R.A. Jr., 1970a, Prairie du Chien Group in the Upper Mississippi Valley: in Ostrom, M.E., Davis, R.A., and Cline, L.M., Field Trip Guidebook for Cambrian-Ordovician Geology of western Wisconsin, University of Wisconsin Geological and Natural History Survey, Information Circular, no. 11, p. 35-42.

Davis, R.A. Jr., 1970b, Stops 9-11 Upper Iowa River Section along Highway 76: in Ostrom, M.E., Davis, R.A., and Cline, L.M., Field Trip Guidebook for Cambrian-Ordovician Geology of western Wisconsin, University of Wisconsin Geological and Natural History Survey, Information Circular, no. 11, p. 73-78.

Emerson, N., Ludvigson, G., Witzke, B., Schneider, C., Gonzalez, L., and Carpenter, S., 2005, Stop 1 – Bruening Rocks Products Quarry on south side of Iowa State Hwy 9: in Ludvigson, G.A. and Bunker, B.B. (editors), Facets of the Ordovician Geology of the Upper Mississippi Valley Region, Iowa Department of Natural Resources, Iowa Geological Survey Guidebook Series no. 24, p. 94-103.

Hallberg, G.R., Hoyer, B.H., Bettis, E.A., III, and Libra, R.D., 1983, Hydrogeology, Water Quality, and Land Management in the Big Spring Basin, Clayton County, Iowa: Iowa Geological Survey, Open-File Report 83-3, 191 p.

Hallberg, G.R., Libra, R.D., Bettis, E.A., III, and Hoyer, B.H., 1984, Hydrogeologic and Water Quality Investigations in the Big Spring Basin, Clayton County, Iowa: Water-Year 1984: Iowa Geological Survey, Open-File Report 84-4, 231 p.

Horick, P.J., and Steinhilber, W.L., 1978, Jordan Aquifer of Iowa: Iowa Geological Survey, Miscellaneous Map Series, no. 6, 3 sheets.

Kiel, A., 2005, Upper Iowa River Watershed GIS Analysis: Upper Iowa River Watershed Project, Northeast Iowa Rural Conservation and Development, 20 p.

Klapper, G., and Barrick, J.E., 1983, Middle Devonian (Eifelian) conodonts from the Spillville Formation of northern Iowa and southern Minnesota: Journal of Paleontology, v. 57, p. 1212-1243.

Levorson, C.O., and Gerk, A.J., 1972a, A preliminary stratigraphic study of the Galena Group in Winneshiek County, Iowa: Iowa Academy of Science Proceedings, v. 79, p. 111-122.

Levorson, C.O., and Gerk, A.J., 1972b, Revision of Galena Stratigraphy: Geological Society of Iowa Field Trip Guidebook no. 25, 11 p.

Levorson, C.O., and Gerk, A.J., 1975, Field recognition of subdivision of the Galena Group within Winneshiek County: Iowa, Minnesota, and Wisconsin Academies of Science, Fall 1975 Gathering, Field Trip Guide, 17 p.

Levorson, C.O., and Gerk, A.J., 1983, Field recognition of stratigraphic position within the Galena Group of northeast Iowa (limestone facies): in Delgado, D.J. (editor), Ordovician Galena Group of the Upper Mississippi Valley – deposition, diagenesis, and paleoecology, Society of Economic Paleontologists and Mineralogists, Great Lakes Section, 13th Annual Field Conference Guidebook, p. C1-C11.

Levorson, C.O., Gerk, A.J., and Broadhead, T.W., 1979, Stratigraphy of the Dubuque Formation (Upper Ordovician) of Iowa: Iowa Academy of Science Proceedings, v. 86, p. 57-65.

Levorson, C.O., Gerk, A.J., Sloan, R.E., and Bisagno, L.A., 1987, General section of the Middle and Late Ordovician Strata of Northeastern Iowa: in Sloan, R.E. (editor), Middle and Late Ordovician Lithostratigraphy and Biostratigraphy of the Upper Mississippi Valley, Minnesota Geological Survey, Report of Investigations, no. 35, p. 25-39.

Libra, R.D., Schilling, K.E., and Wolter, C.F., 2001, Nitrate-N Concentrations and Loads in Iowa Streams and Relations to Land Use: Proceedings, Agriculture and Environment Conference, Iowa State University, Ames, IA, 10 p.

Libra, R.D., Wolter, C.F., and Langel, R.J., 2004, Nitrogen and Phosphorus Budgets for Iowa and Iowa Watersheds: Iowa Geological Survey - Technical Information Series 47, 43 p., 2 appendices.

Liu, H.P., McKay, R.M., Young, J.N., Witzke, B.J., McVey, K.J., and Liu, X., 2006, A new Lagerstätte from the Middle Ordovician St. Peter Formation in northeast Iowa, USA: Geology, v.. 34, no. 11, p. 969-972.

Liu, H., McKay, R., Young, J., and Tassier-Surine, S., 2007, Surficial Geology of the Burr Oak (Iowa) 7.5' Quadrangle: Iowa Department of Natural Resources, Iowa Geological Survey, Open File Map OFM-07-1.

Liu, H., McKay, R.M., Tassier-Surine, S., and Giglierano, J.D., 2008, Bedrock Geology of the Cresco NE (Iowa) 7.5’ Quadrangle: Iowa Department of Natural Resources, Iowa Geological Survey, Open File Map OFM-08-1.

Liu, H., McKay, R.M., Witzke, B.J., Briggs, D.E.G., 2009, The Winneshiek Lagerstätte, Iowa, USA and its Depositional Environment: Geological Journal of China Universities, v. 15, p. 285-289.

Liu, H., McKay, R.M., Witzke, B.J., 2010, The Winneshiek Lagerstätte, stratigraphy and depositional environments of the lower portion of the St. Peter Sandstone: National Science Foundation, award no. 0921245.

Lorenz, P.J., Rodenberg, O.C., Shadle, L.G., Antes, A.C., and Hess, W.D., 1961, Background radioactivity in the Decorah Fault region: Iowa Academy of Science Proceedings, v. 68, p. 397-403.

McKay, R.M., 1993, Selected aspects of Lower Ordovician and Upper Cambrian Geology in Allamakee and northern Clayton counties: Geological Society of Iowa Guidebook 57, 61 p.

McKay, R., Liu, H., Young, J., and Tassier-Surine, S., 2006, Surficial Geology of the Freeport (Iowa) 7.5' Quadrangle: Iowa Department of Natural Resources, Iowa Geological Survey, Open File Map OFM-06-2.

McKay, R.M., Liu, H., Young, J., and Tassier-Surine, S., 2007, Surficial Geology of the Highlandville (Iowa) 7.5' Quadrangle: Iowa Department of Natural Resources, Iowa Geological Survey, Open File Map OFM-07-2.

McKay, R., Liu, H., Tassier-Surine, S., and Giglierano, J.D., 2008, Bedrock Geology of the Ridgeway (Iowa) 7.5’ Quadrangle: Iowa Department of Natural Resources, Iowa Geological Survey, Open File Map OFM-08-3.

McKay, R., Liu, H., Young, J. and Giglierano, J.D., 2008, Bedrock Geology of the Dorchester (Iowa) 7.5’ Quadrangle: Iowa Department of Natural Resources, Iowa Geological Survey, Open File Map OFM-08-5.

McKay, R.M., Liu, H.P., Witzke, B.J., and French, B.M., 2010, Geologic setting of the Winneshiek Lagerstatte; Decorah, Iowa: Geological Society of America Abstracts with Programs, v. 42, no. 2, p. 89.

McKay, R.M., Liu, H.P. Witzke, B.J, French, B.M., and Briggs, D.E.G., 2011 Preservation of the Middle Ordovician Winneshiek Shale in a probable impact crater: Geological Society of America Abstracts with Programs, accepted for publication.

Mossler, J.H., 1995, Bedrock Geology of Fillmore County, Geologic Atlas, Fillmore County, Minnesota: Minnesota Geological Survey, County Atlas Series C-8, Part A.

Prior, J.C., 1976, A Regional Guide to Iowa Landforms: Iowa Geological Survey Educational Series #3, 72 p.

Rowden, R.D, Liu, H., and Libra, R.D., 2001, Results from the Big Spring basin water quality monitoring and demonstration projects, Iowa, USA: Hydrogeology Journal, v. 9, no. 5, p. 487-497.

Runkel, A.C., 1996, Bedrock Geology of Houston County, Minnesota: Minnesota: Minnesota Geological Survey, Open File Report 96-4.

Schilling, K.E., and Libra, R.D., 2000, The Relationship of Nitrate Concentrations in Streams to Row Crop Landuse in Iowa: Journal of Environmental Quality v. 29, no. 6, p.1846-1851.

Tassier-Surine, S., Ludvigson, G., Witzke, B., Young, J., Anderson, R., McKay, R., Liu, P., Bunker, B., and Pals, D., 2005, Surficial Geology of the Decorah (Iowa) 7.5' Quadrangle: Iowa Department of Natural Resources, Iowa Geological Survey, Open File Map OFM-05-1.

Tassier-Surine, S., McKay, R., Liu, P., and Young, J., 2006, Surficial Geology of the Bluffton (Iowa) 7.5' Quadrangle: Iowa Department of Natural Resources, Iowa Geological Survey, Open File Map OFM-06-5.

White, W. B., 1969. Conceptual models for carbonate aquifers: Ground Water, 7 (3), p. 15-21.

Witzke, B.J. and McKay, R.M., 1987, Cambrian and Ordovician stratigraphy in the Lansing area, northeastern Iowa: Geological Society of America Centennial Field Guide – North Central Section, v. 3, p. 81-87.

Witzke, B.J., Bunker, B. J., and Rogers, F.S., 1988, Eifelian through Lower Frasnian stratigraphy and deposition in the Iowa area, central midcontinent, U.S.A.: in McMillan, N.J., Embry, A.F., and Glass, D.J. (editors), Devonian of the World, Canadian Society of Petroleum Geologists, Memoir 14, v. I: Regional Synthesis, p. 221-250.

Witzke, B.J., Ludvigson, G. A., McKay, R. M., Anderson, R. R., Bunker, B. J., Giglierano, J. D., Pope, J. P., Goettemoeller, A. E., and Slaughter, M. K., 1998, Bedrock geology of northeast Iowa, Digital geologic map of Iowa, Phase 2: Northeast Iowa: Iowa Department of Natural Resources, Geological Survey Bureau, Open File Map OFM-98-7.

Witzke, B.J. and Ludvigson, G.A., 1996, Mid-Cretaceous fluvial deposits of the eastern margin, western interior basin: Nishnabotna Member, Dakota Formation. A field guide to the Cretaceous of Guthrie

County: Iowa Department of Natural Resources, Geological Survey Bureau Guidebook Series no. 17, 75 p.

Witzke, B.J. and Ludvigson, G.A., 2005, Stop 6 – The Pole Line Road Cut Section: in Ludvigson, G.A. and Bunker, B.B. (editors), Facets of the Ordovician Geology of the Upper Mississippi Valley Region, Iowa Department of Natural Resources, Iowa Geological Survey Guidebook Series no. 24, p. 122-129.

Witzke, B.J. and Ludvigson, G.A., and Young, J.N., 2005, Stop 4 – The Locust Road Cut Section along the south wall of Canoe Creek Valley: in Ludvigson, G.A. and Bunker, B.B. (editors), Facets of the Ordovician Geology of the Upper Mississippi Valley Region, Iowa Department of Natural Resources, Iowa Geological Survey Guidebook Series no. 24, p. 110-113.

Witzke, B. J., and Anderson, R.R., 2006, Bedrock geology of the quadrangles containing the Yellow River Basin, Allamakee, Clayton, Fayette, and Winneshiek counties, Iowa: Iowa Department of Natural Resources, Geological Survey Bureau, Open File Map OFM-06-1.

Young, J.N., McKay, R.M., and Liu, H.P., 2005, Unusual sections of the Readstown Member, St. Peter Formation, at Decorah, northeast Iowa: Geological Society of America Abstracts with Programs, v. 37, no. 5, p. 78.

APPENDIX A

Geologic Summary of Waterloo Creek Watershed
Allamakee County, Iowa

Bedrock Units in the Watershed

Waterloo Creek heads in Houston County, Minnesota, and flows into the Upper Iowa River in Allamakee County. Figure A-1 is a stratigraphic column depicting the sequence of bedrock units

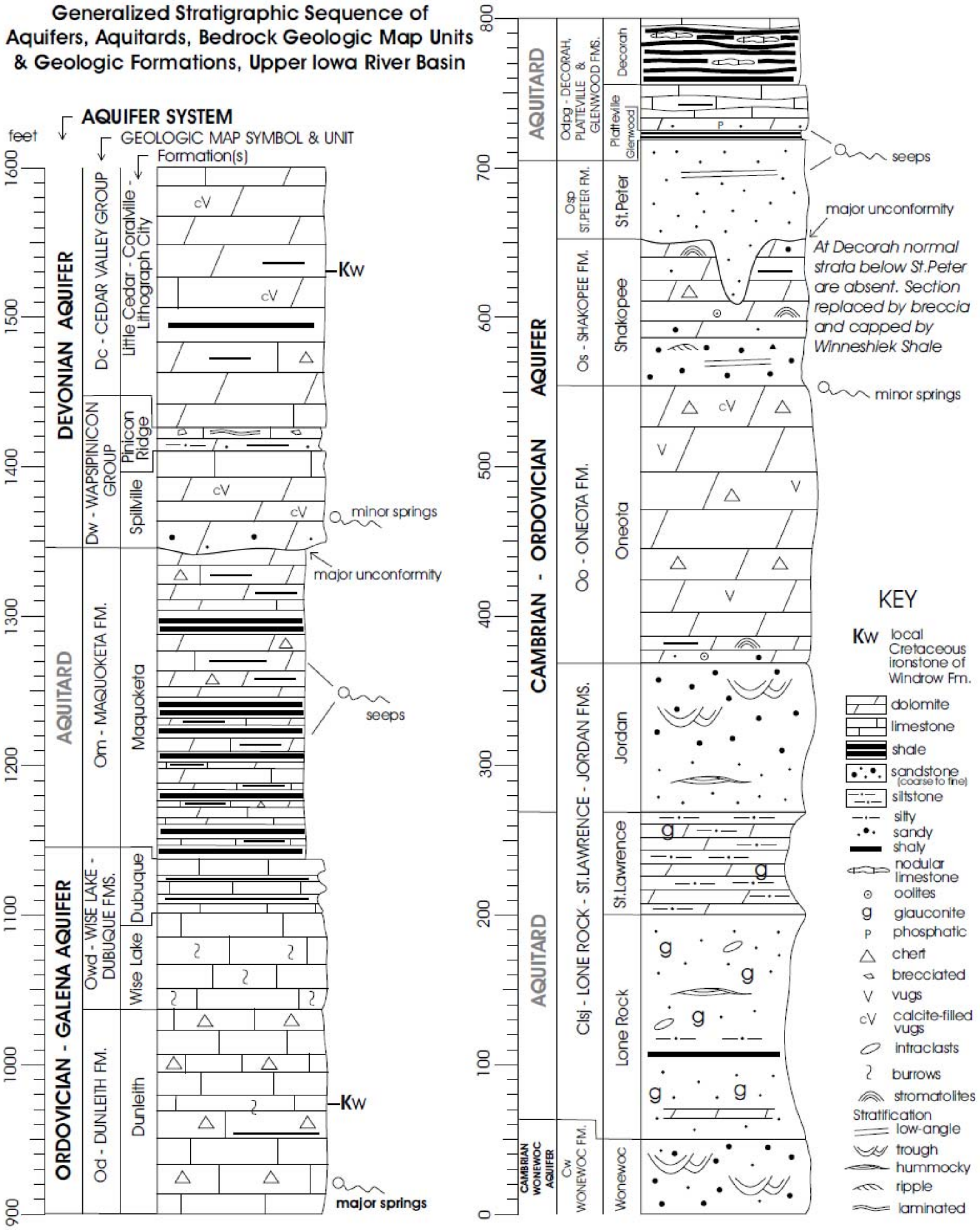


Figure A-1. Stratigraphic column for the Upper Iowa River watershed.

in the Upper Iowa watershed. Figure A-2 is a generalized map of the bedrock units underlying the Iowa portion of the Waterloo Creek watershed. Most of the watershed is underlain by rocks of the Ordovician-age Prairie du Chien Group (Oneota and Shakopee Formations on Figure 1). This unit is largely composed of dolomite (a rock similar to limestone), with minor amounts of sandstone, and approaches 300 feet in thickness where it hasn't been eroded away in the geologic past. The Prairie du Chien rocks are overlain by the St. Peter Sandstone, a medium-to-fine grained, extremely pure quartz sandstone. Typically the St. Peter is about 50 feet thick where not eroded, but in places it fills in old valleys cut into the underlying rocks and can be considerably thicker locally. Along the far west end of the watershed, a thin cover of rocks of the Platteville formation overly the St. Peter.

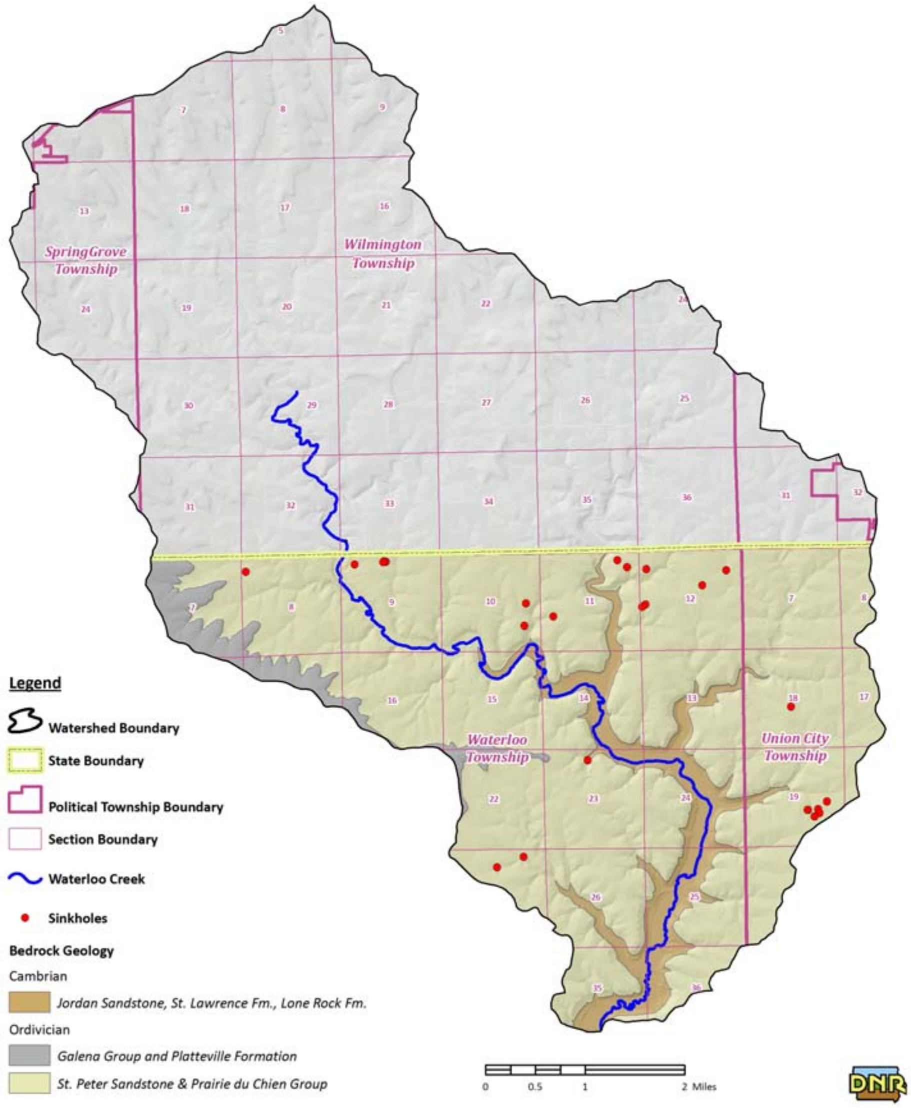


Figure A-2. Bedrock geologic map of Waterloo Creek watershed.

Much of the valley of Waterloo Creek and the lower reaches of its main tributaries have cut deeply into and through the Prairie du Chien rocks and into the underlying Cambrian-age Jordan Sandstone. The Jordan Formation is a porous, fine to coarse grained, sandstone composed of quartz and feldspar that has an average thickness of 100 feet.

The bedrock units in the watershed are overlain by a very thin cover of soils developed in loess (a wind-deposited silt) or weathered remnants of glacial tills. This cover is less than 10 feet thick over most of the watershed.

Figure A-3 shows the area geology as a roughly NE-SW cross-section of the Upper Iowa watershed, drawn to the west of Waterloo Creek watershed. The conditions on the north end of the cross-section (right-hand side) are similar to those in Waterloo Creek.

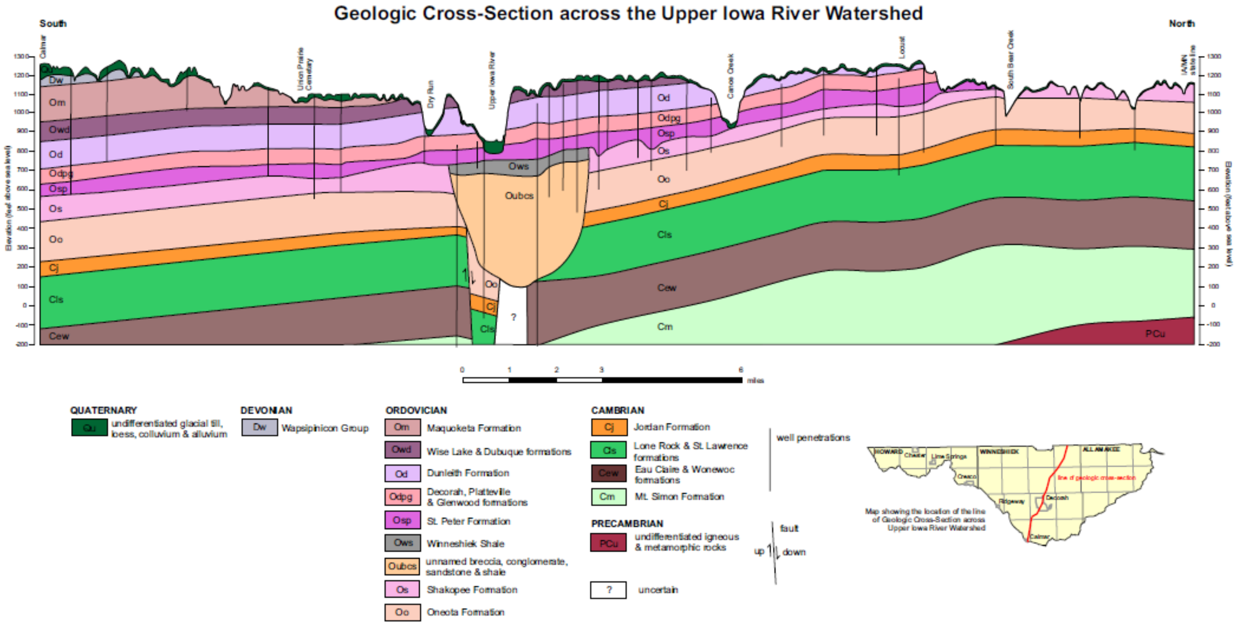


Figure A-3. Cross-section of the Upper Iowa River watershed.

Groundwater Conditions

The Jordan, Prairie du Chien, and St. Peter strata all function as aquifers. They are good sources of groundwater to wells, and supply many domestic wells in the area. Rainfall readily infiltrates and moves through these units. In particular, the Prairie du Chien and Jordan are the main water-producing units in what is commonly called the Jordan Aquifer, which is a major groundwater source across much of the state. Fractures in the rocks, particularly in the Prairie du Chien, add significantly to their ability to transmit groundwater.

Within the watershed, much of the groundwater discharges back to the surface and into Waterloo Creek, supplying the creek's baseflow. Typically northeast Iowa streams, fed by productive aquifers, exhibit a high percentage of baseflow. Over the course of most years, much of the water in the creek originates as rain or snowmelt percolating into the ground, and traveling through the rock strata to the creek and its tributaries.

The rock sequence from the land surface to the base of the Jordan aquifer contains little in the way of shales, which would act as a vertical barrier to groundwater. This fact, combined with the relatively high relief in the watershed, allows groundwater to circulate rather deeply.

Karst Conditions

Karst features such as sinkholes, losing streams, enlarged fractures, and springs may occur in limestones, dolomites or other rocks that dissolve through geologic time. When well developed, these rocks may form subsurface drainage systems that cross watershed boundaries. As shown on Figure A-4, mapping (from county soil surveys, aerial photography, and LiDAR) indicate a few sinkholes are present where the Prairie du Chien dolomite is the uppermost rock. Sinkholes allow for direct surface water run-off to enter the aquifer, without soil filtration. Compared to some other limestone-type aquifers, the Prairie du Chien has a relatively low density of sinkholes, and isn’t known to exhibit well developed subsurface drainage. For perspective, Figure A-4 shows the bedrock units and the distribution of sinkholes for the Upper Iowa watershed. Sinkholes and other karst features are very common where rocks of the Cedar Valley Group or the Dubuque through Dunleith Formations are the uppermost bedrock, and much less so in areas underlain by the Prairie du Chien, as is the case in Waterloo Creek.

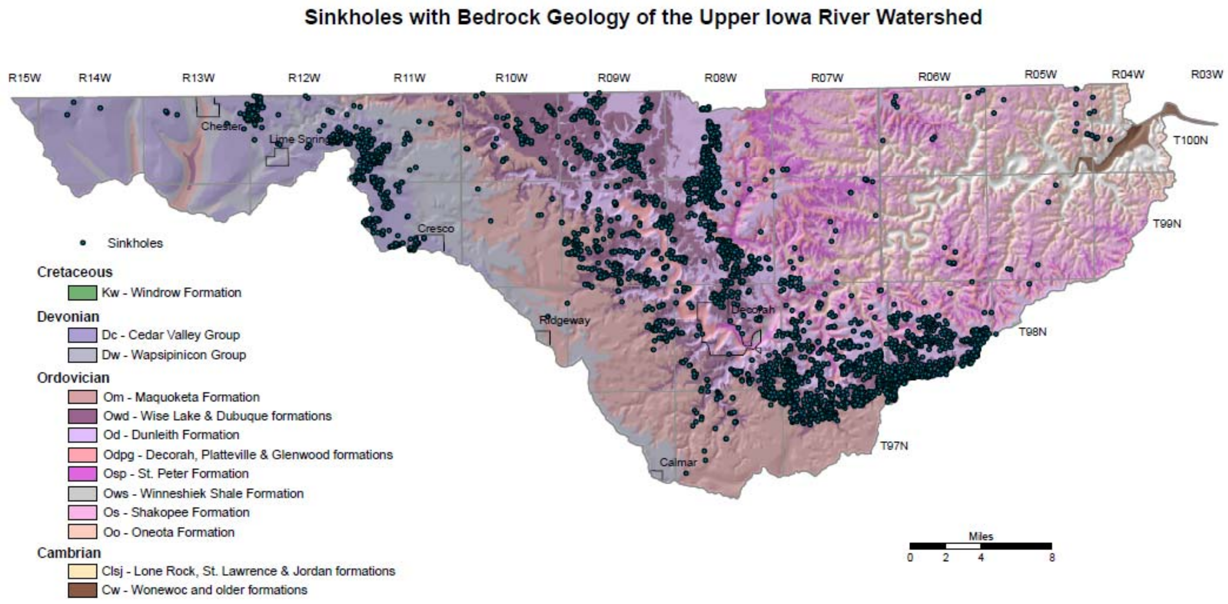


Figure A-4. Bedrock geologic map with sinkholes.

Implications for Water Quality Improvements

The Waterloo Creek watershed is underlain by a thin cover of surficial materials and soils overlying porous, fractured aquifers. No significant barriers to the downward movement of recharge water exist above the base of the Jordan aquifer, which may be several hundred feet below the surface below upland areas. This makes the groundwater in the watershed, including that used for drinking water, very susceptible to contamination from activities on the land surface. Sinkholes are not common, so the main contaminants of concern are those such as nitrate that pass readily though the soil. However, the thin soil cover means that other contaminants such as bacteria, phosphorus, or soluble herbicides are not as effectively filtered out as they are in most parts of the state.

In some karst-affected watersheds, the groundwater system can transmit water below streams and watershed divides. The water discharges back to the surface in a different surface watershed, and therefore management practices may be altering the quality of water outside of the watershed in which they are implemented. This doesn't appear to be the case to any significant degree in Waterloo Creek.

The watershed's geologic "plumbing system" moves groundwater and contaminants readily to Waterloo Creek, and groundwater supplies the majority of the stream flow over the course of the year. Under lower flow conditions virtually all the water is groundwater, while under high-flow conditions (after an intense rain) most of the water is true surface run-off, carrying sediment, and often elevated levels of bacteria, ammonia, and phosphorus. Water quality improvement efforts should keep these hydrologic factors in mind when they are designed and implemented.

APPENDIX B

Geologic Summary of Silver Creek Watershed
Howard and Winneshiek counties, Iowa

Silver Creek watershed heads northwest of Cresco in Howard County, and flows into the Upper Iowa River in eastern Winneshiek County (Fig.B-1). The city of Cresco straddles the watershed divide. Geologic mapping of bedrock units in northeast Iowa shows Silver Creek watershed is underlain by Cedar Valley Limestone (Dc on figures) in the Cresco area, which overlies the Spillville Formation (Dw) of the Wapsipinicon Group (Fig. B-1). These rocks in turn overlie the Maquoketa Fm (Om) and finally rocks of the Galena Group (Owd and Od). These relationships and unit thicknesses are also shown in cross – sectional view in Figure B-2. Past erosion has removed younger, overlying rocks from the lower elevations of the watershed. This has resulted in thinning or complete removal of the younger units as the Upper Iowa River valley is approached.

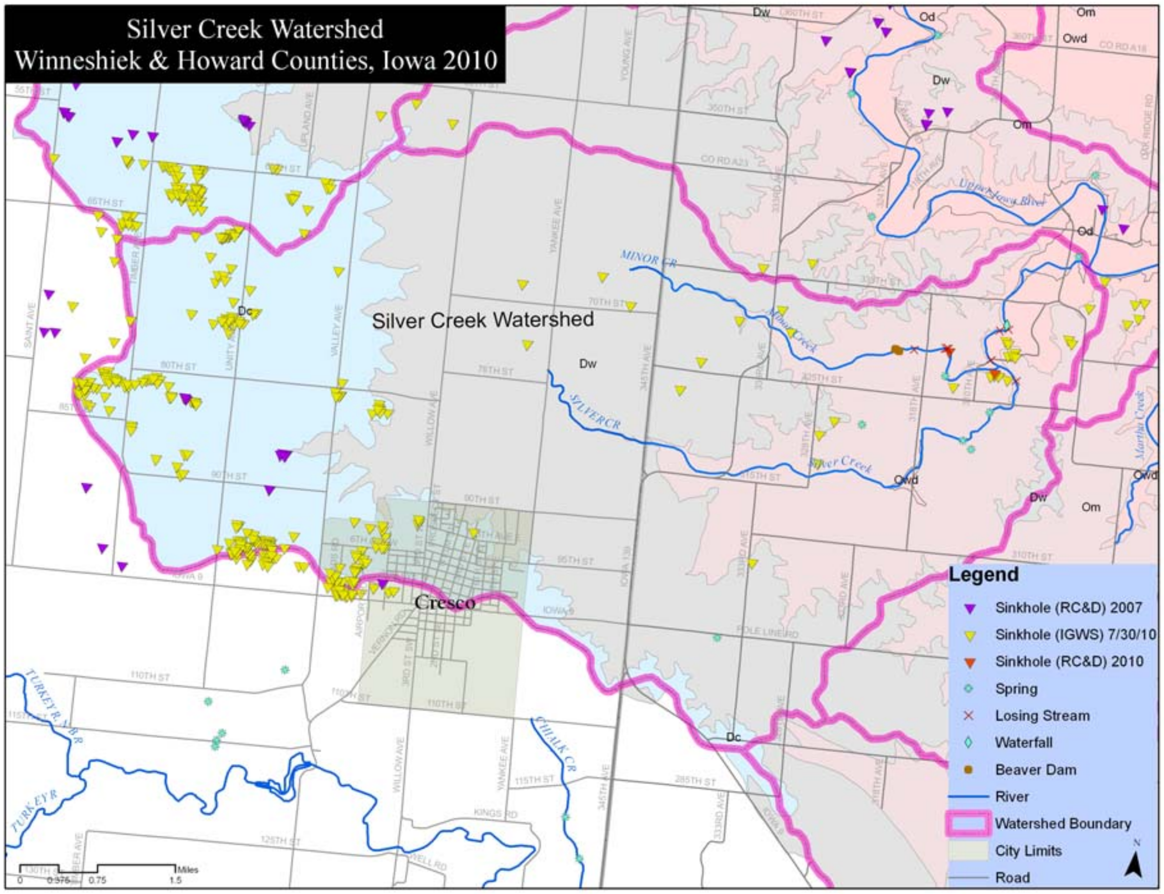


Figure B-1. Bedrock geology and karst features, Silver Creek watershed.

Hydrologically, the Cedar Valley and Galena rocks are aquifers – they will readily transmit and yield groundwater to wells, and deliver significant amounts of water to streams. These units are also subject to karst development. The Spillville is an aquifer but with lesser potential for karst. The Maquoketa Formation contains significant low-permeability shale, and acts as an aquitard (does not readily transmit or yield significant water) in the overall sense. However, parts of the Maquoketa contain interbedded carbonate layers which will transmit water. This is

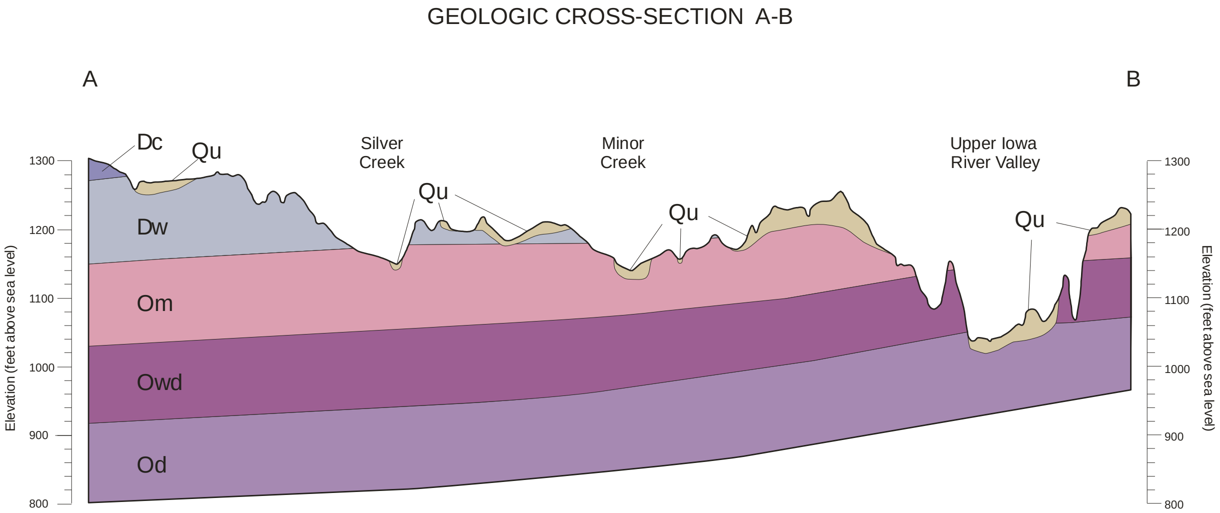


Figure B-2. Geologic cross-section of the Silver Creek watershed.

particularly true in the lowermost part of the formation which is a silty, shaly carbonate. Where most of the Maquoketa has been removed by erosion, and the unit is thin, karst may develop within this carbonate portion and into the underlying Galena rocks.

Field mapping and interpretation of LiDAR and aerial photography indicates sinkholes occur commonly in the Cedar Valley around Cresco, and considerably less so within the Spillville in the surrounding area. Sinkhole inputs in the Cresco area are likely transmitted mainly within the Cedar Valley rocks. Groundwater likely flows from the Cedar Valley rocks into the underlying Spillville rock. However, the lack of sinkholes formed in the Spillville suggests there is unlikely to be extensive "concentrated" flow in pipes, conduits, or cavernous-type zones.

These factors indicate water entering Cedar Valley Group sinkholes in the upper part of the watershed is likely not transmitted in a "regional" karst system. In addition, the Maquoketa Formation separates the upper units from the highly karst-prone Galena. Water entering the ground via sinkholes in the Cedar Valley at Cresco won't be surfacing from a Galena spring.

As Silver Creek is impaired for bacteria, of prime importance are "open" sinkholes that allow free entry of runoff into the groundwater. These recharge points are the most likely to input large volumes of water with a high concentration of bacteria. The area of very shallow Spillville formation and shallow soil-filled depressions allow significant infiltration to groundwater, but do provide filtration that will decrease bacteria concentrations. However, the shallow rock – shallow aquifer nature of most of the watershed does indicate a high potential for leaching of nitrogen, soluble herbicides, and some level of bacterial constituents.