Minnesota Geological Survey
Harvey Thorleifson, Director

HYDRAULIC CONDUCTIVITY AND HYDROSTRATIGRAPHY OF THE PLATTEVILLE FORMATION, TWIN CITIES METROPOLITAN AREA, MINNESOTA

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EXECUTIVE SUMMARY

This report synthesizes a large body of data that provide a better understanding of the hydrogeologic characteristics of the Ordovician Platteville Formation in the Twin Cities Metropolitan Area (TCMA). The carbonate-dominated Platteville Formation plays an important role in the TCMA hydrogeologic system by limiting vertical infiltration of relatively recent water to the more commonly utilized aquifers beneath it. Furthermore, it has been impacted by numerous contaminant plumes, which threaten the water quality in domestic wells and the large number (dozens) of springs along the Mississippi River and its tributaries.

A large number of hydraulic conductivity values for the Platteville Formation collected at various scales and interpreted within a hydrostratigraphic context, especially fracture attributes, provides improved understanding and predictability of its hydraulic properties. Like some other hydrogeologic units in the Paleozoic bedrock of this area, matrix permeability is very low, but secondary pore networks create moderate to very high horizontal hydraulic conductivity sufficient to yield economic quantities of water to wells, and supply springs. The greatly variable and commonly very high hydraulic conductivity, fast flow speeds, and secondary pore observations demonstrate that the Platteville is consistent with the definition of a secondary pore-dominated aquifer. Data from the same collection of sites also supports the traditional classification of the Platteville Formation as an aquitard (confining unit), when considered from a vertical dimension, with discrete stratigraphic intervals serving as key relatively high integrity aquitards. Vertical leakage will be variable, and under certain conditions such as near eroded edges of the formation can be substantial.

Hydraulic conductivity data are synthesized and interpreted across a range of scales, with the recognition of variable user needs. For example, generalized bulk hydraulic conductivity for parts of the Platteville Formation may be useful for modeling water budgets through relatively large areas. In contrast, more site-specific needs such as development of remediation strategies and prediction of flow paths may be facilitated by considering the large range in hydraulic conductivity, measured at a number of scales, and by recognizing the location of fast-flow secondary pore networks as well as key aquitards.

Introduction

The (Late) Ordovician Platteville Formation in the central part of the TCMA (Figs. 1, 2) is a shallowly buried (< 30 m, 100 ft) carbonate-dominated formation near the top of the Paleozoic bedrock sequence. A better understanding of the Platteville hydrogeologic attributes is important to groundwater managers for a number of reasons. As the middle part of the Decorah-Platteville-Glenwood Aquitard (Kanivetsky, 1978), it may play a role in limiting vertical infiltration of relatively recent water to the more commonly utilized aquifers beneath it. Even though classified as an aquitard, it is also used locally as a source of water to domestic wells, and is the source of a large number (dozens) of springs along the Mississippi River and its tributaries. Furthermore, the Platteville has been impacted by numerous contaminant plumes, perhaps more than any other bedrock unit in the TCMA.

For this project, we compiled a relatively large number of hydraulic conductivity values for the Platteville Formation, including values calculated from discrete interval packer tests, injection flowmeter logging, slug tests, specific capacity and larger-scale aquifer tests. Interpretation of these values within a hydrostratigraphic framework that we have developed as part of an ongoing, broader investigation of the Platteville (Anderson and others, 2011) provides improved understanding and predictability of its hydraulic properties.

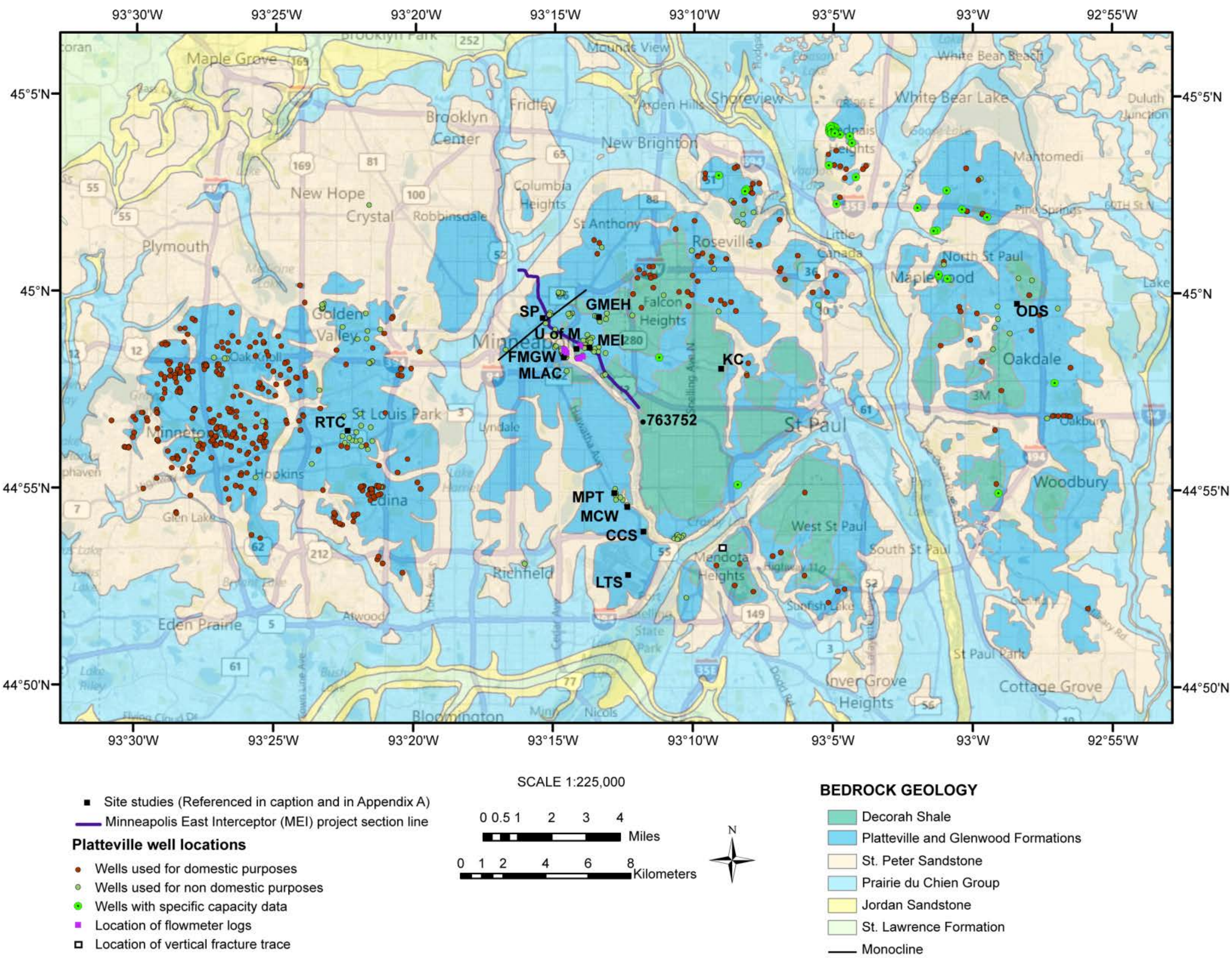

Figure 1. Bedrock geologic map of the TCMA, showing principal sources of data discussed in this report, including sites from which we acquired hydraulic conductivity values for the Platteville Formation. RTC- Reilly Tar and Chemical, ODS- Oakdale Disposal, KC- Koppers Coke, GMEH- General Mills/East Hennepin Avenue, MEI- Minneapolis East Interceptor, MPT- Minnehaha Park Tunnel, MCW- Minnehaha Creek Watershed, CCS- Camp Coldwater Spring, LTS- Lindbergh Terminal Station, FMGW- Former Minneapolis Gas Works, MLAC- Minnesota Library Access Center, SP- Superior Plating, U of M- University of Minnesota.

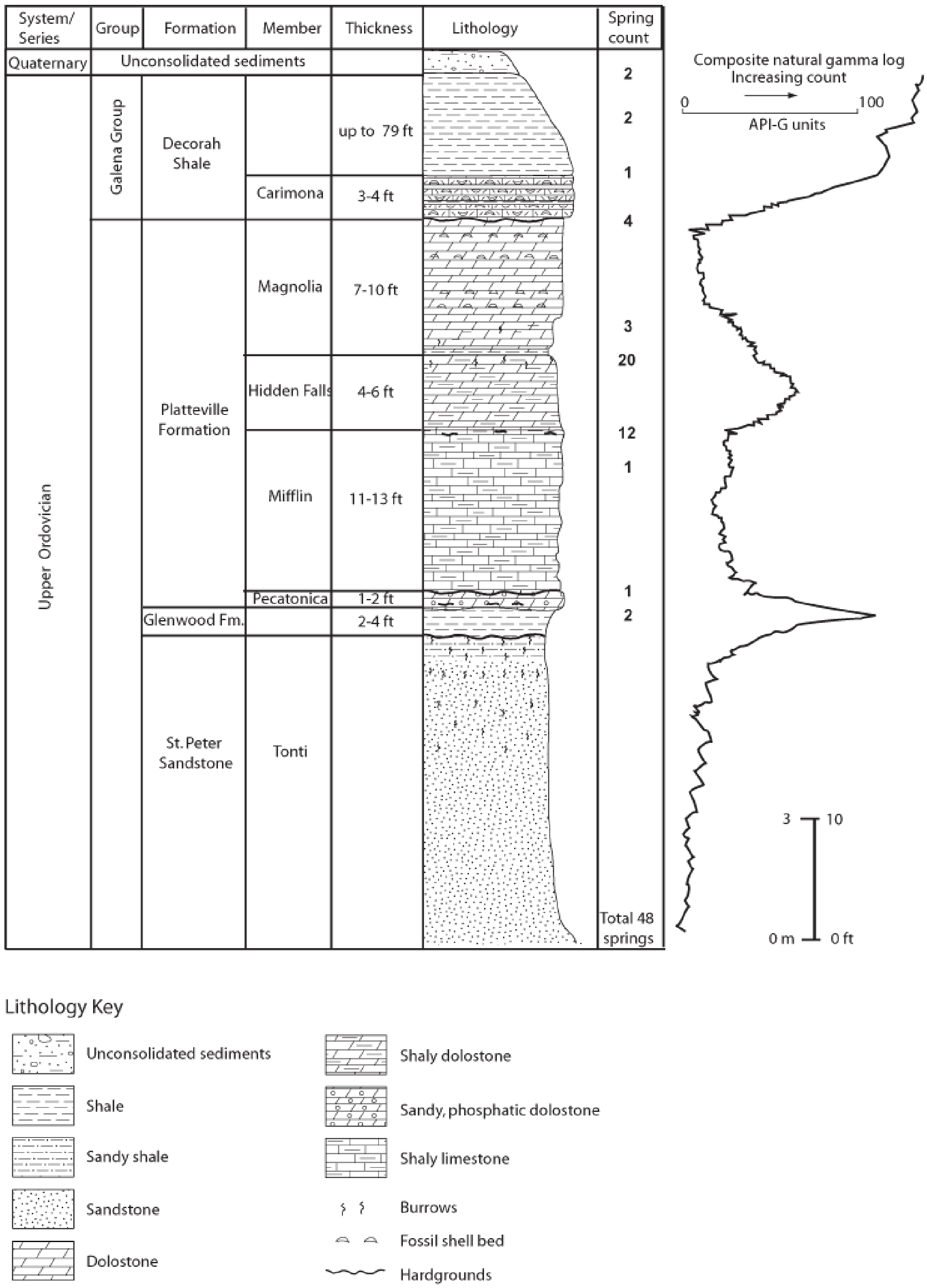

Figure 2. Generalized stratigraphic column depicting the lithology, thickness, and nomenclature for the Upper Ordovician formations in the TCMA. The Decorah Shale thickness is variable across the study area and locally absent. The spring count lists the number of springs emanating from a specific stratigraphic interval. The natural gamma log (units API-G) shown on the right is collected from a water well (County Well Index Unique Number 763752).

Geologic and stratigraphic context

The Platteville Formation in the TCMA was deposited in the Twin Cities basin, a broad regional depression developed in the northernmost regionally preserved extent of Paleozoic bedrock in the Upper Mississippi Valley region (Mossler, 1972). The Platteville ranges from about 26 to 29 feet in thickness, and is subdivided into four members; from bottom to top they are the Pecatonica, Mifflin, Hidden Falls and Magnolia (Mossler, 1985, 2008). These are distinguished mainly by lithology and bedding style and correspond to major depositional facies (Fig. 2).

The Pecatonica Member lies directly on top of the Glenwood Shale, and is a burrowed, reworked, fossiliferous dolostone only 1-2 ft thick. It commonly contains quartz sand, phosphate clasts and bored hardgrounds. The Mifflin Member is a wavy-bedded, nodular, fossiliferous, heavily bioturbated limestone. Ranging from 11-13 ft thick, it is the thickest member within the Platteville. Very thin, siliciclastic-rich carbonate beds are intercalated with the nodular, bioturbated limestone giving it an alternating dark gray and light gray coloration pattern. The Mifflin is overlain by a dolomitic, shaly carbonate known as the Hidden Falls Member. It is massive and nonfossiliferous except for subordinate thin, fossiliferous lenses. The Hidden Falls Member ranges from 4-6 ft thick and is recessive in outcrop. The Magnolia Member overlies the Hidden Falls. It is 7-10 ft thick and characterized by fossiliferous shell beds a few inches thick and spaced about every one foot in an otherwise nonfossiliferous dolomitic mudstone. The lowermost Magnolia, immediately above the contact with the Hidden Falls, is composed of several interbeds of shaly carbonate, and fossiliferous carbonate. Interbedded shale and fossiliferous carbonate of the Carimona Member (Decorah Shale) lies atop the Magnolia Member (Platteville Formation).

Hydrostratigraphic context

Relatively large (visible without magnification) secondary pores, commonly with evidence of enlargement through dissolution, are characteristic of the Platteville Formation throughout its extent. There are two general kinds of secondary pores in the Platteville Formation: vertical to subvertical fractures, and bedding parallel (horizontal) macropores. Vertical fractures include nonsystematic fractures typical of near-surface stress release conditions, as well as systematic fractures, commonly referred to as joints, that are part of a large-scale orthogonal system oriented NE-SW and NW-SE. Apertures generally range from “hairline” fractures with apertures measured in angstroms, to as wide as several inches. Joints with even larger apertures, presumably solution enlarged, have been inferred on the basis of hydraulic or geophysical data (e.g. Kelton Barr Consulting, 2000). The term bedding parallel macropore is used to refer to horizontal secondary pore space larger than inergranular space that preferentially aligns congruent to bedding. Outcrop and large diameter borehole observations indicate that bedding-parallel macropores are part of an anastomosing network of such elongate apertures developed along discrete stratigraphic intervals (Runkel and others, 2003, 2006b, 2014).

Based on outcrop observations, the members of the Platteville each have a distinct style of vertical fracture density and spacing (Fig. 3; and Anderson and others, 2011). The Magnolia Member has a high density of vertical to sub-vertical fractures with a wide range in trace lengths. The Hidden Falls Member has a very high density of vertical to subvertical, straight to curvilinear (conchoidal) fractures, most of which are confined within the member. These appear to be mostly nonsystematic fractures. The Mifflin Member has relatively widely spaced, vertical joints with long traces that typically extend the entire thickness of the member. The Pecatonica has a narrower spacing of vertical, straight fractures with traces that span the thin bed. The members of the Platteville act as mechanical units and vertical fractures typically terminate at the contacts between the members, which act as mechanical interfaces

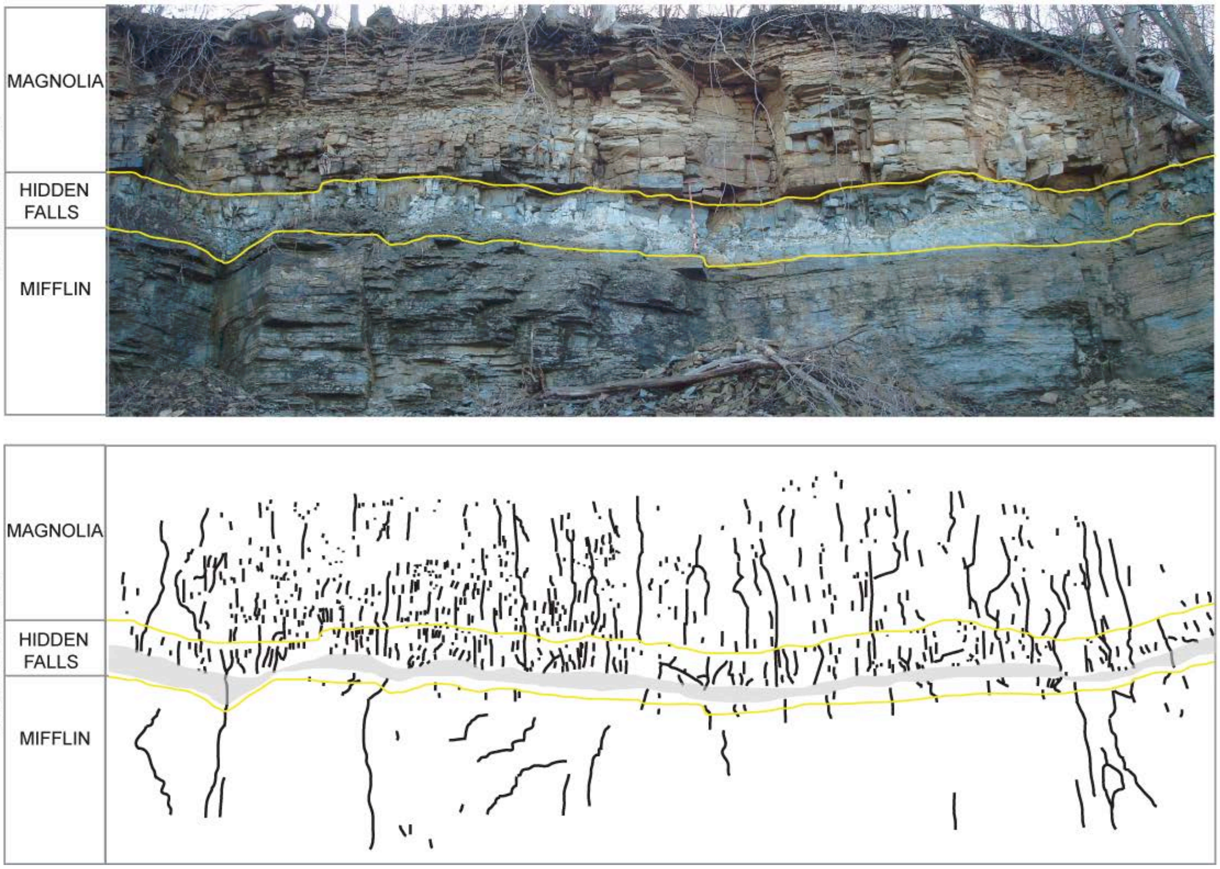

Figure 3. Vertical fracture map of the Mendota locality (see Fig. 1 for location). Vertical fractures are shown as black lines in the lower part of the figure. The yellow lines represent the upper and lower contacts of the Hidden Falls and correspond to the vertical-fracture termination horizons. The gray shaded area represents the rubble zone of very small closely spaced fractures within the Hidden Falls Member. Each member of the Platteville Formation has a distinct style of vertical fracture spacing and density and act as mechanical units with vertical fractures terminating at member contacts, especially pronounced near the top of the Hidden Falls. Exposure is about 25 feet high.

(Anderson and others, 2011). Vertical fractures preferentially terminate at the Hidden Falls and Magnolia contact, as well as at the top of the Mifflin Member. Individual vertical fractures extending through the entire preserved extent of the formation, including across all of the Hidden Falls, are rare and are most commonly present in outcrops where the Platteville is deeply incised and appears more heavily weathered.

Bedding-parallel macropores are concentrated along discrete stratigraphic intervals. They pinch and swell along beds, with a maximum aperture of less than two or three inches. Results from correlating spring positions with stratigraphic intervals (Fig. 2) are consistent with borehole flowmeter logging results, and boring/coring logs at a number of TCMA sites (e.g. Barr Engineering, 1983b; CSC Joint Venture, 1985; Peer, 1999; Anderson and others, 2011), demonstrating preferential development of bedding-parallel macropores at the Hidden Falls-Magnolia contact. Bedding-parallel macropores have also been recognized in the subsurface higher within the Magnolia Member at some sites (e.g. Peer, 1999). Springs discharge at a number of other stratigraphic positions as well (Fig. 2).

Hydraulic conductivity

Overview

A large range in the bulk hydraulic conductivity of the Platteville Formation has been reported for several decades (e.g. Leisch and Associates, 1973; Barr Engineering, 1983a; Hoffman and Alexander, 1998; Peer, 1999). The data we compiled as part of this project (Appendix A, Table 1) are consistent with these earlier characterizations. For example, hydraulic conductivity values reported from aquifer and slug tests of the Platteville Formation across the TCMA range from about 10^{-2} to about 8,500 ft/day. Specific capacity tests of monitor and domestic wells in the Minnesota Department of Health County Well Index (CWI) database converted to hydraulic conductivity, using the method of Bradbury and

Unit	Interval tested	Most or all Platteville preserved	Magnolia eroded (<5ft) and/or on monocline
Decorah Shale	Carimona	Kh^{3} 33.4 (1)	
	Carimona-Magnolia	Kh^{1} 15.3; 2.3 to 28.3+(2)	
PLATTEVILLE FORMATION – UPPER PART	Magnolia	Kh^{1} <16.1; $<10^{-4}$ to 59.7 (9)	
PLATTEVILLE FORMATION – UPPER PART	Magnolia-Hidden Falls	Kh^{1} 46.2; 0.44 to 167.9 (26) Kh^{2} 128.7; 43.9 to 302.4 (8) Kh^{3} 118.4; 49.7 to 187(2) Kv^{3} 2.1; 10^{-3} to 4.3 (6)	Kh^{1} 19.9; <0.5 to 28.3+ (6)
PLATTEVILLE FORMATION – UPPER PART	Magnolia-Hidden Falls contact interval	Kh^{5} 19539; 3754 to 54727 (6)	
PLATTEVILLE FORMATION – UPPER PART	Platteville “BULK” (Magnolia-Hidden Fall-Mifflin/Pecatonica)	Kh^{3} 984.1; 22.5 to 8576 (17)	Kh^{2} 0.29; 0.06 to 0.52 (2) Kh^{3} 211.7; 50 to 392 (3)
PLATTEVILLE FORMATION – UPPER PART	Platteville "Bulk" (members not discriminated)	Kh^{4} 294.3; 0.05 to 7494.1 (63)	
PLATTEVILLE FORMATION – LOWER PART	Hidden Falls	Kh^{1} 32.6; <1.2 to 68.3 (3)	
PLATTEVILLE FORMATION – LOWER PART	Hidden Falls-Mifflin/Pecatonica	Kh^{1} <0.8; $<10^{-4}$ to 5.4 (20) Kv^{6} $<10^{-5}$ to 10^{-3}	Kh^{1} <7.9; $<10^{-2}$ to 28.3+ (9) Kh^{2} 96.5; 10^{-4} to 370 (5) Kh^{3} 112.1; 3.3 to 207 (5) Kv^{6} 10^{-3} to 10^{-1}
PLATTEVILLE FORMATION – LOWER PART	Mifflin/Pecatonica	Kh^{1} <0.6; $<10^{-4}$ to 5.1 (29) Kh^{2} 0.3(1) Kh^{3} 0.2 (1)	Kh^{1} <4.8; $<10^{-4}$ to 28.3+(17) Kh^{2} 0.9; 0.05 to 2.8 (4) Kh^{3} 101.2; 2.7 to 353 (10)
Glenwood Shale		Kv^{7} $<10^{-4}$	

Test method — Range — Number of tests

Kh^{3} 984.1; 22.5 to 8576 (17)

Average conductivity (ft/day)

Kh=horizontal hydraulic conductivity (ft/day)
Kv= vertical hydraulic conductivity (ft/day)

Test methods

1-Packer pressure tests
2-Slug tests
3-Aquifer tests
4-Specific capacity tests
5-Injection flow logging
6-Excavation leakage rate; see comments in Appendix A
7-Various methods; see comments in Appendix A

Table 1. Summary of hydraulic conductivity values for the Platteville Formation (and adjacent units) compiled in this report (Appendix A). Values are divided into categories corresponding to stratigraphic position. The values are also divided into a group of values collected from tests in areas where the Platteville is preserved almost in entirety, and a group of values from tests where less than 5 ft of the Magnolia Member is preserved across much of the site, and/or the site lies on the monoclinal fold (Fig. 1). Hydraulic conductivity values were averaged for wells and individual packed intervals with more than one test in Appendix A. The Magnolia-Hidden Falls contact interval is a very thin (<2 ft) transition between the two members, and the hydraulic conductivity values are calculated using an aquifer thickness corresponding to an estimated aperture of 0.125 ft. See Appendix A explanation for more detailed information.

Rothschild (1985), reveal a generally similar large range, from 10^{-2} to 7,500 ft/day (Fig. 1 for well locations). The inclusion of values calculated from smaller scale, discrete interval (mostly 5 ft or less) packer and flowmeter tests extends the range of hydraulic conductivity to at least eight orders of magnitude, from $<10^{-4}$ to 10^{4} ft/day (Fig. 4).

A relatively large database with such great variability in hydraulic conductivity is by itself, without hydrostratigraphic context, difficult to apply to groundwater management efforts such as parameterization of regional scale models, or for predicting contaminant transport paths and speeds. Therefore, in addition to providing a compilation of hydraulic conductivity measurements for the Platteville Formation, this report includes an evaluation of the controls on hydraulic properties. Our evaluation begins with a characterization of hydraulic conductivity based on tests of relatively small sample size, which contrasts matrix conductivity to secondary pore conductivity at a relatively detailed scale. We follow with an analysis of hydraulic conductivity values compared to stratigraphic position of the tested interval, which in turn corresponds to particular characteristic secondary pore development for that stratigraphic position. We also consider other geologic factors that may impact hydraulic conductivity, such as variability in depth of incision and weathering of the Platteville. Collectively this provides improved predictability of hydraulic conductivity within the Platteville Formation (Fig. 5).

Matrix hydraulic conductivity

The Platteville Formation is similar to most carbonate bedrock in southeastern Minnesota inasmuch as it is a relatively dense, well-cemented unit with minimal matrix porosity and permeability. The lowest measured conductivities are derived from laboratory permeability tests of small diameter (~1 inch) plugs of the formation, at 10^{-7} ft/day or less (Runkel and others, 2003). These same plugs range from about 2 to 3% porosity. Larger-scale tests of discrete intervals, mostly packer tests of 5 ft (or less)

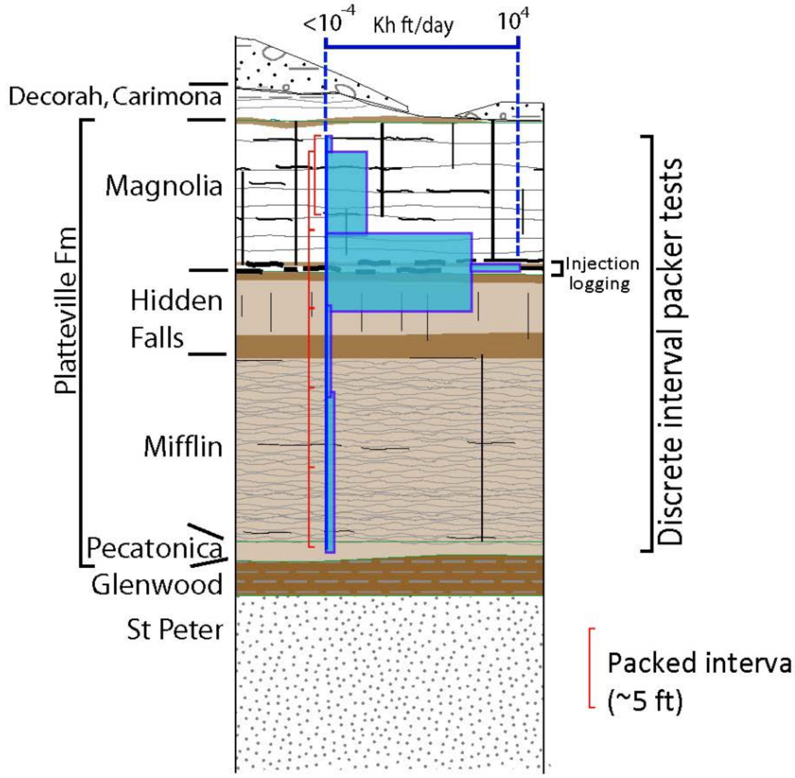

Figure 4. Schematic illustration of typical horizontal hydraulic conductivity test results from discrete interval tests of the Platteville Formation. At such a relatively small scale, hydraulic conductivity can vary over eight orders of magnitude. Blocks of matrix with relatively minor development of interconnected secondary pores have hydraulic conductivity commonly measured at less than 10^{-4} ft/day. Such matrix blocks are characteristic of the lower two thirds of the Platteville (lower Hidden Falls, Mifflin and Pecatonica Members). Other packed 5 ft intervals, that intersect hydraulically more significant secondary pore networks, commonly have hydraulic conductivity measured at tens to over 100 ft/day. Injection flowmeter logs demonstrate that discrete intervals of a few inches or less have hydraulic conductivity commonly measured in tens of thousands of ft/day. See Figures 6 and 7 for additional illustrations of packer test results, and Anderson and others (2011) for additional information on injection flow logging tests of the Platteville. See Figure 5 for key and legend.

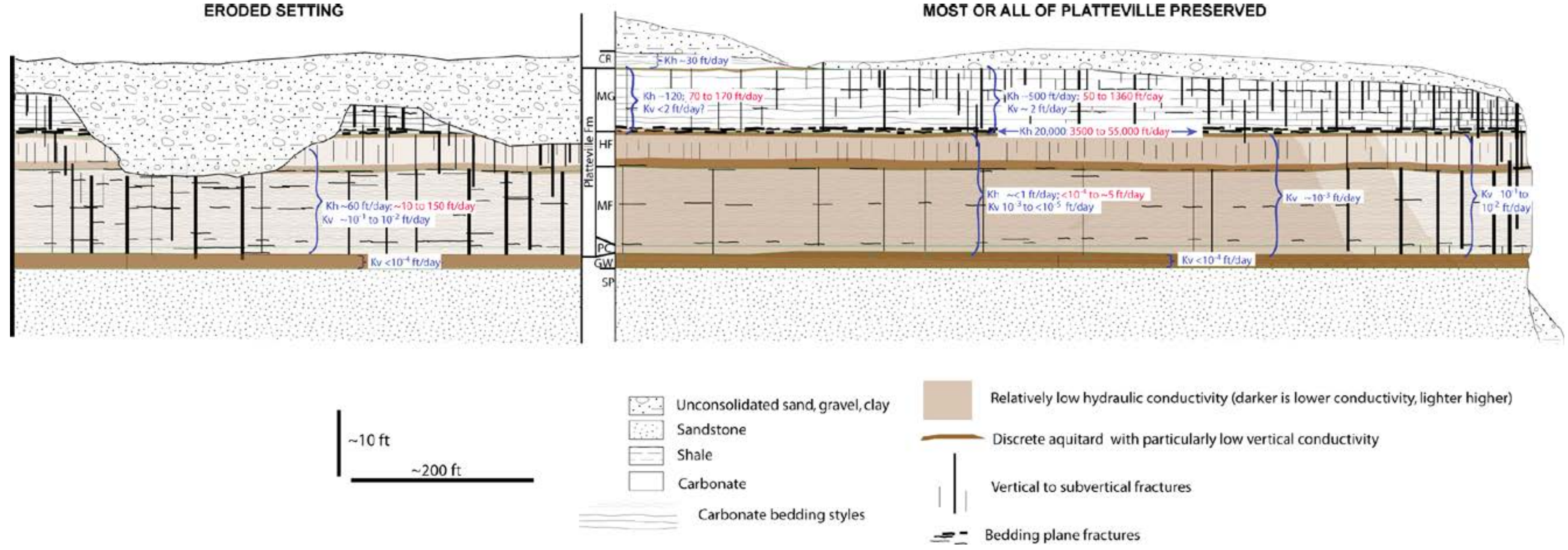

Figure 5. Generalized conceptual model of macropore attributes, and hydraulic conductivity of the Platteville Formation (and adjacent units). In areas where most or all of the Platteville is preserved the formation can be divided into an upper one-third (Magnolia and uppermost Hidden Falls Members) with relatively enhanced development of secondary pores and high hydraulic conductivity, and a lower two-thirds with sparser secondary pore development and a markedly lower conductivity. In eroded settings, where less than 5 ft of Magnolia is preserved over much or all of an area, the lower part of the formation commonly has a higher hydraulic conductivity than it does where the Platteville is more fully preserved. In a vertical direction the lower part of the formation may serve as an aquitard, but with leakiest conditions near bluff edges and in eroded settings. Termination of vertical fractures preferentially at the top and bottom of the Hidden Falls Member result in those stratigraphic positions potentially serving as key, low hydraulic conductivity aquitards (Anderson and others, 2011). The values for horizontal hydraulic conductivity (Kh) shown here emphasize largest scale of testing available. For example, the values for the upper part of the Platteville and for the lower Platteville in an eroded setting are based on aquifer tests that are summarized in Table 2. Aquifer tests of the lower part of the Platteville in settings where most of the Platteville is preserved are scarce, and the values shown here are therefore based mostly on slug and packer tests, in addition to a single aquifer test that yielded a Kh of 0.2 ft/day. This is a schematic, generalized depiction. All parts of the formation are known to at least locally have moderate to very high Kh under certain conditions, and Kh can range over at least eight orders of magnitude. While this generalized depiction of hydraulic conductivity may be suitable for larger scales of modeling, the database compilation (Appendix A; summarized in Table 1) and more detailed information provided in this report are more appropriate for many other needs such as contaminant transport research. Blue values are the average hydraulic conductivity and red values are the range in hydraulic conductivity. CR=Carimona Member (Decorah Shale); MG=Magnolia Member; HF=Hidden Falls Member; MF=Mifflin Member; PC=Pecatonica Member; GW=Glenwood Shale; SP=St Peter Sandstone.

lengths of individual boreholes (Appendix A, Table 1), commonly yield values of less than 10^{-4} ft/day. These are presumably also a measure of the hydraulic conductivity of carbonate matrix blocks in which secondary pores are absent or relatively poorly connected and with narrow apertures (Fig. 4). Because the discrete interval tests compiled for this project have limitations such that only a maximum hydraulic conductivity can be ascertained in relatively low permeability matrix blocks, some tested intervals in the database likely have a conductivity as low as that measured via laboratory tests of small diameter plugs.

Secondary pore hydraulic conductivity

Hydraulic conductivity tests of the Platteville Formation yield values orders of magnitude higher than those of the matrix blocks. Packer tests and injection flowmeter logs indicate that discrete intervals of a few feet or less have conductivities ranging from a few ft/day to tens of thousands of ft/day (Fig. 4). Because matrix hydraulic conductivity is negligible, this range most likely reflects variability in secondary pore development, with the lower end of the range corresponding to intervals with only narrow, relatively poorly connected secondary pores, and the higher end to intervals that include relatively large aperture secondary pores that are part of well-connected networks. The highest values, of tens of thousands of ft/day are derived from injection flowmeter logging tests, and represent the hydraulic conductivity of individual bed-parallel macropores. Flow speeds as fast as 1.25 mi/day via such bedding-parallel macropores in the Platteville Formation have been demonstrated through dye traces near Camp Coldwater Spring (CCS) (Alexander and others, 2001; Anderson and others, 2011).

Hydraulic conductivity within a stratigraphic and geologic context

Previous site-specific investigations have led to a number of important observations about the hydraulic properties of the Platteville Formation, including recognition that the members of the formation differ from one another in hydraulic conductivity in a generally predictable manner. One such observation is that the upper approximately one-third of the formation, which includes the Magnolia and uppermost few inches of the Hidden Falls Members, typically has a significantly greater hydraulic conductivity than the lower two-thirds, which includes the remainder of the Hidden Falls, Mifflin, and Pecatonica Members (e.g. CSC Joint Venture, 1985; Peer, 1999). Additionally, a number of investigations have recognized a discrete, high-conductivity bedding-parallel interval that approximates the Magnolia-Hidden Falls contact (Barr Engineering, 1983b; CSC Joint Venture, 1985; Peer, 1999). The compilation of hydraulic tests conducted for this project, placed in stratigraphic context, supports these observations, leading to the two-fold hydrostratigraphic division of the Platteville Formation described below. Other factors controlling hydraulic conductivity in the Platteville Formation, such as presence of especially large aperture and linearly extensive vertical "master joints" with high conductivity (Kelton Barr Consulting, 2000), and of a monoclinal fold in the TCMA, are also included in our evaluation (Braun Intertec, 2011; Anderson and others, 2011).

Lower Platteville Formation

Horizontal hydraulic conductivity

The lower two-thirds of the Platteville Formation, which includes most of the Hidden Falls, and all of the Mifflin and Pecatonica Members, typically has a markedly lower hydraulic conductivity than the upper third at sites where both are present (Table 1; Figs. 6, 7). In most areas where the Magnolia Member has not been significantly eroded (more than 5 ft preserved) hydraulic conductivity values from packer tests of the lower part of the Platteville commonly range from about 10^{-4} to about 5 ft/day (e.g. CNA, 1997; CSC Joint Venture, 1985) and average less than 1 ft/day (Table 1). Discrete intervals (typically about 5 ft) bracketed by packers are commonly unable to produce water at a sustained rate

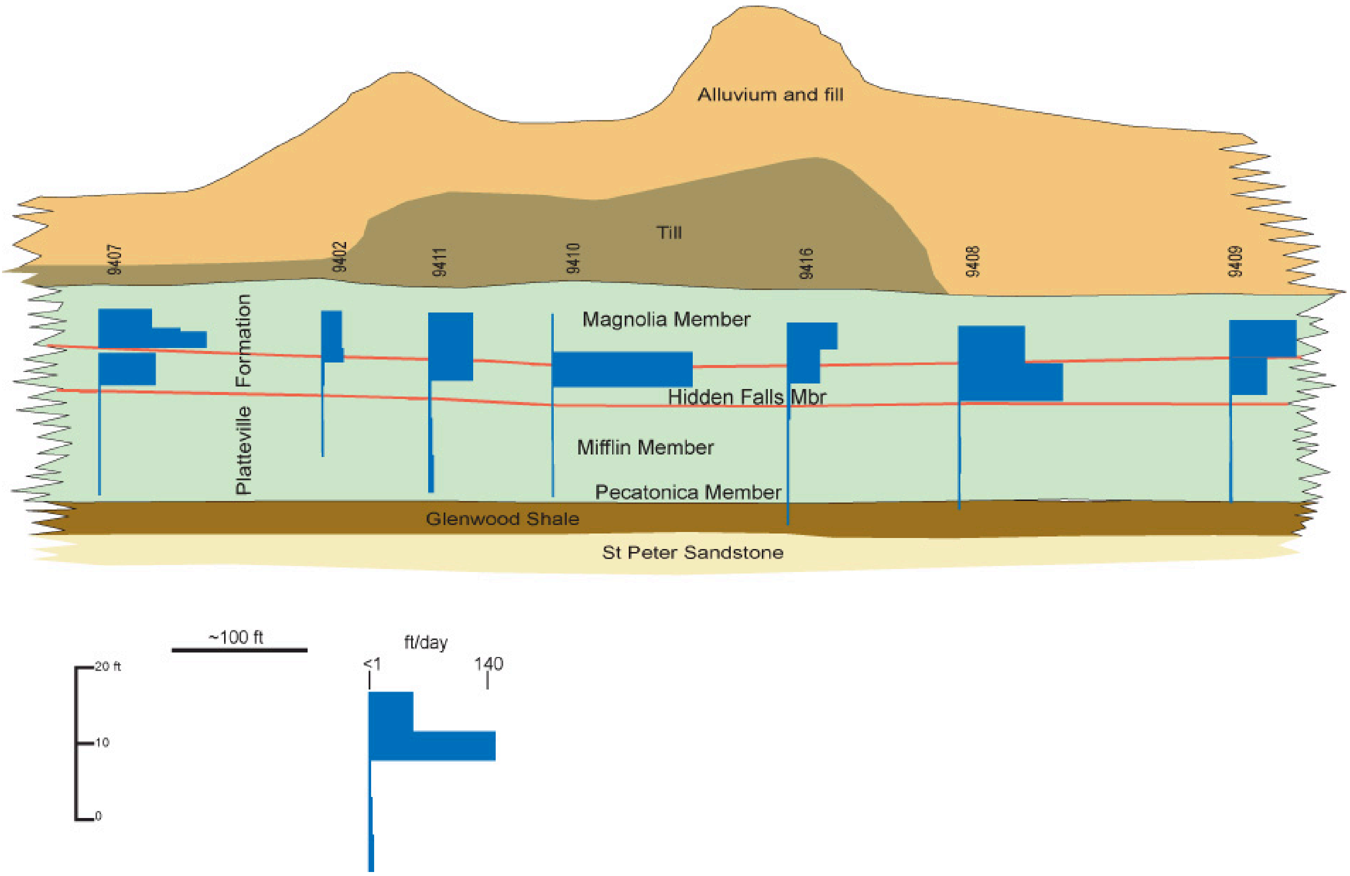

Figure 6. Schematic summary of packer test results at Minnesota Library Access Center (MLAC) (see Fig. 1 for location). Note that moderate to high hydraulic conductivity is characteristic of packed intervals that include the Magnolia or uppermost part of the Hidden Falls Member. Packed intervals that include only the lower Hidden Falls, Mifflin and Pecatonica Members have markedly lower hydraulic conductivity. Test results are from CNA (1997), and details of the individual tests are in Appendix A of this report. 94XX numbers above refer to borehole numbers in CNA (1997). The cross section is highly stylized, as the boreholes are not located along a straight line of section.

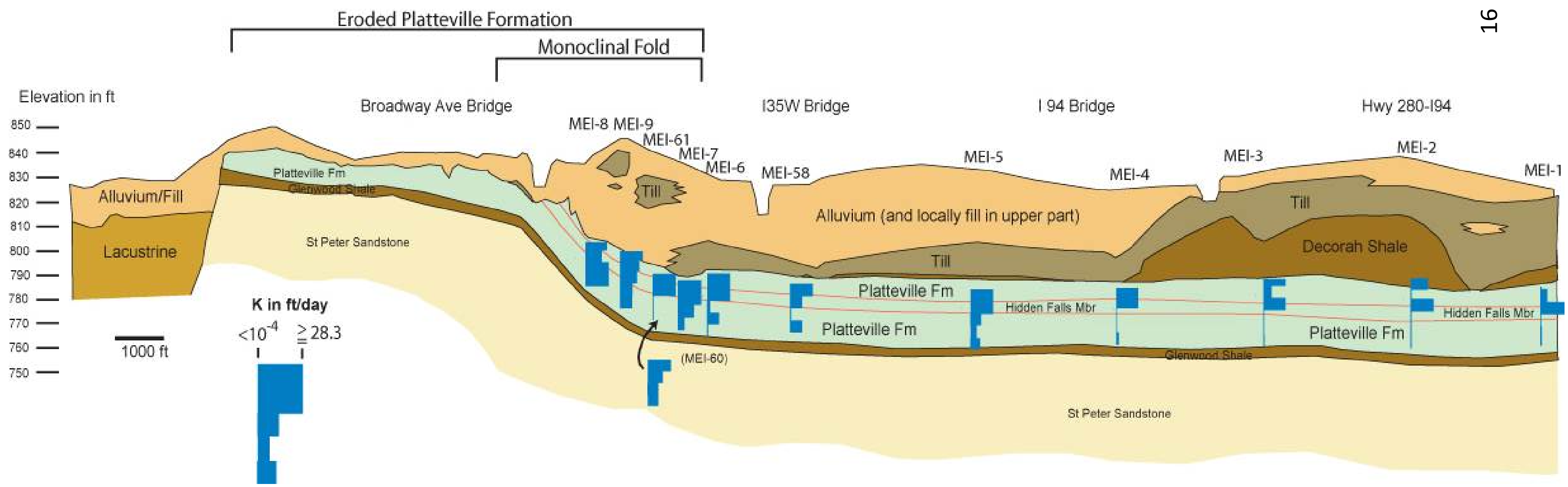

Figure 7. Illustrated summary of packer test results for the Minneapolis East Interceptor (MEI) project. Note that across most of the project extent moderate to high hydraulic conductivity is characteristic of packed intervals that include the Magnolia or uppermost part of the Hidden Falls Member. Packed intervals that include only the lower Hidden Falls, Mifflin and Pecatonica Members have markedly lower hydraulic conductivity. An exception is where the Platteville is relatively deeply eroded along a monoclinal fold. See text for discussion. Test results and cross section are modified from CSC Joint Venture (1985), and details of the individual tests are in Appendix A of this report. MEI-XX numbers above the columns refer to borehole numbers in CSC Joint Venture (1985). See Fig. 1 for location of section line.

above a minimum pumping threshold of about one gallon per minute (gpm). Of the 52 packer tests of the lower Platteville from three sites compiled for this project (Appendix A), only four tests from three boreholes yielded a hydraulic conductivity that exceeded 5 ft/day. Two of these tested intervals are within one foot of the top of the Hidden Falls Member, and therefore the relatively high values may reflect connection to the high hydraulic conductivity bedding-parallel macropore network (described more fully below) at that stratigraphic position. Larger scale tests of hydraulic conductivity of the lower Platteville in conditions where most of the formation is preserved are scarce, but results are consistent with the results of packer tests. A single slug test and an aquifer test yielded relatively low hydraulic conductivity values of about 10^{-1} ft/day (Table 1).

Relatively low hydraulic conductivity for the lower Platteville at sites where most or all of the formation is preserved reflects the relatively minimal development of secondary pores compared to the upper (Anderson and others, 2011). Vertical fractures typically are widely spaced (several feet or more), and hydraulically significant bedding-parallel macropores are apparently uncommon. The limited number of modest hydraulic conductivity values of a few ft/day for the lower Platteville in these conditions likely represents the uncommon borehole intersection of rare, moderately conductive bedding planes and/or proximity to the widely spaced vertical joints in the lower part of the formation (e.g. Barr Engineering, 1987).

The lower part of the Platteville Formation can have a markedly higher hydraulic conductivity in areas where the formation is relatively deeply eroded, with most (< 5 ft remaining) or all of the Magnolia Member removed (Figs. 5, 7). Packer and slug tests commonly yield hydraulic conductivity values of tens to hundreds of ft/day in such areas (Table 1). Aquifer tests of the lower part of the Platteville at two sites (Reilly Tar and Chemical and Superior Plating, Fig. 1) also yielded values of about 10 to hundreds of ft/day in similar conditions (Table 2; ERT, 1987; Barr Engineering, 1989). A

UPPER PLATTEVILLE	Average site Kh in ft/day (number of tests in parentheses)
Minnehaha Tunnel Project	1358 (10)
Reilly Tar and Chemical	293 (2)
Minnesota Library Access Center	58 (5)
Oakdale Disposal Site	968 (3)
Superior Plating/East Hennepin Ave	50 (1)
General Mills	187 (1)
All sites average	486 (6)
LOWER PLATTEVILLE (eroded setting)	
Superior Plating/East Hennepin Ave	37 (3)
Reilly Tar and Chemical	144 (10)
Oakdale Disposal Site	12 (2)
All sites average	64 (3)

Table 2. Summary of hydraulic conductivity (Kh) for the Platteville Formation based on largest scale of testing (aquifer tests). Numbers in parentheses are the number of tests at each site used to calculate an average for that site. The lower Platteville sites are all in settings where across much of the site the upper Platteville was mostly removed by erosion.

higher hydraulic conductivity at such sites is most likely attributed to enhanced secondary pore development, such as greater density, apertures, and linear traces of vertical fractures, and possibly greater solution enlargement in these more deeply eroded settings, a phenomenon we have observed in some outcrops.

A monoclinal fold mapped in the central TCMA (Figs. 1, 7) has also been linked to relatively high hydraulic conductivities in the lower part of the Platteville Formation. The monoclinal fold extends across part of the Superior Plating Superfund site (Barr Engineering, 1989), as well as parts of the Minneapolis East Interceptor project area (CSC Joint Venture, 1985). At the latter site, packer tests of the lower Platteville yielded hydraulic conductivities on average orders of magnitude higher on the monoclinal fold than elsewhere in the project area. Stronger deformation along the fold, causing enhanced secondary pore development, has been suggested to be responsible for these locally higher hydraulic conductivity values (Barr Engineering, 1989). Although such an interpretation has merit, the relative deep incision and enhanced weathering of the Platteville along the monocline (e.g. Fig. 7) could also create enhanced secondary pore development, and result in a relatively high hydraulic conductivity. This makes a cause and effect link to increased deformation alone difficult to confidently test.

Vertical hydraulic conductivity

Parts of the lower Platteville Formation are sufficiently low in hydraulic conductivity to serve as aquitards (Fig. 5). Preferential termination of vertical fractures, along with a systematic lateral change in apertures and likely connectivity, appear to determine the stratigraphic position and relative integrity of these aquitards. Leakage through the ceilings of excavations beneath the Platteville allows quantification of bulk vertical hydraulic conductivity of the combined Hidden Falls, Mifflin, and Pecatonica Members (Anderson and others, 2011; Peer, 2001). Several tens of feet from eroded edges of the Platteville, where a full or nearly full section of the formation is present, leakage rates indicate a bulk vertical hydraulic conductivity of 10^{-4} ft/day or less (Fig. 5). Near bluff edges and in settings where the Platteville is at least locally eroded down to the level of the Mifflin and Hidden Falls, leakage is markedly higher, indicative of vertical hydraulic conductivity that ranges from 10^{-1} to 10^{-3} ft/day.

Identification of discrete intervals that might serve as key aquitards within the combined Hidden Falls, Mifflin and Pecatonica Members (Fig. 5) is an ongoing focus of our research. Hydraulic data compiled thus far suggests that the Hidden Falls Member plays a key role. Heads above and below the Hidden Falls are known to differ by as much as 10 ft based on nested well measurements (Braun, 2011) and packer-derived head measurements (Anderson and others, 2011) also show abrupt head changes across the Magnolia-Hidden Falls contact. Perched water on top of the Hidden Falls, recognized at a number of subsurface sites and expressed also by springs, likewise suggests significant vertical resistance across the member. Collectively, the mechanical stratigraphy and hydraulic data support a model whereby preferential termination of vertical fractures in the interval between the lowermost Magnolia to the upper Mifflin allows parts of the Hidden Falls and immediately adjacent strata to serve as one or more key aquitards (Fig. 5). The integrity of these discrete aquitards likely increases with increasing distance from outcrop or subcrop edges (Anderson and others, 2011).

Upper Platteville Formation

Horizontal hydraulic conductivity

The upper part of the Platteville Formation typically has a markedly greater hydraulic conductivity than the lower part in areas where both are present, with packer, slug and aquifer tests all averaging tens to hundreds of ft/day. Collectively, the values from these tests range from $<10^{-4}$ to a few hundred ft/day. Values in the lower end of the range are derived from 5 ft interval packer tests. Only 7 of 41 of such tests have values less than 1 ft/day, indicating that 5 ft intervals without hydraulically well connected secondary pores are uncommon in the upper part of the Platteville Formation. Longer interval and larger-scale slug and aquifer tests of the upper part of the Platteville exclude the lower end of this range, with values of horizontal hydraulic conductivity from a few tens of ft/day to about 300 ft/day, and averaging over 100 ft/day (Table 1). The relatively high hydraulic conductivity for the upper part of the Platteville is consistent with outcrop, excavation, and boring observations that reveal a relatively densely fractured media (Fig. 5) (e.g. CNA, 1997; Peer, 1999; Anderson and others, 2011), including one or more bedding-parallel macropores (described below), forming a well-connected network.

Most of the relatively large scale aquifer tests of the Platteville Formation are based on pumping and/or observation wells that are open to both the upper and lower parts of the formation. Based on the results of discrete interval tests that allow discrimination of stratigraphic position, summarized previously, these “bulk” Platteville values of hydraulic conductivity are in this report considered representative of the upper part of the formation (Table 1), even though the tested wells may also be open to the lower part of the formation. The hydraulic conductivity values derived from specific capacity tests of domestic and monitor wells in the CWI database are treated in a similar manner (Table 1). The highest hydraulic conductivity values among this group of tests, at the Minnehaha Tunnel Project (MTP) site (Fig. 1), were measured at boreholes located close to linearly extensive vertical joints with large apertures (Kelton Barr Consulting, 2000; Anderson and others, 2011). The inclusion of these “bulk” Platteville hydraulic conductivity values into our characterization of the upper part of the formation extends the range in conductivity, based on aquifer and specific capacity tests, to as high as thousands of ft/day.

Table 2 is a summary of average hydraulic conductivity for the upper Platteville based exclusively on aquifer tests at six TCMA sites. The six sites have average hydraulic conductivity values that range from about 50 to 1,360 ft/day, with an average of about 485 ft/day. This average value is relatively close to the average hydraulic conductivity of 295 ft/day calculated from specific capacity tests (Table 1). This subset of data contains the best approximation of bulk horizontal conductivity for the upper part of the Platteville Formation based on the largest scale of testing, and the results are used in the schematic depiction of properties in Figure 5.

The lowermost approximately two feet of the Magnolia and uppermost Hidden Falls Member, referred to as the “transitional” Hidden Falls-Magnolia contact strata (Anderson and others, 2011), is especially conductive in a horizontal direction. A discrete bedding-parallel macropore network at this position has hydraulic conductivity measured as high as tens of thousands of ft/day in individual boreholes (Fig 4). Borehole geophysical logs (including EM flowmeter logs), core, and underground excavation data collected near the University of Minnesota and at other TCMA sites tens to hundreds of feet away from bluff and subcrop edges, demonstrate that this discrete interval of bedding-parallel macropores at the Hidden Falls-Magnolia contact is widespread across the subsurface extent of the Platteville. Both packer tests and injection flowmeter logs demonstrate the presence of this high hydraulic conductivity interval even where Decorah Shale caps the Platteville Formation.

At the Minnesota Library Access Center (MLAC) (Fig. 1; Peer 1999) and other sites this transitional interval has been shown to be vertically well-connected to the heavily fractured Magnolia Member higher in the section, serving as a lowermost “water-main” that collects and transports horizontally large volumes of water recharged vertically through uppermost bedrock. Dye traces in the Platteville Formation near Minnehaha Falls Park, indicate relatively rapid flow along this discrete interval, with speeds measured as rapid as 1.24 mi/day (Alexander and others, 2001; Anderson and others, 2011).

Our generalized depiction of upper Platteville in Figure 5 indicates that its hydraulic conductivity is lower where the formation is overlain by Decorah Shale, although the data to support such a characterization are very limited. From the perspective of secondary pore development, the upper Platteville is likely to be relatively less fractured and weathered, diminishing hydraulic conductivity, in areas where the Decorah Shale is present compared to areas where the Decorah is absent. A limited number of hydraulic conductivity tests of the upper Platteville where the Decorah Shale is present provide weak support for this hypothesis, with aquifer tests at the General Mills/East Hennepin Avenue and Oakdale Disposal sites yielding values of 187 and 67 ft/day, respectively. Specific capacity tests of eight Platteville wells located where the Decorah Shale is present average 44 ft/day. We used the average value of the two aquifer tests as representative of the bulk hydraulic conductivity for the upper Platteville under such conditions (Fig. 5) to indicate that lower conductivities might be expected based on these limited data.

Vertical hydraulic conductivity

Quantification of vertical hydraulic conductivity is a longstanding problem in hydrogeology (Bradbury and others, 2006). Our database includes only one report of vertical hydraulic conductivity for the upper part of the Platteville Formation. The Moench solution (1993) was applied to the results of a 72 hour multiwell aquifer test at the MLAC site, with vertical hydraulic conductivity values ranging from 10^{-3} to 4 ft/day (Peer, 1999) for four observation wells included in the test. Multi-well aquifer tests, dye traces, mapped contamination plumes, as well as outcrop observations of fracture patterns are collectively indicative of a vertically well-connected system of fractures across the upper part of the formation, and therefore at the site-scale the higher end of this range is likely most applicable, and used in Figure 5. Exceptions may exist, however, especially in areas where the Decorah Shale caps the

Platteville Formation, and vertical fractures may be linearly less extensive and more poorly connected. Flowmeter logging in such conditions demonstrates the presence of stratigraphically discrete vertical head changes across the lower part of the Magnolia Member, and potentiometric mapping by Barr Engineering (1991) also demonstrated vertical hydraulic separation in Platteville-Decorah contact strata (Magnolia-Carimona contact) at the General Mills/East Hennepin Avenue site. These results indicate that discrete intervals within the upper part of the Platteville at least locally may be resistant to through-going vertical fractures and therefore serve as aquitards, although data are inadequate to quantify such resistance.

SUMMARY

Our compilation and evaluation of hydraulic conductivity data support the characterization of the Platteville by Anderson and others (2011), as a hybrid hydrogeologic unit. Like other hybrid units identified in the Paleozoic bedrock of this area (e.g. Runkel and others, 2006; Tipping and others, 2006), matrix permeability is very low, but secondary pore networks create moderate to very high horizontal hydraulic conductivity sufficient to yield economic quantities of water to wells, and supply springs with flow rates over 10 gpm. The greatly variable and commonly very high hydraulic conductivity, fast flow speeds, and secondary pore observations demonstrate that the Platteville is consistent with the definition of a secondary pore-dominated aquifer. Data from the same collection of sites also supports the traditional classification of the Platteville Formation as an aquitard (confining unit), when considered from a vertical perspective, with discrete intervals such as the upper and lowermost Hidden Falls Member perhaps serving as key relatively high integrity aquitards. Vertical leakage will be variable, and under certain conditions such as near eroded edges of the formation can be substantial.

Hydraulic conductivity data are synthesized and interpreted across a range of scales, with the recognition of variable user needs. For example, the generalized depiction of hydraulic conductivity shown in Figure 5 may be suitable for modeling water budgets through relatively large areas. In contrast, more site-specific needs such as development of remediation strategies and prediction of flow paths may be facilitated by considering the large range in hydraulic conductivity, measured at a number of scales (e.g. summarized in Figure 4, Table 1), and by recognizing the location of fast-flow secondary pore networks as well as potential key aquitards.

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Kelton Barr, Braun Intertec Corp., shared his knowledge and information about the Platteville, derived from his work at a number of TCMA sites where the Platteville played an important role. Ray Wuolo of Barr Engineering offered advice on how hydraulic conductivity data are variably used depending on needs.

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Appendix A: Hydraulic conductivity database (see supplementary files to download GIS data)

Geodatabase Name: HydraulicConductivityPointData_Platteville_Report.mdb (personal geodatabase)

Spatially enabled data tables

Name	Description
K_complete	Hydraulic conductivity, complete dataset. 1 row for each measurement

Hydraulic Conductivity field names and descriptions

Field Name	Description
seqno	Unique row identifier
relateid	Unique site identifier – either unique well number or "Q series" number assigned at MGS
unique_no	Minnesota unique well number
wellname_CWI	well name from CWI
wellname_from_file	well name from file or report
elevation	land surface elevation in feet above mean sea level. Info from CWI if available
depth_comp	depth completed in feet, info from CWI if available
case_depth	casing depth in feet, info from CWI if available
depth2bdrk	depth to bedrock in feet, info from CWI if available
depth_bot	depth to bottom of test interval in feet
depth_top	depth to top of test interval in feet
Kh_ftday	K value – horizontal in ft/day
Kv_ftday	K value – vertical in ft/day
minmax	specifies if K value is a minimum or maximum value
unit_tested	Interpreted unit tested
site_conditions	specifies structural or true thickness conditions
first_bdrk	uppermost bedrock unit, info from CWI if available
test_method	K test method
site_name	Site name
analytical_method	K calculation method
report_reference_primary	Primary report reference
meas_date	measurement date as text in format yyyymmdd where equivalent meas_date2 available
meas_date2	Measurement date in date format
test_contact	Test contact person or organization
comments1	comments, set 1
comments2	comments, set 2
comments3	Comments, set 3
utme	Universal Transverse Mercator easting, UTM zone 15 extended, NAD83

utmn	Universal Transverse Mercator northing, UTM zone 15 extended, NAD83
gcm_code	Geographic coordinates method
geoc_src	Geographic coordinates source

Lookup tables

Name	Description
XFIRST_BDRK	Corresponds to field "first_bdrk," contents specify uppermost bedrock penetrated: ODCA Decorah Shale, Carimona Member ODCR Decorah Shale, undifferentiated OPHF Platteville Formation, Hidden Falls Member OPMA Platteville Formation, Magnolia Member OPMI Platteville Formation, Mifflin Member OPVL Platteville Formation, undifferentiated
xGCMCODE	Corresponds to field "gcm_code," code specifies method used to establish sample/test location: A Digitized - scale 1:24,000 or larger A** Digitized from Washington Co. 1/2 section maps, verified by County Survey GPS B Digitized - scale 1:100,000 to 1:24,000 DS1 Digitization (Screen) - Map (1:24,000) DS2 Digitization (Screen) - Map (1:12,000) G3 GPS Differentially Corrected G6A GPS SA On (averaged) G6O GPS SA Off (averaged) I GPS; accuracy 3 to 12 meters (+ 6 to 40 feet) PQ6 Public Land Survey - QQQQQQ Section RD From report description (estimated error +/- 1000 m) SM digitized from georeferenced site map, accuracy unknown SPL UNK Unknown method
xREPORT_REFERENCES	Corresponds to field "report_ref," contents specify author and year associated with data: Anderson and others, 2011 — Anderson, J.R., Runkel, A.C., Tipping, R.G., Barr, K., D.L., and Alexander, E.C., Jr., 2011, Hydrostratigraphy of a fractured, urban, aquitard: in Miller, J.D., Jr., Hudak, G.J., Tittkop, C., and McLaughlin, P.I., eds, *Archean to Anthropocene: Field Guides to*

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xSITE_CONDITIONS	Corresponds to field "site_conditions," contents specify structural or true thickness conditions	
	E	Indicates bedrock unit at site is considered "eroded"
	M	Indicates bedrock unit at site is on monocline
xSITE_NAME	Corresponds to field "site_name", contents specify name of site from which K values were derived:	
	FMGW	Former Minneapolis Gas Works
	GMEH	General Mills/East Hennepin Avenue
	KC	Koppers Coke
	LTS	Lindbergh Terminal Station
	MEI	Minneapolis East Interceptor
	MLAC	Minnesota Library Access Center
	MPT	Minnehaha Park Tunnel
	ODS	Oakdale Disposal
	RTC	Reilly Tar and Chemical
	SP	Superior Plating
	U of M	University of Minnesota east and west bank monitor wells
xTEST_Method	Corresponds to field "test_method," contents specify method used to measure	

	transmissivity/hydraulic conductivity: CH constant head FLMC flowmeter inject/pump - constant head FSRH field rising head, includes slug tests and baildown tests FSU Field Slug Test Unspecified LKG Leakage into excavation beneath Platteville PPPT packer pressure test – discrete interval PTE pumping test - entire open hole
xUNIT_TESTED	Corresponds to field "unit_tested," contents specify unit tested, most often as described in report: CR Decorah Shale, Carimona Member CRMG Carimona (Decorah Shale) and Magnolia (Platteville) members HF Platteville Formation, Hidden Falls member HFL Platteville Formation, Hidden Falls member, likely lower part HFMF Platteville Formation, Hidden Falls and Mifflin members HFMFPC Platteville Formation, Hidden Falls, Mifflin, and Pecatonica members HFMP Platteville Formation, Hidden Falls, Mifflin, and possibly Pecatonica members MF Platteville Formation, Mifflin member MFL Platteville Formation, Mifflin member, likely lower part MFPC Platteville Formation, Mifflin and Pecatonica members MFU Platteville Formation, Mifflin member, likely upper part MG Platteville Formation, Magnolia member MGHF Platteville Formation, Magnolia and Hidden Falls members MGHFMP Platteville Formation, Magnolia, Hidden Falls, Mifflin and possibly Pecatonica members MGL Platteville Formation, Magnolia, likely lower part MP Platteville Formation, Mifflin and possibly Pecatonica members OGWD Glenwood Formation OPVL Platteville Formation, undifferentiated
xVALUE_MINMAX	Corresponds to field "minmax," contents specify if K value is a minimum or maximum value < indicates K value is a maximum value > indicates K value is a minimum value