Minnesota Geological Survey

Harvey Thorleifson, Director

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

Anthony C. Runkel, Julia R. Steenberg , Robert G. Tipping, Minnesota Geological Survey

November 9, 2011

Report submitted as deliverable for contract between University of Minnesota and Metropolitan Council for project titled “Aquifer Recharge and Contaminant Plume Mapping for Portions of the Twin Cities Metropolitan Area” (University of Minnesota contract 10I021). This report has not been edited according to standard Minnesota Geological Survey policy.

Introduction

The (Late) Ordovician Platteville Formation in the central part of the Twin Cities Metro Area (TCMA) (Figs 1, 2) is a shallowly buried (< 30 m, 100 ft) carbonate-dominated formation that occupies a position 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 large number (dozens) of springs along the Mississippi River and its tributaries. Furthermore, the Platteville is also host to a large number of contamination 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, and 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.

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 major preserved extent of Paleozoic bedrock in the Upper Mississippi Valley region (Mossler, 1972). The Platteville ranges from about 26 to 29 ft in thickness, and is subdivided into four members, from bottom to top they are the Pecatonica, Mifflin, Hidden Falls and Magnolia (Mossler, 2008). These are distinguished mainly by lithology and bedding style and correspond to major depositional facies of the formation (Fig 2). The Pecatonica Member lies directly on top of the Glenwood Shale, and is a thin bed of 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, phosphatic, 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 of the Decorah Shale lies atop the Magnolia Member of the Platteville Formation.

Hydrostratigraphic context

Macropores, commonly with evidence of enlargement through dissolution, are characteristic of the Platteville Formation throughout its extent. Vertically oriented macropores include fractures typical of stress release conditions as well as joints that are part of a large-scale orthogonal system oriented northeast-northwest. Based on outcrop observations the members of the Platteville each have a distinct style of vertical fracture density and spacing (Fig. 3; and Anderson et al., 2011). The Magnolia Member has a high density of vertical to sub-vertical fractures with a wide range in trace length, creating a blocky texture. The Hidden Falls Member has a very high density of vertical to subvertical, straight to curvilinear (conchoidal) fractures that. The Mifflin Member has relatively wide spaced vertical, straight fractures 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. 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; most commonly present in outcrops where the Platteville is deeply incised and appears more heavily weathered.

Horizontally oriented macropores are represented by bedding-plane conduit networks concentrated along discrete stratigraphic intervals. Results from correlating spring positions with stratigraphic intervals (Fig. 2) is consistent with the 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 et al., 2011), demonstrating preferential development of bedding plane conduits at the Hidden Falls-Magnolia contact. Bedding parallel conduits have also been recognized in the subsurface higher within

the Magnolia Member at some sites (e.g. Peer, 1999), and at outcrops springs discharge at a number of other stratigraphic positions (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 1, 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 8500 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 (Bradbury and Rothschild, 1985) reveal a generally similar large range, from 10^{-2} to 7500 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.

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 regional scale models or to predict 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 macropore conductivity at a relatively detailed scale. We follow by an analysis of

hydraulic conductivity values compared to stratigraphic position of the tested interval, which in turn corresponds to characteristic macropore development. 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.

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 et al., 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) lengths of individual boreholes (Appendix 1, 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 fractures are absent or hydraulically insignificant (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.

Macropore hydraulic conductivity

Tests of fractured Platteville Formation yield hydraulic conductivity 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 macropore development, with the lower end of the range corresponding to intervals with only narrow, relatively poorly connected fractures, and the higher end to intervals that include relatively large aperture macropores 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 bedding plane fractures. Flow speeds as fast as 1.25 mi/day via such bedding plane conduits have been demonstrated through dye traces (Alexander et al., 2001; Anderson et al., 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, strongly 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 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 et al., 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 5, 6). 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 0.1 ft/day (Table 1). Discrete intervals (typically about 5 ft) bracketed by packers are commonly unable to produce water at a sustained rate 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 1), 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 plane 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 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 macropores compared to the upper part of the formation (Anderson et al., 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 represent the uncommon borehole intersection of rare, moderately conductive bedding plane fractures 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 across much of a site (Figs 3, 6). 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 higher hydraulic conductivity at such sites is most likely attributed to enhanced macropore development, such as greater density, apertures, and linear traces of vertical fractures, and 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. 1,6) 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 (Fig. 6). Stronger deformation along the fold, causing enhanced fracturing, 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. 6) could also create enhanced macropore 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. 3). Preferential termination of vertical fractures, along with a systematic lateral change in fracture 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 et al., 2011). 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. 3). Nearer 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. 3) 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 et al., 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

compartmentalization of vertical fractures from the lowermost Magnolia to the upper Mifflin leads to Hidden Falls and immediately adjacent strata containing one or more key aquitards (Fig. 3). The integrity of these discrete aquitards likely increases with increasing distance from outcrop or subcrop edges (Anderson et al., 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 foot intervals without hydraulically well connected macropores 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. 3) (e.g. CNA, 1997; Peer, 1999; Anderson et al., 2011), including one or more bedding plane fractures (described below), forming a well-connected network of macropores.

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 in this report, 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 et al., 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 1360 ft/day, with an average of about 485 ft/day. This 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 3.

The lowermost approximately two feet of the Magnolia and uppermost Hidden Falls Member, referred to as the "transitional" Hidden Falls-Magnolia contact strata (Anderson et al, 2011), is especially conductive in a horizontal direction. A discrete bedding plane fracture network at this position has hydraulic conductivity measured as high as tens of thousands of ft/day in individual boreholes (Fig 6). 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 plane conduits 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 et al., 2001; Anderson et al., 2011).

Our generalized depiction of upper Platteville hydraulic conductivity in Figure 3 indicates that 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 macropore 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. 3) 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 Environmental, 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 3. 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 has 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 by Anderson et al. (2011), of the Platteville as a hybrid hydrogeologic unit. Like other hybrid units identified in the Paleozoic bedrock of this area (e.g. Runkel et al., 2006), matrix permeability is very low, but macropore 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 conduits, and macropore observations demonstrate that the Platteville is consistent with the definition of a karstic 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.

The hydraulic conductivity data compiled for this effort is presented and summarized in a number of manners with the recognition of the variable needs of users. For example, the generalized depiction of hydraulic conductivity shown in Figure 3 may be suitable for modeling water budgets at the scale of contamination or engineering sites, or at larger scales of investigation. In contrast, 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 recognition of the location of fast-flow conduits as well as potential key aquitards.

ACKNOWLEDGMENTS

Steve Jansen, PEER Engineering, Inc, provided great information on the properties of the Platteville Formation, especially for the MLAC site, which, among other insights, ultimately led to the critically important quantification of vertical hydraulic conductivity of the lower part of the formation. Kelton Barr, Braun Intertec Corp., similarly 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.

CAPTIONS

Table 1. Summary of hydraulic conductivity values for the Platteville Formation (and adjacent units) compiled in this report (Appendix 1). 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 most of all of the Platteville is preserved, 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 1. 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 fracture aperture. See Appendix 1 explanation for more detailed information on testing procedures.

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.

Figure 1. Bedrock geologic map of the Twin Cities Metropolitan Area (TCMA), showing principal sources of data discussed in this report, including sites from which we acquired hydraulic conductivity values for the Platteville Formation. Site abbreviations are in Appendix A.

Figure2. Generalized stratigraphic column, depicting the lithology, thickness, and nomenclature for the Upper Ordovician formations in the Twin Cities Metropolitan Area (TCMA). The spring count lists the number of springs emanating from a specific stratigraphic interval.

Figure 3. 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 macropore development and high hydraulic conductivity, and a lower two-thirds with sparser macropore 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. 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 et al, 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 test of the lower part of the Platteville in setting where most of all 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 1; summarized in Table 1) and more detailed information provided in this report are more appropriate for many other needs such as contaminant transport research. 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.

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 without hydraulically significant macropores 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 significant fracture 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 5 and 6 for additional illustrations of packer test results, and Anderson et al. (2011) for additional information on injection flow logging tests of the Platteville. See Figure 3 for key and legend.

Figure 5. 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 1 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 6. 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 1 of this report. MEI-XX numbers above the columns refer to borehole numbers in CSC Joint Venture (1985). See Figure 1 for location of section line.

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		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)	
		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)
		Magnolia-Hidden Falls contact interval	Kh^5 19539; 3754 to 54727(6)	
		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 "Bulk" (members not discriminated)	Kh^4 294.3; 0.05 to 7494.1 (63)	
	LOWER PART	Hidden Falls	$Kh^1$32.6; <1.2 to 68.3 (3)	
		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}
		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

UPPER PLATTEVILLE	Average site Kh in ft/day
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