Characterization of fracture connectivity in a siliciclastic bedrock aquifer near a public supply well (Wisconsin, USA)

Christopher A. Gellasch · Kenneth R. Bradbury · David J. Hart · Jean M. Bahr

Abstract In order to protect public supply wells from a wide range of contaminants, it is imperative to understand physical flow and transport mechanisms in the aquifer system. Although flow through fractures has typically been associated with either crystalline or carbonate rocks, there is growing evidence that it can be an important component of flow in relatively permeable sandstone formations. The objective of this work is to determine the role that fractures serve in the transport of near-surface contaminants such as wastewater from leaking sewers, to public supply wells in a deep bedrock aquifer. A part of the Cambrian aquifer system in Madison, Wisconsin (USA), was studied using a combination of geophysical, geochemical, and hydraulic testing in a borehole adjacent to a public supply well. Data suggest that bedrock fractures are important transport pathways from the surface to the deep aquifer. These fractured intervals have transmissivity values several orders of magnitude higher than non-fractured intervals. With respect to rapid transport of contaminants, high transmissivity values of individual fractures make them the most likely preferential flow pathways. Results suggest that in a siliciclastic aquifer near a public supply well, fractures may have an important role in the transport of sewer-derived wastewater contaminants.

Keywords Fractured rocks · Sedimentary rocks · Urban groundwater · Water supply · Hydrostratigraphy

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Introduction

In order to protect public water supply wells from a wide range of contaminants, it is imperative to understand physical flow and transport mechanisms in an aquifer system. With regard to microbiological contamination, determining the travel time between source and target has increased importance due to limited timespan of viability for these organisms. Human enteric viruses may only be viable for 1–2 years in a groundwater environment depending on factors such as water temperature (Yates et al. 1985, 1987; John and Rose 2005). If the time of transport to a well exceeds the viability period of the microorganism in groundwater, the risk of infection is low.

Approximately one third of the US population uses public supply wells (PSWs) as their drinking-water source (Eberts et al. 2005). The presence of contaminants in these wells has been variable and unpredictable (US Environmental Protection Agency 1999). During the past decade a greater focus has been placed on assessing the risk of contaminants entering PSWs. Among the many contaminants of concern are chemical and microbiological indicators of wastewater contamination. The US Geological Survey's National Water-Quality Assessment (NAWQA) program has conducted research related to PSW vulnerability as one of its five focus areas. The NAWQA Transport of Anthropogenic and Natural Contaminants to Supply Wells (TANC) study strives to better understand the transport pathways and geochemical processes related to selected contaminants that may be found in groundwater captured by PSWs in a variety of hydrogeological settings (Landon et al. 2010). Many recent studies have highlighted the impact of microbiological contaminants on aquifer systems. Research in the United Kingdom by Powell et al. (2003) has indicated microbial contamination in urban sandstone aquifers at depths up to 90 m below ground surface (bgs). Hunt et al. (2010) have detected viruses in public supply wells that access a variety of aquifer types and are located in

several Wisconsin communities. Previous work by the Wisconsin Geological and Natural History Survey (WGNHS) has revealed the presence of infectious human enteric viruses in public supply wells in Madison, Wisconsin, USA that draw groundwater from a deep (75+ m), confined siliciclastic aquifer system (Borchardt et al. 2007; Bradbury et al. 2010).

It has been challenging to identify specific pathways for viruses and other contaminants to rapidly reach public supply wells in these settings. Standard calculations of porous media transport in siliciclastic aquifer systems are made using the advective transport equation

$$v = -(K/n_e)(\mathrm{dh}/\mathrm{dl}) \quad (1)$$

where v is the average linear velocity (L/T), K is the hydraulic conductivity (L/T), n_e is the effective porosity (dimensionless), and dh/dl is the hydraulic gradient (dimensionless). Using Eq. (1), it does not seem likely that microbiological contaminants could travel these distances quickly enough to remain viable upon entering a public water-supply well. One hypothesis to explain the presence of infectious viruses at depth is that a small quantity of groundwater can travel along the most direct pathways through porous media at rapid, statistically extreme velocities, which enable a portion of the microbiological contamination to reach the target well (Taylor et al. 2004). However, only a very small fraction of the initial contaminant would be able to reach the target well in this scenario. Another transport mechanism that could explain rapid transport in these aquifer systems is groundwater flowing through fractures.

Fracture patterns and fracture flow in carbonate sedimentary rocks have been the focus of many studies (Bradbury and Muldoon 1994; Muldoon et al. 2001; Rayne et al. 2001; Underwood et al. 2003) and carbonate rocks can have a wide range of hydraulic conductivity values that result in the unit acting either as an aquifer or aquitard (Brahana et al. 1988). Although flow through fractures has typically been associated with crystalline and carbonate rocks, there is growing evidence that it is also important to flow in relatively shallow sandstone aquifers. Research by Runkel et al. (2006) on fractures and fracture flow in the Cambrian siliciclastic sedimentary rocks of the North American craton concluded that fracture flow may dominate intergranular flow even in highly permeable coarse-grained sandstone aquifers. These fractures were associated with certain lithostratigraphic intervals and, even at great burial depths, the fractures were hydraulically significant. Recent work on the Cambrian Tunnel City Group of southern Wisconsin (Swanson et al. 2006; Swanson 2007) has demonstrated the importance of bedding parallel fractures to spring flow and also a correlation between changes in lithofacies and the presence of these fractures. Detailed hydraulic head measurements at another site in southern Wisconsin delineated several distinct hydrogeological units within a single formation based on large vertical variations in head related to the vertical connectivity and presence of fractures (Meyer et al. 2008). Thermal tracer tests in open boreholes near Madison, Wisconsin identified hydraulically significant fractures in the local Cambrian age formations (Leaf et al. 2012).

The purpose of this work is to test the hypothesis that fracture connectivity in siliciclastic aquifer systems is a likely mechanism for rapid transport of microbiological organisms and other wastewater contaminants. Urban areas with aging, leaky sanitary sewers in proximity to public water-supply wells may be at increased risk of wastewater derived contaminants entering the municipal water supply. A detailed field investigation at a site near a public water-supply well determined the distribution, orientation, and hydraulic properties of fractures; the response of the fracture system to pumping stress; and the presence of geochemical indicators in individual fractures. Fracture data were obtained from a single borehole, which resulted in limited spatial resolution. The data collected from both the overall aquifer and from individual fractures were utilized to determine the role of fractures in the rapid transport of wastewater contaminants in the upper aquifer. The primary means to identify and characterize fracture connectivity in these settings involved the use of borehole methods, including a combination of geophysical logging, vertical flow assessment, and discrete interval evaluation of physical and chemical groundwater parameters. The construction and use of a custom made, light-weight straddle packer allowed for the isolation and evaluation of individual fractures.

Background

Location

The study area includes Madison Unit Well 7 (UW-7), a public water-supply well where viruses have been detected previously, and the surrounding residential neighborhood in the city of Madison, Dane County, Wisconsin, USA (Fig. 1). The UW-7 was drilled in 1939 and is one of 23 high capacity wells used by the Madison Water Utility as a potable water source. The well is cased and grouted through the Eau Claire aquitard and is a 41-cm open borehole through the full thickness of the Mount Simon aquifer. UW-7 has a maximum discharge of 8,300 L (2,200 gal) per minute that fills an adjacent 568,000 L (150,000 gal) reservoir, which supplies the distribution system. The well had historically been used as a seasonal well (May to November) but more recently it supplied water year-round and produced approximately 950 million liters (250 million gallons) during 2010 (Madison Water Utility 2011). Sanitary sewers in the neighborhood were installed in the late 1940s and consist primarily of vitrified clay pipe. Video logging of the sanitary sewer by the Madison Sewer Utility indicates that some sewer pipe has cracked sections that may allow wastewater to leak out. Madison has separate sanitary sewer and storm sewer systems.

Stratigraphy and geologic setting

The site is underlain by approximately 10 m of unlithified till and more than 200 m of Cambrian age sandstone, siltstone, and shale units as depicted in Fig. 2. Bedding within these units is primarily horizontal, with only a slight regional dip of 2–3 m/km southeast away from the Wisconsin Arch (Cline 1965). The Cambrian units are

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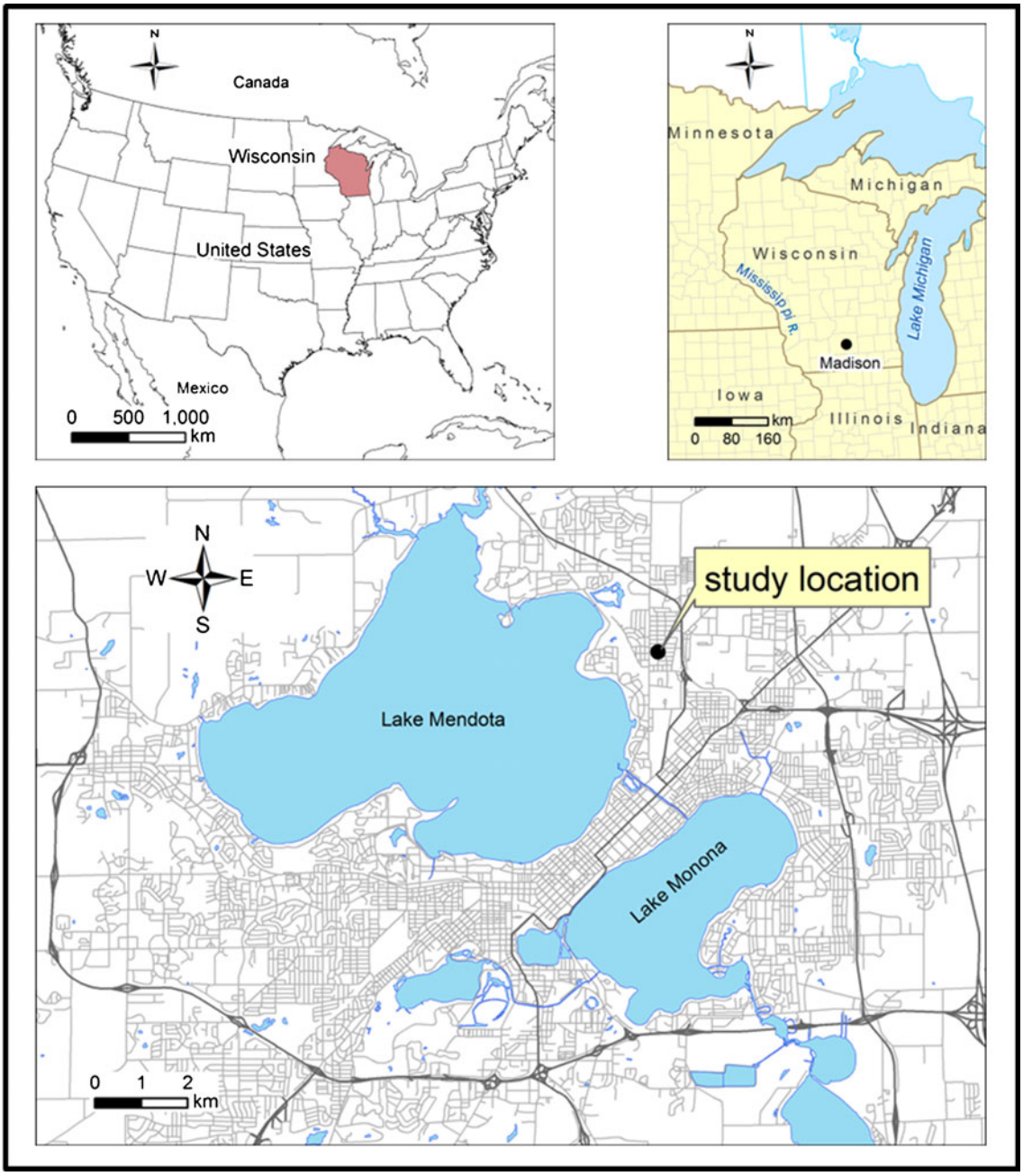

Fig. 1 Study area location

underlain by Precambrian age granite that is considered a barrier to groundwater flow. The Mount Simon Formation, a sandstone unit that forms the confined lower bedrock aquifer, is used as a primary water source by the city of Madison and surrounding Dane County. The shale and siltstone intervals of the overlying Eau Claire Formation act as a regional aquitard (Aswasereelert et al. 2008). The Wonewoc Formation and Tunnel City Group form a semi-confined upper bedrock aquifer at this location. The Tunnel City Group consists of several lithofacies that contain either glauconitic layers or thin silt and clay drapes (Swanson 2007). These fine-grained layers act as a leaky confining unit. Public supply wells pump tens of millions of gallons per day from the Mount Simon aquifer beneath Madison, resulting in a substantial cone of depression across the area. Hydraulic gradients due to this cone of depression result in downward vertical flow from the upper aquifer to the lower aquifer in Madison (Bradbury et al. 1999).

Installation of monitoring wells

Three monitoring wells were installed at the site in order to investigate the upper aquifer. Figure 3 illustrates the position of the monitoring wells in relation to the public supply well and the geological units. A rotary drill rig was used to complete boreholes on site with an air rotary technique and a 15 cm (6 in.) tricone bit. The boreholes

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Age		Stratigraphic Unit		Thickness (m)	Hydrostratigraphy	Description
Cenozoic	Pleistocene	Holy Hill Fm. (Horicon Mbr.)		10	Unsaturated	Unconsolidated till consisting of gravelly, clayey, silty sand [a]
Paleozoic	Cambrian	Tunnel City Group	Lone Rock Fm. Mazomanie Fm.	20	Upper Aquifer	Yellowish brown to brown, very fine to fine grained silty sandstone with some dolomite cement and glauconitic layers [b]
		Elk Mound Group	Wonewoc Fm.	32		Very pale brown to orange brown, medium to coarse grained sandstone with minor glauconite and some iron oxide coated intervals [b]
			Eau Claire Fm.	11	Aquitard	Very pale yellow brown fine sand interbedded with gray green shale [b]
			Mount Simon Fm.	150	Lower Aquifer	White, yellow, and brown clean, well sorted, fine- and medium-grained sandstone, quite friable in some sections [a]

Fig. 2 Study area stratigraphy. *a* Ostrom (1978), *b* description from MW-C geological log based on drilling cuttings (Roger Peters, WGNHS)

are located approximately 6 m from UW-7 and approximately 2 m from each other. Table 1 summarizes the construction details of each borehole and monitoring well. Cuttings were collected at 1.5-m intervals from MW-B and MW-C and used to create geologic logs. The two shallower wells (MW-A and MW-B) were drilled in April 2010 and 5 cm (2 in.) diameter schedule 40 PVC monitoring wells were installed the same day. The shallowest well (MW-A) is screened across the water table and the intermediate well (MW-B) is screened across the Tunnel City–Wonewoc contact. The deepest well, MW-C, was drilled a year later, in April 2011, to the top of the Eau Claire aquitard as an open borehole with a 15 cm (6 in.) steel casing driven approximately 10 m to the top of bedrock. This open borehole was utilized for most of the subsurface characterization at the site. When the MW-C borehole was not in use, a blank FLUTe flexible liner system was installed to minimize vertical circulation of groundwater in the borehole. The MW-C 5 cm (2 in.) diameter schedule 80 PVC monitoring well was completed in December 2011.

Motivation and initial work

Results of previous work that detected human enteric viruses in Madison public supply wells were the motivation for this study (Borchardt et al. 2007; Bradbury et al. 2010). Two previous rounds of time-sequenced sampling detected viruses in both the sanitary sewer and at several public supply wells in Madison. The temporal pattern of virus detections in the sewers and the public supply wells indicated that the viruses reached the wells on a time scale (days to weeks) much faster than expected for porous media flow (years to tens of years). Preferential flow pathways between the sewers and the deeper monitoring well appeared necessary to explain these apparently rapid transport rates. The earlier studies did not investigate the upper aquifer or the specific pathways responsible for virus transport to the public supply wells.

The sanitary sewer, UW-7, MW-A, and MW-B were sampled six times over a 12-week period during the summer of 2010. Each sample was evaluated for the presence of human enteric viruses and major ions. Virus sampling required pumping 1,000 L of groundwater through electropositive glass wool filters at less than 5 L/min. As expected, the sanitary sewer chemistry samples contained high levels of typical wastewater indicators including nitrate, chloride, and bromide. In addition, most homes in Madison use water-softening devices that require sodium chloride salt. Backflushing these systems discharges high levels of chloride and sodium into the sanitary sewer. The deeper groundwater samples from MW-B contained significantly higher levels of wastewater indicators than samples from the water table well MW-A. Data provided in Table 2 demonstrate that wastewater indicators are higher at 29 m bgs (MW-B) than at the water table (MW-A) or in the confined aquifer (unit well). It is important to note that the relatively low levels of nitrate in the sanitary sewer are due to reducing conditions under which the

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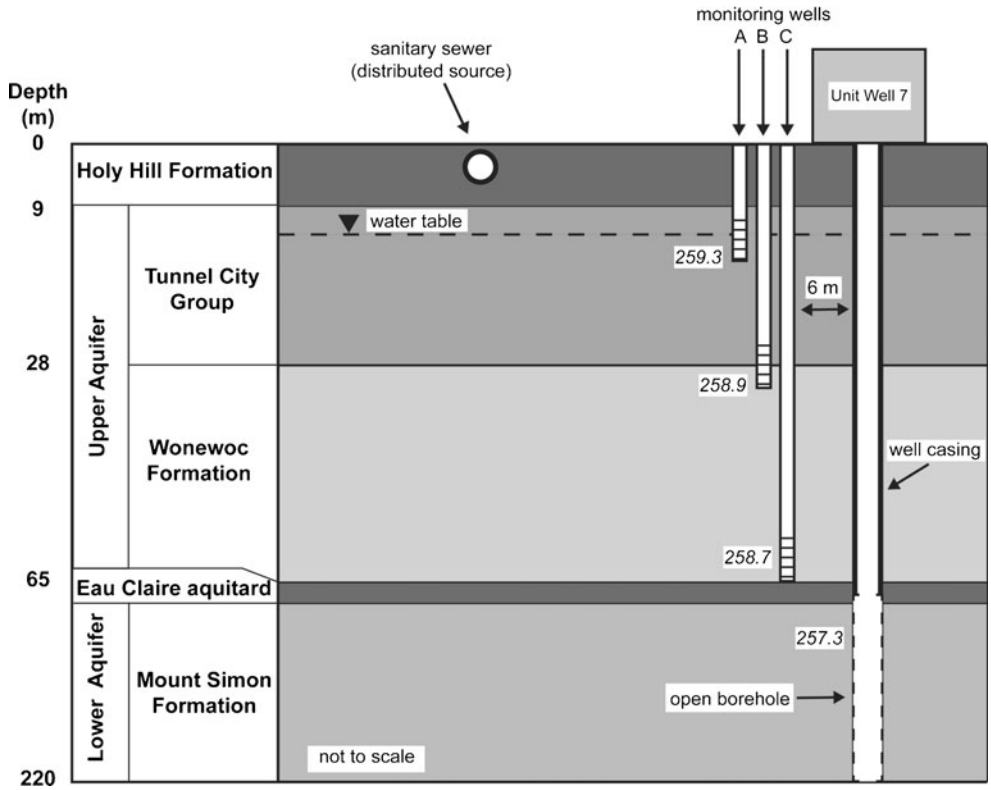

Fig. 3 Cross section of field site with location of monitoring wells with respect to the unit well. Numbers next to each monitoring well screen and the UW-7 borehole are hydraulic head elevations (in meters) from May 2012 while the aquifer system was at steady state during well maintenance

primary nitrogen species in wastewater is ammonia, which then oxidizes to nitrate in groundwater. Ammonia was not analyzed in these samples. The distinct pattern of wastewater indicators at depth suggested that a preferential flow pathway exists that allows sewer effluent to rapidly migrate to discrete intervals within the upper aquifer.

In May 2010, pressure transducers were placed in the monitoring wells to continuously record water level readings at 5-min intervals. The shallower monitoring well (MW-A) did not respond noticeably to pumping but the deeper monitoring well (MW-B) responded almost immediately each time UW-7 began pumping. The MW-B water level dropped by approximately 50 cm after three UW-7 pumping/recovery cycles over a 12-h period. Between MW-B and the unit well, the Eau Claire Formation acts as a regional aquitard (Fig. 3). The strong hydraulic connection between MW-B and the unit well suggested fracture flow between 30 m bgs and the Mount Simon aquifer may be influencing the water level response in MW-B. Well construction records indicate UW-7 is cased and grouted through the upper part of the Eau Claire Formation and this was confirmed by recent geophysical logging of the Unit Well. This portion of the upper Eau Claire Formation includes a silty shale interval approximately 3-m thick, while the rest of the formation consists mainly of fine-to-medium-grained sandstone. Other possible explanations for a hydraulic connection between the upper and lower aquifers are that the casing and/or grouting has failed, or the drilling of the well may have compromised the integrity of the aquitard near the borehole.

Methods and results

Borehole logging and fracture identification

The MW-C borehole was geophysically logged with several downhole tools during the spring and summer of 2011 in order to characterize the aquifer system and identify fractures. Several of the borehole logs are presented in Fig. 4. An Advanced Logic Technology (ALT) OBI-40 optical borehole imager captured an

Table 1 Construction data for monitoring wells adjacent to UW-7

Well name	Date drilled	Borehole diameter (cm)	Borehole depth (m)	PVC well casing diameter (cm)	MW screen interval (m)	Screen length (m)
MW-A	13 April 2010	15	14.6	5	10.0–14.6	4.6
MW-B	13 April 2010	15	30.5	5	27.5–30.5	3
MW-C	20 April 2011	15	66.4	5	62.5–65.5	3

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Table 2 Wastewater indicator concentrations from 2010 sampling locations

Sample location		Wastewater indicators			
Depth (m)	Name	Sodium (mg/L)	Chloride (mg/L)	Nitrate as N (mg/L)	Bromide (μg/L)
2.0	Sanitary sewer	183	263	0.024	138
12.3	MW-A	45	105	0.72	29
29.0	MW-B	194	488	6.1	228
75+	Unit well	8	14	0.026	29

oriented 360° visual image of the borehole at 3-mm intervals and the ALT ABI-40 acoustic borehole imager transmitted ultrasonic pulses at 3-mm intervals to collect data on the diameter of the borehole. The OBI-40 images were used to identify potential fractures, bedding planes, and color changes. The ABI-40 data identified changes in borehole diameter that may indicate fractures. Gamma logging measured background levels of gamma radiation at 1.5-cm intervals that reflect differing percentages of potassium feldspar clasts, glauconite layers, and clay drapes in siliciclastic units (Swanson 2007). At this site,

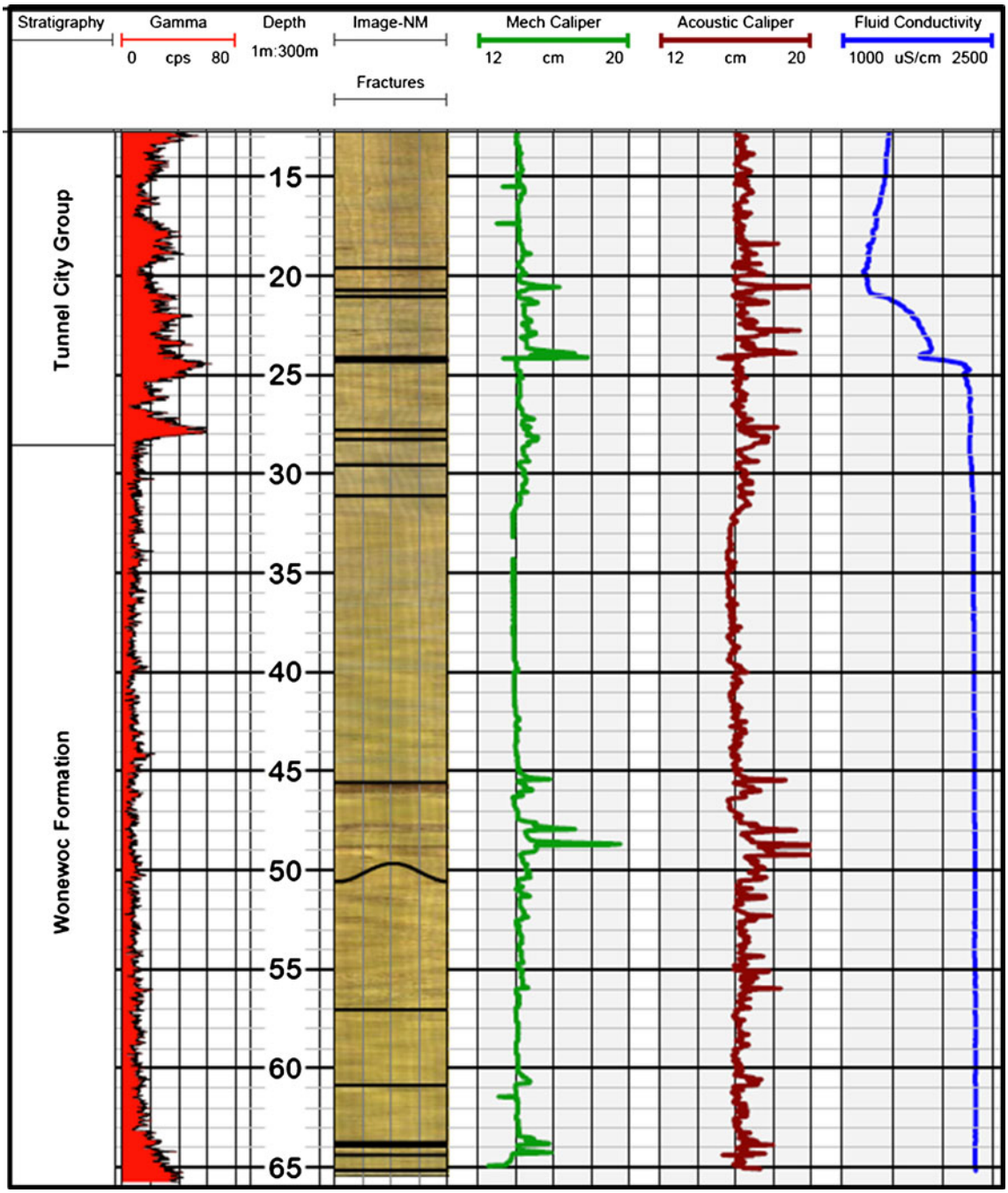

Fig. 4 Selected borehole logging data from MW-C. The *Image-NM* log was generated using the optical borehole imager (OBI) and the *Acoustic caliper* log was generated using the acoustic borehole imager (ABI)

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the Tunnel City Group and Eau Claire Formation have higher gamma readings while the clean, quartz sandstone of the Wonewoc Formation has a relatively low gamma signature (Fig. 4). Fluid temperature and electrical conductivity of the groundwater in the borehole were measured at 3-cm intervals and a mechanical caliper determined borehole diameter at 3-cm intervals.

Fracture identification in borehole MW-3 was accomplished with a combination of logs from the mechanical caliper, ABI, and OBI tools. One or more of these methods identified a total of 12 potential hydraulically significant fractures (Fig. 5). The OBI log identified all fractures but that method was subjective and based on a visual examination of the log for sections that appeared to be fractures. The OBI produces a "virtual core" that can be examined as a three-dimensional (3D) cylinder or "unrolled" and viewed as a flat, oriented surface as depicted in Fig. 4. Fractures are typically bedding parallel with an extremely narrow apparent aperture, and some surface oxidation or staining. A log of fracture position and orientation was created from the OBI data and is superimposed on the OBI log (Fig. 4). The mechanical caliper and ABI both were more quantitative and measured the diameter of the borehole, with sharp increases of more than 1.5 cm taken as an indication of a potential fracture. The mechanical caliper log identified the fewest fractures (four) and was the least sensitive of the three methods used.

Packer slug tests

The MW-C borehole was evaluated at discrete intervals with an inflatable straddle-packer assembly. The straddle packer was constructed using customized flow through packers designed for use in isolating sections of sewer pipe. These devices are lightweight but only suitable in settings with less than 10 m of head difference across the packer. When used with 5 cm (2 in.) PVC riser pipe, the packer assembly has the advantage of being light enough that it can be deployed down a borehole with a hand winch. Construction and operation details are given in the electronic supplemental material (ESM). The straddle packer was deployed at a total of 16 intervals in the borehole with 11 of those containing fractures. The open interval between the packers was 70 cm, which, in most cases, allowed the isolation of single fractures for physical testing and water-chemistry sampling.

At each interval, the packer was inflated and the water level in the riser pipe was monitored with a pressure transducer using a direct read cable to ensure equilibrium with the packed interval hydraulic head. After the head measurement was recorded, the transducer was set to record water levels at 1-sec intervals. A 2.5-cm-diameter and 1.5-m-long solid slug was rapidly inserted fully below the water level in the riser pipe for the "slug-in" test. After the water level stabilized, the slug was rapidly removed from the water column as a "slug-out" test. Two sets of slug-in and slug-out tests were conducted at most intervals. The results of the head measurements and hydraulic-conductivity values calculated from slug-tests analysis for the straddle-packer intervals are shown in Fig. 6.

Hydraulic conductivities for many packer intervals were evaluated using the KGS, Hvorslev, and Bower-Rice methods for unconfined aquifers (Butler 1998). Some intervals with particularly rapid responses and/or oscillation in the recovery data required utilization of the Springer-Gelhar method (Butler 1998) instead of the KGS method. Although there is some variation in values obtained by the three different methods at each interval, most vary by less than 15 %. The unit well was inactive for the majority of the testing but was pumped intermittently based on requirements of the Madison Water Utility. This pumping of the lower aquifer influenced water levels in the isolated zones of the upper aquifer. Changes in water levels due to pumping drawdown or recovery after pumping ceased were accounted for during slug-test data analysis by using a trend-removal function in the software.

Interval hydraulic conductivity values from the slug tests (Fig. 6) vary by more than three orders of magnitude.

		Fracture Identification Method			
Fracture Number	Depth (m)	Mechanical Caliper	Acoustic Borehole Imager	Optical Borehole Imager	Straddle Packer Hydraulic Conductivity (cm/sec) 0.01 0.1 1
1	19.5		X	X	
2	20.9	X	X	X	
3	24.1	X	X	X	
4	27.7		X	X	
5	28.0		X	X	
6	29.0		X	X	
7	30.8		X	X	
8	45.4	X	X	X	
9	50.0		X	high angle	
10	57.0			X	
11	60.7			X	
12	64.3	X	X	X	

Fig. 5 Summary of downhole logging methods that indicated potential fractures in borehole MW-C. Hydraulic conductivity values based on straddle-packer slug tests for selected intervals reveal which fractures are hydraulically important. Fractures *4* and *5* have the same hydraulic conductivity value because they were in the same packer interval

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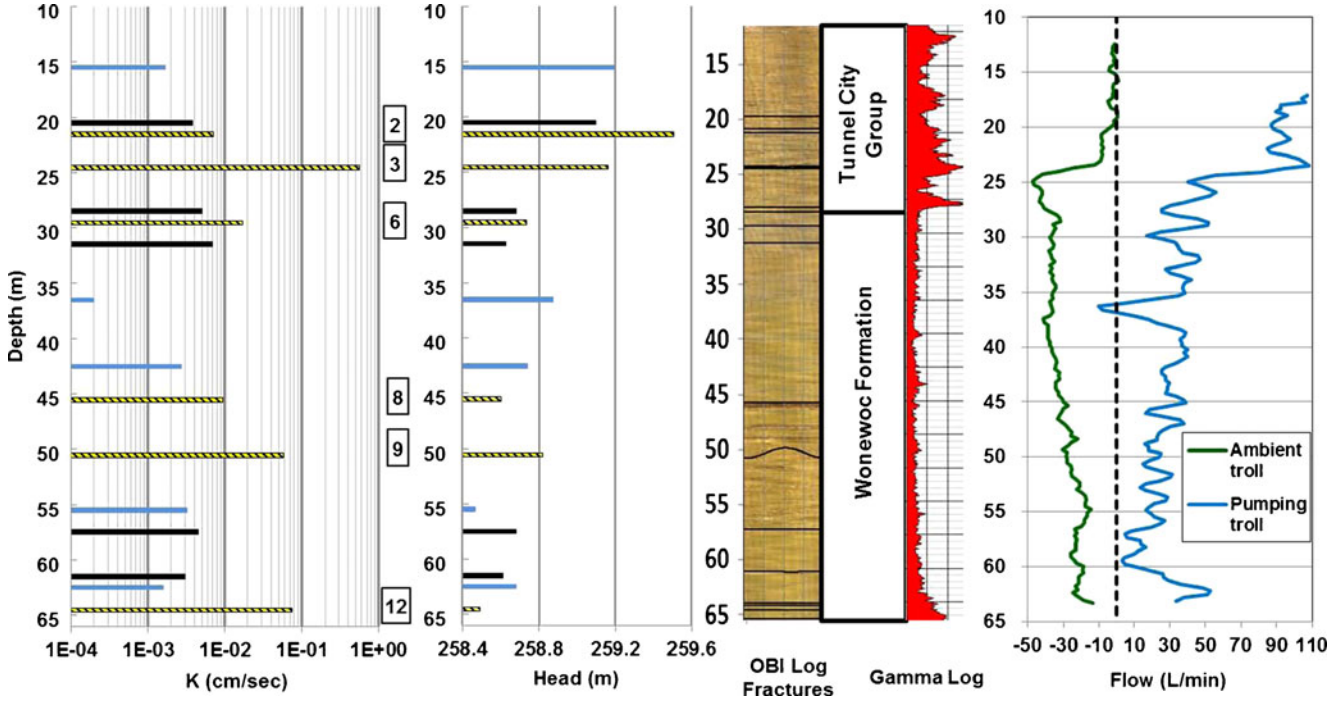

Fig. 6 Flow characterization results from borehole MW-C. Head and hydraulic conductivity and measurements from straddle-packer testing. *Lighter bars* are measurements from unfractured intevals, *solid bars* are fractured intervals, and *striped bars* are key fractures highlighted in this paper and indicated by *fracture numbers in boxes*. Fractures are shown by *lines on OBI log* with the *gamma log* used to show changes in lithology. Flow logging data presented under *ambient* and *pumping* conditions with negative flow in the downward direction

The highest value was from a fractured interval in the Tunnel City Group while the lowest value was from an unfractured interval in the Wonewoc Formation. Although some fractured intervals had higher hydraulic conductivities, other fractured intervals had values similar to those of unfractured intervals. An interval with fractures was considered to be matrix dominated if the hydraulic conductivity was similar to unfractured intervals. Fractured dominated interval values range from 9.4×10^{-3} to 5.5×10^{-1} cm/sec with a geometric mean of 5.2×10^{-2} cm/sec. Values for the matrix dominated intervals range from 2.0×10^{-4} to 7.0×10^{-3} cm/sec with a geometric mean of 2.7×10^{-3} cm/sec. Changes in hydraulic conductivity do not appear to be related to depth or lithology.

In addition to identifying fractures, it is important to determine which methods are best for identifying the most hydraulically significant fractures. The results of straddle-packer-slug-test hydraulic conductivity values for 12 of the fractured intervals identified in the borehole are listed in Fig. 5. The hydraulic conductivity values range from 3.1×10^{-3} to 5.5×10^{-1} cm/sec but only four of the values exceed 10^{-2} cm/sec. The two fractured intervals with the highest hydraulic conductivity values were detected by all three logs, while the third and fourth highest values were only detected by the OBI and ABI logs. In order to locate the most hydraulically significant fractures for rapid transport of contaminants, a combination of all three methods is ideal. However, the ABI and OBI tools appear to be superior to using only the mechanical caliper tool for identification of the most hydraulically significant fractures. The potential fractures were considered confirmed when they were detected by both the OBI log and either the mechanical caliper or the ABI log.

Borehole pumping test

A pumping test in the MW-C borehole was conducted in May 2011 to evaluate aquifer properties. The borehole was pumped for approximately 20 h at a discharge of approximately 95 L/min. Water levels from the shallower monitoring wells and the pumped borehole were analyzed using the Moench (1984) solution for a fractured aquifer with slab blocks. The bulk transmissivity of the borehole was calculated as 49.9 cm^2/sec with a fracture system value of 28.8 cm^2/sec and a matrix system value of 21.1 cm^2/sec based on a saturated borehole thickness of 54.25 m.

Vertical flow assessment

Vertical groundwater flow in the borehole was measured with two devices: an impeller flow meter for higher flows and a heat pulse flow meter for flows below 3.8 L/min. Data were recorded while trolling the tools both upward and downward in the borehole. Flow-meter logging was conducted initially under ambient conditions and with the unit well inactive, followed by dynamic-flow-meter logging by pumping the borehole to stress the system. Logging under ambient conditions initially used the heat pulse flow meter. This instrument was not useful due to high vertical flow in the borehole and the impeller flow

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meter was required for ambient and dynamic flow logging. The first iteration of dynamic logging utilized a submersible pump with a maximum discharge of approximately 15 L/min, but this did not adequately stress the system. The second iteration used a larger submersible pump with a discharge of approximately 95 L/min. The pumps were placed at the top of the water column and the flow meter logged from the bottom of the borehole upward and then from near the top of the water column downward.

The vertical flow assessment allowed for characterization of the flow in the borehole and identified locations that substantially contributed to changes in flow. Figure 6 shows the results of the ambient and pumping flow logging in the borehole using the impeller flowmeter. The ambient flow data are from upward trolling only because at some points during downward logging the tool was moving at nearly the same velocity as the flow in the borehole. This resulted in relative flow velocities too low to accurately measure with the impeller. Flow at the top of the ambient log is initially downward at approximately 1 L/min, then increases to approximately 5 L/min at 23 m bgs before rapidly increasing to greater than 40 L/min after 24 m bgs. This rapid increase in downward flow corresponds to the large fracture at 24.1 m (fracture 3). The flow decreases steadily between 24 and 55 m and then remains relatively stable until a sharp decrease at the bottom of the borehole. The reduction in downward flow is probably due to a loss of water into fractures 8 and 9, although some loss into the matrix of the Wonewoc Formation is possible. Due to a concern of fouling the impeller at the bottom of the borehole, logging was not conducted below 63 m. Because the downward flow has to exit the borehole in order to balance the inflow (i.e. there is no increase in well bore storage), it is assumed that remaining flow exits the borehole from the lowest fractures near 64 m. The pumping flow-log data were highly variable and a 3-point moving average is shown in Fig. 6 to reduce the signal noise. Even with this attempt to smooth the data, two data points near 37 m bgs deviate enough to indicate an apparent reversal of flow in an unfractured, relatively low hydraulic conductivity zone of the Wonewoc Formation. The apparent flow reversal is likely due to an error with the flow meter, possibly due to sediment becoming temporarily lodged in the impeller. It is unlikely that flow reversed in this section of the borehole. Even with the variability in the data it is still possible to see the same sudden shift in flow as was observed in the ambient flow log at fracture 3.

Conceptual model for fracture connectivity

Analysis of the shapes of the fracture traces from the OBI log implemented in the software package WellCAD version 4.3 (Advanced Logic Technologies Inc 2009) yielded the orientation of each fracture. Many of the fractures in the OBI log have dip angles between 3 and 11° from the horizontal. The true dip angle may be several degrees different than the measured values due to errors in manually drawn fracture traces on the OBI log. Table 3 lists the orientation of the six most important fractures discussed in this paper. The Tunnel City Group and Wonewoc Formation are nearly horizontal at the regional scale but locally some beds may dip at higher angles (Swanson 2007). It is possible that many of the low angle fractures listed in Table 3 are bedding-plane-controlled and detailed analysis of the OBI log indicates these fractures do not cross bedding planes within the MW-C borehole.

High angle fractures are difficult to detect in vertical boreholes but are important for understanding fracture connectivity. One high angle fracture was discovered in the borehole at 50.0 m (fracture 9). This fracture has a dip azimuth of 12° (strike of 102°) and dips to the north at 84° from the horizontal. At this dip angle and direction, if the fracture continues downward, it would intersect the Eau Claire aquitard between the monitoring wells and the unit well with the potential of intersecting UW-7 in the Mount Simon Formation open borehole. Projecting fracture 9 upward, it would not intersect the other two monitoring wells but would intersect other fractures within a few meters of the MW-A and MW-B well screens.

Work by Runkel et al. (2006) and Swanson (2007) used several methods to identify bedding parallel fractures in these same Cambrian-age siliclastic units based on lithological controls. These methods sought to associate fractures with either stratigraphic position or physical properties of the bedrock in order to facilitate identification of connected fractures between locations. Those methods are useful for fractures that run parallel to bedding planes in a stratigraphic section that does not vary laterally. However, fractures that are not parallel to bedding or not controlled by changes in lithology may be difficult to identify with those methods. Work by Meyer et al. (2008) described the presence of many low-angle bedding-plane fractures in these units in addition to some vertical and oblique fractures present in the Tunnel City Group. Data from Table 3 indicate some fractures are not horizontal and may not be associated with bedding planes. This is especially true for fracture 9, which is nearly vertical.

To best visualize the relationships among the fractures, monitoring wells, and the unit well, a conceptual model was created from data obtained from the site. The fractures, monitoring wells, and the unit well were incorporated into a 3D model with the software package FracMan version 7.3 (Golder 2010). The 3D model was then projected onto a north–south oriented plane viewed

Table 3 Orientation of selected fractures in borehole MW-C based on WellCAD analysis of fracture log. Transmissivity and head data are from straddle-packer slug testing of those intervals

Fracture No.	Depth (m)	Azimuth (deg)	Dip (deg)	Transmissivity (cm^2/sec)	Head (m)
2	20.9	183	5	0.5	259.5
3	24.1	178	9	39.0	259.2
6	29.0	148	5	1.2	258.7
8	45.5	168	4	0.7	258.6
9	50.0	12	84	4.0	258.8
12	64.3	126	3	5.2	258.5

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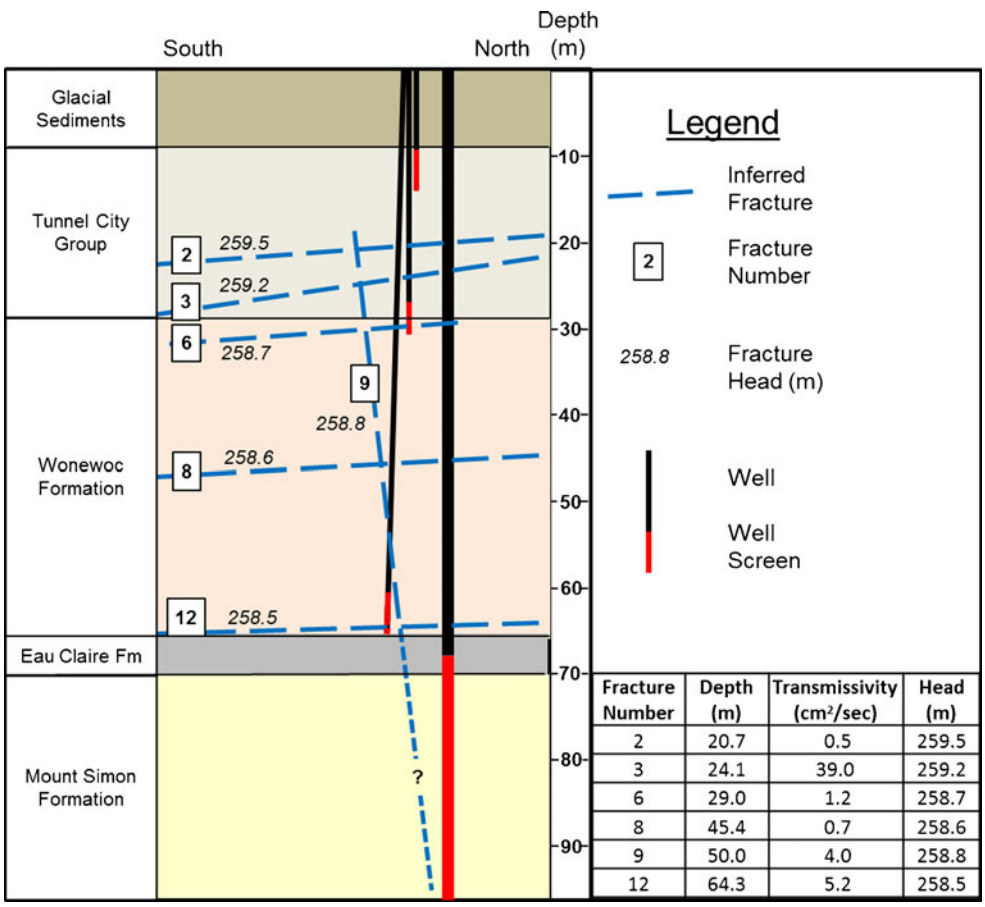
from the east in order to create a two-dimensional (2D) model similar to Fig. 3. This conceptual model of fracture connectivity (Fig. 7) was completed by including information about the stratigraphy and fracture hydraulic heads. The data on the orientation and position of the fractures in the upper aquifer are from the MW-C borehole OBI log but the model assumes the fractures extend far enough to connect with each other.

During May 2012 the Madison Water Utility removed the pump from UW-7 in order to perform maintenance. The unit well is cased to 72 m bgs, which is the middle of the Eau Claire Formation, and beneath a 3-m-thick shale layer. Geophysical logging data from the UW-7 borehole revealed fractures in the lower portion of the Eau Claire Formation and the Mount Simon Formation. The UW-7 borehole has a much larger diameter than MW-C, ranging from 41 cm to more than 1.0 m in several open voids. This greater diameter reduced the resolution of the OBI and ABI tools. The OBI log indicated a vertical fracture along most of the UW-7. This fracture is likely to be related to blasting of the borehole during well construction to increase production. The fracture in UW-7 is probably not the same high-angle fracture (fracture 9) discovered in MW-C. It is possible a high-angle fracture may connect the upper and lower aquifers, but in Fig. 7 the extension of fracture 9 in these formations is given a dotted line due to the amount of uncertainty.

When placed in their proper spatial orientations, the fracture hydraulic heads provide a good match to the expected vertical hydraulic gradient in the upper aquifer that would generate downward flow. In Fig. 7, the fracture heads in the near horizontal fractures steadily drop with depth from 259.5 to 258.5 m. The head in fracture 9 is 258.8 m, which is close to the 258.9 m average value of the other five fractures and supports the view that this high-angle fracture is connected to the others. If fracture 9 were either not connected to other fractures or terminated before reaching fractures 8 and 12, the expected head would be between 258.5 and 258.6 m, based on the vertical gradient in this section of the upper aquifer. The head in UW-7, which is open to the Mount Simon Formation, was measured after the well had not been pumped for more than week. In this approximately static condition the head in the lower aquifer was 1.4 m less than the head measured at the base of the upper aquifer in MW-C (Fig. 3). This is approximately the head difference between the Mount Simon aquifer and the upper aquifer simulated using the numerical groundwater flow model for Dane County, Wisconsin (Krohleski et al. 2000) under similar conditions. Based on head data, it appears that if



Fracture Number	Depth (m)	Transmissivity (cm²/sec)	Head (m)
2	20.7	0.5	259.5
3	24.1	39.0	259.2
6	29.0	1.2	258.7
8	45.4	0.7	258.6
9	50.0	4.0	258.8
12	64.3	5.2	258.5

Fig. 7 Conceptual model of fracture connectivity at UW-7 based on a FracMan model projected onto a north–south plane viewed from the east. The deepest monitoring well (MW-C) deviates approximately 3 m to the south at the bottom of the hole, and fracture orientations were adjusted to account for the deviation. Hydraulic head data for each fracture is based on straddle-packer testing in the MW-C borehole. The lower 100+ m of the Mount Simon Formation and UW-7 are not shown (for location of wells see Fig. 3)

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fracture 9 extends through the Eau Claire Formation, it is not well connected to the Mount Simon Formation while UW-7 is not pumping. During pumping, the head in the UW-7 borehole can drop up to 49 m from static levels. It is possible that based on the head drop in both MW-B and MW-C that the head in fracture 9 might drop substantially when UW-7 is pumping and reflect a hydraulic connection with the lower aquifer as the head difference increases substantially.

Evaluation of hydrogeological properties

As described in previous sections, three methods were used to evaluate hydrogeologic properties of flow in the MW-C borehole: pumping test, straddle-packer slug tests, and flow logging. The pumping test investigated bulk properties of the entire saturated thickness of the borehole while the straddle-packer-determined properties of distinct intervals, many of those containing fractures. The pumping test data indicate that approximately 60 % of the borehole transmissivity is from fractures. Since the fractures are assumed to be responsible for the much higher interval hydraulic conductivities determined from analysis of packer slug tests, the effective hydraulic conductivity value for each packed-off interval containing a fracture was attributed entirely to flow through the fracture. The hydraulic conductivity was multiplied by the 70-cm straddle-packer open interval to determine the fracture transmissivity (T_{fi}) [L^2/T] for each fracture using the following formula

$$T_{fi} = K_{fi} \times b_{fi} \quad (2)$$

where K_{fi} is the hydraulic conductivity [L/T] of packed interval i and b_{fi} is the length of packed interval i [L]. (Note that the slug tests actually measured transmissivity for the intervals but each T had been converted to effective K by dividing by the interval length of 70 cm during the initial data analysis.)

The five fractured intervals accounting for 96 % of the fractured transmissivity (fractures 3, 6, 8, 9, and 12) were added together to calculate the total T_f value of 50.1 cm^2/sec. The other fractured interval data were similar to unfractured intervals and assumed to be dominated by matrix flow. Each of the five fractures was estimated to have a negligible aperture. Therefore, the total matrix thickness (b_m) was assumed to be equal to the saturated thickness of 54.25 m. The matrix hydraulic conductivity (K_m) values of the five unfractured packer intervals had a geometric mean of 1.4 x10^{-3} cm/sec and T_m was determined by the formula

$$T_m = K_m \times b_m \quad (3)$$

as 7.6 cm^2/sec. The total transmissivity of 57.7 cm^2/sec is the sum of the matrix and fracture transmissivity values. Based on packer data, these five fractures represent more than 80 % of the total transmissivity in the borehole.

The borehole flow logging provided data for analyzing the contributions of different zones to overall flow. The vertical flow assessment (Fig. 6) revealed several important pieces of information about flow in the borehole and the importance of fractures. The ambient-flow-log inflow data from 12 m to 23 m account for approximately 20 % of the maximum flow and may be due to a combination of inflow from fractures and aquifer matrix. The remaining 80 % of maximum inflow can be attributed to fracture 3, which had the highest transmissivity value (Table 3). Below 25 m the flow decreases, but not uniformly. Approximately 20 % of the flow is lost in the vicinity of fracture 6. Approximately 50 % of flow is lost in the next 27-m interval, which contains fractures 8 and 9, both with high transmissivity values. One of these is the high angle fracture 9 at 50 m that had the third highest straddle-packer transmissivity value. The remainder of the flow (approximately 30 % of maximum flow) exits the borehole via fracture 12, which had the second highest straddle-packer transmissivity value.

A more quantitative approach to analyzing borehole flow logging data involves the use of a numerical model to determine transmissivity values of fractured intervals (Paillet 1998, 2000). The computer program FLASH (Flow-Log Analysis of Single Holes) provides an easy-to-use interface for modeling flow in boreholes using a multi-layer Thiem solution based on data from ambient and pumping conditions (Day-Lewis et al. 2011). The FLASH program was used in "fracture" mode instead of "layer" mode because even with a combination of fracture and porous media flow in the data, it appeared fracture flow dominated the system. The left side of Fig. 8 contains the flow logging data overlain with an interpreted profile required by the FLASH program to determine each layer. Interpreted profiles were used as a best fit to the field data and highlighted substantial changes in borehole flow. The greatest inflections in the interpreted data were used as the depths of fracture zones.

The FLASH solution is a good match to the fracture zone boundaries. The solution slightly overestimates the flow at the top of both ambient and pumping flow but closely matches all other sections of the graphs. The transmissivity results of the analysis are presented in Table 4. The majority of the transmissivity in the model is from zones D and C, which approximate the positions of fractures 12 and 9 respectively. Zones B and A also contain hydraulically significant fractures 6 and 3 respectively, which account for a substantial portion of the overall transmissivity. Only four layers with substantial borehole flow changes were evaluated with the FLASH program and consequently not all of the transmissivity was accounted for in this analysis. The transmissivity of the borehole related to these four layers associated with fracture flow was calculated at 39.3 cm^2/sec, which compared with straddle-packer data is approximately 80 % of the fracture T and 65 % of the total T.

The three methods used to evaluate the aquifer provide similar information about the nature of fracture contribution to flow in the upper aquifer. The total T value for the pumping test data was 49.9 cm^2/sec with 60 % (29.9 cm^2/sec) of the contribution from fractures. The straddle-packer data indicate a total T of 57.7 cm^2/sec with 80 % (46.2 cm^2/sec) of the contribution from fractures. The flow

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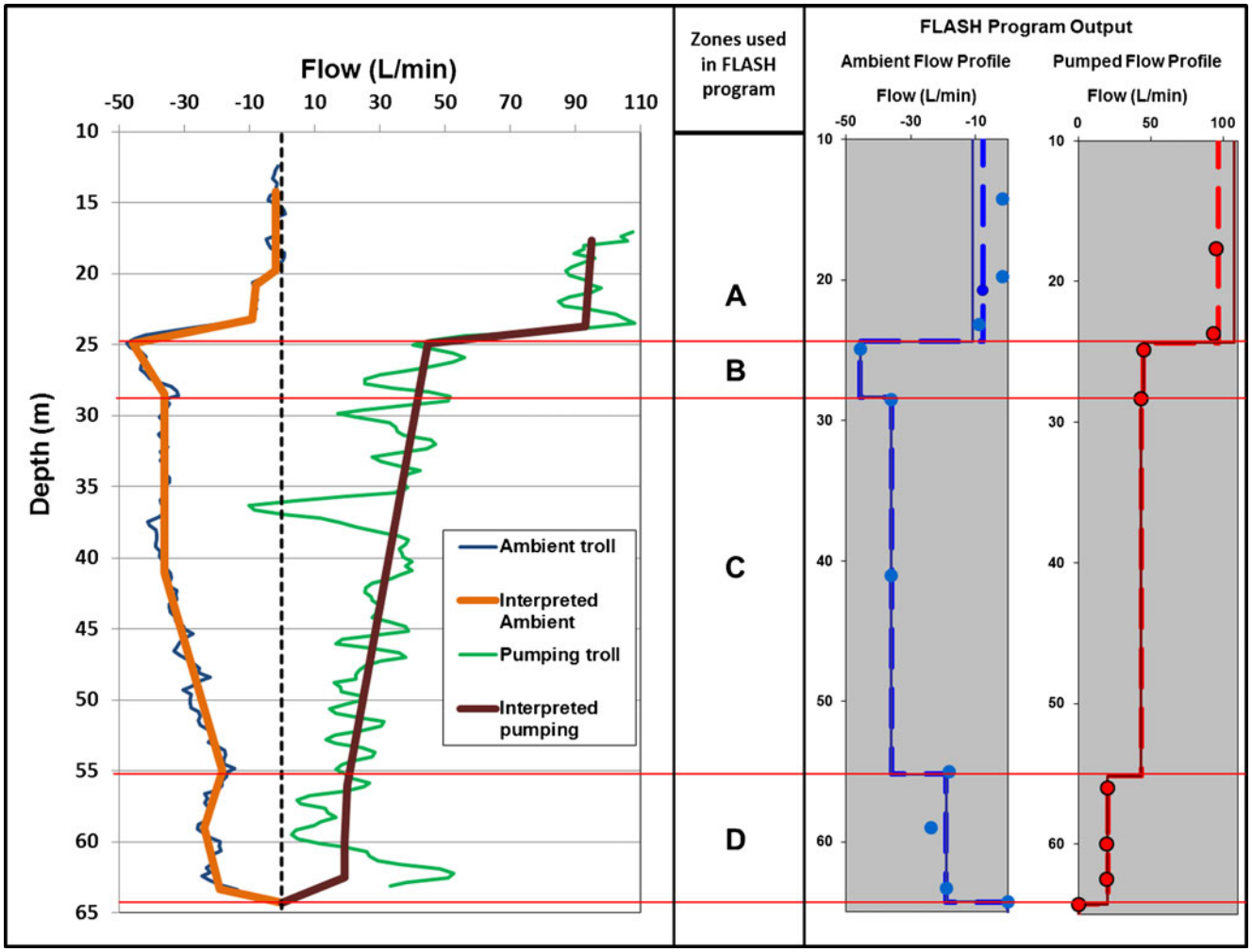

Fig. 8 Results of borehole flow logging including data from both ambient and pumping conditions. Interpretated lines and layer numbers were used for determining transmissivity values in the FLASH computer program. The *right side* of the figure is the FLASH output, which includes field data (*circles*), user-defined fracture zone boundaries (*dashed lines*), and a program simultaneously generated a best fit solution (*solid line*) for both ambient and pumping data

logging analysis with the FLASH computer program only evaluated the four intervals with the greatest change in flow. Those fractured intervals had a T value of 39.9 cm^2/sec, which is comparable to the fracture values of the other methods. Based on these methods, the majority of transmissivity in the MW-C borehole can be attributed to fractures.

Comparison of groundwater chemistry between fractures

During August and September 2011 water-chemistry samples were collected from 12 of the 16 packed intervals. A submersible pump was used to purge three well volumes from the 5 cm (2 in.) riser pipe before collecting a 1-L grab sample. Each sample was sent to a laboratory and analyzed for major anions, major cations, and alkalinity. Field measurements of pH, temperature, and electrical conductivity were also recorded from the pumped water at the time of sampling. Plots of selected water chemistry parameters are shown in Fig. 9. For reference, the position of fractured intervals and monitoring well screens are given on the right side of the figure.

The water chemistry data from the summer 2010 preliminary sampling (Table 2) revealed higher concentrations of sodium, chloride, bromide, and nitrate in the deeper monitoring well (MW-B) compared with the water-table monitoring well. The straddle packer was used in borehole MW-C to sample groundwater with greater spatial resolution than possible using the monitoring wells. The focus was primarily on isolating fractures for sampling, but unfractured intervals were also sampled for comparison. Intervals with fractures were evaluated to determine if they contained high levels of wastewater indicators similar to those found in MW-B. It proved impossible to sample an interval at the same depth as the MW-A well screen because the interval pumped dry during purging and the recovery period following purging was very long.

A comparison of chemical parameters at each interval sampled in the borehole MW-C (Fig. 9) highlights several interesting relationships. Specific intervals had concentrations that were either significantly above or below the

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Table 4 Transmissivity data from the FLASH computer program for layers in borehole MW-C

FLASH layer	Fracture No.	Depth [m]	Layer T [cm^2/sec]	Fraction of total transmissivity
A	3	24.9	9.2	0.23
B	6	28.3	3.7	0.10
C	9	55.2	13.3	0.34
D	12	64.3	13.0	0.33

average values for all straddle-packer samples. Fracture 2 contained elevated levels of several constituents also found in MW-B samples. However, the screened interval of MW-B is from 27.5–30.5 m and none of the fractures (4–6) in that zone that were sampled with the straddle packer contained similar levels of chloride, bromide, or sodium. The wastewater indicator values from Table 2 are compared with the addition of data from fracture 2 in Fig. 10. The concentrations of chloride, bromide, and sodium in both MW-B and fracture 2 were higher than other intervals. Electrical conductivity values for fracture 2 and MW-B (2,900 and 2,428 μS/cm respectively) were approximately twice the values from other sampling locations at the site. The concentration of nitrate was elevated in all packer samples below 20 m and not correlated with other potential wastewater indicators. The source of these wastewater indicators was most likely not groundwater from fractures that intersect the MW-B well screen, but from fracture 2 that is located at a shallower depth in the aquifer.

A preferential flow pathway is the most probable mechanism to allow the groundwater in fracture 2 to reach the MW-B well screen during sampling. Based on the fracture conceptual model (Fig. 7), it is likely that the pumping of 1,000 L of groundwater from MW-B over several hours during virus sampling lowered the head in fracture 6 and likely the high angle fracture 9. This enabled the groundwater from fracture 2 to travel though these other fractures to reach MW-B. The head in fracture 2 is higher than that for any of the other intervals tested although the *T* value is lower than that of other fractures in the conceptual model. The reduction in head in fractures 6 and 9 near the MW-B well screen during sampling may have generated a head difference that was great enough to allow groundwater to rapidly travel to the MW-B well screen.

Electrical conductivity measurements (Table 5) taken from several packer intervals in MW-C and the adjacent MW-B well screen under a variety of conditions provide additional evidence of fracture connectivity. Water-conductivity measurements during static conditions within the straddle packer were collected with a combination pressure/conductivity logger lowered into the screened interval after heads reached equilibrium with the packed interval. Conductivity measurements from a shallow fracture (fracture 2) and fractures at the same depth as the MW-B screen (fractures 4–6) during static (non-sampling) conditions were much lower than during sampling conditions. Conductivity measurements collected during geophysical logging of MW-C (Fig. 4) also show distinct changes near fractured intervals.

Changes in conductivity values from static to pumping conditions are useful in analyzing the transient nature of transport through fractures. Beside static conditions, two other types of measurements are listed in Table 5. During straddle-packer sampling in MW-C, the unit well was inactive and the packed interval was pumped with a submersible pump at a rate of 8–10 L/min for approximately 10 min to purge the temporary piezometer and collect water-chemistry samples. Conductivity readings in all intervals taken after sample collection were somewhat elevated compared with the static readings but the conductivity at the fracture 2 interval was substantially higher than those in the intervals at the same depth as the MW-B screen. During six virus-sampling rounds

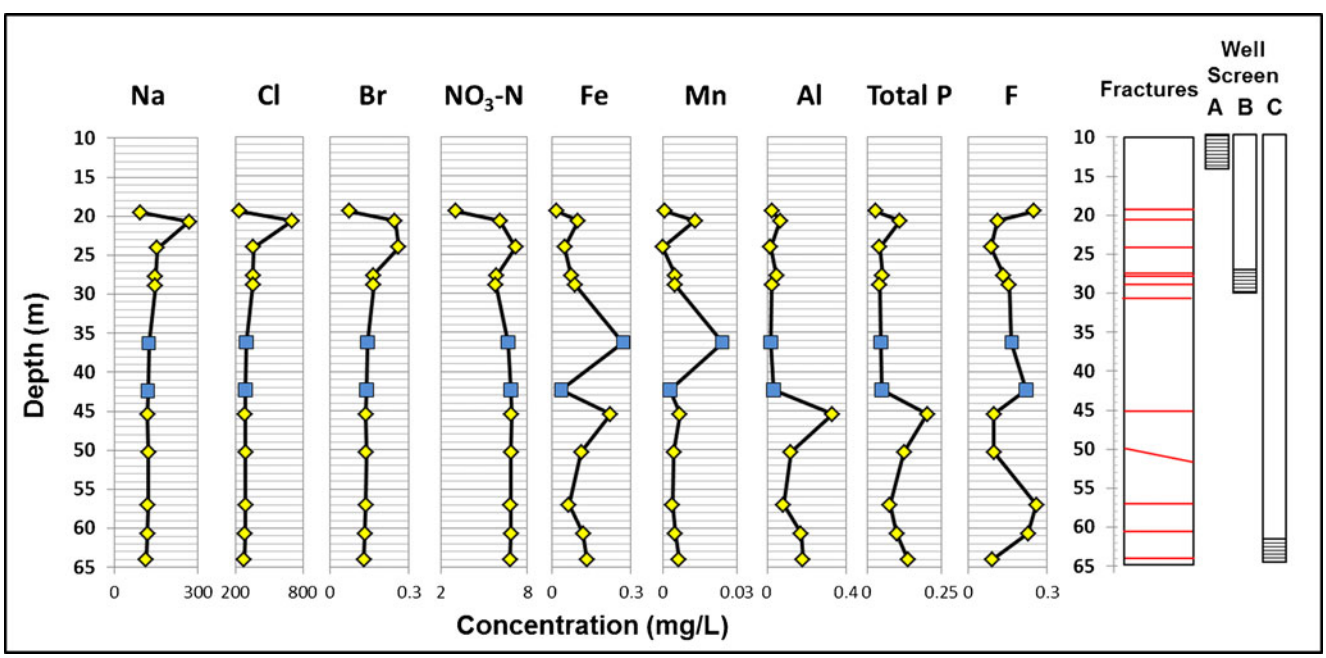

Fig. 9 Water-chemistry data from straddle-packer intervals. *Diamond data points* are fractured intervals and *square data points* are matrix intervals. Fractured intervals and position of monitoring well screens are included for reference

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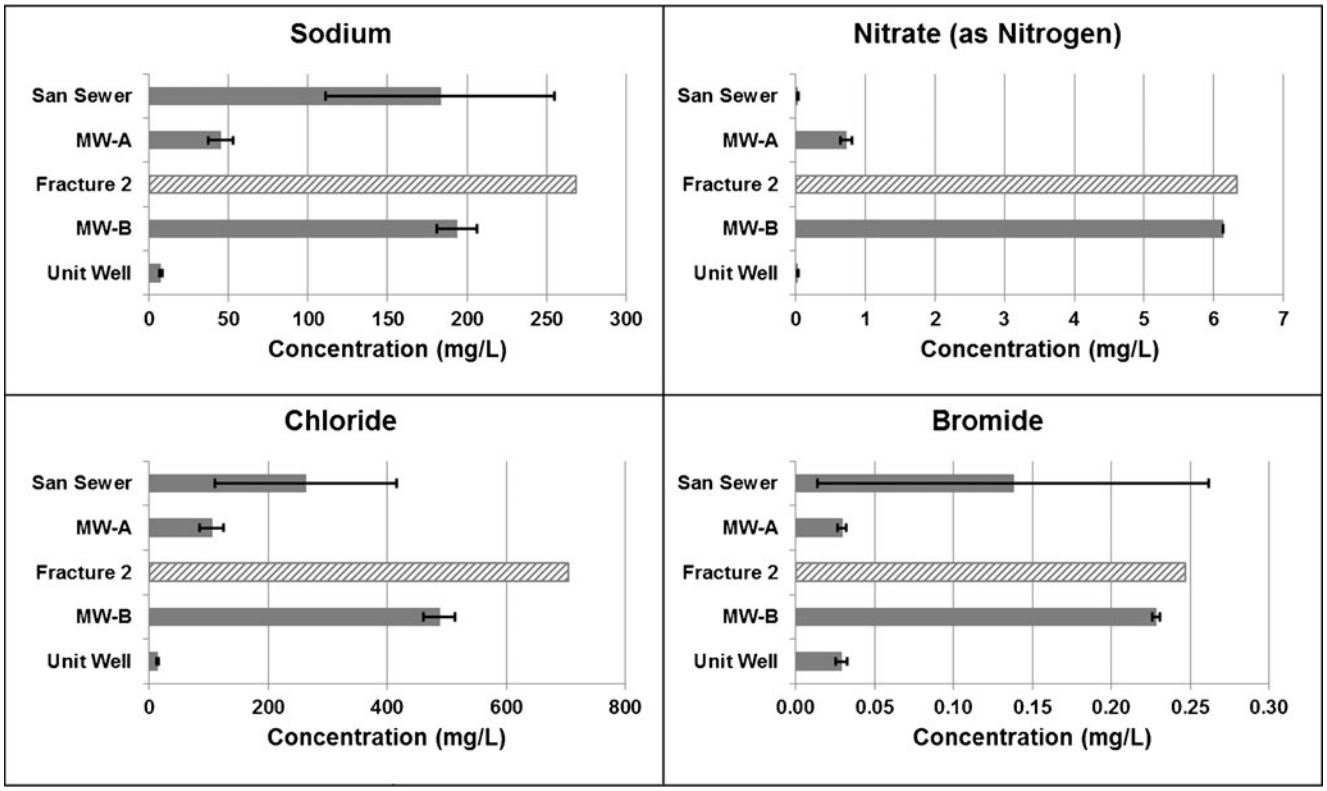

Fig. 10 Water chemistry data from 2010 sampling (Table 2) with the addition of data from *fracture 2* straddle-packer interval. *Error bars* indicate one standard deviation from six sampling events

of the monitoring wells in 2010, the unit well was pumping due to the need to collect virus samples from that well. A submersible pump sampled MW-B at a low rate (4 L/min) for several hours in order to obtain the required volume of 1,000 L for the virus sample. Conductivity readings were usually taken from MW-B near the beginning and at the end of sampling and readings were significantly higher than either static levels in MW-B or in the other sampled wells. As mentioned earlier, pressure transducer data indicate pumping of the unit well causes a head change in MW-B on the order of tens of centimeters. Sampling of MW-B likely allowed water with higher conductivity and wastewater indicators to reach the MW-B screened interval. Under conditions where sampling is conducted at a higher discharge but for a shorter period of time, the conductivity and wastewater indicator values were much lower.

The data in Fig. 9 indicate that some fractures in the MW-C borehole contain groundwater with a distinctive chemical composition characterized by either above average or below average concentrations of major ions compared with other sampled intervals. The sample from fracture 2 contained groundwater with elevated levels of chloride, bromide, and sodium while the sample from fracture 8 contained high levels of aluminum, iron, and total phosphorus. Although some fractures may have a distinct chemical signature, many other fractures share a similar profile of major ions. These fractures are likely to be more hydraulically connected to each other than fractures with a different major ion profile. Based on the head data from Fig. 6, there appears to be no uniform hydraulic gradient in the upper aquifer. However, only looking at fracture head data (Fig. 7) there appears to be a uniform vertical gradient indicating downward flow. Comparison of fractured-interval water chemistry revealed correlations that may indicate they are part of the same flow pathway. The high angle fracture (fracture 9) and fracture 6 have similar concentrations of major ions and have similar head values. Fractures that have similar groundwater chemistry and similar head measurements are more likely to be connected to each other.

Discussion

Recognition of fractures in an aquifer system may alter the way in which the hydrostratigraphy of the system is evaluated. Although hydrostratigraphic units have been in use for several decades, the general trend is to define units based on the ability of lithologic units to transmit and store groundwater (Maxey 1964; Seaber 1988). More recent work by Meyer et al. (2008) divided the bedrock aquifer system at a site near Madison, Wisconsin using a hydrogeological unit (HGU) concept, which is based on changes in detailed head measurements with depth in a borehole. A head loss of between 2 and 35% of the total head in the borehole was used as a basis for delineating distinct HGUs and head values showed a progressive decrease with depth. The boundaries between HGUs are explained by Meyer et al. 2008) as poorly connected bedding parallel fractures which limit vertical flow.

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Table 5 Electrical conductivity (EC) measurements of groundwater from selected MW-C straddle-packer intervals and MW-B well-screen interval

Fracture No.	Fracture depth (m)	EC measurements (μS/cm)		
		MW-C straddle-packer data		MW-B well screen
		Static conditions	1-L chemistry grab sample (Unit Well off)	1,000-L virus sampling at ~4 L/min (unit well pumping)
2	20.9	1,125	2,900	–
4–5	27.7–28.0	1,250	1,760	2,220–2,630 (6 samples)
6	29.0	1,240	1,773	

However, at locations near an active public supply well these changes in head may be dynamic and reflect differences in responses to pumping.

Hydraulic heads measured using a straddle packer in borehole MW-C varied substantially between individual fractures (Fig. 6) and did not decrease uniformly with depth. In most cases, heads increased or decreased between individual intervals with a range of 5 and 46% of the total head loss. The unit well was pumping during shallow interval testing but not during periods when data were collected below 30 m. The unit well was pumped each night during the several days of straddle-packer testing. This dynamic system likely resulted in fractured intervals achieving steady-state heads quickly while the matrix heads took longer to respond. If analyzed separately from other data, the heads in the low angle, high *T* fractures (fractures 2, 3, 6, 8, and 12 in Fig. 6) show a uniform decrease with depth.

In general, straddle-packer tests yielded greater interval hydraulic conductivities for intervals containing fractures (Fig. 6). Both straddle-packer and vertical-flow logging data indicate the majority of transmissivity in the borehole is related to flow from a small number of fractures. When considering contaminant transport in settings similar to UW-7, the individual fractures may be considered the actual "aquifers" due to much higher transmissivity and contribution to overall flow. The siliciclastic bedrock (mostly sandstone) may therefore act as a "relative aquitard" (especially in the vertical direction) due to transmissivity values several orders of magnitude lower than those of adjacent fractures. This is especially relevant for issues of transport related to viruses and other contaminants that are an acute health threat at very low levels. Fractured sandstone may act as a dual porosity system horizontally and vertically, with certain fractures containing wastewater contaminants under static conditions. Other fractures may function as vertical and horizontal pathways through which those contaminants migrate under the influence of pumping and the resulting change in hydraulic gradients within the fracture network.

High angle and/or vertical fractures are important for connectivity in a system where the majority of fractures have low dip angles. Logs from the MW-C borehole revealed only one high angle fracture in the Wonewoc Formation that may serve as a near vertical conduit of contaminants. The OBI-40 tool revealed a vertical fracture along most of the UW-7 borehole. The vertical fracture in UW-7 is possibly related to blasting in the borehole during well construction. Detecting vertical or high angle fractures can be problematic in a vertical borehole due to relative orientations. In addition, high-angle fractures may terminate at lithologic boundaries making it difficult to determine if a single fracture extends vertically through the aquifer system to connect several important fractures. It is likely that the high-angle fracture (fracture 9) in MW-C extends upward and connects to the other important fractures previously mentioned. It is also possible fracture 9 extends downward through the Eau Claire and Mount Simon Formations and connects directly with UW-7. Other boreholes in the Madison area logged by the Wisconsin Geological and Natural History Survey using the same methods as this study have intersected multiple high-angle fractures in the same bedrock units involved in this study, specifically high angle fractures in both the Eau Claire and Mount Simon Formations.

Conclusion

Microbiological contamination of deep, confined public supply wells in siliciclastic bedrock has generally been considered to be minimal due to assumed travel times that exceed the periods for which viruses remain infective. Advective-flow calculations based on porous-media assumptions indicate that viruses from sanitary sewers will not reach Madison UW-7 during the 1–2 year period in which the viruses are able to infect humans. However, infectious human enteric viruses have been detected in UW-7 and other deep, confined public supply wells in Madison. Rapid travel times required for infectious viruses to reach public supply wells suggests a preferential flow pathway is the most likely mechanism.

The results of this study support the hypothesis that fractures play an important role in movement of groundwater and transport of sewer-derived wastewater contaminants near a public supply well. Based on the work reported here, fracture flow can serve as the primary mechanism of horizontal and vertical contaminant transport in a siliciclastic aquifer system. We have shown that fractures are present and have individual transmissivities several orders of magnitude higher than the remainder of the aquifer system. Most fractures at the study site dip less than 10° from the horizontal and could allow long range, shallow transport of near surface contaminants.

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Groundwater chemistry is variable among fractures on spatial and temporal scales. The presence of wastewater indicators in fracture 2 make it the likely source of contaminants detected in MW-B. These contaminants may also reach UW-7, although dilution minimizes the level of major ions to near background levels. Viruses, with their much lower detection limit, can be detected in a public supply well even after large amounts of dilution. This work has demonstrated a combination of geophysical logging, straddle packer, pumping test, and flow logging data that can be used to quantify the amount of transmissivity attributed to fractures. Furthermore, these methods can be used to identify the most hydraulically important fractures, which is essential to development of a conceptual model of fracture connectivity.

The identification and characterization of fracture flow and its contribution to contaminant transport is an important component of assessing the vulnerability of public supply wells in these settings. In urban areas with sandstone aquifers and public supply wells, leaking sewer effluent may travel greater lateral distances more rapidly than previously considered. The presence of vertical or high angle fractures adjacent to a public supply well could allow contaminants to rapidly migrate downward and enter the well. In fractured aquifers at risk of groundwater contamination, the proximity of a high-capacity well is a major factor in contaminant transport. The frequent pumping of a high-capacity public supply well can cause rapid, substantial head changes that may propagate through a fracture network. These head changes may alter the flow through the fracture network and allow contaminants to migrate into wells on time scales much faster than under steady-state conditions. Wellhead protection strategies for this and similar sites must account for the presence of fractures and their potential role in contaminant transport.

Even in sandstone aquifers it is important to identify fractures and characterize their role in groundwater flow to wells. Unlike traditional applications of hydrostratigraphy, in fractured siliciclastic aquifer systems, a small number of individual fractures with high transmissivity values may serve as the relative "aquifers" supplying the majority of flow to wells and serving as conduits for contaminant transport. The sandstone matrix that may normally be considered the aquifer (but with a much lower transmissivity than the fractures) may serve as a relative "aquitard" that inhibits the migration of viruses and other near-surface contaminants on a time scale of several years.

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