Groundwater

# Reverse Water-Level Fluctuations Associated with Fracture Connectivity

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## Abstract

Reverse water-level fluctuations (RWFs), a phenomenon in which water levels rise briefly in response to pumping, were detected in monitoring wells in a fractured siliciclastic aquifer system near a deep public supply well. The magnitude and timing of RWFs provide important information that can help interpret aquifer hydraulics near pumping wells. A RWF in a well is normally attributed to poroelastic coupling between the solid and fluid components in an aquifer system. In addition to revealing classical pumping-induced poroelastic RWFs, data from pressure transducers located at varying depths and distances from the public supply well suggest that the RWFs propagate rapidly through fractures to influence wells hundreds of meters from the pumping well. The rate and cycling frequency of pumping is an important factor in the magnitude of RWFs. The pattern of RWF propagation can be used to better define fracture connectivity in an aquifer system. Rapid, cyclic head changes due to RWFs may also serve as a mechanism for contaminant transport.

## Introduction

Pumping a confined or semiconfined aquifer can affect hydraulic heads in overlying aquitards and aquifers. In some instances, a "reverse water-level fluctuation" (RWF) is observed in which the initial head responses during pumping are the opposite of what is normally expected (Andreasen and Brookhart 1963); pumping of a well in one aquifer causes heads in adjacent units to temporarily rise before falling. Similarly, when pumping ceases, the heads rapidly decrease for a period of time before increasing. The increase in head at the initiation of pumping is termed the "Noordbergum effect" based on the location in the Netherlands where it was first described (Verruijt 1969). The initial decrease in head after the cessation of pumping is called the "Rhade effect" after the location in Germany where it was studied (Langguth and Treskatis 1989). The head changes associated with these RWFs may only be in the order of centimeters and last for a few minutes, which make them difficult to detect unless the aquitard and/or unpumped aquifers are monitored closely. Anecdotal reports from well drillers and hydrogeologists indicate these phenomena may be more common than reported in the literature and, when observed, they are often ignored.

A RWF in a well is normally caused by poroelastic (also referred to as hydromechanical) coupling between the solid and fluid components in an aquifer system (Wang 2000). An increase in effective stress on the aquifer or aquitard skeleton results in a pore pressure increase. The change in pore pressure is temporary, as the increased pressure diffuses horizontally and vertically through the aquifer system. Aquitards generally show more pronounced RWFs than aquifers and play key roles in generating RWFs because of slower head changes and faster mechanical changes across aquitards (Kim and Parizek 1997, 2005). The terms "Noordbergum effect" and "Rhade effect" generally refer to poroelastically coupled responses in aquitards and aquifers at the start of pumping and the start of recovery, respectively. In this article, the terms "Noordbergum response" and "Rhade response" are used to apply more generally both to RWFs that are directly attributed to poroelastic effects and also to RWFs that may involve transmission of a poroelastically generated RWF through fractures.

RWFs have also been observed recently as part of hydromechanical slug testing using both an injection well and several monitoring wells in a fractured biotite gneiss

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(Slack et al. 2013). The injection well was 60 m deep and the monitoring wells were located between 5.3 and 13.4 m away. In these tests, the RWF in the monitoring well was observed in the same fracture as that into which injection occurred rather than in an adjacent aquitard, as might be expected for typical Noordbergum or Rhade effects. Injection pressures were in the order of 1.2 MPa and the pressure drops were between 0.008 and 0.025 m. The hydromechanical explanation given by Slack is that the fracture dilates to counteract the diffusive pressure pulse.

While poroelastic water-level changes induced by pumping are most intriguing, direct loading of an aquifer skeleton may also cause water-level changes. A classic example of water fluctuations in a well caused by poroelastic loading was described by Jacob (1939). In Jacob's study as a train entered a station, the additional weight compressed the aquifer and resulted in a temporary increase in water level in a nearby well. When the train left the station the load was removed from the aquifer and the water level decreased. The release of upstream dam water and resulting increase in stream stage has also been shown to increase poroelastic loading of an aquifer and generate water-level changes in wells (Boutt 2010). Hsieh (1996) developed a model to simulate deformation-induced effects of pumping on a confined multiaquifer system.

Work by the Wisconsin Geological and Natural History Survey (WGNHS) has detected human enteric viruses in multiple public supply wells in Madison, Wisconsin (Borchardt et al. 2007; Bradbury et al. 2010). The viruses probably originate in leaky sanitary sewers and travel through the aquifer system before entering the deep public supply well. The WGNHS work did not determine transport pathways or how the pumping rate, duration, and cycling frequency of the public supply wells may contribute to the rate of virus transport. An unresolved question is whether the cased and grouted portions of the public supply wells have failed and now act as preferential flow pathways for near surface contaminants to enter the well. Anecdotal reports from Madison water utility workers indicate that RWFs in observation wells occur commonly during pumping tests of many Madison wells, though these short-term effects are usually ignored.

The purpose of the research described in this article is to determine the mechanisms by which RWFs are generated and propagate in a fractured siliclastic aquifer system. Pressure transducers were placed in six wells in a shallow, fractured sandstone aquifer to assess the impact of pumping from a deeper confined aquifer. Monitored wells varied in depth and distance from the public supply well. The RWF data were analyzed to determine magnitude and duration of the fluctuations with respect to depth in the aquifer and distance from the pumping well. Parameters that may affect RWFs include pumping rate, pumping cycle duration, fracture connectivity, and the integrity of the public supply well casing. Hydromechanical modeling of a simulated layered aquifer system by Kim and Parizek (1997) suggested that irregular pumping and associated poroelastic effects may increase vertical transport of solutes. There may be additional effects on contaminant transport due to the presence of fractures and RWFs caused by public supply well pumping.

## Site Location and Setting

The study area is centered on Unit Well 7 (UW-7), a public supply well located in Madison, Wisconsin, that was constructed in 1939 and has a capacity of approximately 8300 L/min. The well is cased and grouted through two Cambrian-age units: the Tunnel City Group and Wonewoc Formation, two sandstone units that form the upper aquifer, and partially cased through the Eau Claire Formation, a regional aquitard that includes a 3-m thick shale interval at the field site (Figure 1). The well is open to the primary sandstone aquifer in Madison, the confined Cambrian Mount Simon Formation, and well logs from the time of construction report a diameter of 41 cm within the uncased interval. Owing to the fine grained and heterogeneous nature of the Tunnel City Group in southern Wisconsin and equivalent units in Minnesota, the upper aquifer is considered to be semiconfined (Runkel et al. 2006; Swanson et al. 2006). Three 5-cm-diameter PVC monitoring wells (MW-A, MW-B, and MW-C) were constructed near UW-7 to evaluate the upper aquifer.

Most of the neighborhood surrounding UW-7 consists of single family homes that predate the construction of the unit well. Many of these houses were built before public water supply was available in the area and, therefore, most houses had a private well that was open to the upper aquifer. Although the neighborhood eventually connected to the city water supply, not all private wells were properly abandoned. Some of these wells are still present in basements as open conduits to the subsurface, including three in the neighborhood that were recently identified by the Madison Water Utility. Instead of being immediately abandoned, these were temporarily left open and included in the study as additional monitoring wells. Details of these house wells are listed in Table 1 and the location of each is shown schematically in Figure 1 and in map view in Figure 2.

To determine the impact of UW-7 pumping on the upper aquifer, the wells listed in Table 1 were each instrumented with a data-logging pressure transducer. Both MW-A and MW-B were instrumented shortly after construction in April 2010; MW-C received a transducer in December 2011. The three house wells were instrumented during the summer of 2011, after they were identified by the Madison Water Utility and the home owners agreed to participate in the study. From April 2010 to April 2011, data were collected at 5 min intervals; after April 2011, the sampling interval was decreased to 1 min to allow for greater resolution.

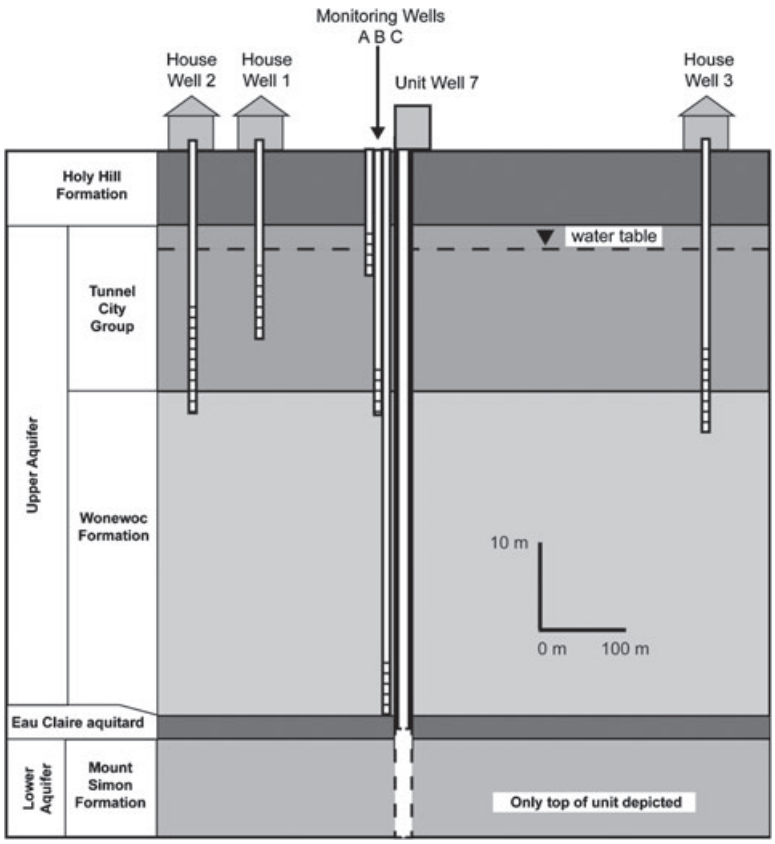


**Figure 1. Cross section including Unit Well 7, monitoring wells, and house wells. The three monitoring wells are approximately 6 m from the unit well. Open intervals for House Wells 1 and 2 are unknown and estimated but the total depths are known. The total thickness of the Mount Simon Formation is more than 150 m and the unit well is open to most of the Mount Simon Formation, but only the top portion is shown.**

## Methods and Results

### Initial RWF Observations

The data collected during 2010 from MW-A and MW-B revealed RWFs in the upper aquifer. The hydraulic head in MW-A was 77 cm higher than in MW-B under the relative steady-state conditions prior to UW-7 pumping on June 14, 2010 (Figure 3a). This head difference indicates that vertical flow was in the downward direction. Once UW-7 began pumping from the lower aquifer at approximately 7:00 AM (Figure 3b), the situation in the upper aquifer changed. The head in UW-7 declined on the order of 10 to 30 m during each pumping cycle. The water table (MW-A) remained relatively stable, but the water level in the deeper well (MW-B) experienced a sudden, reverse response of 10 to 20 cm at the beginning and end of each of the three pumping cycles.

A more detailed view of the unusual MW-B responses (Figure 3c) displays four separate components, which are identified as (1) an initial Noordbergum response, (2) drawdown due to pumping, (3) a Rhade response as the well ceased pumping, and (4) recovery. These four

**Table 1**
**Construction Data for Monitoring and House Wells in the Study**

| Location | Diameter (cm) | Top of Casing Elevation (m) | Well Depth (m) | Open Interval (m) | Distance from UW-7 (m) |
|---|---|---|---|---|---|
| MW-A | 5 | 271.2 | 14.6 | 4.6 | 6 |
| MW-B | 5 | 271.1 | 30.5 | 3 | 6 |
| MW-C | 5 | 271.2 | 65.5 | 3 | 6 |
| House 1 | 13 | 267.2 | 20.4 | Unknown | 155 |
| House 2 | 13 | 265.1 | 24.8 | Unknown | 235 |
| House 3 | 13 | 268.6 | 32.0 | 10.7 | 345 |

Notes: The house well top of casing elevations were measured in the basement of each house. Open interval refers to slotted screen for monitoring wells and open borehole for house wells.

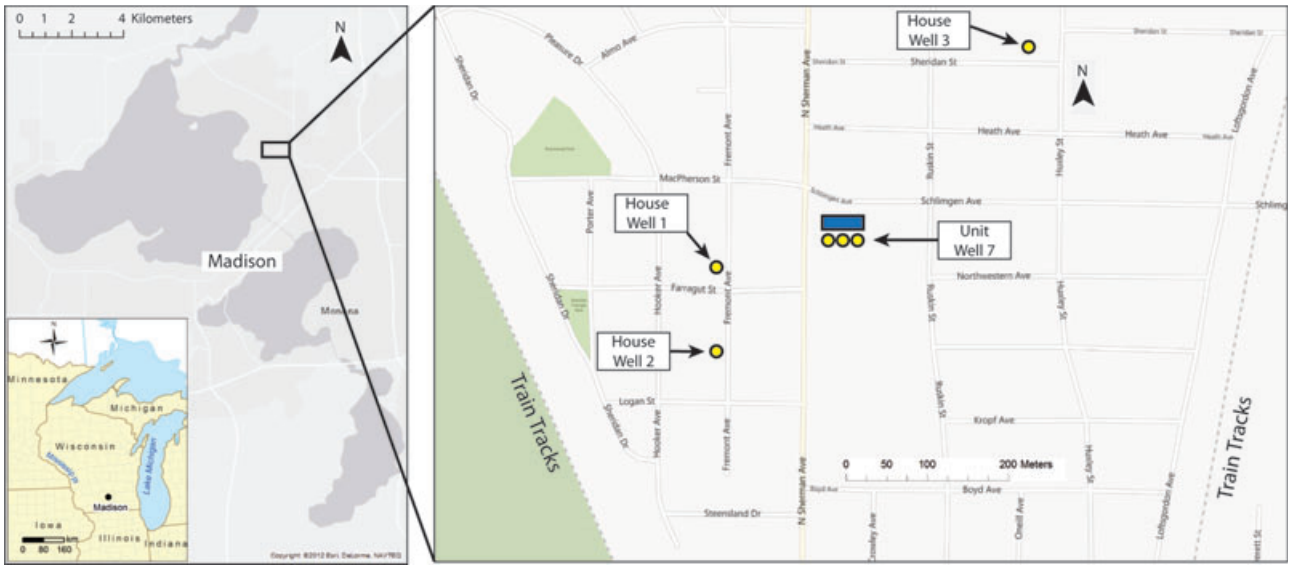


**Figure 2. Location map of Unit Well 7 with monitoring well nest and instrumented house wells in Madison, Wisconsin.**

components of response in MW-B were seen consistently each time the unit well was pumped. The presence of RWFs suggested, first, a poroelastic response in the Eau Claire formation and, second, a hydraulic connection between the upper and lower aquifer.

### Subsequent Site Changes

Between June 2010 and June 2012, UW-7 pumping rates changed and a new monitoring well MW-C was installed at the site. During June 2010, UW-7 produced approximately 8300 L/min (Table 2). From summer 2011 until May 2012, the UW-7 pump discharge steadily decreased, apparently because of a failing pump, and pumping duration was increased to compensate. During February 2012, with discharge at approximately 3500 L/min and other unit wells offline for maintenance, pumping at UW-7 was almost continuous to meet demand. The larger than expected Noordbergum value for February 2012 (Table 2) may be because of the brief periods (15–20 min) when the well was inactive, compared with other periods when the well would typically be idled for most of the night and experience greater recovery. The Rhade values show a monotonic decline that corresponds with well discharge. In June 2012 a new pump motor was installed, which allowed the well to again produce approximately 8500 L/min but the well pump cycled more frequently than during June 2010.

In April 2011, the MW-C borehole was drilled to a depth of 65 m. This borehole was left open for approximately 5 months to allow for analysis of fracture connectivity in the upper aquifer using borehole geophysics, vertical flow logging, straddle packer slug testing, and pumping tests (Gellasch et al. 2013). While the borehole was not being logged or tested, a blank FLUTe® flexible borehole liner was installed and pressurized by filling it with water to approximately 30 cm above the static water level. The liner was used in a manner similar to that described by Keller (2012) to seal the wall of the borehole and minimize vertical flow that may allow contaminants to migrate rapidly.

Well responses to pumping during the time periods listed in Table 2 were compared to determine what factors may contribute to the occurrence of RWFs in the upper aquifer. The relative magnitude and duration of RWFs in MW-B for each period are presented in Table 2. The responses of the other wells are presented as ratios with respect to MW-B in Table 3. Unexpected responses in MW-A, MW-B, and the three house wells were observed after the liner was installed in MW-C. These responses over a 48-h period in August 2011, spanning two pumping cycles, are displayed in the left column of Figure 4. Unlike the initial responses from June 2010 (Figure 3), MW-A responses to UW-7 pumping included noticeable RWF events. The three house wells also responded in a similar manner as MW-A. The responses in all wells were nearly simultaneous. For each pumping cycle the magnitudes of the corresponding Noordbergum and Rhade responses were roughly equal, as quantified by the magnitude ratios listed in Table 3.

It is important to note that although the arrival of RWFs during August 2011 occurred at similar times in all wells, the magnitudes of the RWFs were largest in MW-B (Table 3). The two farthest wells (Houses 2 and 3) had larger magnitude ratios than MW-A and House 1 but are also deeper than MW-A and House 1. Both MW-A and House 1 are completed entirely within the Tunnel City Group and are less likely to intersect the high transmissivity fractures detected in MW-C by geophysical logging (Gellasch et al. 2013). Greater RWF magnitudes are more closely correlated to increasing well depth and to shorter distances from the pumping well. The durations of RWFs in the house wells appear to increase with increasing

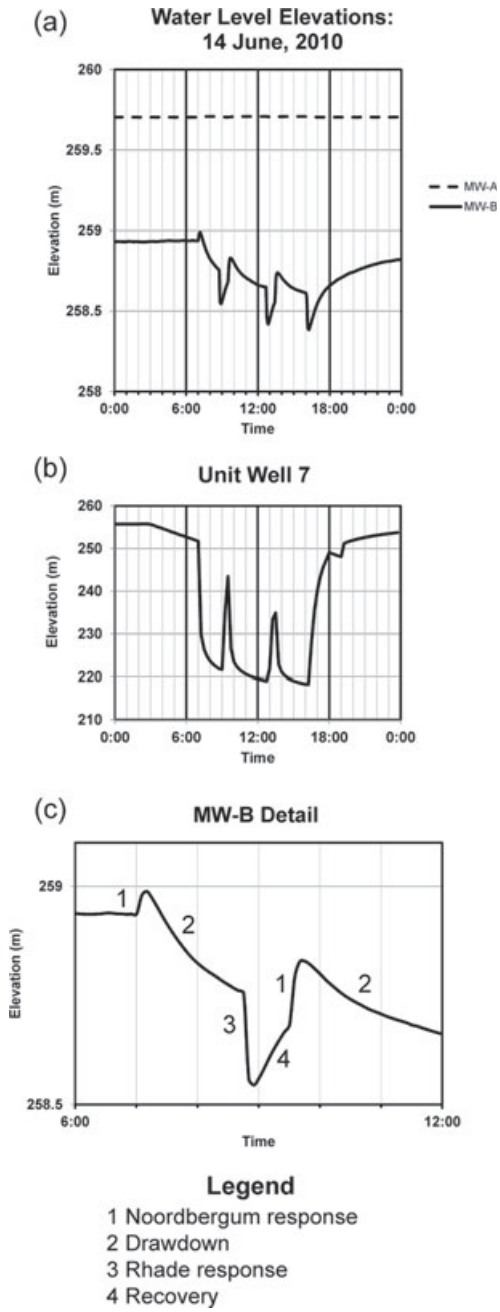


**Figure 3. (a) Monitoring well water elevation data from a 24-h period in June 2010 showing both MW-A and MW-B. (b) Unit well elevation for the same period with three pumping and recovery cycles during this time span and (c) the detailed figure of MW-B highlights the four responses related to pumping of the unit well over a 6-h period.**

distance from the unit well. However, the longest durations are for MW-A, which is closest to the unit well.

In addition to changes in water levels due to pumping, there were minor fluctuations uncorrelated to pumping, as seen in the interval between two pumping events on 19 and 20 August 2011 (Figure 4, left side). These smaller fluctuations may have been caused by passing freight trains (see Figure 2 for locations of train tracks to the east and west of the study area) or pumping of other, more distant, wells. They appear strongest in the open borehole house wells and weakest in the cased and screened monitoring wells. This behavior is similar to that observed by Schweisinger et al. (2011) during pumping tests in fractured gneiss. In that study, drawdown during pumping tests varied depending on whether the borehole was open or packed off to isolate fractured intervals. They concluded that in fractured rock settings the open monitoring well was an important part of flow in the aquifer system.

Once MW-C was installed, instrumented, and the annular space grouted in December 2011, another set of unexpected changes occurred in the instrumented wells. The right side of Figure 4 displays water levels in all instrumented wells over a 24-h period in February 2012, which included a recovery cycle between two long pumping cycles. Wells MW-B, MW-C, House 2, and House 3 display RWFs (Table 3). The magnitudes of RWFs in MW-B were much lower compared with MW-C grouted than they had been when the borehole was lined with the FLUTe. The responses to pumping of the lower aquifer that were detected in the house wells and MW-A during August of 2011 appear enhanced by the presence of the borehole liner in MW-C.

## Discussion

### Mechanisms for RWF Generation

The first step required to understand the observed RWFs is to determine the mechanism by which they were generated. All the observation wells, except MW-C, are open in the upper aquifer tens of meters vertically and/or located hundreds of meters laterally from the location of pumping in the lower aquifer. Several hypotheses are considered and rejected before discussing the two likely mechanisms for RWF generation. Inducing and sustaining a classic "Noordbergum effect" in the aquifer as described originally by Verruijt (1969) is unlikely because a poroelastic mechanism at such distances requires the high compressibility and low hydraulic conductivity common in aquitards, but uncommon in aquifers. Another unlikely hypothesis is that reduced heads in the lower aquifer may generate a poroelastic effect in the overlying aquitard, which then may subsequently affect the overlying aquifer. In a setting with RWFs at distance of more than 100 m radially from a pumping well, Burlingame (2008) used inverse hydromechanical modeling to match field data from the pumped aquifer and two overlying aquitards. However, the RWFs were observed only in aquitards, the RWF durations lasted for several hours, and there was a time lag between pumping and the observed RWFs. The modeling did not simulate any wells adjacent to the pumping well to evaluate RWF propagation or radial head change. It does not appear that this scenario is the same as that at UW-7.

It is unlikely that pumping of UW-7 caused simultaneous poroelastic effects in the Eau Claire aquitard both adjacent to the unit well and at a radial distance of more than 100 m. Using hydrogeologic data for Dane County,

## Table 2
**Comparison of Noordbergum and Rhade Responses and Unit Well 7 Discharge in MW-B for Five Periods During the Study**

| | MW-B Comparison Data | | | | |
|---|---|---|---|---|---|
| | Jun 2010 | Aug 2011 | Dec 2011 | Feb 2012 | Jun 2012 |
| Noordbergum | | | | | |
| Magnitude (cm) | 12.42 | 10.14 | 1.53 | 3.08 | 21.94 |
| Duration (min:s) | 10:00 | 13:47 | 02:52 | 05:04 | 15:12 |
| Rhade | | | | | |
| Magnitude (cm) | −20.24 | −10.03 | −3.80 | −3.21 | −24.29 |
| Duration (min:s) | 06:40 | 14:00 | 03:52 | 03:58 | 09:20 |
| Unit well discharge (L/min) | 8300 | 5400 | 4400 | 3500 | 8500 |

## Table 3
**Ratio of Reverse Water-Level Fluctuation Magnitude and Duration in Instrumented Wells for Several Periods Compared with the Same Parameter Measured in MW-B**

| | | MW-A | MW-B | MW-C | House 1 | House 2 | House 3 |
|---|---|---|---|---|---|---|---|
| August 2011 | Noordbergum | | | | | | |
| | Magnitude | 0.12 | 1.00 | No data | 0.06 | 0.35 | 0.30 |
| | Duration | 4.41 | 1.00 | | 1.38 | 2.58 | 3.51 |
| | Rhade | | | | | | |
| | Magnitude | 0.16 | 1.00 | | 0.06 | 0.31 | 0.28 |
| | Duration | 3.86 | 1.00 | | 1.39 | 2.43 | 3.36 |
| December 2011 | Noordbergum | | | | | | |
| | Magnitude | — | 1.00 | 12.49 | — | — | — |
| | Duration | — | 1.00 | 9.13 | — | — | — |
| | Rhade | | | | | | |
| | Magnitude | — | 1.00 | 3.18 | — | — | — |
| | Duration | — | 1.00 | 8.86 | — | — | — |
| February 2012 | Noordbergum | | | | | | |
| | Magnitude | — | 1.00 | 4.13 | — | 0.74 | 0.61 |
| | Duration | — | 1.00 | 4.99 | — | 6.30 | 9.22 |
| | Rhade | | | | | | |
| | Magnitude | — | 1.00 | 4.69 | — | 0.63 | 0.34 |
| | Duration | — | 1.00 | 5.80 | — | 5.81 | 7.60 |
| June 2012 | Noordbergum | | | | | | |
| | Magnitude | — | 1.00 | 1.16 | — | 0.20 | 0.14 |
| | Duration | — | 1.00 | 1.66 | — | 2.01 | 2.83 |
| | Rhade | | | | | | |
| | Magnitude | — | 1.00 | 1.21 | — | 0.21 | 0.11 |
| | Duration | — | 1.00 | 2.13 | — | 2.05 | 1.74 |

— No reverse water-level fluctuation detected.

Wisconsin (Bradbury et al. 1999), a Theis drawdown solution for the Mount Simon Formation was calculated for radial distances of 6 and 150 m while UW-7 was pumping at 8300 L/min. After 1 min of pumping, the Theis solution predicted 8.2 m of drawdown at a radial distance of 6 m from UW-7. This rapid drawdown would likely generate a poroelastic response in the overlying aquitard near UW-7. The same 8.2 m drawdown was not predicted at a distance of 150 m until after 10 h of pumping and only 34 cm of drawdown was predicted to occur after 5 min. Rapid head changes in an aquifer are required to generate a poroelastic response in the overlying aquitard. The lack of a rapid drawdown 150 m from UW-7 suggests that it is unlikely a poroelastic effect of the same magnitude could be generated simultaneously adjacent to UW-7 and at 150 m. The pumping rate also varied substantially over the 2-year study period and the reduced pumping rate during part of the study period would have reduced the likelihood of a large poroelastic response at 150 m.

Another rejected possibility is that surface loading may be responsible for generating the RWFs. Adjacent to the UW-7 pump house is a 568,000 L aboveground reservoir. As the reservoir fills and drains, it changes the surface load similar to the trains described by Jacob (1939). If surface loading were the cause of the RWFs then the shallowest wells would experience the greatest

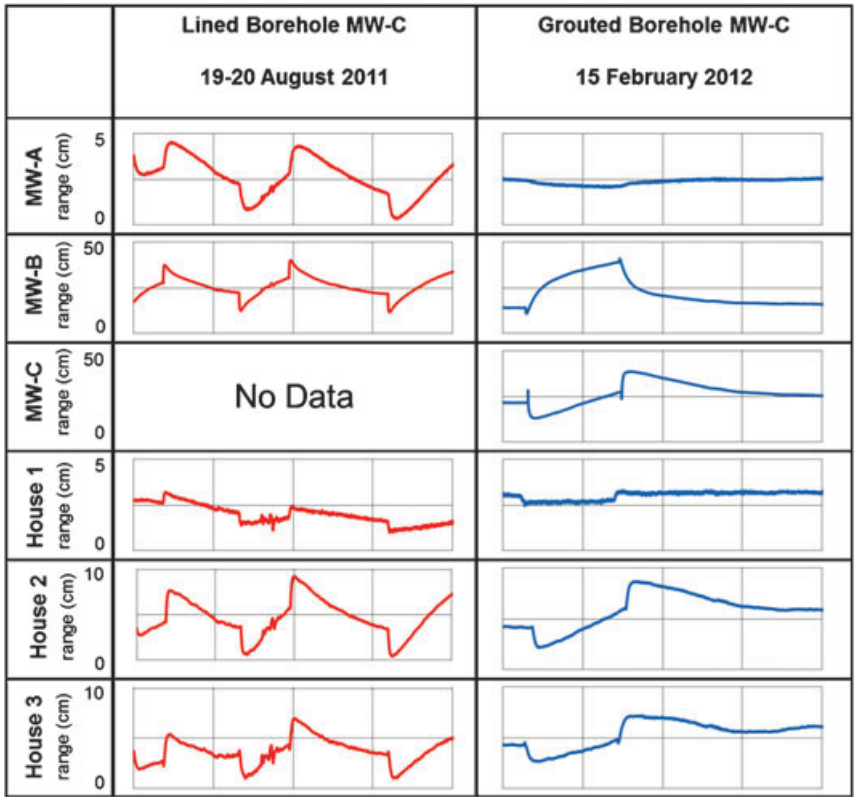


**Figure 4. Water-level data from monitored wells during August 2011 and February 2012. The vertical scale is different for each site with a total range between 5 and 50 cm.**

magnitude fluctuations and the RWF magnitude would diminish rapidly with radial distance. The water table well (MW-A) close to UW-7 exhibited typical RWFs only when MW-C was lined. It should also be noted that during the near constant pumping of UW-7 in early 2012 the reservoir was not filling and draining but RWFs were still observed when the unit well briefly ceased pumping. Therefore, it is unlikely that surface loading at UW-7 is the mechanism for generating RWFs at this site.

After considering and rejecting the hypotheses above, two likely hypotheses are discussed below. The first is that the RWF is generated just ahead of the pressure front in a fracture (Slack et al. 2013) as described in Introduction. Slack constructed a numerical model using deformable fracture (DFrx; Murdoch and Germanovich 2006), which consisted of a single, horizontal fracture pressured by a vertically intersecting well. For a head change of 17.4 m and other parameters appropriate to the multiwall slug test, the RWF amplitude reaches a maximum value of 2.4 cm at a radial distance of 15 m before decreasing an order of magnitude at a distance of 100 m. The RWF arrival time is proportional to the square of the radial distance from the well. Slack's results show that this mechanism, in which the RWF leads the pressure pulse from the well due to fracture deformation associated with the pulse, can propagate with sufficient magnitude over distances of tens of meters and is a viable hypothesis for explaining the observed RWFs associated with pumping of UW-7.

The second, and our preferred, hypothesis to explain the observed RWFs at this site is that they originate from a poroelastic response in the Eau Claire aquitard adjacent to UW-7 during pumping. The presence of the aquitard between the lower pumped aquifer and the upper aquifer in which the RWFs are observed suggests a poroelastic response is the likely mechanism for RWF generation. In contrast, the fracture generation hypothesis involved RWFs observed in the same fracture that intersected the slug test well. Once the RWF is generated in the aquitard, it is then subsequently channeled vertically and laterally via matrix flow, fracture flow, or thin-annulus flow between the wellbore and liner. These different pathways are examined in an order-of-magnitude way in the following section.

### Propagation of an RWF by Fracture Flow

Assuming the RWFs arise from an initial poroelastic Noordbergum effect in the Eau Claire Formation near UW-7, the next step is to examine how RWFs can propagate tens of meters above and hundreds of meters radially outward from the unit well through the upper aquifer. One scenario is that the sudden poroelastic fluid pressure changes in the Eau Claire aquitard at the bottom of the borehole MW-C propagate through a thin layer of water between the borehole wall and the FLUTe liner. The hydraulic head inside the liner was initially 30 cm greater than the head in the borehole. Although the FLUTe liner is constructed of flexible urethane coated nylon,

there are limits to its ability to conform to irregularities in a borehole. The acoustic caliper log from the MW-C borehole indicated many irregularities in the borehole wall in addition to the identified fractures (Gellasch et al. 2013). Previous work in carbonate rocks indicated that a FLUTe liner can seal voids more than several cm in diameter (Cherry et al. 2007) but the irregularities in the siliciclastic MW-C borehole are much smaller (millimeter scale) in thickness, extend outward several centimeters radially, and might not be completely sealed by the liner. Information provided on the manufacturer's website (http://www.flut.com) indicates the liners are unlikely to provide a complete seal, especially in boreholes that are not smooth.

The lined borehole pathway can be visualized as a cylindrical vertical fracture extending along the entire saturated portion of the borehole. The liner is unable to conform perfectly to the borehole wall and leaves small, connected pockets of water. These pockets have a similar aperture as the natural fractures present in the upper aquifer but with more asperities. The pressure inside the liner is greater than the pressure wave that propagates upward along the borehole. Therefore, the change in water pressure outside the liner is not transmitted into the lined portion of the borehole. The amount of wellbore storage in MW-C makes it unlikely that the entire borehole could be pressurized in order to propagate a pressure wave. However, the small amount of storage in the space between the liner and borehole wall would allow the propagation of the pressure wave.

The Noordbergum response observed at the top of the Eau Claire could increase the hydraulic head at the bottom of the borehole enough to allow a pressure change to propagate along the outside of the liner. The fluid pressure change outside of the liner propagates outward as a pore pressure change based on hydraulic diffusivity. In order to test the feasibility of this mechanism, hydraulic diffusivity was calculated for the aquifer matrix as

$$C = \frac{K}{S_S} = \frac{T}{S} \tag{1}$$

where $C$ is hydraulic diffusivity, $K$ is hydraulic conductivity, $S_s$ is specific storage, $T$ is transmissivity, and $S$ is storativity. Slug tests of matrix intervals for the MW-C borehole yielded estimates of these parameters, which are listed in Table 4. Matrix $S$ values varied between $10^{-1}$ and $10^{-11}$ for KGS slug test analyses and ranged from $10^{-1}$ to $10^{-9}$ using the Moench (1984) solution for pumping test analyses. The highest matrix $S$ value of $5.4 \times 10^{-2}$ (Table 4) was used because it was within the range of expected values for the semiconfined upper aquifer.

Once the hydraulic diffusivity, $C$, was estimated, the travel time of a pore pressure signal between points was calculated as

$$t = \frac{x^2}{4C} \tag{2}$$

**Table 4**
**Aquifer Matrix and Fracture Properties Based on Straddle Packer Slug Test Data and Pumping Test Data**

| | Transmissivity ($cm^2/s$) | Storativity (dimensionless) | Hydraulic Diffusivity ($cm^2/s$) |
|---|---|---|---|
| Aquifer matrix | 7.6 | $5.4 \times 10^{-2}$ | $1.4 \times 10^2$ |
| Horizontal fracture (max $T$) | 39 | $5.0 \times 10^{-6}$ | $7.8 \times 10^6$ |
| Horizontal fracture (base of Wonewoc) | 5.2 | $5.0 \times 10^{-6}$ | $1.0 \times 10^6$ |
| Vertical fracture | 4.0 | $5.0 \times 10^{-6}$ | $8.0 \times 10^5$ |

an equation derived from heat flow literature (Carslaw and Jaeger 1959) and adapted for poroelasticity (Wang 2000) where $t$ is travel time and $x$ is distance between points. Assuming the poroelastic effect originates near the bottom of the MW-C borehole, vertical and horizontal distances were calculated for the other monitoring wells and the house wells. The results of travel time calculations for each location are presented in Table 5.

It would take hours to days for pore pressure changes to propagate outward by matrix diffusion. Therefore, it is unlikely that a change in borehole pressure propagating outward by matrix diffusion is the cause of the house well RWFs.

A more likely case is to assume that the pressure pulse propagates along preferential pathways within highly transmissive fractures. To evaluate this hypothesis, a set of calculations for propagation of a pressure pulse through fractures was made using available parameter estimates in order to provide an "order of magnitude" comparison between pressure pulse propagation times in a fracture and the matrix. Values of fracture $T$ were taken from slug tests of fractured intervals in MW-C (Gellasch et al. 2013). Most fractures identified at the site are horizontal or have a dip of less than 5 degrees. Two sets of $T$ and $S$ values for horizontal fractures were used in these calculations and are listed in Table 4. One is the highest $T$ measured for a horizontal fracture, located more than 40 m above the Eau Claire Formation (labeled "max $T$" in the table); the other is for a fracture located at the base of the Wonewoc Formation (labeled "base of Wonewoc" in the table). Only one high angle, near vertical fracture was identified in the MW-C borehole and that $T$ (4.0 $cm^2/s$) was used for vertical calculations.

Slug tests for the fractured intervals yielded responses that were too rapid to allow estimates of fracture storativity. For that reason, a rough estimate of this parameter was obtained using results from the pumping test conducted on MW-C. Moench's (1984) double porosity solution for pumping tests provides a specific storage value for the entire "fracture system" that includes all fractures in the total saturated thickness of the aquifer.

**Table 5**
**Estimated Travel Time (in Seconds) Between the Base of the Wonewoc Formation at Borehole MW-C and Other Instrumented Locations**

| | Vertical | | Horizontal | | |
|---|---|---|---|---|---|
| **Name** | **MW-B** | **MW-A** | **House 1** | **House 2** | **House 3** |
| Distance | 35 m | 53 m | 155 m | 235 m | 345 m |
| Aquifer matrix | $2 \times 10^4$ | $5 \times 10^4$ | $4 \times 10^5$ | $1 \times 10^6$ | $2 \times 10^6$ |
| Horizontal fracture (max $T$) | | | 8 | 18 | 38 |
| Horizontal fracture (base of Wonewoc) | | | 60 | 130 | 290 |
| Vertical fracture | 4 | 9 | | | |

The "fracture system" $S_s$ value of $1.1 \times 10^{-8}$ cm$^{-1}$ was obtained from observations in MW-B, which have the best early time type curve fit of the three wells and also approximated values based on similar research (Rutqvist et al. 1998). The average individual fracture $S$ of $5.0 \times 10^{-6}$ (Table 4) was obtained by multiplying the "fracture system" $S_s$ by the saturated thickness of 54.25 m and then dividing by the total number of fractures (12) identified in the upper aquifer. Travel times to the house wells calculated for the fractures (listed in Table 5) range from 8 s to about 5 min, short enough to account for the rapid propagation of RWFs observed at these locations.

On the basis of these calculations, as well as the fact that RWFs continued to be observed in multiple wells following grouting of the annular space in MW-C, it appears likely that the RWFs propagate through fractures. The increased water pressure at the top of the Eau Claire Formation could propagate radially outward away from UW-7 through one of the several low angle, high transmissivity fractures identified in the MW-C borehole. The responses in wells indicate that the pressure pulse travels in both vertical and horizontal directions. The high angle fracture is likely to also propagate the RWFs vertically, although less effectively than through the MW-C borehole liner annular space. Figure 5 shows the conceptual model of the generation and propagation of pressure changes due to pumping of UW-7.

### Water-Level Changes Prior to RWFs

While examining the data related to the RWFs, another effect was also detected in some wells. At the initiation of pumping, the water level in MW-C suddenly dropped for one recording intervals (between 15 s and 1 min) before the Noordbergum response caused the water level to increase. In some instances two data points collected from MW-C at 15 s intervals indicate a sudden drop. The opposite occurred when pumping ceased and there was a brief increase in water level before the Rhade response caused levels to decrease. These effects are evident in the MW-C data from December 2011 and June 2012 in Figure 6 and had magnitudes approximately one tenth of the subsequent RWFs. The sudden initial changes in water level were normally detected in MW-C, House 2, and House 3; when the FLUTe liner was installed in August 2011 the effect was also observed in MW-B. Although it lasted 1 min or less in MW-C, the initial change lasted approximately 2 min in House 2 and approximately 5 min in House 3.

A likely mechanism for these short duration water-level fluctuations before the RWFs is a rapid response to pumping transmitted via fractures. When pumping begins, a head drop can propagate from the lower aquifer through a fracture network that includes the Eau Claire aquitard and the upper aquifer. Based on geophysical logging data from UW-7 during May 2012, fracture flow is suspected between the upper and lower aquifers while UW-7 is pumping (Gellasch 2012). This small head drop can then be briefly detected in some wells before it is negated by a RWF. The drop in water level at the beginning of pumping will be referred to as the fracture flow initial drawdown (FID) and the increase in water level as pumping ceases will be referred to as the fracture flow initial recovery (FIR).

The observation of FID and FIR is indicative of the complexity of flow paths in fractured systems. Their occurrence prior to RWF implies a different pathway if the FID/FIR source is the well drawdown/recovery, whereas the RWF source is the induced RWF in the Eau Claire. The distribution of FID and FIR observations in the instrumented wells can be used to shed light on fracture connectivity in the upper aquifer. Only the deepest wells (MW-C, House 2, and House 3) consistently experience FIDs and FIRs. This indicates that these wells are likely the best connected by fractures to the lower aquifer. It is possible for both the fractures at the base of the Wonewoc Formation and a shallower, higher $T$ fracture to be pathways for propagation of RWFs (Table 5). The higher $T$ fracture is shallower than the screened interval of MW-B. Any FIDs or FIRs that traveled along this fracture are likely to influence MW-B, but that well does not normally experience them. It is more likely that the basal fracture is the preferred pathway connecting MW-C, House 2, and House 3. The duration of the FIDs and FIRs in House 2 and House 3 agree with estimated travel times for the RWFs propagating along the basal fracture (Table 5). The FIDs and FIRs observed in MW-B while the MW-C borehole was lined indicate that during this time the pathway was altered to include the borehole. This temporary pathway allowed MW-B to be influenced by these effects.

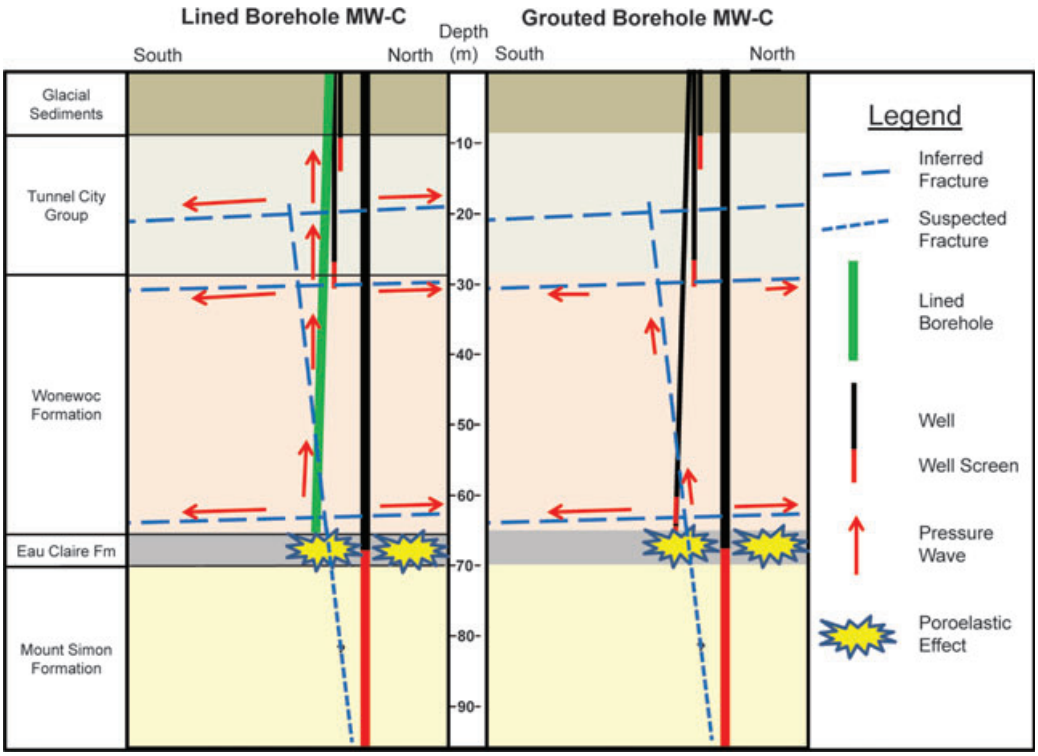


**Figure 5. Conceptual model of RWF generation and propagation under two different conditions: (a) while the FLUTe flexible liner was installed in MW-C and (b) after the MW-C monitoring well was installed and the annular space grouted. Length of the pressure wave arrows corresponds with the general magnitude of the pressure change.**

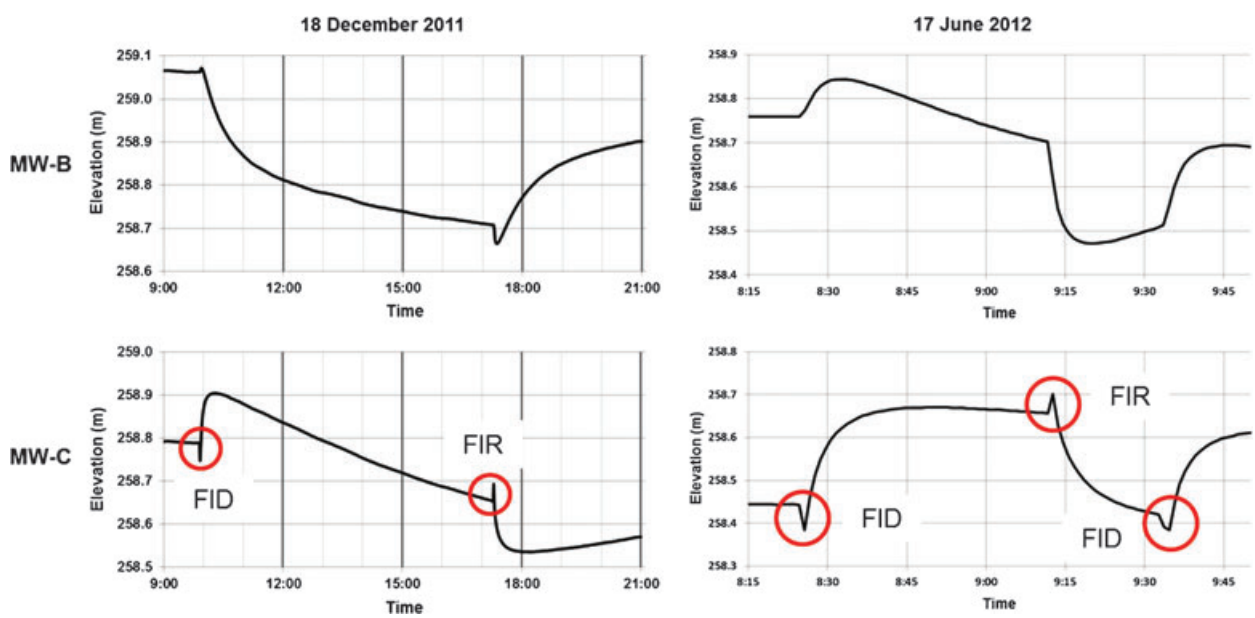


**Figure 6. Comparison of MW-B and MW-C RWF effects after the MW-C borehole was grouted during December 2011 and June 2012. Each plot represents one pumping cycle although the time period in June is much shorter because of a higher pumping rate. The circled sections highlight FID and FIR.**

## Evaluation of Unit Well Annulus as a Preferential Flow Pathway

Rapid transport of near surface contaminants into a deep, confined aquifer requires a preferential flow pathway. One hypothesis to explain the detection of viruses in UW-7 is that the grouting outside the UW-7 casing, which extends through the upper aquifer and Eau Claire Formation, had failed to the point where it created a highly transmissive conduit between the water table and well pump. In this scenario, contaminants at the water table would migrate rapidly downward during unit well pumping and enter the water supply. It is possible

to test this hypothesis with the data collected in this study.

The borehole liner installed in MW-C likely formed an imperfect seal along the borehole wall that, while preventing vertical fluid flow, allowed propagation of a pressure pulse along the annular space (Figure 5). During this time (August 2011 in Table 3) each of the five instrumented wells experienced RWFs in response to UW-7 pumping. The water table well (MW-A) adjacent to UW-7 experienced low magnitude, but distinctly visible RWFs (August 2011 in Figure 4). After MW-C was grouted, MW-A no longer experienced distinct RWFs (February 2012 in Figure 4) even though it was closer to UW-7 than were House 2 and House 3. The absence of RWFs following grouting of MW-C suggests that RWFs in MW-A while the FLUTe was installed were caused by propagation of RWF head changes from the top of the Eau Claire Formation upward along the MW-C borehole liner and then radially outward along shallow fractures (Figure 5). House 2 and House 3 must then intersect deeper fractures that are connected to a high angle fracture, as is also suggested by analysis of head data (Gellasch et al. 2013). When pumping discharge increased substantially in June 2012, and the RWFs in MW-B were the largest of any time period (Table 2), RWFs were still absent from the shallowest wells (Table 3).

The comparison of water-level responses while the liner was installed and after its removal can be used to evaluate whether the UW-7 annulus is a preferential flow pathway. Although not intended, the lined borehole served as a proxy for a leaking public supply well annulus. The lack of RWFs in MW-A after the borehole liner was removed and MW-C grouted suggest that the lined borehole, and not a defective unit well, was responsible for those responses. If faulty UW-7 grout extended to shallow depths, the shallowest, closest well would be expected to respond to pumping at all times. A faulty annular seal would also allow rapid propagation of FID and FIR effects such that these would be observed in MW-A and MW-B at all times. Thus, it appears unlikely that a failure in the UW-7 grouting is the source of the preferential flow pathway responsible for rapid transport of contaminants between the water table and the UW-7 pump.

### Effect of Pumping Rate and Amplitude on RWF Magnitude and Duration

A comparison of head data from December 2011 and June 2012 for both MW-B and MW-C (Figure 6) highlights the impact of pumping on RWFs. The unit well pumping rate in December was 4400 L/min. In June, the pump was replaced and the well discharge increased to 8300 L/min. The Noordbergum response in MW-B increased substantially from 1.5 to 21.9 cm (Table 2). While MW-C also experienced an increase in RWF magnitude, the ratio of magnitudes in MW-C to MW-B decreased from more than 12:1 in December to nearly 1:1 in June. It is evident that higher pumping rates not only increase the magnitude of RWFs, they also expand the portion of the aquifer that experiences large RWFs. The lack of observable RWFs in the house wells during December is likely because they were too small to be detected as evidenced by the low magnitude of the RWFs in MW-B (Table 2).

In addition to a higher pumping rate in June 2012, the unit well also began to cycle more frequently when compared with the 1 cycle per day observed during December 2011. Unlike the June 2010 cycles, which lasted 3 to 4 h each, June 2012 cycles each lasted an hour or less, as the adjacent reservoir quickly filled and the well ceased pumping while the reservoir drained. The shortened pumping cycles resulted in the Noordbergum response persisting through a substantial portion of the period when the well was active. Instead of the pumping-induced head change in MW-C occurring over several hours as drawdown and recovery, the majority of the head change occurred over tens of minutes and shifted to the initial portion of the RWFs at the beginning and end of each pumping cycle. The result was rapid changes in head during each of the ten daily cycles and may have served as a mechanism for contaminant transport in a similar manner as barometric pumping may induce gas transport in fractured rocks (Nilson et al. 1991). First, the magnitudes and durations of RWFs are not equal for each pumping cycle (Table 2), with Rhade water level declines generally exceeding Noordbergum water level rises. This suggests that flow in the fractures might result in net transport toward UW-7. Second, the dual porosity nature of the system might result in contaminants migrating from the fractures into the aquifer matrix during periods of higher head (Noordbergum response) and subsequently migrating back into the fractures during periods of lower head (Rhade response) and then traveling along the fracture toward the pumping well. Combined with high transmissivity fractures, these rapid fluctuations in head may promote rapid transport of contaminants through high $T$ fractures in the upper aquifer. Additional work is needed to fully evaluate the role of these RWFs in contaminant transport.

## Summary and Conclusion

The RWFs caused by pumping may be more common than generally reported, and were studied in several wells in the vicinity of a public supply well, UW-7, in Madison, Wisconsin. The RWF magnitude in instrumented wells was more closely related to well depth and to apparent connections to low angle fractures than to radial distance from UW-7. The lack of RWFs in the shallowest, closest well (MW-A) and the lack of FIDs and FIRs in both MW-A and MW-B suggest that the unit well casing is neither defective nor the source of the preferential flow pathway between the upper and lower aquifers.

The presence of RWFs in a well is commonly attributed to poroelastic effects in an aquitard due to pumping of an adjacent aquifer. The initial RWFs observed in MW-C at the top of the Eau Claire Formation are likely generated by such poroelastic effects. However, it is suggested here that RWFs observed in the other

wells originated near MW-C and propagate by pressure changes transmitted rapidly through fractures over 300 m radially from the pumping well. This behavior allows RWFs to appear in wells more quickly and much farther from the pumping well than expected. The link between RWFs and fractures is important for the evaluation of pumping impacts on transport in the aquifer. The pattern of RWF propagation can be used to better define fracture connectivity in an aquifer system.

The unit well pumping discharge and duration of pumping cycles affected not only the drawdown in the upper aquifer but also the short-term head changes due to RWFs. A combination of rapid, pumping induced head changes and fracture flow are a potential mechanism for rapid transport of contaminants into UW-7. Analysis of RWF magnitude data for several time periods under a variety of pumping conditions indicates that pumping UW-7 at a lower discharge but for longer periods of time will result in RWFs that occur less often and with a smaller magnitude. Pumping at high rates with multiple pumping cycles per day will maximize the number and magnitude of RWFs in the upper aquifer and might lead to more rapid transport of contaminants into the unit well. Additional work is required to fully understand the mechanisms by which the presence of RWFs may result in rapid contaminant transport. By developing a better understanding of how public supply well pumping in a fractured aquifer system influences contaminant transport, it may be possible to identify strategies such as modified pumping schedules and the use of variable frequency drive well pumps to minimize risk of near surface contaminants entering the public water supply.

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