Appendix D

Aquifer Testing Data and Data Reduction

Table D-1

Hydraulic Conductivity Values
Groundwater Assessment Report
UMore Mining Area
Dakota County, Minnesota

Geologic Unit	Sample		USCS	Test Type		Hydraulic Conductivity Values			
	Boring/Well ID	Depth (feet bgs)	Soil Description[1]	Lab	Field	Horizontal (feet/day)	Vertical (feet/day)	Testing Method[2]	Approximation Method [3]
Outwash	MW-C2-nest	65-75, 137-147	SP		X	290	101	Pumping Test	Moench , 1997
Outwash	MW-B1-001	61-71	SP		X	51		Specific Capacity	TGuess2005
Outwash	MW-C2-002	65-75	SP		X	49.1		Specific Capacity	TGuess2005
Outwash	MW-C2-202	137-147	SP		X	1.5		Specific Capacity	TGuess2005
Outwash w/ ML lenses	MW-A3-003	72-82	SP with ML		X	16		Specific Capacity	TGuess2005
Outwash w/ ML lenses	MW-C7-004	80-90	SP with ML		X	16		Specific Capacity	TGuess2005
Outwash - Lower	MW-A6-006	102-112	SP		X	152		Specific Capacity	TGuess2005
Outwash	MW-D3-007	60-70	SW		X	16		Specific Capacity	TGuess2005
Intra-Diamicton Sand	MW-E2-209	116-126	SP/CL		X	6.8		Specific Capacity	TGuess2005
Outwash	MW-E4-010	62-72	SW		X	44		Specific Capacity	TGuess2005
Outwash	A6-Pilot	130	SP	X		73		Particle Size Analysis	Hazen Approximation
Outwash - Lower	A6-Pilot	158	GP-GM	X		73		Particle Size Analysis	Hazen Approximation
Outwash	C2-Pilot	104	SP-SM/SM	X		NA		Particle Size Analysis	NA
Outwash - Lower	C2-Pilot	158	SP-SM	X		73		Particle Size Analysis	Hazen Approximation
Outwash - Lower	E1-Pilot	155	SP-SM	X		56		Particle Size Analysis	Hazen Approximation
Outwash	MW-B1-001	65	SP	X		48		Particle Size Analysis	Hazen Approximation
ML in Outwash	MW-B1-001	73-74	ML	X		NA		Particle Size Analysis	NA
Outwash	MW-A3-003	75	SP	X		64		Particle Size Analysis	Hazen Approximation
ML in Outwash	MW-C7-004	86-88	CL-ML	X		NA		Particle Size Analysis	NA
Outwash w/ ML lenses	MW-C7-004	88	SM	X		NA		Particle Size Analysis	NA
Outwash	MW-D3-007	60	SP	X		125		Particle Size Analysis	Hazen Approximation
Outwash	MW-E2-009	68	SP	X		102		Particle Size Analysis	Hazen Approximation
Outwash	MW-E4-010	65	SP	X		125		Particle Size Analysis	Hazen Approximation
Outwash	A6-Pilot	130	SP	X		4.5		Constant Head Permeameter	Laboratory Permeability
Outwash - Lower	C2-Pilot	158	SP-SM	X		2.1		Constant Head Permeameter	Laboratory Permeability
Outwash - Lower	E1-Pilot	155	SP-SM	X		0.43		Constant Head Permeameter	Laboratory Permeability
ML in Outwash	MW-A3-003	81	CL/CL-ML	X			0.013	Falling Head Permeameter	Laboratory Permeability
Diamicton	C2-Pilot	120	CL	X			3.4E-04	Falling Head Permeameter	Laboratory Permeability
Diamicton	E1-Pilot	103	CL	X			1.0E-05	Falling Head Permeameter	Laboratory Permeability
Diamicton	MW-E2-209	113	CL	X			6.8E-05	Falling Head Permeameter	Laboratory Permeability
Diamicton	MW-C4-311	70	CL	X			1.4E-04	Falling Head Permeameter	Laboratory Permeability
Diamicton	B2-Pilot	86-88	CL	X				NA	NA
Diamicton	E1-Pilot	126-127	SC	X		NA		NA	NA
St. Peter Sandstone	MW-E2-305	64-74	*		X	1.7		Specific Capacity	TGuess2005
St. Peter Sandstone	MW-D5-308	65-75	*		X	0.83		Specific Capacity	TGuess2005
St. Peter Sandstone	MW-C4-311	82-92	*		X	0.68		Specific Capacity	TGuess2005
St. Peter Sandstone	MW-E2-305	70	*	X		0.21		Falling Head Permeameter	Laboratory Permeability
St. Peter Sandstone	MW-D5-308	65	*	X		NA		Particle Size Analysis	NA

Notes:

[1] USCS descriptions for lab samples are from laboratory particle size analyses; for field measurement descriptions are from well/boring logs.

[2] Permeameter testing of granular outwash soils (SP & similar) and St. Peter Sandstone were conducted on re-packed samples. Permeameter tests of diamicton and silt were conducted on undisturbed core samples.

[3] TGuess calculations are shown in Appendix D; Hazen Approximation calculations are shown in Appendix D.

* indicates laboratory analysis of pulverized bedrock sample, therefore the USCS description is not applicable

NA - Not applicable. Particle size analysis only; Hazen approximation is not valid due to D10 fraction < 0.1 mm.

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Technical Memorandum

To: File

From: Dave Dahlstrom, Ellen Considine

Subject: Pumping Tests at PW-C2-202

Date: March 6, 2009

Project: 23/19-0B05.03

This memorandum provides a summary of the aquifer tests conducted at PW-C2-202 on February 5, 2009 and February 19, 2009.

INTRODUCTION

The Groundwater Assessment Work Plan (Barr, 2008) stated that three pumping wells would be installed in the UMore Mining Area (UMA) in order to conduct aquifer tests. However, only one of the three planned pumping well locations was found to be suitable for installation of a pumping well. The lithology in the other two locations was dominated by diamicton till, which could not be pumped at a high enough rate to conduct a pumping test.

Therefore one pumping well (PW-C2-202) was installed near the intersection of Station Trail and 160th Street. The aquifer in the vicinity of the pumping well is unconfined and is composed entirely of sand and gravel. The aquifer extends to a depth of approximately 147 feet bgs, where it is underlain by Prairie Du Chien limestone. The depth to water at PW-C2-202 is approximately 65 feet bgs. The pumping well is screened from 125 to 145 feet bgs with a 6-inch diameter stainless steel screen.

Two monitoring wells were installed near the pumping well. The deep monitoring well (MW-C2-202) is located 60 feet west of the pumping well and is screened from 137 to 147 feet bgs. The shallow monitoring well (MW-C2-002) is located 30 feet west of the pumping well and is screened from 65 to 75 feet bgs, approximately at the water table. Both monitoring wells are 2 inches in diameter.

The pumping well and the deep monitoring well were drilled using mud rotary drilling; the shallow monitoring well was drilled using rotasonic drilling. The mud rotary wells were developed immediately after well installation by airlifting. The pumping well produced approximately 4500 gallons of development water, at a rate of approximately 75 gpm. Both monitoring wells were then developed by pumping and surging. A pumping test was subsequently attempted. However, the test revealed that the well screen was poorly connected to the aquifer due to inadequate well development, i.e. residual clay from the drilling mud clogging the filter pack. The pumping well was subsequently re-developed by injecting a polymeric dispersant (NW-220, manufactured by Water Systems Engineering, Inc.), surging for approximately two hours, allowing the well to rest overnight, then airlifting to remove sediment and dispersant. During the re-development, airlifting produced a discharge rate of approximately 150 gpm, and approximately 16,000 gallons of development water was removed from the well. A second pumping test was conducted (described below), which showed that the re-development was successful. All 13 monitoring wells were later re-developed using the polymeric dispersant.

FIELD METHODOLOGY

After re-development, a step-drawdown test was conducted in PW-C2-202 on February 18. Pumping rates of 60, 100, 150, 200, and 270 gpm were tested. Although it appears that the aquifer could have supported a pumping rate greater than 270 gpm, the pump was at its maximum capacity. Therefore PW-C2-202 was pumped at a rate of 250 gpm for the constant rate pumping test on February 19 (selecting a rate slightly lower than the pump's maximum rate ensures a more constant discharge rate). The constant-rate test was run for approximately 9 hours and water levels were monitored in PW-C2-202, MW-C2-202, and MW-C2-002 using LevelTrolls and electronic water level indicators. Water levels were allowed to recover overnight before removing the pump and dataloggers from the wells. The results from this pumping test are discussed below.

DISCUSSION/RESULTS

The pumping phase was affected by backpressure in the discharge line. The initial instantaneous pumping rate was approximately 260 gpm, however, once the discharge line filled with water, the additional head that the pump had to work against caused a decline in pumping rate to 250 gpm. The result of the reduction in pumping rate is apparent in the time-drawdown plots as drawdown in the wells peaked early (approximately 0.7 to 1.1 minutes into the test), then declined somewhat, then stabilized in the pumping well and resumed in the observation wells (Figure 1).

Overall, the responses in the observation wells are consistent with the unconfined setting of the aquifer. After the backpressure effects dissipated, there was an intermediate period during which the rate of drawdown was lower, known as the delayed gravity response (Neuman, 1975), followed by a period of additional drawdown toward the end of the test. A pronounced inflection in the time-drawdown curve for MW-C2-002 after about 45 minutes of pumping suggests that the cone of depression due to pumping may have expanded into a portion of the aquifer with a higher transmissivity and/or specific yield. The data beyond this point fall further and further below the type curve as the test progressed.

The principle of superposition was applied to the recovery phase data so those data could be analyzed using the same approach as the pumping phase data (Figure 2). In order to do this, the drawdown trend from the late-time pumping data was projected through the recovery phase and interpolated to each of the times at which water levels were measured during the recovery phase. Recovery was then calculated as the projected pumping drawdown trend minus the measured residual drawdown. This approach is shown conceptually in Figure 9.37 of Driscoll (1986, p. 252).

The recovery data were then analyzed as pumping phase data using the average pumping rate from the pumping phase. The water level in the pumped well had no apparent drawdown trend, so the residual drawdown was subtracted from the final drawdown measurement prior to turning off the pump.

The advantage of the recovery data is that variations in pumping do not occur. A disadvantage is that the calculated drawdown depends on the accuracy of the projection of the drawdown trend from the pumping phase through the recovery phase. The limitations of the projection are smaller early in the recovery phase. The inflection due to the delayed gravity response occurred relatively early in the recovery phase data from MW-C2-002 (from approximately 1.3 to 7 minutes) and later in the data from MW-C2-202 (1.8 to 66 minutes) due to its greater distance from the pumping well.

The Moench (1997) method was applied to the pumping and recovery phase data. This solution assumes the following:

- the aquifer has infinite areal extent
- the aquifer is horizontal, homogeneous, and of uniform thickness
- vertical flow across the lower boundary of the aquifer is negligible
- the aquifer piezometric surface is initially horizontal
- the change in saturated thickness of the aquifer is small compared with the initial saturated thickness
- pumping and observation wells are fully or partially penetrating
- the aquifer is unconfined and exhibits delayed gravity response

The Moench solution also accounts for wellbore storage and well skin (inefficiency) of the pumping well. The solution was applied using all of the data for each phase of the test simultaneously. This approach requires that a single set of aquifer parameters satisfy the various responses.

Figures showing the actual drawdown and recovery superimposed over the Moench solutions are included in Figures 1 and 2 (attached). Results for hydraulic conductivity are shown below:

Data Analyzed	**K_H (ft/day)**	**K_V (ft/day)**
Pumping Phase	330	81
Recovery Phase	250	120
Average	290	101

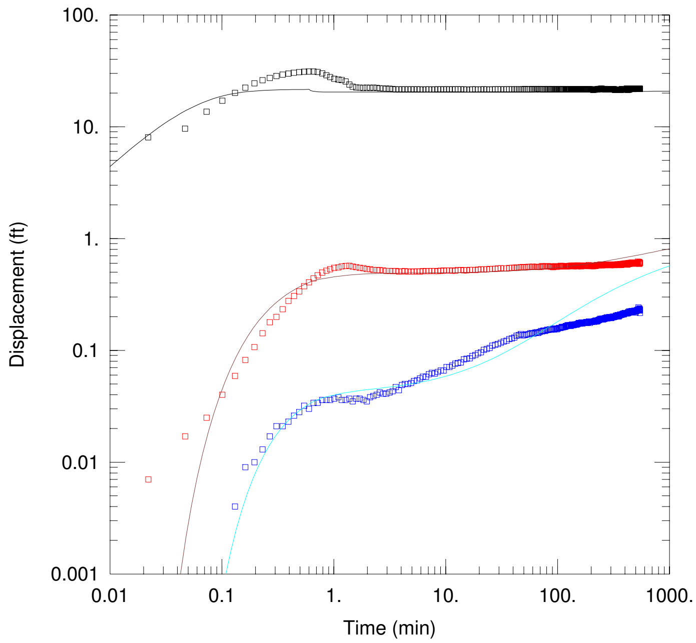
REFERENCES

Driscoll, F.G., 1986. Groundwater and Wells, 2nd edition. Johnson Filtration Systems, Inc., St. Paul, MN, 1089 p.

Moench, A.F., 1997. Flow to a Well of Finite Diameter in a Homogeneous, Anisotropic Water Table Aquifer, Water Resources Research, Vol. 33, No. 6, p. 1397-1407.

Neuman, S.P., 1975. Analysis of pumping test data from anisotropic unconfined aquifers considering gravity response, Water Resources Research, Vol. 11, No. 2, p. 329-342.

Figure 1
PUMPING PHASE ANALYSIS
Pumping Test at PW-C2-202
UMore Park
Dakota County, Minnesota



UMORE AQUIFER TEST #2

Data Set: P:\...\pumping_phase_moench.aqt
Date: 03/04/09 Time: 14:51:21

PROJECT INFORMATION

Company: Barr Engineering
Client: U of M
Project: 23/19-0B05
Location: UMore Park
Test Well: PW-C2-202
Test Date: 02/19/2009

AQUIFER DATA

Saturated Thickness: 80. ft Anisotropy Ratio (Kz/Kr): 0.48

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW-C2-202	56.5	0

Observation Wells

Well Name	X (ft)	Y (ft)
PW-C2-202	56.5	0
MW-C2-202	0	0
MW-C2-002	28	0

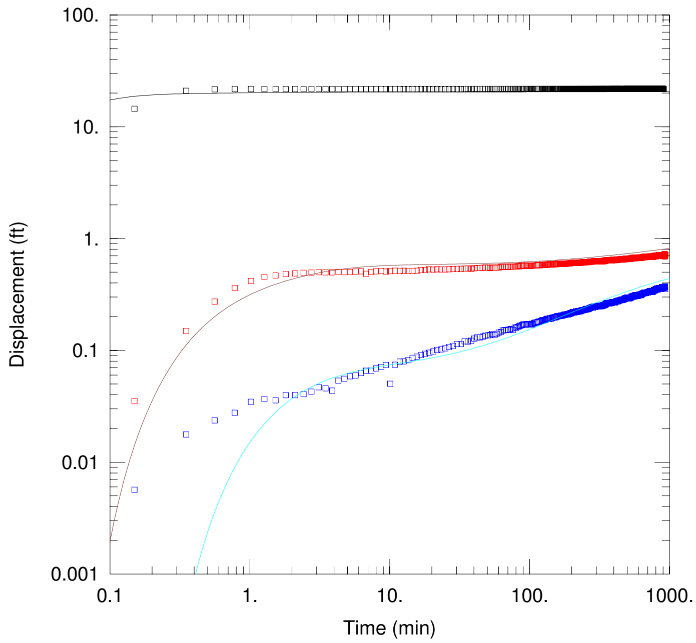
SOLUTION

Aquifer Model: Unconfined Solution Method: Moench

T = 2.0E+4 ft^2/day
Sy = 0.36
Sw = 8.85
r(c) = 0.25 ft

S = 0.0018
Kz/Kr = 0.48
r(w) = 0.4 ft
alpha = 19. min^{-1}

Figure 2
RECOVERY PHASE ANALYSIS
Pumping Test at PW-C2-202
UMore Park
Dakota County, Minnesota



UMORE AQUIFER TEST #2

Data Set: P:\...\recovery_phase_as_pumping_moench.aqt
Date: 03/04/09 Time: 14:52:50

PROJECT INFORMATION

Company: Barr Engineering
Client: U of M
Project: 23/19-0B05
Location: UMore Park
Test Well: PW-C2-202
Test Date: 02/19/2009

AQUIFER DATA

Saturated Thickness: 80. ft
Anisotropy Ratio (Kz/Kr): 0.25

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW-C2-202	56.5	0

Observation Wells

Well Name	X (ft)	Y (ft)
PW-C2-202	56.5	0
MW-C2-202	0	0
MW-C2-002	28	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Moench

T = 2.6E+4 ft^2/day
Sy = 0.25
Sw = 12.5
r(c) = 0.25 ft

S = 0.0062
Kz/Kr = 0.25
r(w) = 0.4 ft
alpha = 0.035 min^{-1}

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Technical Memorandum

To: File

From: Ellen Considine

Subject: Specific Capacity Tests at Monitoring Wells

Date: April 28, 2008

Project: 23/19-0B05.03

This memorandum provides a summary of the analysis conducted using well development data to estimate hydraulic conductivity. This approach is called the Specific Capacity Method (for estimating hydraulic conductivity).

BACKGROUND

The Specific Capacity Method is described on p. 1021 of Driscoll's *Groundwater and Wells* (Driscoll, 1989). It is an empirical method for approximating hydraulic conductivity from specific capacity data, i.e. the ratio of given pumping rate to steady-state drawdown. The method solves the Cooper-Jacob approximation of the Theis Equation, which essentially simplifies the Theis Equation into a linear form which is more easily solved and requires fewer input parameters. The method is therefore limited by the assumptions behind the Theis Equation, as well as the assumptions necessary to linearize the Theis Equation. These assumptions include: homogeneous, isotropic, non-leaky, confined conditions; infinite aerial extent and uniform thickness of aquifer; instantaneous release of water from storage; and a known storage coefficient. Although several of these assumptions (isotropic, confined, instantaneous release) are violated by the monitoring wells' configurations and aquifer's properties, the Specific Capacity Method is commonly used as a preliminary approximation of hydraulic conductivity.

The Specific Capacity Method was implemented with the TGuess program (Bradbury and Rothschild, 1985). TGuess is an spreadsheet application of a computerized technique (Bradbury and Rothschild, 1985) for solving the Cooper-Jacob approximation. The advantage of TGuess is that it includes Bradbury and Rothschild's corrections for well loss and partial penetration. For more information about TGuess, see the documentation provided with the software.

To: File
From: Ellen Considine
Subject: Specific Capacity Tests at Monitoring Wells
Date: April 28, 2008
Project: 23/19-0B05.03

FIELD METHODOLOGY

The data used for this analysis was collected during well development. The tests were conducted at the conclusion of development. The wells were pumped at a relatively low rate, using a Tornado-type submersible pump. Both the pumping rate and the water level in the well were monitored. At 12 of the 13 monitoring wells, the water level stabilized during pumping. MW-E2-009 was repeatedly pumped dry, therefore the Specific Capacity Method could not be applied.

RESULTS

Table 1, attached, shows the input parameters and hydraulic conductivity calculated for each well.

REFERENCES

Driscoll, F.G., 1986. Groundwater and Wells, 2nd edition. Johnson Filtration Systems, Inc., St. Paul, MN, 1089 p.

Bradbury, K.B., and E.R. Rothschild, 1985. A computerized technique for estimating the hydraulic conductivity of aquifer from specific capacity data: Ground Water vol. 23, No. 2, pp. 240-246.

Table 1

TGuess Calculations from Specific Capacity Tests at Monitoring Wells
UMore Mining Area
Dakota County, Minnesota

Maximum iterations	10
Error tolerance (as drawdown)	0.001 feet

	Field Data							*Estimated Parameters*		
Location	Well Diam.	Depth to Water: Initial	Depth to Water: Final	Test Duration	Mean Pumping Rate	Screened Interval: Depth to Top	Screened Interval: Depth to Bottom	Storage Coeff. (S)	Well loss Coeff. (C)	Aquifer Thickness (b)
	inches	feet	feet	hours	gpm	feet	feet	-	sec^2/ft^5	feet
MW-B1-001	2	64.1	64.8	0.83333	1.7	61.0	71.0	0.1	1	36
MW-C2-002	2	64.4	64.9	0.78333	1.7	65.0	75.0	0.1	1	80
MW-C2-202	2	64.7	77.1	2.56667	1.3	137.0	147.0	0.1	1	80
MW-A3-003	2	69.9	71.2	2.03333	1.3	72.0	82.0	0.1	1	100
MW-C7-004	2	69.7	71.3	0.96667	1.7	80.0	90.0	0.1	1	85
MW-E2-305	2	52.4	67.0	0.65	1.7	64.0	74.0	0.1	1	110
MW-A6-006	2	82.0	82.1	0.91667	1.0	102.0	112.0	0.1	1	70
MW-D3-007	2	60.0	62.3	0.7	2.5	60.0	70.0	0.1	1	110
MW-D5-308	2	62.7	72.5	1.8	0.6	65.0	75.0	0.1	1	100
MW-E2-209	2	61.1	64.8	0.88333	1.7	116.0	126.0	0.1	1	100
MW-E4-010	2	56.1	56.7	0.63333	1.7	62.0	72.0	0.1	1	100
MW-C4-311	2	61.8	83.0	1.91667	1.0	82.0	92.0	0.1	1	80

	Calculated Results							*Diagnostics*					
								Solution Integrity			***Sensitivity of T:***		
Location	Measured Drawdown (s_m)	Saturated Screen Length (L)	Well loss (s_w)	Partial Penetration Parameter (s_p)	Specific Capacity	**Transmissivity (T)**	**Conductivity (K)**	Calculated Drawdown	Error as Drawdown	Well Bore Storage Test	to S at ± 1 factor of 10	to s_w at 10% of s_m	to b at ± 25%
	feet	feet	feet	-	gpm/ft	**sq ft/sec**	**ft/day**	feet			sq ft/sec	sq ft/sec	sq ft/sec
MW-B1-001	0.66	6.9	1.4E-05	17.45	2.53	**2.1E-02**	**50.8**	0.66	0.07%	pass	1.1E-03	2.4E-03	1.1E-02
MW-C2-002	0.51	10.0	1.4E-05	32.69	3.27	**4.5E-02**	**49.1**	0.51	0.01%	pass	1.4E-03	5.1E-03	2.4E-02
MW-C2-202	12.41	10.0	8.4E-06	32.69	0.10	**1.4E-03**	**1.5**	12.41	0.00%	pass	4.3E-05	1.6E-04	7.6E-04
MW-A3-003	1.22	10.0	7.8E-06	42.92	1.02	**1.8E-02**	**15.5**	1.22	0.02%	pass	4.2E-04	2.0E-03	9.5E-03
MW-C7-004	1.60	10.0	1.4E-05	35.21	1.04	**1.5E-02**	**15.5**	1.60	0.03%	pass	4.3E-04	1.7E-03	8.1E-03
MW-E2-305	14.57	10.0	1.4E-05	48.16	0.11	**2.2E-03**	**1.7**	14.57	0.00%	pass	4.7E-05	2.4E-04	1.2E-03
MW-A6-006	0.10	10.0	5.0E-06	27.70	10.00	**1.2E-01**	**151.6**	0.10	0.30%	pass	4.1E-03	1.4E-02	6.1E-02
MW-D3-007	2.30	10.0	3.1E-05	48.20	1.09	**2.1E-02**	**16.4**	2.30	0.01%	pass	4.5E-04	2.3E-03	1.1E-02
MW-D5-308	9.82	10.0	1.5E-06	42.92	0.06	**9.6E-04**	**0.8**	9.82	0.00%	pass	2.3E-05	1.1E-04	5.3E-04
MW-E2-209	3.67	10.0	1.4E-05	42.92	0.46	**7.8E-03**	**6.8**	3.67	0.03%	pass	1.9E-04	8.8E-04	4.2E-03
MW-E4-010	0.57	10.0	1.4E-05	42.92	2.93	**5.1E-02**	**44.3**	0.57	0.01%	pass	1.2E-03	5.8E-03	2.7E-02
MW-C4-311	21.11	10.0	5.0E-06	32.69	0.05	**6.3E-04**	**0.7**	21.11	0.00%	pass	2.0E-05	7.1E-05	3.4E-04

Table 1

Hazen Method Calculations of Hydraulic Conductivity
UMore Park

$$K_{Hazen} = Ad_{10}^{2} \text{ (for reference see footnotes)}$$
where
$$K_{Hazen} = \text{Hydraulic conductivity in } \text{cm}/\text{sec}$$
$$A = 1.0$$
$$d_{10} = \text{Effective grain size in mm}$$

Location/Boring	Depth ft	d_{10} mm	Hydraulic Conductivity cm/s	Hydraulic Conductivity ft/d
A6-Pilot	130	0.16	0.026	73
A6-Pilot	158	0.16	0.026	73
B2-Pilot	86-88	0.0017	NA	NA
C2-Pilot	104	0.069	NA	NA
C2-Pilot	120	0.0017	NA	NA
C2-Pilot	158	0.16	0.026	73
E1-Pilot	103	--	NA	NA
E1-Pilot	126-127	--	NA	NA
E1-Pilot	155	0.15	0.023	64
MW-A3-003	75	0.16	0.026	73
MW-A3-003	81	0.0031	NA	NA
MW-B1-001	65	0.13	0.017	48
MW-B1-001	73-74	0.028	NA	NA
MW-C4-311	70	--	NA	NA
MW-C7-004	88	0.03	NA	NA
MW-C7-004	86-88	0.0064	NA	NA
MW-D3-007	60	0.21	0.044	125
MW-D5-308	65	0.011	NA	NA
MW-E2-009	68	0.19	0.036	102
MW-E2-209	113	--	NA	NA
MW-E2-305	70	0.008	NA	NA
MW-E4-010	65	0.2	0.040	113

Notes:
-- d_{10} not determined during test
NA = Hazen method could not be applied because d_{10} value either not determined or too low (< 0.1)
Hazen Method Approximation implemented per Freeze and Cherry, 1979