Hydrogeologic Characterization of Fractured Dolomite for Regulatory Monitoring– A Multiple Method Approach

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1 INTRODUCTION

Purpose -- identify preferential flow zones in the dolomite and monitor them for the proposed expansion of Veolia ES Hickory Meadows Landfill (VHML), Calumet Co., northeastern Wisc.

- Research on groundwater flow in the Silurian dolomite in other parts of northeastern Wisconsin indicates multiple, continuous preferential flow zones related to lithologic contrasts within the dolomite (Gianniny & others, 1996, WG&NHS Open File Report, and Muldoon & others, 1999, WG&NHS Open File Report).
- In part based on this research the Wisconsin Department of Natural Resources required investigating the entire thickness of Silurian dolomite to the top of the underlying Ordovician Maquoketa shale.

2 METHODS

- Reviewed regional bedrock information, private well logs and observed outcrops.
- Cored (~2" diameter core) the Silurian dolomite to the top of the Maquoketa shale at 3 locations and the upper 64 feet of the Silurian dolomite at a 4th location.
- Used standard core-logging procedures noting general rock type and properties, fracture frequency, percent recovery, rock quality designation (RQD), etc. Described vugs, fractures, bedding-plane partings, other voids, etc., evidence of oxidation indicating preferential flow zones; and observations of water production while drilling.
- Geophysical and flow logging conducted at the four deep bedrock borings (B301, B304, B311, and B317) and the VHML Office Well. Logging included:
  - fluid temperature,
  - fluid resistivity
  - caliper
  - optical televiewer
  - natural gamma
  - spontaneous potential (SP)
  - single-point resistance (SPR)
  - normal resistivity (8", 16", 32", and 64")
  - heat pulse flowmeter (HPF), and impeller flowmeter (Office Well only) run under: 1) ambient conditions, and 2) pumping or injecting conditions.
- Short pumping tests conducted at wells MW301D, MW301E, MW304D, MW304E, MW311D, MW311E, MW314D, MW317D, MW317E, MW325, and MW327, and borehole B304.
- Long pumping test conducted at MW301E (Drawdown recorded for 27 hrs; Recovery recorded for 28 hrs).
- Eight rounds of baseline groundwater quality samples collected.
- Water levels at all wells measured on the same day, monthly for 6 months. Calculated vertical gradients from the level measurements.

3 RESULTS

Regional

- The Silurian dolomite dips toward the E-SE into the Michigan Basin at about 8 m/km.
- Based on regional dip, beds exposed along the Silurian escarpment on the east side of Lake Winnebago are in the subsurface beneath the landfill.
- Private wells in the area with the highest specific capacities are constructed with an open hole in the upper 25 ft of the dolomite.

Core and Geophysical Logs

Core and geophysical logs (primarily the optical televiewer logs) indicated the bedrock beneath the landfill is generally very fine to medium crystalline, medium- to thick-bedded (beds generally are about 0.3 ft to a few ft thick) non-fossiliferous dolomite, with some secondary porosity and mineralization in vugs and fractures, and with beds containing chert nodules.

- Total core recovery was 80 to 100%. Solid core recovery was generally slightly lower, and modified core recovery was 0% to 100%. RQD generally improved with depth below the top of the dolomite.
- Optical televiewer, SP, SPR, and normal resistivity logs indicate generally uniform dolomite
- Natural gamma logs indicate lower gamma ray production in the uppermost dolomite, and higher gamma ray production in shaley zones or zones with more abundant styolites.
- The dolomite is generally very pale brown (10YR 7/3) or light gray (7.5YR 7/1) in the upper part, and is grayish-brown (10YR 5/2) and dark gray (10YR 4/1) lower in the section. The color change is;
  - Present at elevations 841 to 828 ft.
  - Distinct in the optical televiewer logs, and the gamma logs indicate a lower gamma count from the lighter colored dolomite .
  - Generally very abrupt and does not appear to be related to a bedding contact or change in lithology.
  - Color variations are likely associated with geochemical processes in a paleoenvironment as the color changes have no clear relationship with the water table or zones of preferential flow as currently observed.

3 RESULTS CONTINUED

Flow Logging and Water Level Measurements

The groundwater flow net is drawn along a Geologic Cross Section, parallel to the direction of groundwater flow in the upper part of the dolomite aquifer. This conceptual model of flow in the glacial deposits is supported by the water level measurements, calculated gradients, and estimated vertical and horizontal hydraulic conductivities.

- Vertical gradients measured at monitoring well nests and in the borehole flow logging indicate that vertical flow is generally converging toward the zone of maximum hydraulic conductivity at the top of the bedrock.
- Vertical flow in the glacial deposits is downward, and vertical flow in the upper 25 ft of dolomite is upward at most locations.
- Borehole flow logging indicates the most transmissive zone in each borehole was within 5 ft of the top of the dolomite and the second most transmissive zone was generally 10 to 15 ft deeper than the uppermost transmissive zone. These two transmissive zones in each borehole were selected for installation of the "D" and "E" wells at the B301, B304, B311, and B317 locations.
- Transmissivity estimates for the uppermost transmissive zone ranged from 589 ft^2/day at the office well to 85,000 ft^2/day at borehole B317.
- The second, slightly deeper transmissive zone had estimated transmissivity values ranging from 37 ft^2/day at the Office Well to 2,100 ft^2/day at B304.
- On average for all five boreholes, 88 % of the bedrock transmissivity was estimated to occur in the upper 25 ft of the dolomite.
- In spite of the varying bedrock surface elevations, the pattern of having most of the transmissivity near the top of the bedrock was consistent at all locations.

Pumping tests

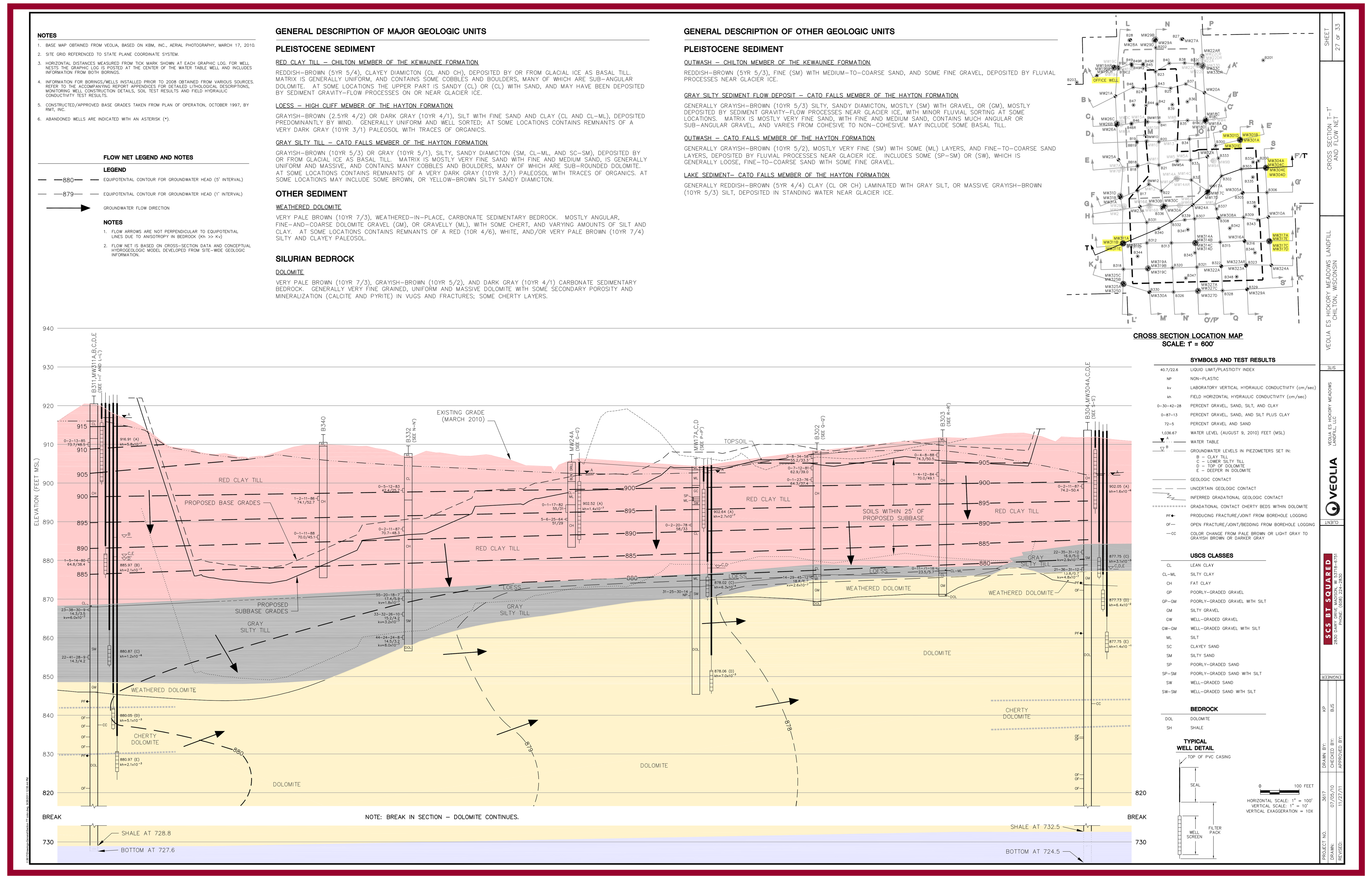
- Estimated hydraulic conductivity values for the dolomite based on the single-well pumping tests ranged from 2.1×10^{-3} cm/sec to 3.0×10^{-1} cm/sec with a geometric mean of 3.6×10^{-2} cm/sec.
- Estimated hydraulic conductivity for the upper 25 ft of dolomite (including weathered dolomite) based on the long-term pumping test at MW301E is 0.33 cm/sec, and the transmissivity is 23,000 ft^2/day.
- For comparison, the estimated transmissivity for the upper 25 ft of dolomite based on the borehole flow logging at B301 was 5,400 ft^2/day, and the geometric mean for boreholes B301, B304, B311, and B317 was 11,000 ft^2/day.

All of the bedrock monitoring wells at the site showed a response to pumping at MW301E, with the exception of well MW325D, located approximately 2,000 ft southwest of MW301E, which showed little or no response. This well was used to represent background water level changes during the test due to causes other than pumping at MW301E, including long-term trends and shorter-term variation due to barometric pressure changes.

Water Quality

Upward flow in the bedrock and a shallow base of the local flow system are also indicated in the baseline water quality data. The "D" and "E" well depths are only separated by 10 to 11 ft, but the water quality monitoring results are significantly different for some parameters, particularly those indicating possible contamination related to agricultural land use.

- Nitrate+nitrite exceeded groundwater standards at MW304D and MW317D, but was not detected or was below the limit of quantitation at the corresponding "E" wells.
- Chloride and sodium are also elevated at MW304D and MW317D relative to the "E" wells.
- At MW311D, nitrate+nitrite and chloride are lower than at MW304D and MW317D, but are still slightly elevated in comparison to MW311E.



Borehole Flow Logging Results
Veolia ES Hickory Meadows Landfill Expansion

Borehole	Ground Surface (ft amsl)	Bottom of Casing / Top of Bedrock (ft amsl)	Bottom of Borehole (ft amsl)	Flow Zone Elevation (ft amsl)	Flow Zone Depth Below Casing / Top of Bedrock (ft)	Estimated Zone Transmissivity (ft^2/day)	Estimated Total Transmissivity (ft^2/day): Full Borehole	Estimated Total Transmissivity (ft^2/day): Top 25 Ft	% of T in Top 25 Ft	Estimated Zone Head (ft amsl)	Estimated Vertical Gradient Direction Above Zone	Monitoring Well Installed
Office Well	907.0	830.3	726.0	825.6	4.7	589				867.94	--	
				824.1	6.2	37				868.44	Up	
				741.7	88.6	2	628	626	99.7%	868.64	Up	
B301	925.8	873.3	810.0	870.6	2.7	4,050				871.14	--	MW301D
				860.8	12.5	1,350				871.34	Up	MW301E
				835.4	37.9	2,700				870.84	Down	
				824.0	49.3	900	9,000	5,400	60%	870.84	Down	
B304	913.7	875.4	724.7	874.5	0.9	11,039				871.83	--	MW304D
				861.5	13.9	2,128				872.02	Up	MW304E
				756.4	119.0	332	13,499	13,167	98%	870.83	Down	
B311	920.7	846.2	728.1	843.6	2.6	2,150				874.03	--	MW311D
				829.6	16.6	43				874.81	Up	MW311E
				813.5	32.7	22				874.13	Down	
				754.5	91.7	4	2,219	2,193	99%	874.13	None	
B317	901.0	865.8	722.0	864.0	1.8	85,000				873.20	--	MW317D
				852.9	12.9	850				873.68	Up	MW317E
				812.4	53.4	3,400				873.18	Down	
				748.4	117.4	1,700	90,950	85,850	94%	873.18	None	
Average Estimated Transmissivity								21,447	90%			
Geometric Mean								6,091				
Average Excluding Office Well								26,653	88%			
Geometric Mean Excluding Office Well								10,756				

NOTES:
1. Borehole logging results from report prepared by Golder Associates titled *Veolia ES Hickory Meadows Landfill, Borehole Geophysical Investigation, Chilton, Wisconsin, September 2010*.
2. Vertical gradient direction is based on the estimated head difference between each pair of vertically adjacent flow zones, and is shown in the row for the lower zone in each pair.

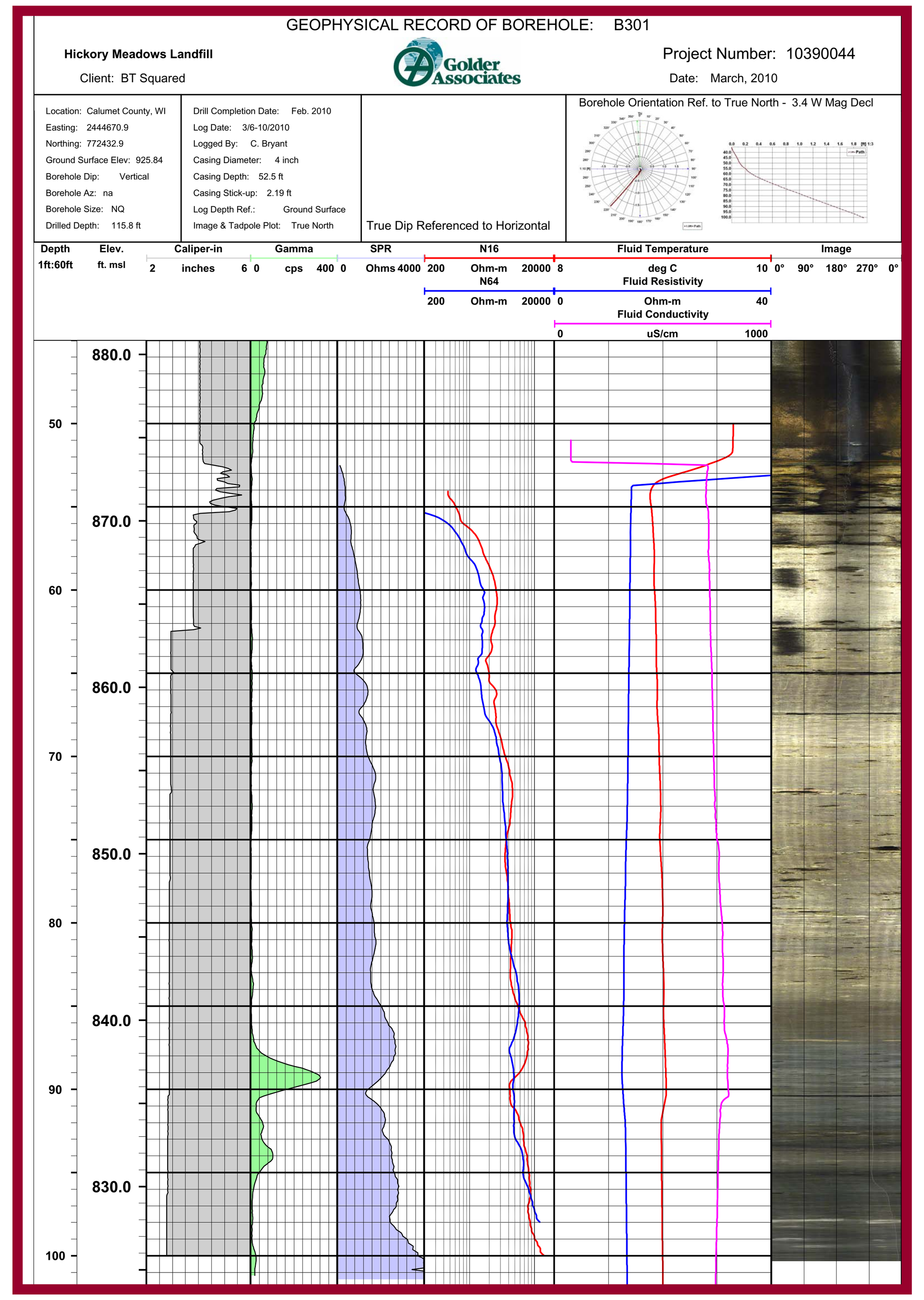
Single Well Pumping Test Results
Veolia ES Hickory Meadows Landfill Expansion

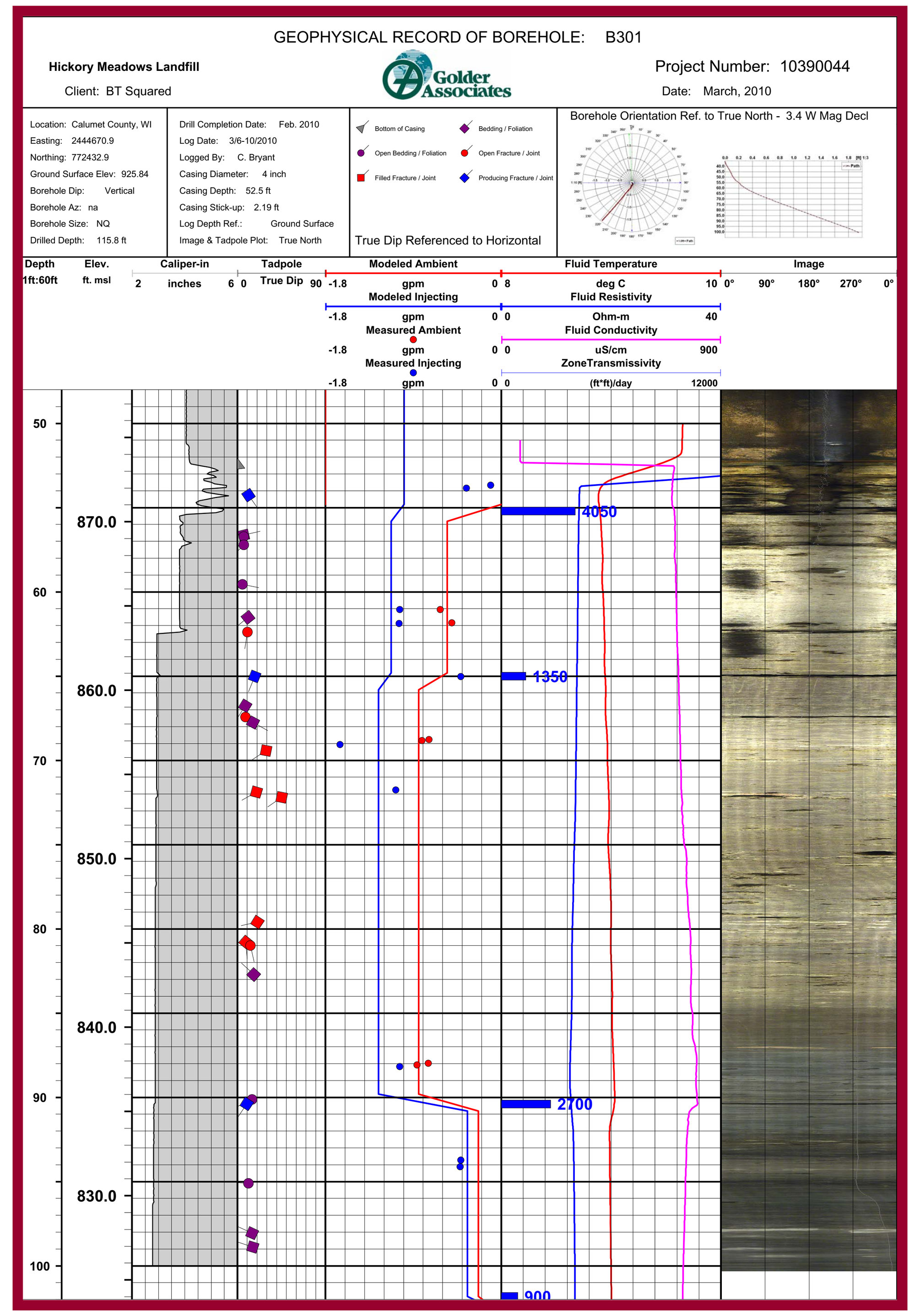
Test Well	Static Water Level (ft, btoc)	Static Water Column (ft)	Pumping Rates (gpm)	Total Minutes Pumped	Drawdown at Max. Rate (ft)	Aquifer Thickness (b, ft)	Estimated Transmisivity (ft^2/day)	Hydraulic Conductivity K = T/b (cm/s)	Storage Coefficient S (-)
MW301D	52.51	9.49	5, 10, 15, 20	50	5.28	25	2,000	2.9E-02	1.0E-04
MW301E	52.10	19.10	10, 20, 29.5	60	2.61	25	22,000	3.0E-01	1.0E-04
MW304D	39.56	8.94	2, 5, 10	25	5.94	25	4,600	6.4E-02	1.7E-04
MW304E	39.75	19.75	5, 4, 20, 30	50	11.08	25	10,200	1.4E-01	5.6E-04
B304	39.56	151.3	5, 20, 30	54	0.11	143	110,000	2.7E-01	1.5E-04
MW311D	43.56	42.87	5.4, 10	112	37.45	25	360	5.1E-03	1.4E-04
MW311E	43.15	54.25	5	111	29.53	26	150	2.1E-03	6.6E-04
MW314D	26.41	22.89	10, 1, 5	32	14.81	25	560	7.9E-03	4.6E-04
MW317D	26.45	19.22	5, 10, 15	60	14.17	25	900	1.3E-02	1.9E-04
MW317E	26.67	29.76	10, 20, 30	67	19.19	25	2,500	3.6E-02	3.5E-04
MW325D	30.91	41.59	5, 15, 30	65	11.76	25	8,700	1.2E-01	4.2E-04
MW327D	16.24	33.16	10, 30	60	11.35	25	3,000	4.7E-02	1.9E-04
Geometric Mean							2,900	3.6E-02	2.4E-04
Minimum							150	2.1E-03	1.0E-04
Maximum							110,000	3.0E-01	6.6E-04
Sensitivity Analysis for Assumed Aquifer Parameters									
MW317D	26.45	19.22	5, 10, 15	60	14.17	25	900	1.3E-02	1.9E-04
Thinner aquifer						12	440	1.3E-02	9.2E-05
Thicker Aquifer						50	1,700	1.2E-02	3.6E-04
Less anisotropy						25	780	1.1E-02	1.8E-04
More anisotropy						25	1,100	1.5E-02	2.5E-04

4 SUMMARY OF RESULTS

- The bedrock cores and the geophysical logging indicate a zone of extensively fractured and weathered dolomite beneath the landfill site just below the contact of the dolomite with the overlying unconsolidated sediments.
- Borehole flow logging documents the contrast in flow between the extensively fractured and weathered top of the dolomite and the flow zones deeper in the underlying dolomite at each location investigated.
- Borehole flow logging indicates that most of the transmissivity is in the upper 25 ft of the dolomite, and that the most transmissive zone in each boreholes was within 5 ft of the top of the dolomite, rather than in several zones generally at contacts between contrasting lithology as found by Gianniny et al (1996).
- Vertical flow in the upper dolomite is upward at most locations.

The depths for the "D" and "E" wells were selected based on the results of the coring and borehole logging. As proposed in the investigation program, the "D" wells were installed in the uppermost transmissive zone in the bedrock, and the "E" wells were installed in the next deeper relatively transmissive zone.





Site-Wide Pumping Test Results
Veolia ES Hickory Meadows Landfill Expansion

Observation Well	Well Parameters: Distance from Pumping Well (ft)	Well Parameters: Well Depth Below Top of Aquifer (ft)	Maximum Drawdown (ft)	Estimated Transmissivity T (ft^2/day)	Estimated Hydraulic Conductivity, K = T/b (cm/sec)	Estimated Storage Coefficient, S (-)
Pumping Well						
MW301E	0	19.2	13.38	11,000	1.5E-01	0.49**
Observation Wells (in order of increasing distance from pumping well)						
MW301D	8	10.2	0.23	22,000	3.1E-01	1.6E-01
MW304E	589	20.7	0.33	27,000	3.9E-01	1.6E-04
MW304D	592	9.7	0.24	22,000	3.2E-01	3.3E-03
MW18D	613	20.3	0.31	27,000	3.8E-01	2.8E-04
MW17D	955	24.3	0.30	27,000	3.7E-01	1.9E-04
MW33DR	1280	23.5	0.33	17,000	2.5E-01	1.8E-04
MW317E	1632	21.7	0.31	19,000	2.7E-01	1.1E-04
MW317D	1634	10.2	0.30	20,000	2.9E-01	8.6E-05
MW314D	1740	10.7	0.32	21,000	2.9E-01	1.1E-04
MW29D	2039	11.6	0.32	17,000	2.4E-01	1.0E-04
MW31D	2052	12.7	0.11	29,000	4.1E-01	6.7E-04
MW311D	2420	12.2	0.09	28,000	4.0E-01	1.1E-03
MW311E	2425	23.2	0.06	25,000	3.5E-01	3.4E-03
MW327D	2428	7.7	0.08	28,000	3.9E-01	1.0E-03
Geometric Mean for Observation Wells**				**23,000**	**3.3E-01**	**5.5E-04**

** Est. aquifer parameters based on drawdown in the pumping well, MW301E, are biased low due to high well losses during pumping, so the MW301E results were not included in averaging.

Notes:

1) For all analyses, assumed aquifer thickness (b) is 25 feet, and assumed anisotropy ratio (Kz/Kr) is 0.005.

2) Transmissivity and storage coefficient were estimated using Aqtesolv for Windows, Version 4.50.
T was estimated using both the Theis/Hantush type curve solution for a pumping/recovery test in a confined aquifer with partial penetration and the Theis straight-line solution for recovery data.
Storage coefficent was estimated using the Theis/Hantush type curve solution.

5 EVALUATION OF METHODS

- The bedrock cores and optical televiewer logs provided excellent information about lithology, weathering and fracturing at each location. The geophysical logs were not as useful given the lithological information from the cores and optical televiewer logs.
- Fluid temperature and resistivity were very useful in identifying small transmissive zones.
- Borehole flow logging was the only method that identified the local vertical flow that was used as the basis for determining depths of the "D" and "E" wells.
- The long-term pumping test results indicated site-wide hydraulic connection in the uppermost dolomite, and provide the basis for estimation of aquifer parameters at a much larger scale than the borehole logging or single-well tests,
- Overall the multiple investigative methods produced scale-dependent but compatible results indicating the highly transmissive uppermost dolomite as an important focus for long-term monitoring of bedrock groundwater quality.