January 21, 2014

Madison Water Utility
Attn: Joe Demorett
119 East Olin Avenue
Madison, WI 53713

Subject: Technical Evaluation of Assessments of the Potential for PCE in Groundwater Associated with the MKC site to Impact Unit Well #8

Dear Mr. Demorett,

I have completed my technical evaluation of the assessment of the potential for PCE in groundwater associated with the Madison-Kipp Corporation site to impact Unit Well #8. I have provided a list of the documents I considered in my evaluation, a summary of my approach, major observations, and options for future work for you to consider in the attached document. Please contact me if you have any questions or require any clarification.

Regards,

Jessica Meyer, Ph.D.
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TECHNICAL EVALUATION OF ASSESSMENT OF THE POTENTIAL FOR PCE IN GROUNDWATER ASSOCIATED WITH THE MADISON-KIPP CORPORATION SITE TO IMPACT UNIT WELL #8

Prepared for:

City of Madison Water Utility

Prepared by:

Jessica Meyer, PhD

January 21, 2015

Contents

1.0 Introduction

A plume of volatile organic contaminants (VOCs) has been recognized in the unconsolidated deposits and fractured sedimentary rock aquifer system beneath and adjacent to the Madison-Kipp Corporation property located at 201 Waubesa Street in Madison, Wisconsin, referred to here as the MKC site. Tetrachloroethene (PCE) is the primary VOC of concern in the groundwater. One of the Madison Water Utility's supply wells, Unit Well #8, is located downgradient of the observed extent of the PCE groundwater plume. Currently, Unit Well #8 is only used seasonally due to naturally occurring iron and manganese (http://www.cityofmadison.com/water/water-quality/whats-next-for-well-8). However, the Madison Water Utility is considering returning Unit Well #8 to full service and is concerned about potential PCE impacts to Unit Well #8.

In fractured, sedimentary rocks, the large matrix porosity (2-20%) provides substantial storage space for contaminants due to its relatively large volume and low permeability in comparison to the fractures. The process of diffusion transfers contaminants from the higher permeability fractures, where most groundwater flow occurs, into the lower permeability rock matrix. The transfer of contaminants from the high permeability fractures into the low permeability matrix effectively slows the propagation of the contaminants compared to the faster flowing groundwater in the fractures. The importance of matrix diffusion on the transport of dissolved constituents in porous, fractured rocks was first noted by (Foster, 1975) and a number of other field and numerical modeling studies have demonstrated the importance of matrix diffusion on the transport and fate of contaminants in fractured, porous media (e.g., Grisak and Pickens, 1980; Tang et al., 1981; Sudicky and Frind, 1982; Parker et al., 1994; VanderKwaak and Sudicky, 1996; Parker et al., 1997; Lipson et al., 2005). Transverse lateral spreading of the contaminants in the fracture networks and degradation can also contribute to attenuation of plumes in sedimentary rocks (Parker et al., 2012). Additionally, at many sites the source of contamination occurred decades ago. Matrix diffusion occurring over these decadal time periods results in the majority of the contaminant mass now existing in the rock matrix (Parker et al., 2012). The combined result is that aged plumes in fractured sedimentary rocks are expected to be strongly attenuated and no longer moving rapidly forward Parker et al. (2012). Based on the MKC site investigations (Arcadis, 2013), this is also a reasonable general expectation for the MKC site PCE plume. However, the particular time and distance scales over which the contaminant transport is occurring at the MKC site will be dictated by site specific parameters and processes requiring characterization and evaluation of uncertainty. Robust characterization and uncertainty analysis is central to evaluating risks and decision making.

2.0 Objective of Evaluation

This evaluation assesses the technical basis for the conclusion and supporting statements presented in "Evaluation of Plume Stability and Fate and Transport Modeling for PCE in Bedrock Groundwater" (Arcadis, 2014b), referred to as the 'plume stability report' in this document. The plume stability report concluded "… that Unit Well 8 will likely not be impacted by PCE in groundwater at the site if Unit Well 8 were to become operational in the future." The plume stability report listed the following as the primary lines of support for this conclusion:

> "In summary, the PCE plume in bedrock groundwater beneath the site is stable and no longer expanding as demonstrated by empirical site groundwater monitoring data. The most probable mechanisms controlling the extent and stability of the PCE plume in site groundwater are matrix diffusion (i.e., diffusive transfer and storage of PCE into low-permeability bedrock matrix zones) and in-situ PCE degradation, respectively. Results of the modeling analysis indicate that the PCE plume stabilized after approximately 45 years of transport, approximately three years ago."

The following additional lines of support were also provided (Arcadis, 2014b):

- "The vertical extent of PCE has been delineated at the site and is limited to a depth of approximately 170 ft below ground surface (bgs)."
- "The intake portion of Unit Well 8 starts at approximately 280 ft bgs and, therefore, there are at least 110 feet of vertical separation between the bottom of the PCE plume and the top of the intake screen of Unit Well 8, as well as approximately 800 feet of horizontal separation."
- "The intake portion of Unit Well 8 is screened below the Eau Claire shale which is regional in extent, has a very low vertical hydraulic conductivity (0.0006 ft/day), and strongly restricts vertical groundwater flow and transport above the confining layer from migrating vertically downward and into the deeper aquifer in which Unit Well 8 is screened."
- "Pumping at Unit Well 8 for water supply purposes will result in radial flow of groundwater from all directions toward Unit Well 8 to the extent that the vast majority (e.g., ~90%) of groundwater entering Unit Well 8 will be from other areas not associated with the site."
- "The PCE source area at the site (i.e., the zone with the highest PCE concentrations) will be hydraulically contained by Madison-Kipp's proposed groundwater extraction system."

3.0 Summary of Approach

My approach to the evaluation consisted of several parts.

- Review of the documents provided by the Madison Water Utility in order to become familiar with the site history, hydrogeological characterization methods applied at the site, available data, design of the monitoring network, and the conceptual site model.
- Assessment of the flow system characterization with emphasis on the hydrogeologic unit conceptual model for the site.
- Evaluation of the specific lines of evidence (data and information) for the conclusion presented in the plume stability report.
- Identify limitations to the assessment of potential PCE impact to Unit Well 8 based on obvious data gaps and inconsistencies, existing literature or other site information available to me, and through my personal experience and experience through interaction with colleagues experienced with characterization and numerical modeling of contaminant transport and fate in sedimentary rocks.
- Provide options for additional work to consider focused on enhanced data analyses of site conditions and evaluation of the likelihood of PCE impact to Unit Well 8.

4.0 Documents Considered in the Evaluation

The following documents, provided by the Madison Water Utility, were reviewed with particular emphasis on those in bold type.

Arcadis. 2014. Basis of design for proposed groundwater extraction and treatment system, Madison-Kipp Corporation, Madison, Wisconsin. April 1, 2014. 83 p.

Arcadis. 2012. Bedrock Characterization Work Plan. May 22, 2012. 26 p.

Arcadis. 2012. Site Investigation Work Plan. May 31, 2012. 69 p.

Arcadis. 2013. Implementation Summary and Recommendations – In Situ Chemical Oxidation Groundwater Piolet Test. February 15, 2013. 69 p.

Arcadis. 2014. Evaluation of plume stability and fate and transport modeling for PCE in bedrock groundwater, Madison Kipp Corporation, Madison, Wisconsin. April 16, 2014. 45 p.

Arcadis 2013. Site Investigation and Interim Actions Report, February 2012 – January 2013. March 15, 2013. 118 p.

Arcadis. 2013. Supplemental Site Information/Addendum 1. May 29, 2013. 190 p.

Arcadis. 2013. Groundwater Remediation Program Presentation. July 10, 2013. 40 p.

Ruekert/Mielke, Inc. 2011. Wellhead Protection Plan, Unit Well 8, City of Madison, Wisconsin. March 2011. 55 p.

5.0 Summary of Major Observations

The following section provides a summary of my major observations derived from review of the reports, available site data, and CRAFLUSH modeling. These observations form the basis for a list of options for future work for the Madison Water Utility to consider if further assessments of the potential for PCE to impact unit well #8 are pursued.

5.1 Monitoring Network

Groundwater concentrations of PCE collected from the site monitoring network are used in several ways in the plume stability report (Arcadis, 2014b) to assess potential PCE impact to Unit Well #8:

- Characterize the proximity of the groundwater PCE plume to Unit Well #8
- Assess temporal PCE concentrations trends to evaluate potential plume stability
- Calibrate the Craflush model used to predict plume migration at future points in time and further assess potential plume stability

A summary of the site monitoring network derived from available reports is provided below.

Based on the information provided by in Table 3-1 (Arcadis, 2013) and in Figure 3 (Arcadis, 2014b) there are 39 monitoring intervals from conventional wells and 20 monitoring intervals from Westbay multilevel systems for a total of 59 monitoring intervals. The minimum, maximum and average screen length for the conventional wells is 5, 60, and 12.8 ft respectively with 79% of the wells with screens lengths of 10 ft or less. The minimum, maximum and average screen length for the Westbay multilevel systems is 4, 10, and 5 ft respectively. Relatively short screen lengths, like the majority of those at the MKC site, are desirable for characterization because they minimize blending and uncertainty.

Based on the cross-sections provided in Arcadis (2013), the monitoring intervals are distributed throughout the geologic section as shown below.

- 13 (22%) – Unconsolidated Deposits
- 22 (37%) – Lone Rock Formation
- 7 (12%) – Ironton Member of the Wonewoc Formation
- 14 (24%) – Galesville Member of the Wonewoc Formation

- 3 (5%) – Ironton and Galesville Member of the Wonewoc Formation

Although the monitoring intervals are distributed throughout the geologic formations there is a relative lack of three-dimensional monitoring between the inferred source area (MP-13 multilevel system location (Arcadis, 2014b)) and Unit Well #8. For example, the cross-section used to inform the Craflush modeling (Figure 3, (Arcadis, 2014b)) shows that about 300 ft downgradient of the inferred source there is a relatively dense cluster of monitoring wells distributed throughout the vertical section (MW-19D, MW-19D2, MW-20D, MW-20D2, MW-2D, MW-2D2, MW-3D, MW-3D2, MW-3D, MW-21D, MW-21D2, MW-3S, MW-18S). However, along this cross-section in the approximately 2,300 ft between this cluster of wells and Unit Well #8 there are only 5 monitoring points completed below the Lone Rock Formation. The three-dimensional density and arrangement of monitoring zones downgradient of the inferred source zone is not well suited to the characterization and temporal monitoring of the PCE plume necessary to make reliable assessments of potential impacts to Unit Well #8.

Options for future work include:

- Addition of monitoring intervals downgradient of the inferred source area to improve three-dimensional characterization of the PCE plume, provide additional information for further assessment of potential impact to Unit Well #8, and monitor for any further migration of the PCE plume toward Unit Well #8 in the future.

5.2 Hydrogeologic Unit Conceptual Model

A key element of any conceptual site model is delineation and characterization of hydrogeologic units, also referred to as hydrostratigraphic units. Hydrogeologic units describe the three-dimensional geometry of hydraulic conductivity contrasts in the subsurface. These contrasts strongly influence the flow of groundwater and transport of contaminants in the subsurface. Furthermore, the hydrogeologic unit conceptual model serves as a guide for the length and placement of monitoring well screens, preparation of potentiometric surfaces and calculations of the hydraulic gradient, and statistical analysis of site data.

The hydrogeologic unit framework described for the MKC site (Arcadis, 2013) was translated directly from the Dane County groundwater flow model described by Bradbury et al. (1999). The Dane county flow model delineates four hydrogeologic units (from top to bottom): unlithified aquifer, upper Paleozoic aquifer, Eau Claire aquitard, and the Mt. Simon aquifer. Bradbury et al. (1999) explain that this hydrogeologic unit framework was developed based on a regional analysis of data, and as such, it addresses large scale groundwater conditions and is not intended as a replacement for site-scale investigations.

Therefore, it is an option for future work to consider is re-evaluation of the current hydrogeologic unit conceptual model using site specific data. For example, Meyer et al. (2008) and Meyer et al. (2014) showed that plots of hydraulic head versus depth (referred to as head profiles) collected using detailed, depth discrete multilevel systems (MLS) are effective at identifying the thickness and position of contrasts in vertical hydraulic conductivity in sedimentary rock flow systems. Understanding contrasts in vertical hydraulic conductivity is useful for delineating the thickness and boundaries of hydrogeologic units in layered and anisotropic sedimentary rock systems but is also critical to evaluating downward components of flow.

Four Westbay MLS installed at the MKC site provide vertical head profile data; however, hydraulic head profiles are not presented in the site documentation reviewed here. Therefore, head data from the four MLS (Arcadis, 2013, table 4-1) were plotted in order to provide an example of how such data can be utilized and evaluate the existing site hydrogeologic unit conceptual model (Figure 1). The MP-13 head profile shows a sharp decrease in head of 1.07 ft between 780 and 763 ft AMSL. A similar, but less resolved, change in head appears in the MP-14 and MP-16 profiles. This distinct head change roughly coincides with the upper most portion of the Wonewoc Formation which has been described as the Ironton transition zone at the site (Arcadis, 2013). The MP-15 MLS does not include monitoring intervals in the Tunnel City Group and therefore does not include the head change. The distinct change in head observed at three locations bracketing the site to the north, west, and east indicates a contrast in hydraulic conductivity that potentially extends across the entire area of the PCE plume. The presence of a laterally extensive hydraulic conductivity contrast within the upper Paleozoic aquifer (Tunnel City Group, Wonewoc Formation, and portion of Eau Claire Formation above the aquitard) would not be consistent with the conceptual model where the upper Paleozoic aquifer functions as a single hydrogeologic unit.

The hydraulic head profiles (Figure 1) also provide additional insight regarding the vertical hydraulic gradients at the site. Arcadis (2013) notes that the vertical gradients are predominantly downward and vary in magnitude between 0.012 and 0.033 for the conventional wells and 0.013 and 0.019 for the Westbay MLS. However, calculation of the vertical gradient associated with the 1.07 ft of head lost across the transition zone in the MP-13 MLS yields a vertical gradient of 0.063. This vertical gradient is calculated by dividing the head loss (1.07 ft) by the distance between the bottom of the upper monitoring interval and the top of the lower monitoring interval (17 ft). The calculation assumes the contrast in hydraulic conductivity responsible for the head loss is 17 ft thick and located between the two monitoring intervals. Research at a nearby field site (Meyer et al., 2008; Meyer et al., 2014) suggest the hydraulic conductivity contrasts associated with this head loss is substantially thinner than 17 ft and therefore the vertical gradient of 0.063 is likely underestimated.

Options for future work include:

- Utilizing the site specific data to refine the hydrogeologic unit conceptual model for the site.
- Re-evaluating site specific data within the context of the refined hydrogeologic unit conceptual model
    - Redefine potentiometric surfaces
    - Re-calculate horizontal and vertical components of gradient
    - Reassess range and average values of hydraulic conductivity
    - Provide statistical estimates of other important flow and contaminant transport parameters such as fracture spacing and aperture, matrix porosity, and fraction of organic carbon.

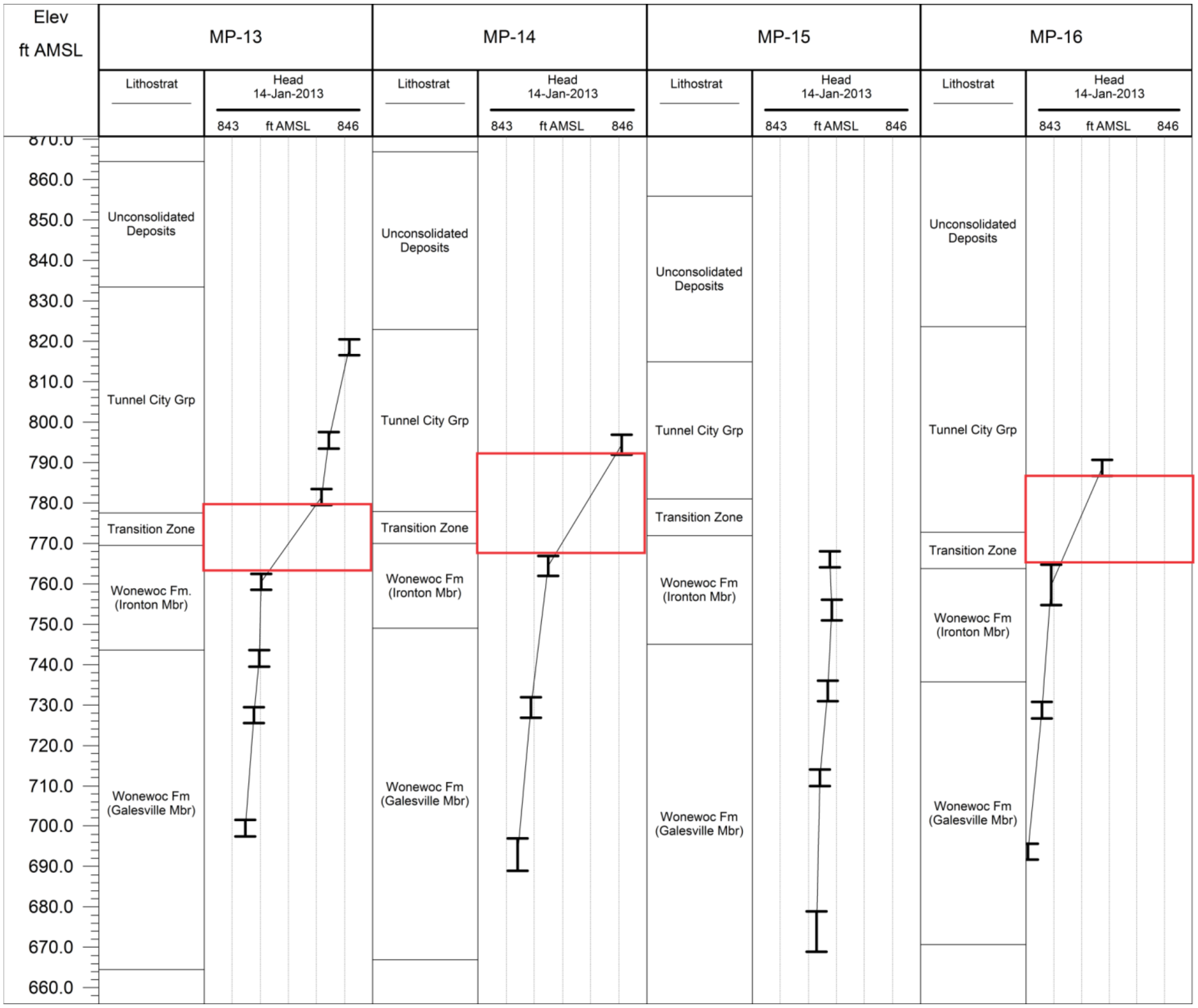

Figure 1. Hydraulic head profiles calculated using the MKC site Westbay multilevel system data (Arcadis, 2013). Lithostratigraphic data is approximated from figures provided in Arcadis (2013).

5.3 Specific Support for the Conclusion Provided in the Plume Stability Report

The following observations and options for future work are specific to the conclusion and supporting statements from the plume stability report.

5.3.1 Empirical Monitoring Data

The historical groundwater monitoring data was used to evaluate the stability of the PCE plume. In a summary of the results, Arcadis (2014b) stated "results of the statistical analysis indicate that all of the monitoring wells tested within the PCE plume or at the plume margin showed decreasing or stable PCE concentration trends over time." This was followed by the conclusion that "the PCE plume in bedrock groundwater beneath the site is stable and no longer expanding" (Arcadis, 2014b).

The following is a summary of how the historical groundwater monitoring data were analyzed based on the information provided by (Arcadis, 2014b). The PCE concentration data were plotted as time versus the natural log of the PCE concentration. Data sets with more than 8 points that were not affected by the December 2012 in-situ chemical oxidation pilot testing categorized as 'quantitative' and analyzed using a linear regression technique. Standard statistical parameters evaluated the 'goodness of fit' of the regression (R^2 values) and the significance of the slope (p-values). P-values of less than 0.1 were interpreted as significant (essentially representing a 90% confidence interval). Data sets with less than 8 points were categorized as 'qualitative' and best fit lines and the trends of those lines were visually identified for these results.

However, a re-evaluation of the PCE data rigorously following the guidelines for the method indicates uncertainty in the conclusion of a stable plume.

- Over 50% (12/22) of the evaluated wells have monitoring histories of about 1 year or less. These short monitoring records may not represent long term concentration trends needed to evaluate plume stability.
- Data sets collected from all of the monitoring zones of a multilevel system were analyzed together (e.g., MP-14 and MP-16) mixing the concept of a temporal trend at a monitoring point with spatially distinct data. This results in a data set with more than 8 data points even though the multilevel systems were sampled less than 8 times. It also results in regression of PCE concentrations from potentially different hydrogeologic units and is not suitable for temporal trend analysis.

- Over 60% (8/12) of the data sets categorized as quantitative had R^2 values less than 0.45 and 42% (5/12) had p-values greater than the stated cut off limit of 0.1. These statistics do not support identification of a trend in the data.
- 5 of the 22 analyzed data sets were from the unconsolidated aquifer. The current conceptual site model treats the unconsolidated deposits as a separate hydrogeologic unit. Therefore, trends in these data are not directly relevant to the question of plume stability in the Upper Paleozoic bedrock aquifer units.
- In several instances, data sets that are entirely non-detect (MW-11S and MW-25D2) are qualitatively analyzed for a concentration trend. The changes in these "concentrations" represent fluctuations in the laboratory detection limits and do not provide direct insight regarding plume stability. Rather, these data sets indicate the monitoring wells are currently outside the PCE plume.

Table 1 is a modification of (Arcadis, 2014b) Table 1 with the addition of the lithostratigraphic units associated with the concentration data and an indication of whether the data sets extend for more than 1 year. Of the data sets from the Upper Paleozoic bedrock units with records longer than 1 year, only three monitoring wells (shaded grey in Table 1) indicate statistically supported concentrations trends (defined here as R^2 values greater than 0.4, and p-values less than 0.1), all of which are decreasing.

Options for future work include:

- Re-analysis of time concentration data when monitoring records extend at least 2 years with at least 8 separate monitoring events.
- Analysis of the time concentration data within the context of the site specific hydrogeologic unit conceptual model (i.e., analysis of concentration trends in each aquifer unit using only wells screened in that unit)
- Calculation and reporting of several additional parameters useful in the evaluation of the data
    - Slope values
    - Standard error of the regression

Table 1. PCE concentration trend analysis table (Table 1 presented by Arcadis (2014b)) with supplemental information

Monitoring Well	Approximate Lithostratigraphic Position of Screened Interval [a]	Record About 1 year or less [a]	R^2 Value	p-value	Location Relative to PCE Plume	Quantitative or Qualitative Analysis	Trend Direction
MW-14	Upper Lone Rock Ironton Upper Galesville Lower Galesville	Yes	0.01	0.59	Margin	Quantitative	Decreasing
MW-2S	Unconsolidated Deposits	No	0.58	5.00E-08	Within	Quantitative	Decreasing
MW-2D	Upper Lone Rock	No	0.85	3.00E-06	Within	Quantitative	Decreasing
MW-5S	Upper Lone Rock	No	0.54	4.00E-06	Within	Quantitative	Decreasing
MW-5D	Lower Lone Rock	No	0.45	1.00E-08	Within	Quantitative	Decreasing
MW-5D2	Upper Galesville	No	0.01	0.61	Within	Quantitative	Decreasing
MW-5D3	Lower Galesville	Yes	--	--	Within	Qualitative	Decreasing
MW-22S	Unconsolidated Deposits	Yes	--	--	Within	Qualitative	Decreasing
MW-22D	Upper Lone Rock	Yes	--	--	Within	Qualitative	Decreasing
MW-16	Lower Lone Rock Ironton Upper Galesville Lower Galesville	Yes	0.06	0.26	Margin	Quantitative	Decreasing
MW-23S	Unconsolidated	Yes	--	--	Within	Qualitative	Decreasing
MW-23D	Upper Lone Rock	Yes	--	--	Within	Qualitative	Stable
MW-11S [b]	Unconsolidated	Yes	--	--	Within	Qualitative	Decreasing
MW-4S	Upper Lone Rock	No	0.08	0.14	Margin	Quantitative	Increasing
MW-4D	Middle Lone Rock	No	0.23	0.01	Margin	Quantitative	Decreasing
MW-4D2	Lower Lone Rock	No	0.31	0.003	Margin	Quantitative	Decreasing
MW-24	Unconsolidated	Yes	--	--	Margin	Qualitative	Decreasing
MW-17	Upper Galesville	Yes	--	--	Within	Qualitative	Decreasing
MW-6S	Upper Lone Rock	No	0.24	0.003	Within	Quantitative	Decreasing
MW-6D	Middle Lone Rock	No	0.01	0.65	Within	Quantitative	Stable
MW-25D	Upper Wonewoc	Yes	--	--	Margin	Qualitative	Stable
MW-25D2 [b]	Lower Wonewoc	Yes	--	--	Margin	Qualitative	Stable

[a] Data amended to Table 1 (Arcadis, 2014b)

[b] All data presented were non-detect.

5.3.2 Craflush Modeling

Craflush (Sudicky and Frind, 1982), a one-dimensional analytical discrete fracture network model, was used to assess the potential for PCE contamination to migrate from the MKC site to Unit Well #8. In order to evaluate the suitability of Craflush to assess plume stability and the likelihood of PCE reaching Unit Well #8, the processes, simplifying assumptions, boundary conditions, and parameter values used to represent site conditions included in the model were assessed here.

The flow and contaminant transport processes represented by Craflush are (paraphrased from Sudicky and Frind, 1982):

- Advective transport along each fracture
- Molecular diffusion and mechanical dispersion along the fracture axis
- Molecular diffusion from the fracture into the matrix
- Instantaneous and reversible adsorption within the matrix
- First order decay (degradation) of the contaminant

It is my opinion that this list of processes is adequate for representing general flow and contaminant transport at the aquifer/site scale for the MKC site. The represented processes include diffusion from fractures into the rock matrix which is an important control on migration of chlorinated solvents in sedimentary rocks demonstrated by Lipson et al. (2005), Parker et al. (2010), and Parker et al. (2012). Site specific, quantitative evidence for matrix diffusion was provided by rock core contaminant samples from two locations at the site (Arcadis, 2013).

Analytical models provide exact solutions for equations representing groundwater flow and/or contaminant transport for simple cases. Consequently, a number of simplifying assumptions are necessary (paraphrased from Sudicky and Frind, 1982):

- Width of each fracture is smaller than its length
- Transverse diffusion and dispersion within each fracture assures complete mixing across its width at all times
- The permeability of the porous matrix is low and transport in the matrix will be mainly by matrix diffusion
- Transport by advective flow in the fractures is much faster than transport by diffusion in the matrix

The assumption that the matrix permeability is low has two main consequences. 1) Advective flow in the matrix is not represented and 2) transport in the matrix is mainly by matrix diffusion. The latter assumption is typically valid in fractured rocks. In my opinion, at the MKC site, this assumption is likely appropriate at the aquifer/site scale for the Tunnel City Group, the upper Wonewoc Formation (Ironton Mbr.), and the lower Wonewoc Formation (Galesville Mbr.) although the Galesville Mbr. can be very poorly cemented locally leading to high matrix hydraulic conductivities.

In addition to the simplifying assumptions stated explicitly by Sudicky and Frind (1982), there are several implicit assumptions that are made by choosing Craflush to represent flow and contaminant transport.

- Flow and contaminant transport can be represented by two one-dimensional but coupled systems
- The fracture network can be represented by a system of evenly spaced, 'parallel plate' fractures and intervening homogenous matrix block slabs

The Craflush model represents one-dimensional flow with a non-varying hydraulic gradient and contaminant transport along the axis of each fracture and one-dimensional diffusion into the matrix perpendicular to the axis of each fracture. Therefore the model takes a three-dimensional system where groundwater flow magnitudes and directions change in time and simplifies it to coupled one-dimensional systems where flow magnitudes and directions are constant. In my opinion, this is a reasonable simplification for preliminary assessment of the potential for PCE to impact Unit Well #8. However, it is important to recognize that bringing Unit Well #8 back online as a full time municipal supply well will change flow system conditions and these changes should be assessed.

The fracture networks observed in nature are more complex than represented in Craflush. For example, they are not always evenly spaced and likely contain intersecting fracture sets with different orientations and dips. In addition, the term 'parallel plate' implies that the fractures are open everywhere across their width and length which is a simplification of the 'roughness' observed for fractures in nature. In my opinion, given that a focus of the investigation is on the lateral transport of groundwater and contaminants toward Unit Well #8 and that a number of studies have documented the importance of bedding parallel fractures to flow and contaminant transport in the Tunnel City Group (Swanson and Bahr, 2004; Swanson et al., 2006; Swanson, 2007; Meyer et al., 2008) and other units (Runkel et al., 2006) these assumptions are appropriate. However, as noted by (Arcadis, 2014b), it is important to recognize that high angle fractures exist in these bedrock units (Runkel et al., 2006; Meyer et al., 2008; Gellasch et al., 2012; Meyer et al., 2014) providing important connectivity and vertical flow and contaminant migration pathways. It is also important to note that, although it is reasonable to use Craflush to simulate bedding parallel flow with transverse diffusion in this system of sedimentary rocks, the simulations do not represent the orientation of the actual three-dimensional flow paths. Plume transport distances derived from rigorous Craflush simulations could be used to inform the potential three-dimensional flow paths from the source zone to Unit Well #8.

In order to solve the equations for flow and transport the model has to be provided with important starting points or boundary conditions. The boundary conditions are stated below (paraphrased from Sudicky and Frind, 1982):

- The concentration of the contaminant at position 0 along the fractures is equal to a constant and specified concentration (i.e., constant source)
- The concentration of the contaminant at a position infinitely distant from the source along the fractures at all times is equal to zero
- The concentration of the contaminant at the fracture surfaces at all positions along the fractures and all times is equal to the concentration in the fracture
- The change in concentration of the contaminant with distance into the matrix (concentration gradient) at a position halfway between two fractures and at all positions along the fractures and all times is equal to 0

The first boundary condition listed above specifies that the contaminant concentrations associated with the source zone are constant throughout the simulated time period (68 years in this case). Although this assumption is a pre-requisite to using the Craflush model as written, it is likely a considerable simplification of real conditions at the site over the simulation period.

The characteristics of the site are represented in the model by assigning values for parameters that describe flow and transport in the model (Table 2). Reviewing how these parameters were estimated, the range in their possible values, their uncertainty, and the sensitivity of simulated results to key parameters is critical to evaluating the sensitivity of the model output (predictions) to uncertainty in site conditions as measured and to the uncertainty contributed by the simplification of actual site conditions to accommodate the model assumptions.

Table 2. Parameters required by Craflush

Parameter	Description	Estimated Using	Range of Values Evaluated[1]	Final Parameter Value[1]
Source Concentration	represents the source zone as a constant concentration	Site monitoring well data		7,900 µg/L
Initial Concentration in Fracture and Matrix	starting concentration in the fractures and matrix	Assumed to be 0		0 µg/L
Velocity in the Fracture	rate of groundwater flow through the fractures	Estimated using the estimate of the fracture aperture (see below), site specific estimates of the horizontal component of hydraulic gradient, and the form of Darcy's Law shown below. $v = \frac{e^2 \rho g}{12\mu} \Delta h$ Where: v is the velocity in the fracture, e is the fracture aperture, ρ and µ are the density and viscosity of water respectively, g is the acceleration due to gravity, and Δh is the hydraulic gradient.	3-96 ft/d	23.5 ft/d
Fracture Dispersivity	represents mixing processes along the length of the fracture	Based on literature values		1.0 ft
Fracture Aperture	describes the distance between the upper and lower surfaces of a fracture (the fracture opening)	Estimated using site specific measurement of the bulk hydraulic conductivity, fracture spacing, and the relationship between the three parameters described by the cubic law (Snow, 1968) $e = \sqrt[3]{\frac{12K\mu s}{\rho g}}$ Where: K is the hydraulic conductivity, e is the fracture aperture, ρ and µ are the density and viscosity of water respectively, g is the acceleration due to gravity, and s is the fracture spacing.	93-544 µm	270 µm
Fracture Spacing	describes the distance between fractures which can also be thought of as the thickness of the rock matrix blocks between fractures	Estimated using site data collected from cores and image logs	0.74 – 9.2 ft	2.6 ft
Matrix porosity	volume of void space in the rock matrix compared to its total volume; this serves as storage space for water and contaminants	Measured on core samples	17 – 29%	25%
Matrix Tortuosity	represents the complexity of flow paths in the rock matrix	Literature values considered; set to final value through calibration of model		0.1
Diffusion Coefficient in Water	describes the rate of diffusion for a particular solvent in pure water; this is used to estimate the rate of diffusion in the rock matrix	Set to literature value		8.79×10^{-4} ft^2/d
Fracture Retardation Factor	represents sorption of the contaminant onto the fracture surface	Sorption to fracture surface is assumed to be negligible so parameter set to 1.0 which represents no sorption/retardation		1.0
Matrix Retardation Factor	represents sorption of the contaminants onto the solid surfaces in the rock matrix	Estimated using the relationship shown below and measured values of fraction of organic carbon (foc), matrix porosity (ϕ_m), and dry bulk density ($\rho_{b\text{-}dry}$) and literature values for the PCE partition coefficient (K_{oc}) $1 + \frac{\rho_{b-dry}}{\phi_m}(K_{oc})(foc)$	1.3 - 2.4	1.4
Bedrock Matrix Fraction of Organic Carbon	describes the relative amount of organic material in the rock matrix	Measured on core samples	0.01 – 0.07%	0.019%
Bedrock Matrix Bulk Density	represents the dry bulk density of the rock matrix	Measured on core samples	2.16 – 2.37 g/cm^3	2.26 g/cm^3
PCE Partition Coefficient	represents the affinity of PCE to sorb to organic matter	Literature value used		238 cm^3/g
Contaminant Half-Life	represents PCE degradation rate	Calibrated value		1,775 days

[1] Values from Arcadis (2014b)

The model was constructed to "approximate the structure of the Wonewoc Formation" and the calibration targets were chosen as PCE concentrations in wells screened in the upper Wonewoc Formation (Arcadis, 2014b). However, based on the information provided in the plume stability report (Arcadis, 2014b), the parameter values were estimated using data from both the Lone Rock Formation and the Wonewoc Formation, and the calibration targets are screened in the unconsolidated deposits, Lone Rock Formation, and Wonewoc Formation. The choice of data used to parameterize and calibrate the model seems inconsistent with the goal of representing the approximate structure and transport specific to the Wonewoc Formation.

In the MKC site Craflush model, the source condition was specified as a constant PCE concentration of 7,900 μg/L (Arcadis, 2014b). The source concentration of 7,900 μg/L was based on recent groundwater concentrations measured in wells in the source area and a lack of observable dense non-aqueous phase liquid (DNAPL) PCE during site investigations. The assumption of a constant source concentration is likely a considerable simplification of actual conditions at the site over the past 40+ years. In addition, PCE, and other chlorinated solvents, were generally produced and utilized as DNAPLs (Pankow and Cherry, 1996). Therefore, it's likely that the PCE originally entered the bedrock as a DNAPL. Consequently, dissolved phase concentrations in the source area were most likely substantially higher than 7,900 μg/L for some period of time (the aqueous solubility of PCE is about 150,000 μg/L at 25^{0}C). Several studies have shown that dissolution of the DNAPL combined with matrix diffusion (e.g., Parker et al., 1994; VanderKwaak and Sudicky, 1996; Parker et al., 1997) can result in complete disappearance of the DNAPL phase in relatively short time periods (years) which is consistent with the lack of observable DNAPL during the course of site investigations. The use of a constant, late time source concentration to represent the source for the entire simulation period in the model is strongly non-conservative for determining plume migration distances in a dual porosity/permeability system because largest transport distances occur in fractures during early years and decades when source concentrations are also very high (B.L. Parker, personal communication, January 21, 2015).

Many of the other parameters (e.g., fracture velocity, fracture aperture, fracture spacing, fraction of organic carbon) included in the Craflush model were estimated using field derived data. Each of the field derived estimates for these parameters is associated with uncertainty. In some instances, several field measured parameters each with associated uncertainty are necessary to estimate a single parameter required by Craflush (e.g., fracture velocity includes estimates for the fracture spacing, hydraulic conductivity, fracture aperture, and hydraulic gradient) (Table 2). In addition, the values for some of the estimated parameters vary relatively widely. Therefore, documenting the site specific effect of changes in these parameters on the simulated results is an important step in this process that was not presented in the plume stability report (Arcadis, 2014b). In addition, based on my experience at a nearby field site the magnitude of sorption in the matrix reported and used in the model seems high compared to results obtained for the same formations. In my experience, the fraction of organic carbon values are susceptible to over-estimation (resulting in over estimation of the matrix retardation factor) due to persistence of the organic contaminants in the samples being analyzed for fraction of organic carbon. Over estimating the matrix retardation factor will provide over-estimates of plume retardation and shorter times for plume stability. Therefore, I would consider performing sensitivity analysis on this parameter including use of a matrix retardation factor of 1 which is the most conservative estimate in this case.

The Craflush model was calibrated by "assigning average or reasonable values to parameters constrained by site investigation data and scientific literature, and adjusting the only two remaining uncertain parameters, namely (1) matrix tortuosity and (2) PCE degradation rate, until modeled PCE concentrations were consistent with measured PCE concentrations at calibration target locations along a conceptual flow-path" (Arcadis, 2014b). In my opinion, the approach of 'fitting' the modeled plume to field observations to determine best-fit parameters otherwise unknown does not result in a verified or calibrated model useful for reliable prediction. Independent data are required to determine the reasonableness of these parameters. Lacking these independent data, sensitivity analysis to the degradation term based on typical ranges of values, including slow degradation rates, found in the literature will show this parameter's importance to the model output and conclusions.

Options for Future Work Include:

- Assess the impact of the specified constant source concentration on simulated results. Determine if options exist that would allow for variation in the source concentration through time using the Craflush model.
- Consider using a refined hydrogeologic unit conceptual model to guide revised Craflush modeling
    - re-calibrate the model using parameters and calibration targets for the individual hydrogeologic unit of most concern (additional models could be built for additional hydrogeologic units if desired)

- Avoid 'fitting' the model to current observed data using unknown or unmeasured parameters. Rather, conduct site specific sensitivity analyses for field and literature derived parameters that address the observed range and/or estimated uncertainty in these parameters.
- Assess how changes in the three-dimensional flow system (e.g., full time pumping of Unit Well #8) will influence plume behavior

5.3.3 Source of Unit Well #8 Water

The following statement is provided as additional support for the conclusion that PCE in groundwater is not likely to impact Unit Well #8 in the plume stability report.

"Pumping at Unit Well 8 for water supply purposes will result in radial flow of groundwater from all directions toward Unit Well 8 to the extent that the vast majority (e.g., ~90%) of groundwater entering Unit Well 8 will be from other areas not associated with the site" (Arcadis, 2014b).

However, no direct or referential support for this statement was provided in the report. Analysis of the Unit Well #8 capture zone in relation to the groundwater PCE plume is required to support this statement.

Options for Future Work Include

- Analysis of the three-dimensional capture zone for Unit Well #8 under the range of pumping conditions observed at the site and under expect future conditions

5.3.4 Hydraulic Containment of the PCE Source Area

The plume stability report states that hydraulic containment of the PCE source area by MKC's proposed groundwater extraction system is additional support for the conclusion that Unit Well #8 will not likely be impacted by PCE in groundwater. The report titled "Basis of design for proposed groundwater extraction and treatment system, Madison-Kipp Corporation, Madison, Wisconsin" (Arcadis, 2014a) describes the groundwater extraction system which consists of a single pumping well and plans for above ground groundwater treatment systems. The extraction well is located approximately 100 ft south-east of MP-13 which is the presumed source zone. The well construction diagram indicates that the extraction well is screened from 55-175 ft bgs. This screened interval includes the Lower Lone Rock Formation and the Upper and Lower Wonewoc Formation and may also include the upper Lone Rock Formation. Hydraulic conductivities measured for the Upper Lone Rock, Lower Lone Rock, Upper Wonewoc, and Lower Wonewoc Formations range between 0.08 and 13.2 ft/d and the average values for each unit are 5.5, 5.9, 2.8, and 12.9 ft/d, respectively. The range of hydraulic conductivities suggests the extraction well may draw water from specific intervals preferentially. The report presents the areal zone of influence for the extraction well under a pumping rate of 40 gallons per minute. It is unclear which monitoring intervals were used to create the drawdown map and the variation in drawdown with depth is not addressed. In addition, delineation of the zone of capture in addition to the zone of influence is critical to evaluating the percentage of the source flux captured by the extraction well and effective monitoring of the downgradient portion of the plume not captured by the extraction well.

Although the source zone extraction well should hydraulically contain the high concentration source, it's important to consider that it may not have any influence on plume front mobility as illustrated by Parker et al. (2010).

Options for Future Work Include:

- Evaluation and presentation of the vertical influence of the extraction well
- Delineation of the three-dimensional capture zone for the extraction well in order to characterize the percentage of the source zone flux captured by the extraction well
- Appropriate monitoring of the downgradient portion of the plume not captured by the extraction well using the existing monitoring network

5.4 Additional Considerations

The primary objective of this review was to evaluate the conclusion from the plume stability report that " . . . Unit Well 8 will likely not be impacted by PCE in groundwater at the site if Unit Well 8 were to become operational in the future" (Arcadis, 2014b). However, a clear definition of what is defined as an 'impact' to Unit Well #8 was not presented. A clear definition of what constitutes an impact is necessary when evaluating site monitoring data and simulation results from analytical or numerical models.

Arcadis (2014b) point out in their evaluation that the vertical separation between the bottom of the current PCE plume and the open interval of Unit Well #8 provides a degree of protection to Unit Well #8. They also point out that the well construction information indicates the presence of a test hole adjacent to Unit Well #8 which is open from the top of rock into the Mt. Simon Formation. The construction information also indicates that hydraulic connectivity between the Unit Well #8 and the test hole was deliberately enhanced. Consequently, the test hole can potentially serve as a pathway for contaminants to flow from the upper bedrock units into the Mt. Simon formation.

Options for Future Work Include:

- Development of a clear definition for 'impact to Unit Well #8'
    - Definition might include a list of contaminant or contaminants of concern, magnitude of concentrations, timing, persistence, etc.
- Reiteration of the recommendation from Arcadis (2014b) to seal the test hole adjacent to Unit Well #8 to minimize potential cross-contamination

6.0 Summary of Options for Future Work

Although I generally agree that the MKC site PCE plume is likely strongly attenuated and not moving rapidly forward, I do not think the potential of PCE to impact Unit Well #8 has been assessed to an acceptable level of certainty based on the current monitoring network, data and analysis methods, key assumptions, and numerical modeling effort. The following list of options for future work is provided for your consideration. These options focus on evaluating and potentially reducing the uncertainty in any further assessments of the potential for PCE to impact Unit Well #8.

Additional Characterization and Temporal/Monitoring Data

- Addition of monitoring intervals downgradient of the inferred source area to improve three-dimensional characterization of the PCE plume, provide additional information for further assessment of potential impact to Unit Well #8, and monitor for any further migration of the PCE plume toward Unit Well #8 in the future

Assessment of the Site Conceptual Model

- Utilizing the site specific data to refine the hydrogeologic unit conceptual model for the site

Revised Analysis of Data

- Re-evaluating site specific data (hydraulic conductivity, fracture network parameters, rock matrix parameters, hydraulic gradients, etc.) within the context of the refined hydrogeologic unit conceptual model to better inform conceptual and numerical models
- Analysis of the time concentration data within the context of the site specific hydrogeologic unit conceptual model (i.e., analysis of concentration trends in each aquifer unit using only wells screened in that unit) to improve the evaluation of potential plume stability
- Re-analysis of time concentration data when monitoring records extend at least 2 years with at least 8 separate monitoring events to improve the evaluation of potential plume stability (including any new monitoring intervals installed at the site)

Additional Evaluation of the Flow System in Three-Dimensions for the Current and Future Conditions

- Evaluation and presentation of the vertical influence of the source zone extraction well
- Delineation of the three-dimensional capture zone for the extraction well in order to characterize the percentage of the source zone flux captured by the extraction well

- Analysis of the three-dimensional capture zone for Unit Well #8 under the range of pumping conditions observed at the site and under expect future condition
- Reiteration of the recommendation from Arcadis (2014b) to seal the test hole adjacent to Unit Well #8 to minimize potential cross-contamination

Revision of Craflush Modeling

- Development of a clear definition for 'impact to Unit Well #8'
- Consider using a refined hydrogeologic unit conceptual model to guide revised Craflush modeling
- Assess the impact of the specified constant source concentration on Craflush simulation results
- Avoid 'fitting' the model to current observed data using unknown or unmeasured parameters. Rather, conduct site specific sensitivity analyses for field and literature derived parameters that address the observed range and/or estimated uncertainty in these parameters.
- Assess how changes in the three-dimensional flow system (e.g., full time pumping of Unit Well #8) will influence plume behavior

7.0 References

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