January 27, 2020

Mr. Patrick Patterson, Regional Director
Pennsylvania Department of Environmental Protection
2 E. Main St.
Norristown, PA 19401

Re: **Bishop Tube 2019 Remedial Investigation Report and Feasibility Study**

Dear Regional Director Patterson:

The Delaware Riverkeeper Network has significant concerns with the Remedial Investigation and Feasibility Study submitted with regards to the Bishop Tube site. We provide for your consideration two detailed expert reports that identify many ways in which the RI & FS reports provided by Roux fails to accurately assess site conditions and in so doing undermines the ability of the state to identify the most effective long-term solutions for the site. The attached analysis supports even more strongly our position that while DEP undertakes the necessary steps to assess, identify and secure effective remediation of the site, the state needs to quickly undertake near-term removal (or other mitigation) of the site soil sources.

The Delaware Riverkeeper Network notes that Roux has been working on its investigation since 2008/2009, and it is disappointing (to say the least) that after all this time it still has not produced accurate and adequate RI and FS reports and a predictive fate and transport model of the plume. These deficiencies make the selection of an appropriate final remedial response difficult since there has not been a proper analysis of the site conditions and future conditions. Moreover, there is a serious disconnect between the proposed development of the site for residential use (which we have and continue to oppose) and the analysis which assumed a present and future non-residential use only.

Of grave concern to the Delaware Riverkeeper Network, the passage of all this time with no effective interim response or final remediation has not been benign – throughout this period the toxins and contaminants in the source material have continued to migrate into

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groundwater and into Little Valley Creek, an Exceptional Value Stream, and have continued to subject the environment and nearby communities to significant threats of harm.

Among other things, the PA DEP should have required an effective interim response to remove (or mitigate) known source-area contamination from the Bishop Tube property. Such an interim response remains necessary and could be undertaken immediately, putting in place important advancement towards community and environmental protection while the full and complete remediation necessary is properly identified, selected, and implemented.

And we remind all parties, DRN reserves the right to seek reimbursement of its expert expenses incurred in the investigation and evaluation of the contamination and appropriate remediation as response costs against the responsible parties.

Respectfully,

Maya K. van Rossum
the Delaware Riverkeeper

cc:
East Whiteland Board of Supervisors
East Whiteland Environmental Advisory Council
Regional Administrator Cosmo Servidio, EPA Region 3
Senator Andy Dinniman
Representative Kristine Howard
Bucks County Commissioners
Bucks County Planning Commission

Green Toxicology LLC

Memorandum

To: *Delaware Riverkeeper Network*

Edmund Crouch

From: *Edmund A.C. Crouch, Ph.D.*
Date: *January 26, 2020*
Subject: *Comments on the Bishop Tube 2019 Remedial Investigation Report and Feasibility Study Report*

Introduction and Summary

I write to provide comments on the *Remedial Investigation Report* (RIR) and *Feasibility Study Report* (FSR) regarding the Former Bishop Tube Property, East Whiteland Township, Chester County, Pennsylvania, authored by Roux Associates, Inc. (2019a and 2019b). As you will read, I find that the analyses presented in the RIR are deficient in several respects; and I offer suggestions for improving upon these analyses. Because the FSR is based on the RIR, it too is unreliable.

The technical issues detailed below, are:

- The history of the site provided in the RIR omits salient facts that would assist evaluation of the current and future site conditions; in particular, there are no estimates of the quantities and timings of releases of trichloroethylene (TCE) (and other volatile organic compounds, VOCs) that might (i) bound the quantities currently present in the plume and/or in dense non-aqueous phase liquid (DNAPL; that is, undissolved TCE) in the deep bedrock, and (ii) assist the evaluation of decay half-lives of contaminants. The RIR fails to present any estimates of these quantities, ignoring an earlier report (Baker, 2003) that had indicated a total of 3.7 tons down to 10 to 20 ft depth in the hot spots on site; moreover the RIR plume delineation in Figure 45 implies a plausible range of from 6.5 to 56 tons (omitting any DNAPL), although both these estimates use implausible assumptions such as assigning the maximum measured concentration in any well or boring throughout the entire depth range considered.
- The methodology used in the RIR to evaluate the half-life of decay of TCE in groundwater is deficient in many ways, and cannot provide a reliable estimate of that half-life on this site. It is (i) theoretically incorrect, (ii) biased to low values, (iii) not consistently applied, and (iv) omits multiple measurements meeting its own inclusion criteria. The methodology also assumes the same value everywhere in the plume, an assumption which is provably incorrect.

- At least some of the contaminant measurements in groundwater made at the site have been omitted from the summary tables.
- The RIR modeling takes no account of potential variations in the quantities and timings of TCE releases, and assumes that there is no continuing source of TCE present, despite acknowledging, correctly but inconsistently, the presence of DNAPL in deep bedrock. The first (failing to account for variation in quantities and timings of TCE releases) affects the interpretation of time-series of concentrations in wells, and entirely invalidates the methodology used for estimating TCE decay half-lives. The second (assuming no continued source) affects the predicted future plume behavior, so that the modeling applied is inaccurate.
- The modeling performed by the RIR fails to build on previous extensive and more comprehensive modeling of contaminant behavior in groundwater at this site (Baker, 2004). The model used is needlessly simplistic, and results in unjustified conclusions.
- Indeed, a straightforward calculation of the flow velocity of TCE according to the parameters used in the model used in the RIR shows that it could not possibly account for the extent of the current plume. The earliest that TCE could have been used at the site is the early 1950s, approximately 70 years ago. With the RIR modeling, TCE could only have travelled about 1,100 feet in that time, compared with a plume that actually extends some 3,500 feet (and the additional distance to the plume front due to dispersivity cannot account for the difference). The RIR authors should have made, but apparently did not make, this simple check on their work.
- The RIR modeling also includes unrealistic assumptions about the boundary of the plume, both currently and in the future. Previous (more comprehensive) modeling showed that the plume potentially could, at some depth, (i) extend beneath Little Valley Creek to the north, in areas where the RIR model deliberately prevents that possibility; and (ii) extend into the Northwest corner of General Warren Village, another possibility that the modeling apparently deliberately omits.
- While the modeling implies contaminated discharges to Little Valley Creek, there is no attempt to evaluate the resulting contaminant concentrations in Little Valley Creek by evaluating the flow of groundwater and its entrained contaminants into the Creek.
- There is no evaluation of VOCs other than TCE in the future plume, although they have different subsurface transport behavior — in particular vinyl chloride (which is most worrisome, being a confirmed, and potent, cause of cancer in humans and other animals), which may be carried by groundwater about four times faster than TCE.
- While some limited assessments of risks to public health and the environment are performed for the current situation, there is no attempt to evaluate risks from future plume configurations, neither in the RIR nor the FSR. The FSR requires such evaluations to adequately compare the potential health and environmental effects of various clean-up schemes.
- The FSR is inadequate in that it relies on incomplete and incorrect evaluations in the RIR. In particular, the evaluation of monitored natural attenuation is incorrect, in that it is based on the incorrect evaluation of future plume behavior in the RIR.

The RIR clearly requires amendment to adequately evaluate future plume behavior, in particular delineation of the extent of, and concentrations in, the future plume, not only for TCE but also for other contaminants. The FSR subsequently must be modified to account for such corrections.

1. Timing and mass of trichloroethylene (TCE) released to groundwater

The RIR provides a summary history of the site that, unfortunately, omits salient facts that might assist in bounding the mass of TCE that was released to groundwater, and the timing of such release, which information is necessary (or must be inferred) in modeling of plume extent and persistence. For example, Section 5.1 of the RIR mentions only that "During certain periods of time, chlorinated solvents were used for degreasing at the Property." Evaluation, even if only approximate, of total receipts (and specification as to identity of each such solvent, if more than just TCE had been used), for example, would serve to place an upper bound on the quantity of these solvents. The total potential time frame runs from approximately 1951 (when the building was built; RIR Section 5.1) through approximately 1991. TCE was stored for some of this time in a 4,000 gallon aboveground storage tank (which, when full, would contain approx. 24 tons of the solvent), installed in 1975 (RIR Section 5.2), that was removed in 1992 (Armstrong, 2018, Exhibit 43). All releases should have ceased prior to 1991 (Marcegagalia USA, Inc letter, DEP 000055090–55091, and RIR Section 5.1), although earlier documentation assumed TCE release to have ceased by 1983, based solely on assumed implementation/enforcement of federal RCRA regulations (Baker, 2004, pp84–85).

The combined mass of TCE present in (i) the shallow soil down to approximately 10.7 ft depth below the vapor degreaser area in building 8, (ii) 8 ft depth below the vapor degreaser area in building 5, and (iii) 20.7 ft depth below the former drum storage area was estimated by Baker (2003, Tables 8.1–8.3 and Appendix D) as approximately 3.7 tons. This is likely an overestimate, in that maximum concentrations in each borehole evaluated were assumed to apply through the entire soil column. The estimated plume provided as Figure 45 of the RIR corresponds to approximately 56 tons of TCE in the groundwater and adsorbed to soil (omitting any non-aqueous phase TCE), assuming an average groundwater thickness of 440 ft, porosity of 0.05, retardation coefficient of 9 (all from RI, Appendix S). Approximately half of that mass is within the 100,000 μg/L contour. This probably represents an upper bound on the mass of TCE; a lower bound (for the groundwater as modeled in the RIR) can be obtained by assuming no adsorption to soil (e.g. no organic carbon in the soil[1]), which gives approximately 6.5 tons dissolved in groundwater in the plume. Both of these estimates are likely overestimates, since the assumption is made in the RIR that the maximum concentration measured at any depth in a well applies throughout that entire groundwater thickness.

[1] There appear to have been no measurements of soil organic carbon over the entire history of the site, though some should have been made.

2. Methodology for estimating the half-life of TCE in groundwater

The methodology used in the RIR (Roux, 2019a, Appendix S) for estimating the half-life of TCE in groundwater is incorrect, undefined, and/or inconsistently followed.

First, and most important, the methodology is theoretically incorrect, and cannot under any circumstances (except by chance) give an accurate estimate of half-life. For the methodology to be accurate, the groundwater concentration of TCE at every point evaluated would have to be decreasing at the same first-order rate, implying that the spatial variation (factoring out this exponential term) was constant. That is, the TCE plume would have to have exactly the same shape and location throughout time, and simply be everywhere (or at least at all measured points) decreasing at the same rate. This conclusion is model independent, but can also be inferred from the solute transport model used in the RIR. Moreover, such a plume would be physically impossible in advecting groundwater — in order to maintain the same plume shape and location, concentrations would have to rise sufficiently in downgradient directions so that dispersion could cancel the effect of advection (which moves the location of the plume). The appendix to this report demonstrates this physical impossibility analytically for a 1-dimensional simplification of the model used in the RIR. The actual rate of change of concentration at any point in a plume depends on the time, advection velocity, and the time course of the source term of the plume, as illustrated below by simplified examples in this case.

Second, the methodology was specified as, "Monitoring wells considered for this calculation required: 1) at least 4 data points over an extended period of time (i.e., at least 4 years); and 2) evidence of attenuating TCE concentrations (i.e., declining concentrations with time)." This approach is problematic for several reasons, including:

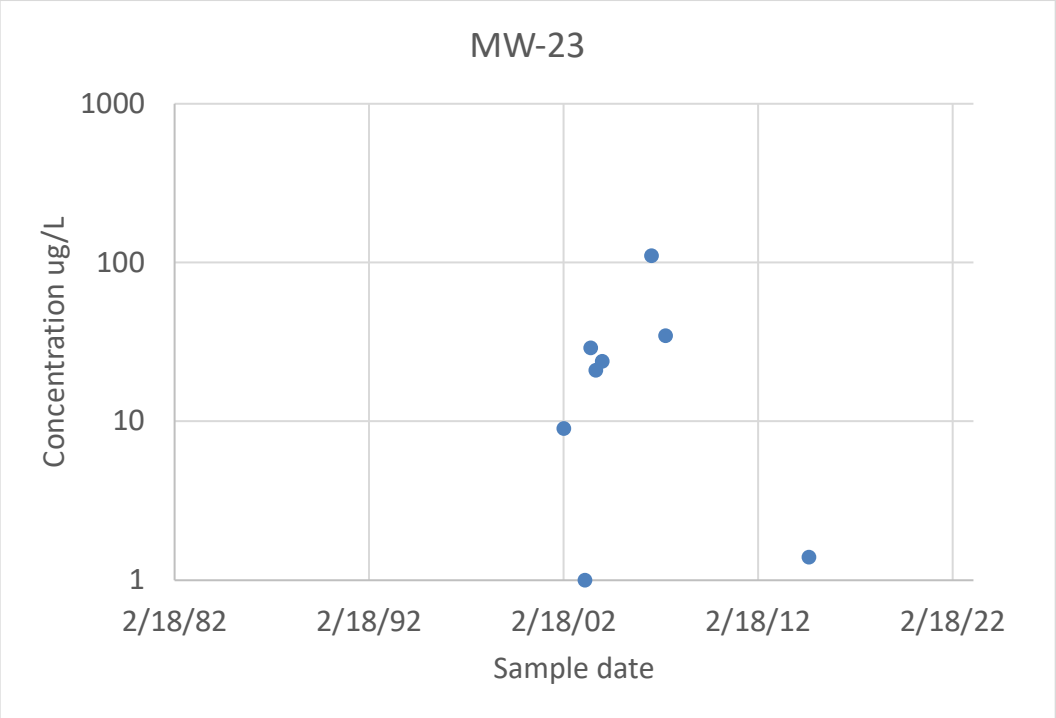
a. The second specification arbitrarily omits any wells without such a declining concentration, so will necessarily bias any estimate of "decay rate."[2]
b. The second specification is also undefined; no operational definition of "declining concentrations with time" is provided. The natural interpretation would be that the value of λ, the "decay rate" defined on page 11 of Appendix S of the RIR, is positive. However, examination of the data in Appendix B-1 shows that this cannot have been the operational definition, since multiple wells meeting the first specification (4 or more data points over 4 or more years) and with positive λ are in fact not included in Table 2 of Appendix S (e.g. MW-06, MW-14, MW-19, MW-20). Indeed, there are 51 monitoring wells (MW-XX) listed in Table B-1 of the RIR that meet the first criterion, 44 of which have a positive λ, but only 30 are included in Table 2 of Appendix S. No explanation for omission of data from these wells is offered.

[2] Since the methodology cannot evaluate the degradation half-life of TCE in the plume, the only quantities estimated are time-variations in particular wells over particular time periods; I distinguish these quantities from the decay rate and half-life associated with TCE degradation by quoting the terms "decay rate" and "half-life."

c. It is difficult to conceive of any consistent specification that would include MW-23 but exclude MW-06, as is done in the RIR (see Figure 1).
d. The methodology adopted in the RIR was to average the "half-lives" calculated by linear regression over all available measurements in Table B-1 for the wells in Table 2 of Appendix S. This methodology is incorrect, however, for at least two reasons. First, if such averaging over wells were appropriate, then the correct methodology requires averaging over all "decay rates" (both positive and negative), not averaging over "half-lives" (essentially the inverse of "decay rates"). Second, performing such averaging assumes that the average has some physical meaning — that the "decay rate" measurements in individual wells are all (imperfect) measures of the same quantity applicable to the whole site — but in this case, examination of the distribution of "decay rates" shows that the measurements are in fact not of the same quantity. Figure 2 shows a normal probability plot of the "decay rate" (λ) for all 51 monitoring wells satisfying the first criterion ($\geq$ 4 points, $\geq$ 4 years). This distribution is indistinguishable from normal,[3] and clearly the measurements are not all consistent with a single mean value. A formal likelihood ratio test confirms this — maximum likelihood estimates of mean and standard deviation of a normal distribution are 0.00029 per day and 0.00024 per day respectively, taking account of all the individual uncertainties, and the standard deviation estimate is non-zero ($p = 1e{-}97$).

The implication of the non-zero standard deviation is that the "half-life" varies in different places on the site. This variation (if the methodology used to derive the value had any meaning; but see above and below) would need to be taken into account in any modeling. Indeed, approximately one third or more of the "half-life" measurements are consistent *with no "decay" at all* that those locations (see Figure 2). This conclusion is not surprising, given the results shown below, since the concentration at any particular well can be increasing, decreasing, or constant, dependent on multiple factors of which TCE degradation is only one. And in view of the microcosm tests (Baker, 2009, Appendix A; Roux, 2015a, Appendix B), such a finding for actual TCE degradation rates would also not be surprising; and such degradation rates remain to be measured, particularly any variation of half-life with depth and/or location.

[3] There are no standard tests that can incorporate the uncertainties in individual measurements, but application of the Shapiro-Wilk test to the point estimates, omitting the most negative which clearly is so uncertain as to provide only negligible information on the distribution shape, shows a p-value of 0.67, indicating the distribution is indistinguishable from normal.



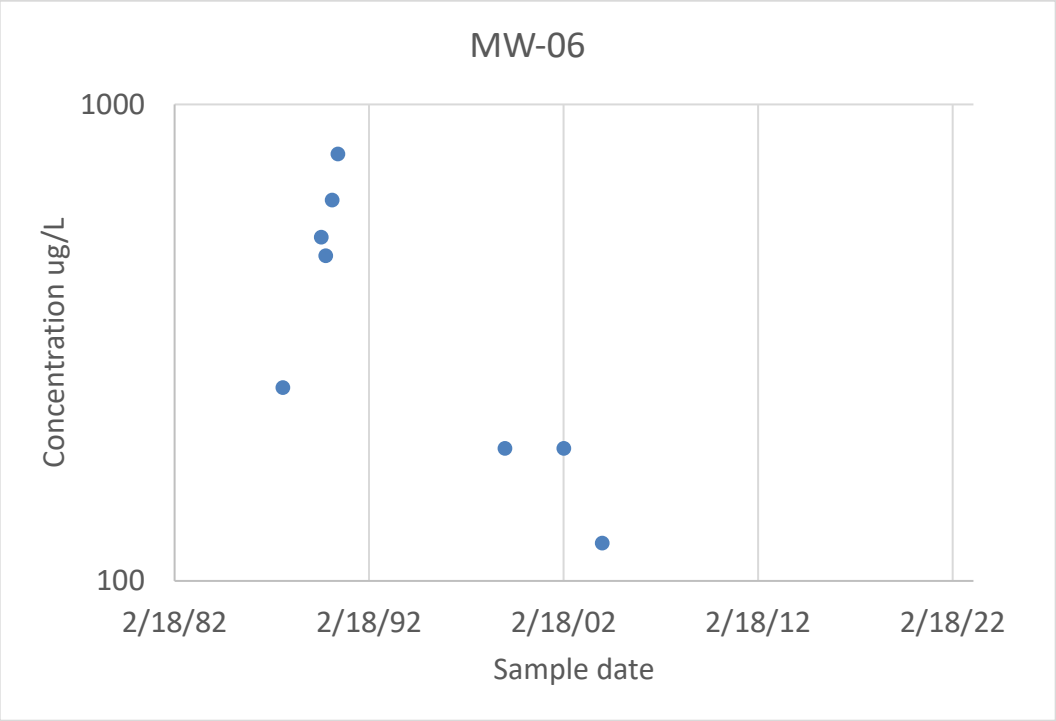


Figure 1 Comparison of sampling in MW-23 and MW-06

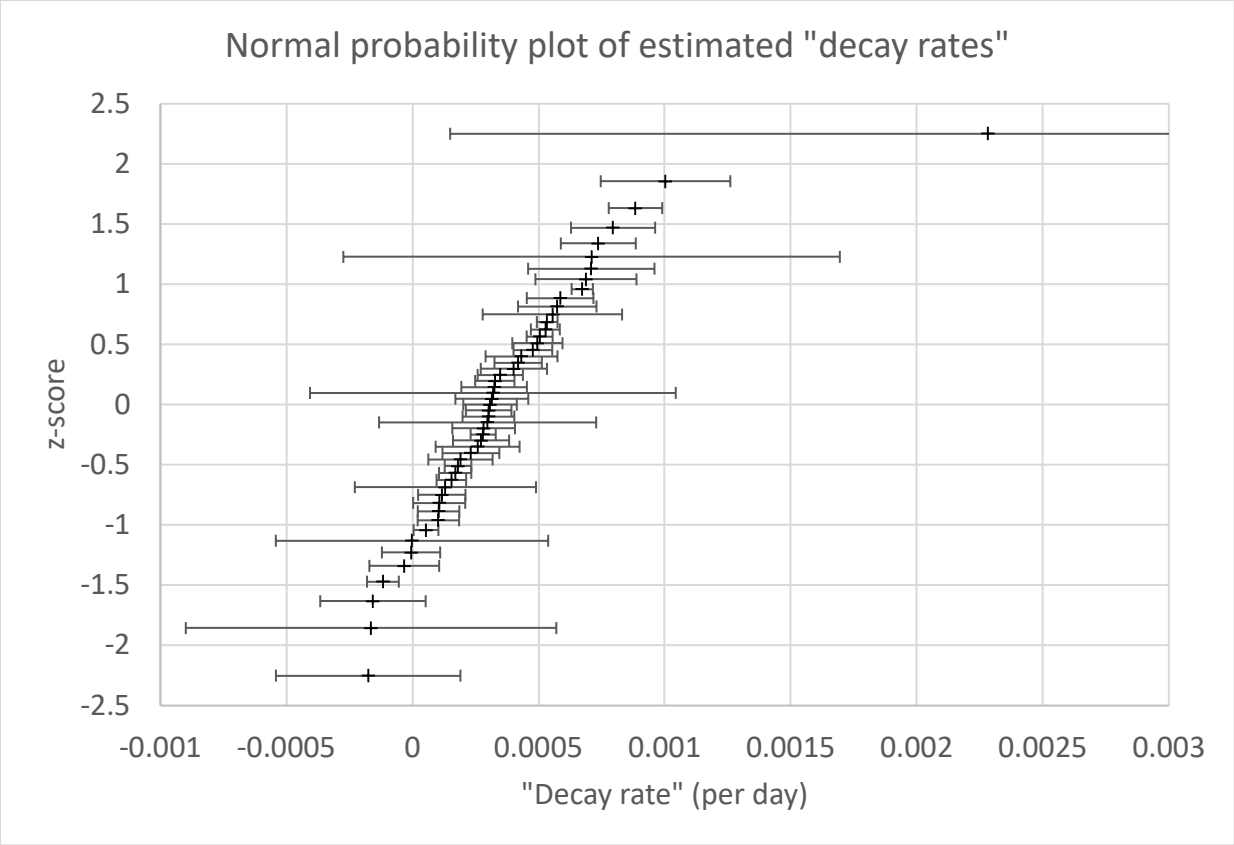


Figure 2 Normal probability plot of "decay rates" in the 51 monitoring wells, with standard errors

3. Missing data from time series

Some of the groundwater measurements have been excluded from the RIR. Specifically, the measurements documented in the microcosm study of Appendix B of the 2015 Treatability Study (Roux, 2015a) in MW-08, MW-25C, MW-26A, VDA8-1, VDA8-3, and VDA8-4 (from 10/10/11) and MW-25C (from 10/11/11) are not included in the summary data in Appendix B of the RIR; although apparently the sample (possibly a split sample) taken in 8/23/06 from MW-02 and used in the earlier microcosm study (Baker, 2009, Appendix A) is included.

4. Failure to account for source variation

The RIR makes the factually incorrect assumption that there is no continuing source present — only the TCE present in groundwater and adsorbed to soil/rock (with no non-aqueous phase TCE). It also implicitly assumes the lack of any source prior to the start of the modeling timeframe, through the methodology used to evaluate "half-life" of TCE in the various wells. Suppose instead that there was a source at some time in the past (which is obviously true), and this source varied in strength with time. Then variations in concentration can be expected to occur at the source location; and these variations in concentration would propagate into the plume, so that variations in concentration at each well will occur due to such variations in

source strength. Moreover, the variations in concentrations in wells will represent variations in source strength at earlier times. Thus any analysis of concentrations in wells that attempts to estimate true decay (degradation) rates must account for variations in source strength at those earlier times, and must untangle such variations from any decay that is occurring. No such attempt was made in the RIR.

There are some wells in which variations in source strength are much more likely than decay to account for a major part of some concentration variations. Several wells have a very substantial decrease in concentration between measurements made prior to the mid 1990s and those made subsequent to that time. Particular examples in which decay as the only determinant of substantial reductions occurring between the 1980 to early 1990s and early 2000s seems unlikely are MW-15 (Figure 3) and MW-03 (Figure 4), with less obvious examples being MW-02 (Figure 5), MW-06 (Figure 6), and MW-08 (Figure 7), although such an effect cannot be ruled out in *any* well without adequate analysis that takes account of the propagation time and dispersion occurring between source and well. The example wells mentioned here are close to the putative source(s) of the TCE, so would reflect changes in source terms relatively soon after such source changes, and the changes would not be substantially extended in time by dispersion. The effect of source changes in wells further downgradient would occur later and be slower. Since the source term probably ceased sometime in the 1980s or as late as 1991, abrupt changes in nearby wells between the 1980s and late 1990s may quite plausibly be due to source changes.

Figure 3 (MW-15) also illustrates the disconnect between measured concentrations and the RIR modeling, for this well at least. The initial peak in the modeling is due to a higher concentration part of the plume passing by MW-15, and the faster drop-off in concentration at large times (compared with the decay rate, illustrated by the dashed black line) is due to the reducing concentration behind that higher concentration part of the plume (MW-15 is situated so that, in the modeling, a kink in the assumed 10,000 μg/L contour will sweep across it as the whole plume migrates down-gradient; see Figure 46 of the RIR).

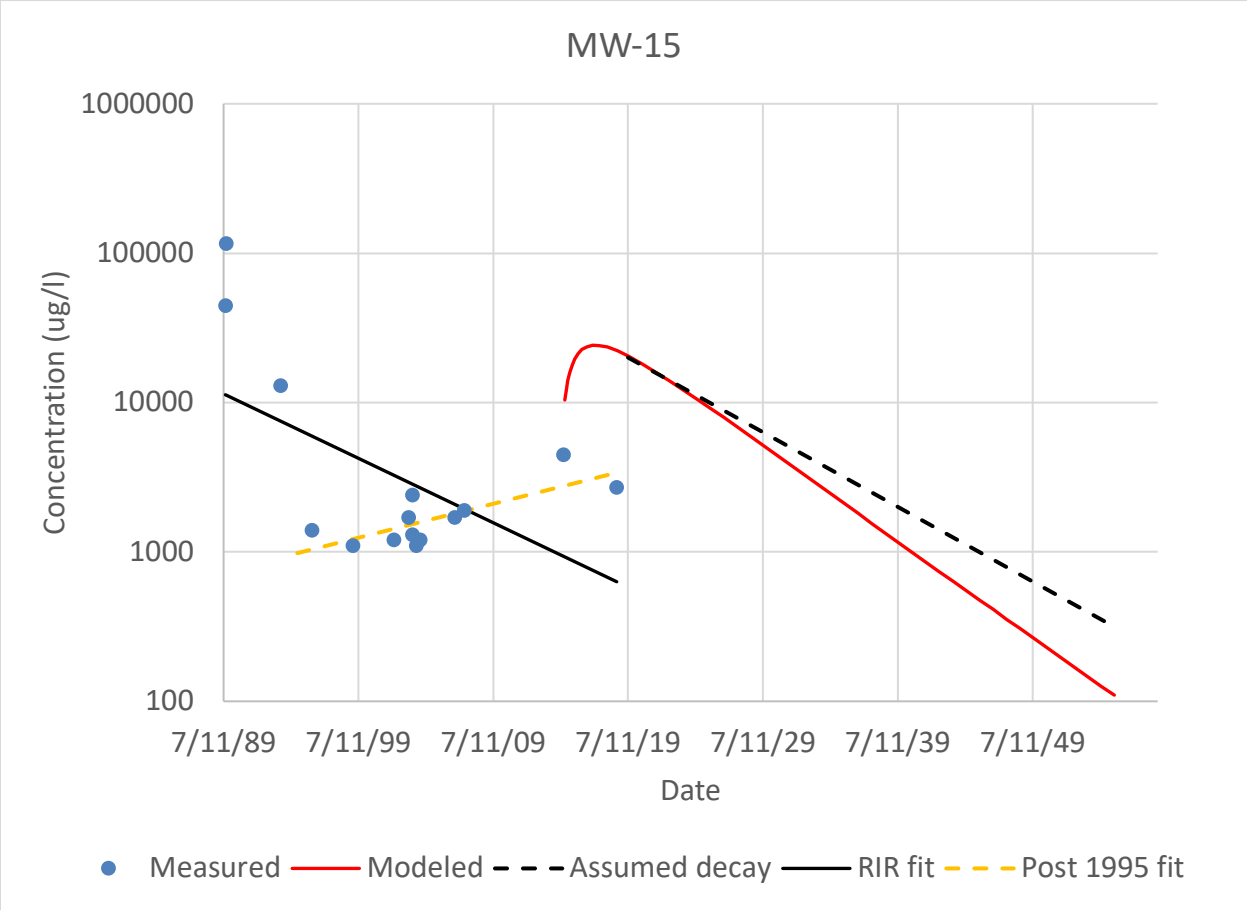


Figure 3 Measured concentrations, the RIR "fit" to those concentrations, and a fit to those after 1995, and the modeled concentration in MW-15, with a line showing the assumed decay rate.

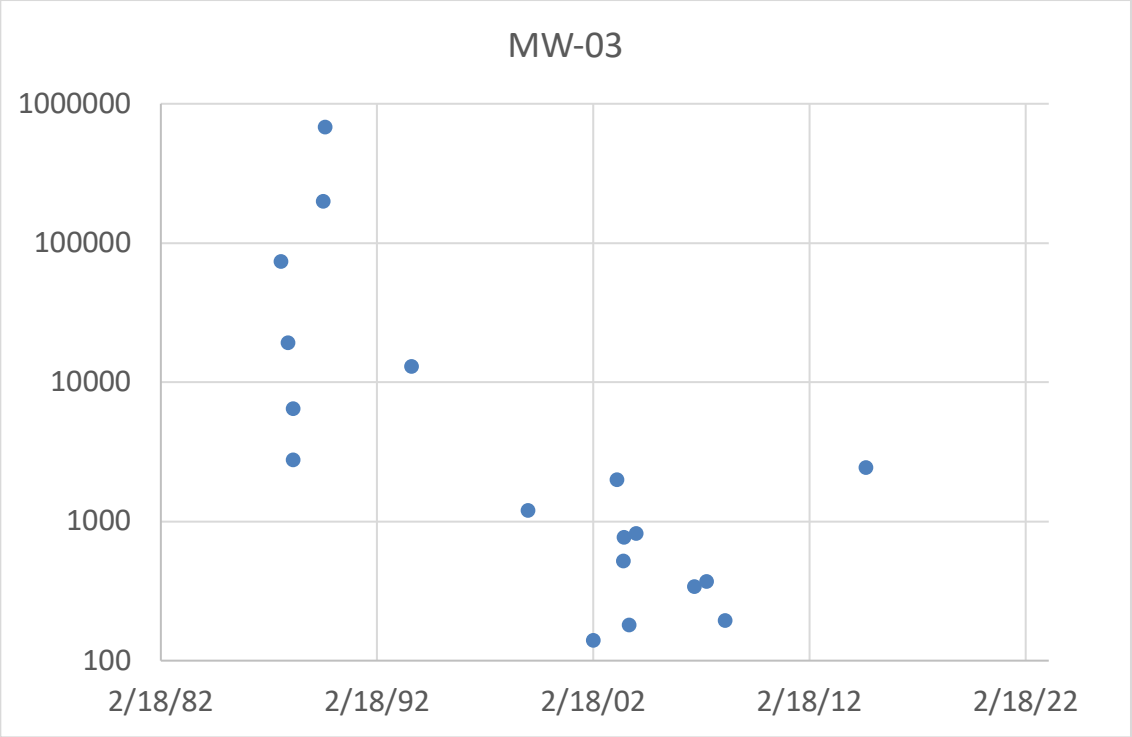


Figure 4 Concentrations measured in MW-03, showing a substantial drop in the mid 1990s

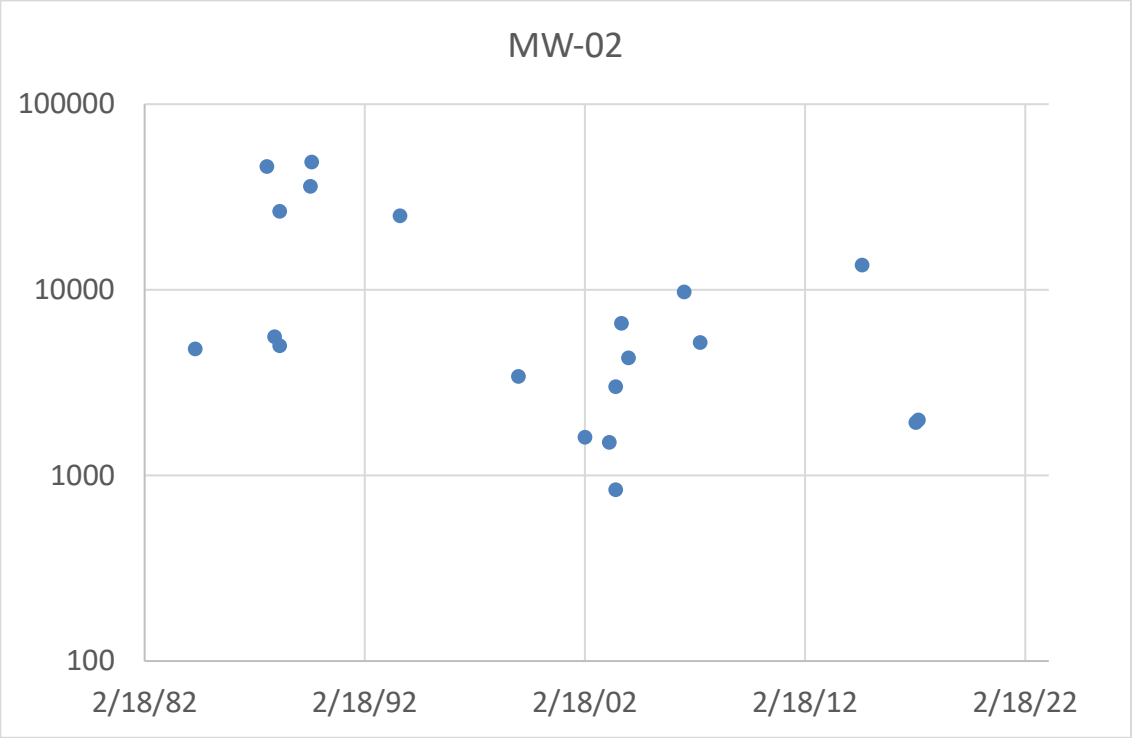


Figure 5 Concentrations measured in MW-02

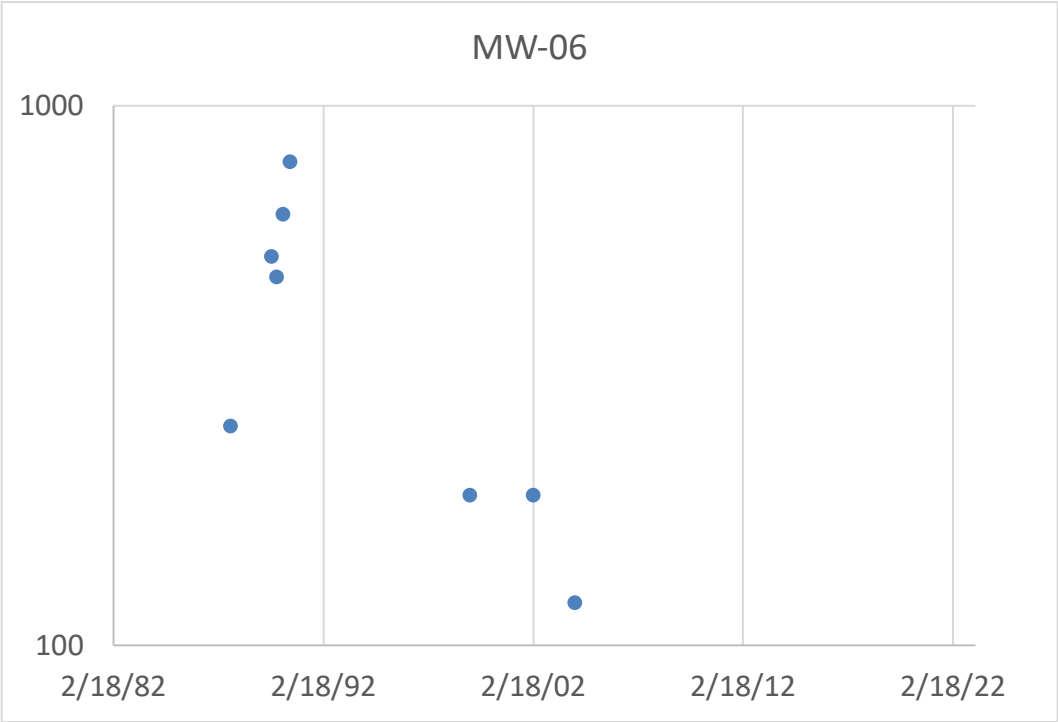


Figure 6 Concentrations measured in MW-06

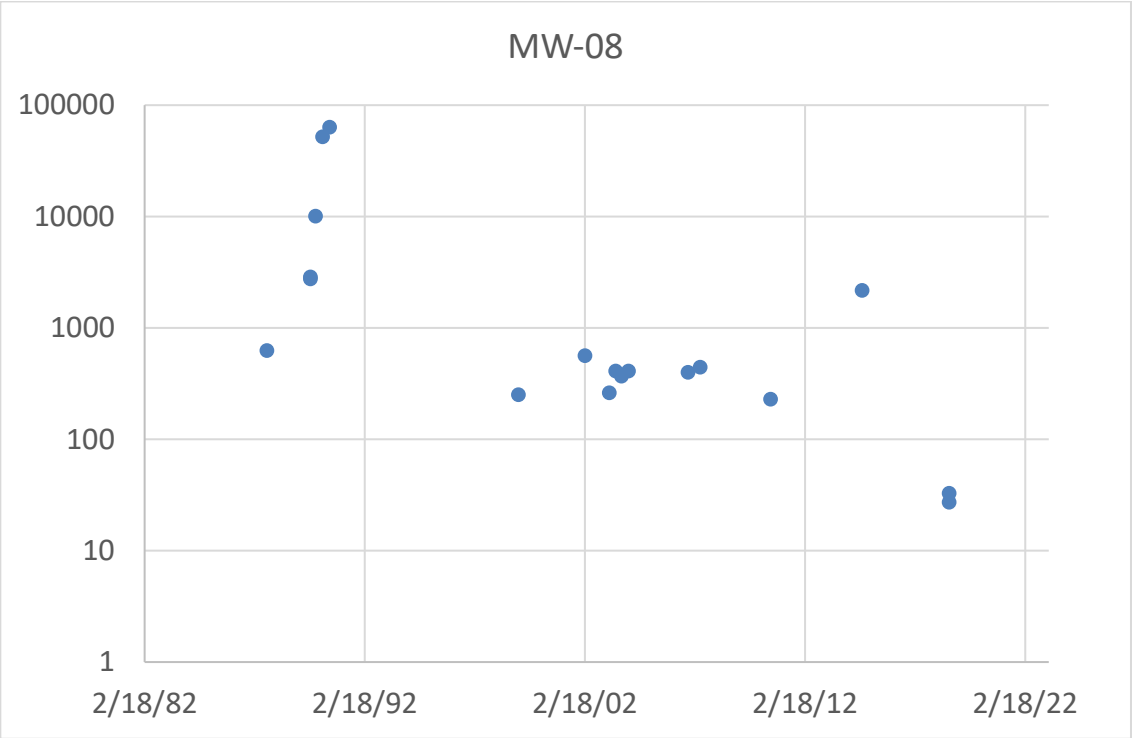


Figure 7 Concentrations measured in MW-08

5. Failure to cite, evaluate, and build on previous analyses

While a previous extensive groundwater characterization report (Baker, 2004) is mentioned, none of its findings or analyses are cited within the RIR, and the model used in the RIR takes nothing from that previous modeling. As explained below, this failure to build upon prior work is inappropriate, and should be remedied.

Baker (2004) presented a groundwater model that better characterized the site than the model adopted by the RIR, by (i) using the MODFLOW/MODPATH/RT3D model system, (ii) using four depth layers, and (iii) accounting for the different hydrogeologic units in the modeling domain (Baker, 2004, Tables 29 and 30), building on the previous hydraulic modeling by Sloto (1990). This approach allowed taking account of the variation of hydraulic conductivity with depth (acknowledged in the RIR, p121) and hydrogeologic unit, which variation is not included in the RIR model. Critically, many of the formations and depth ranges have hydraulic conductivity substantially higher than the 1.1 ft/day assumed to apply uniformly by the RIR (Appendix S).

The substantial improvement (a reduction in residual statistics by a factor of about 2) of the Baker (2004) model over the model adopted in the RIR can be inferred from the fit to measured hydraulic heads over a near-site hydraulic head range of 90–100 feet (Table 1).

Residual statistic	2019 RIR	Baker (2004)	Unit
Mean	0.899	-0.091	feet
Mean absolute value	6.883	3.793	feet
Root mean square	9.004	4.789	feet
Number of wells	14	~33	(count)

Table 1 Statistics of residuals of modeled versus observed hydraulic heads near the site (RIR: Attachment B to Appendix S, table and figure; Baker, 2004, Figure 28)

6. Impossibility of the RIR modeling to account for TCE plume extension

The essential need to account for variation in hydraulic conductivity in modeling the plume behavior, and in particular for including paths with higher hydraulic conductivity, may be illuminated by some simple calculations. The RIR modeling assumed a constant hydraulic gradient of 0.019, a constant hydraulic conductivity of 1.1 ft/day, a constant porosity of 0.05 (RIR, Appendix S, Table 1), and a retardation coefficient of 9 for TCE. These assumptions imply a linear velocity for a TCE plume (ignoring longitudinal dispersion), or approximately of the center of a plume front (including longitudinal dispersion) of $(1.1\times 0.019/(0.05 \times 9) = 0.0464$ ft/day. After a modeling time of 41 years (2014 to 2055; RIR, Appendix S, Attachment C, Table C1) the distance traveled by a plume front would be approximately 700 feet, which is only about 1/5 the length of the current plume. The model is thus *incapable* of explaining the current plume, which extends at least 3,500 feet after at most 69 years (1951 to 2020),

corresponding to 1171 feet using the RIR model parameters, so cannot be expected to evaluate the extension of the plume, which was, of course, the claimed purpose of this modeling.

In contrast to the RIR modeling, Baker (2004, Table 30) estimates the hydraulic conductivity in the top 100 feet of the Ordovician Conestoga Formation (in which most of the RIR modeling grid presumably[4] lies) at 10.4 ft/day, decreasing to 1.2 ft/day only in the 300–400 foot depth range.

In the modeling sensitivity analysis, the RIR notes that increasing the hydraulic conductivity by a factor of just 5 would result in the plume extending beyond the modeling domain, but claims that, "The value chosen in the calibrated model is based on Site-specific data (slug tests) for the shallow bedrock zone and represents the highest Site-specific K value of all bedrock aquifer zones at the Site." The slug tests (Roux, 2015b, Table 43) however, show that hydraulic conductivity decreases with depth; and for the first 100 ft depth (center of screen; including both overburden and bedrock), the average value[5] measured in the slug tests is 2.6 ft/day (and the screen-length-weighted average is 2.84 ft/day), with individual values up to 22 ft/day (in a bedrock measurement with screen 46–63 feet, MW-22). Thus, a calibrated model value as high as 10.4 ft/day is quite plausible, and a value at higher than the RIR value of 1.1 ft/day is necessary to explain the current plume size (see below).

An alternative possibility not considered in the RIR is that most groundwater flow is through fractures, with little involvement of the bulk of the soil or rock. Flow through fractures only requires equilibrium with the surfaces of those fractures, not the surrounding rock/soil, so that adsorption to rock and soil would be negligible compared with an assumption of equilibrium with the entire rock/soil mass.[6] In such circumstances, the retardation factor for VOCs could be substantially lower than estimated; and ultimately a retardation factor close to unity is likely. The sensitivity analysis performed for the modeling fails to account for this quite likely scenario.

To further explore the adequacy of the RIR modeling even for evaluation of plume extension, I examined a one-dimensional simplification (see appendix) to overestimate the center-line concentration of the plume. This simplification provides an overestimate because it omits

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[4] The RIR does not provide a diagram of the location of the modeling grid, nor its dimensions, and does not provide any other method of identifying its exact location except by obtaining the model input file and a copy of the model.

[5] For flow through multiple layers driven by the same hydraulic gradient, the total flow per unit width is the sum over layers of the product of layer hydraulic conductivity and layer thickness, so that the average hydraulic conductivity is the layer-thickness-weighted average of layer hydraulic conductivities; in the absence of information on layer thicknesses (and not too extreme differences) the best estimate is the straight arithmetic average.

[6] Diffusion into the rock surrounding fractures would occur, but the time-scale for such diffusion is likely to be long enough to result in negligible effect. A fracture-transport model would take such effects into account.

dispersion to the sides; however, I expect that the results provided could be reproduced in the two-dimensional case with slight adjustment to the parameters. The simplest possible example, and an absolute worst case, assumes that the source has been maintained at a concentration equal to the solubility limit of TCE, approximately 1,100,000 µg/L (e.g. Baker, 2004, Tables 1–18) from the initial possible time of 1951 through 2013, the mid-point of the times used in the RIR to construct the contours shown in Figure 46 of the RIR, and continues forever. Figure 8 shows the result, which demonstrates that even in this worst-case scenario, the model adopted by the RIR (with the parameter values in the RIR, Appendix S, Table 1) cannot account for the distance to the 10 µg/L plume contour (nor the predicted 5 µg/L contour).

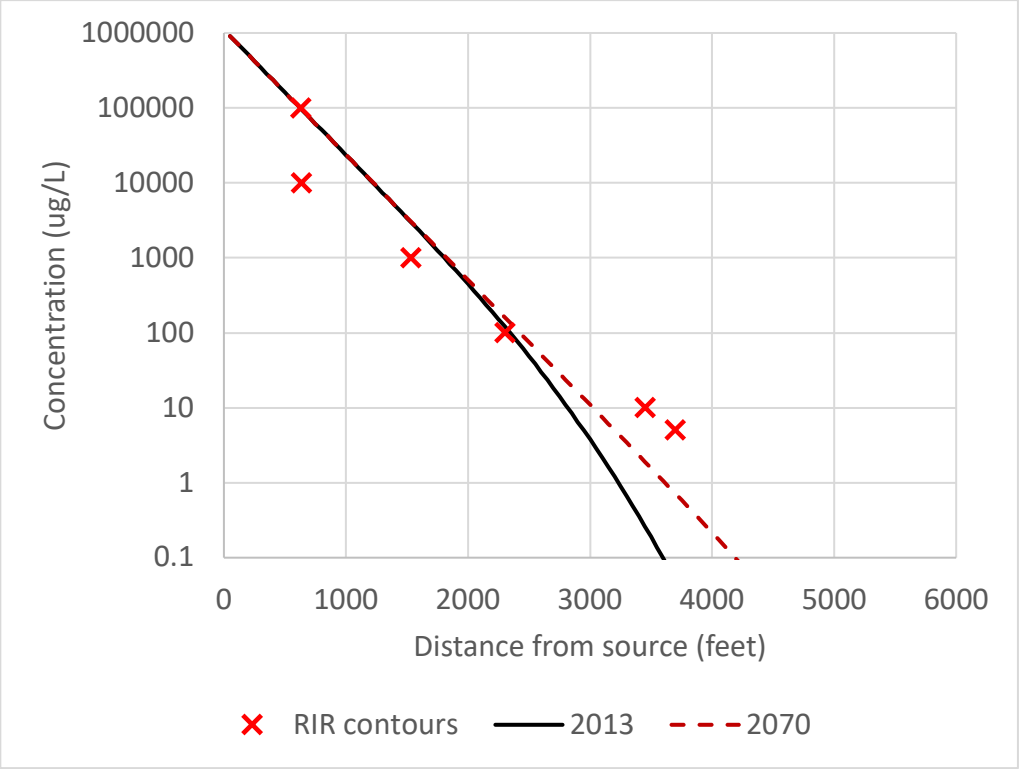

Figure 8 The absolute worst-case estimate of plume centerline concentration using the RIR model.

Clearly, with the parameter values used in the RIR, this worst-case plume would be in steady state out to 2,000 feet in 2013, and out to beyond 4,000 ft by 2070, and the 5 µg/L contour would never extend beyond about 3,200 feet.

It is, however, not difficult to find parameter estimates within the range discussed in the RIR or in previous modeling (Baker, 2004), that allow matching the plume estimates of RIR Figure 46, at least beyond the 100,000 µg/L contour. I consider that contour to simply reflect the anisotropy of the subsurface, with insufficient distance from the source(s) for the averaging effect of dispersion to have had sufficient effect for any smooth model to match it. For

example, simply increasing the estimated hydraulic conductivity to 2.129 ft/day and reducing the assumed (constant forever after 1951) source term gives Figure 9, which shows a plume in practical equilibrium to about 2,500 ft by 2013, and beyond 5,000 feet in 2070.

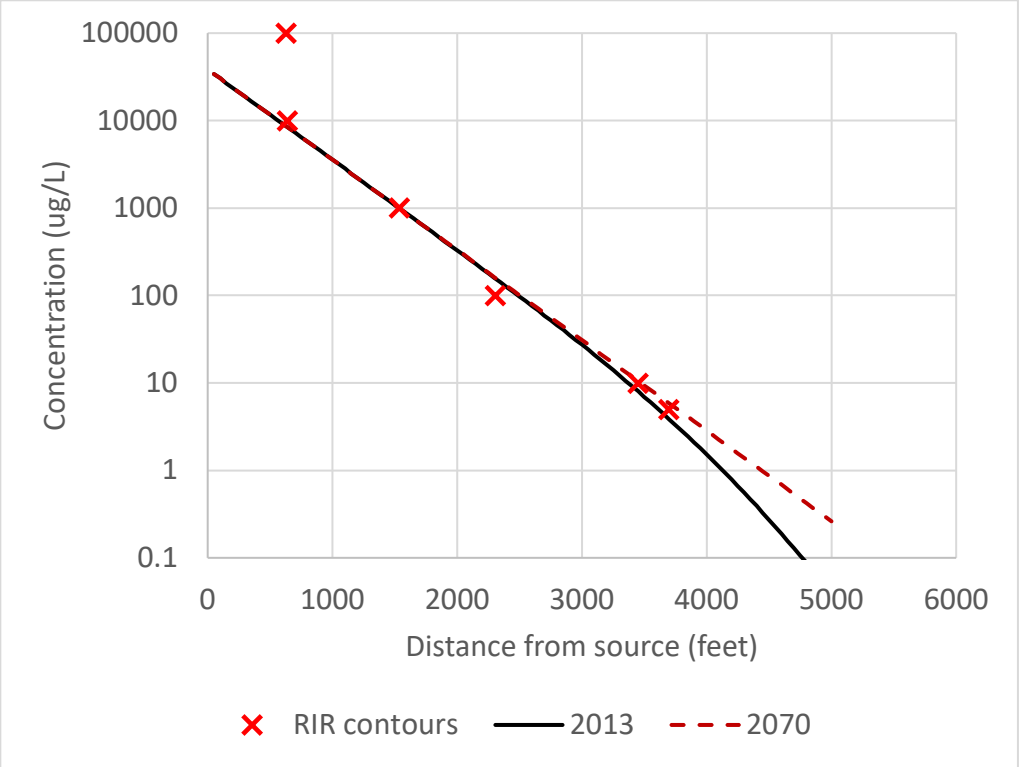

Figure 9 Showing that a constant source can match the RIR results with just a change in hydraulic conductivity.

However, while it is possible to find combinations of parameters agreeing with the RIR conclusions, it is also possible to find combinations that disagree substantially. Thus Figure 10 shows an example with variable source term that matches the RIR estimated plume in 2013, but demonstrates that the plume might extend considerably further by 2070 (indeed, in this case, the 5 μg/L contour would extend to approximately 4,500 ft by about 2100). This particular solution corresponds to a hydraulic conductivity of 1.776 ft/day and a degradation half-life of 3,506 days,[7] which are fully as plausible as the values used in the RIR and are "calibrated" to the observed plume in 2013.[8]

[7] Combined with a source term that varies from 1,100,000 μg/L starting in 1954, dropping to 3,000 μg/L in 1954.25, increasing to 103,907 μg/L in 1988, then decreasing to 31,172 μg/L in 1991.

[8] The source term dates were chosen (not quite arbitrarily) and then the other parameters obtained by a constrained optimization. The fit to the 2013 RIR plume contours (omitting 100,000 μg/L or higher) is well within any uncertainties in the contour locations.

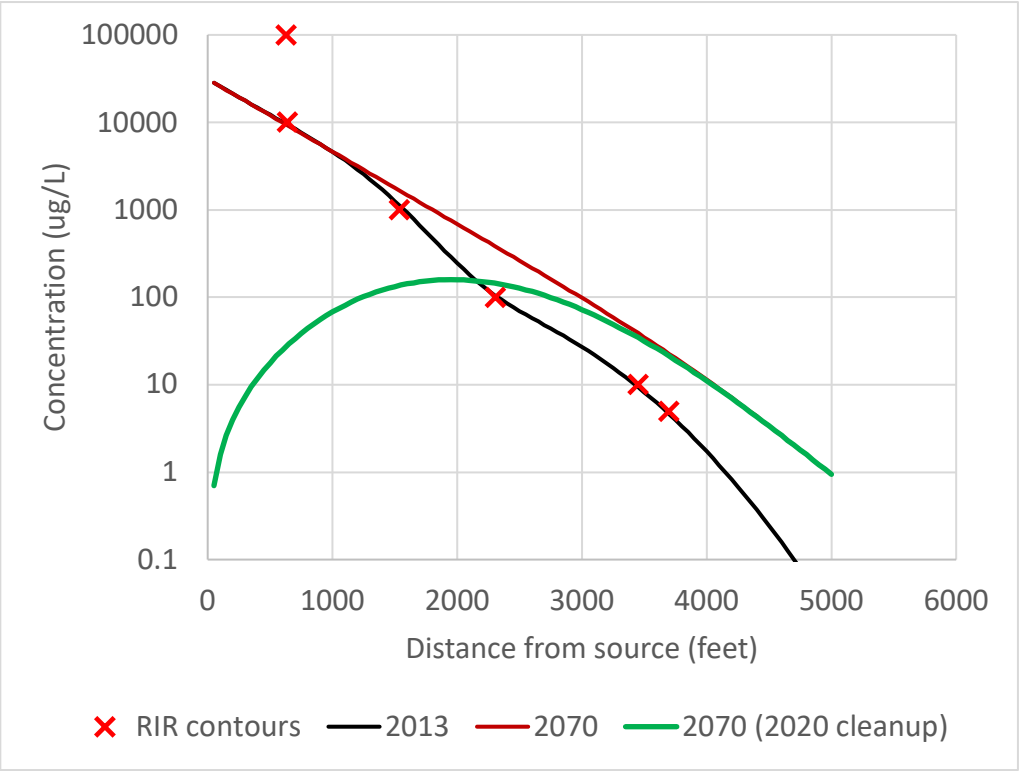

Figure 10 An example showing that the RIR might have substantially underestimated potential plume extent; and the effect of an immediate source term cleanup.

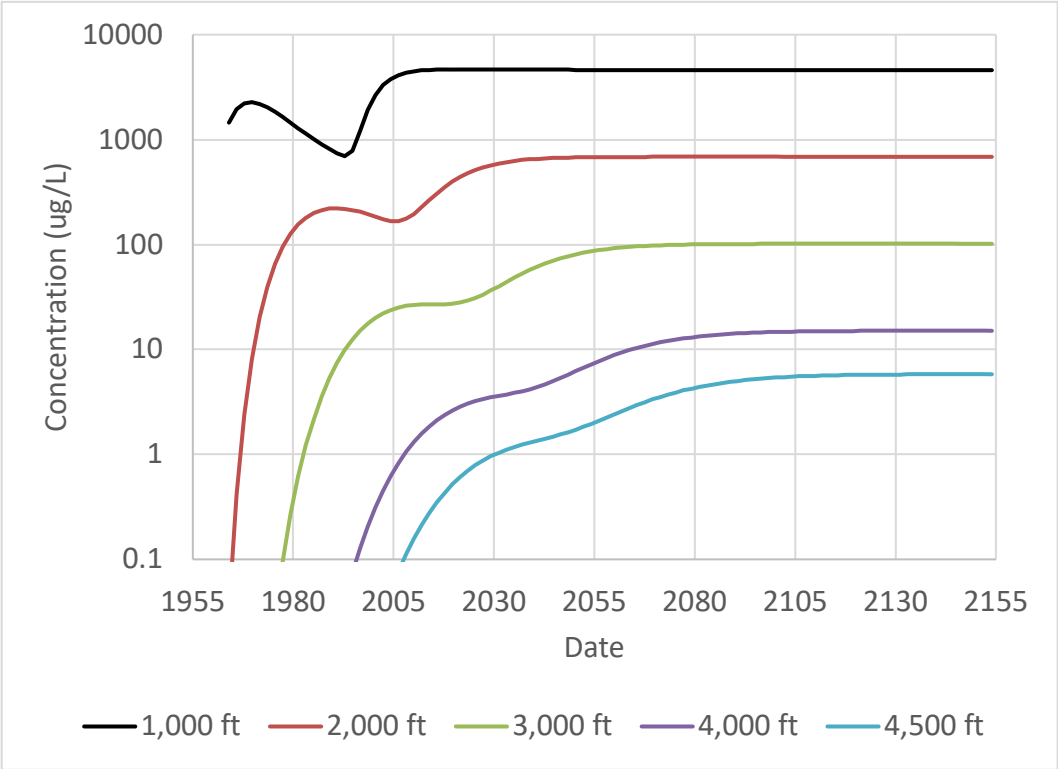

Figure 11 Concentration versus time at various distances for the example in Figure 10

Concentration versus date curves at various down-gradient distances for the example shown in Figure 10 are shown in Figure 11. Noteworthy features include:

- Periods of decreasing concentration have nothing to do with TCE degradation. They are controlled by variations in source terms.
- The "decay rates" estimated from such periods would certainly vary by location, and probably by time frame.
- Ultimately, all concentrations tend to a constant value (this occurs because of the assumption of a continuing source).
- The time to reach the ultimate value can extend well beyond the modeling time-frame of the RIR (which was limited to 2055).

This example is probably not entirely compatible with all the measurements in individual wells at the site, although short term fluctuations in source term (not included here) could provide better correlations with such measurements while retaining the overall average effect. It is included to illustrate the potential effect of variations in source term. An adequate RIR would investigate the inverse problem of estimating the source terms from the well measurements, and obtain a consistent solution that would allow accurate estimates of the future plume.

Also shown on Figure 10 is the effect of stopping the entire source completely in 2020, to illustrate the importance of immediate action. The hypothetical source term was selected so that, in 1991, 70% of the source at that time was removed in an effort to illustrate the potential effect of stopping TCE releases at the site at that time. Any DNAPL TCE in the bedrock at that time would sink to deeper levels, with some presumably remaining trapped in blind pockets throughout the rock column. Gradual dissolution of both sources would probably provide a substantially reduced source strength compared with DNAPL TCE still flowing through the rock column. However, TCE present as DNAPL in or adsorbed to soil above the rock column would not be so affected by such a change — that would still be available for leaching into groundwater. Unfortunately, the RIR makes no attempt to evaluate the relative sizes of these sources, but merely assumes that both vanish entirely — the TCE in the rock column by implicit omission, and the TCE in the soil by simply assuming it away. Figure 10 arbitrarily assumes that the rock column is a negligible source after 1991, and that leaching from the soil could amount to 30% of the total at that time (and could continue forever). Removing the soil in 2020 would then correspond to the green curve, showing a substantial reduction in concentrations over the first 3,000 ft of plume by 2070.[9]

[9] Nothing done at the site can have any effect beyond about 3,000 ft (for the combination of hydraulic conductivity and half-life simulated) by 2070, since there is insufficient time for any effect to propagate that far in that time

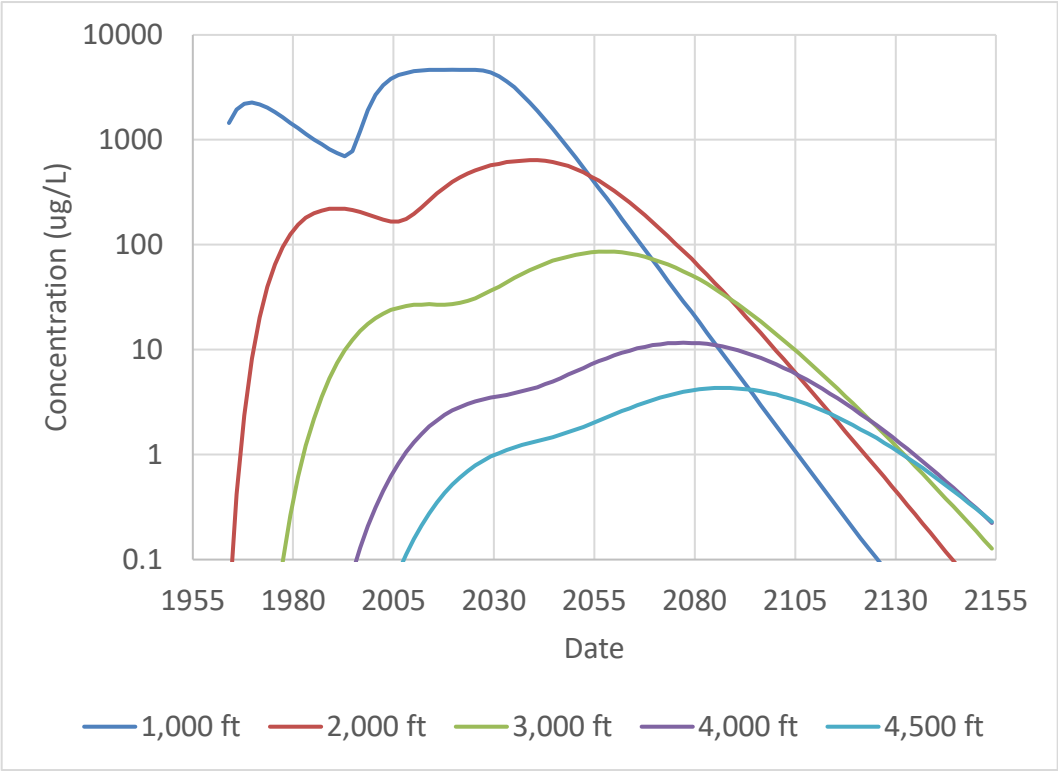

Figure 12 Concentration versus date curves at various distances for the clean-up scenario in Figure 10

The concentration versus date curves corresponding to the cleanup scenario of Figure 10 are shown in Figure 12. Further noteworthy (and generic) features (compared with Figure 11) are:

- After a time delay corresponding to the propagation time from the source, the concentrations start to decline almost exponentially with time.
- Despite the appearance on Figure 12 that the declining curves could be parallel and straight, the exponential declines are different at different times and distances, and none of them correspond to the TCE degradation half-life (they are more rapid).

7. Inadequate boundary conditions on the modeling

The RIR model imposes a line sink boundary condition at the Little Valley Creek (LVC) in the part of the modeling domain where the LVC was measured as gaining. This condition, however, is artificial, since it implies (in the model) that no TCE can be advected under the location of the LVC. However, the more complex and realistic MODFLOW/MODPATH/RT3D modeling by Baker (2004) demonstrated such flow beneath the LVC (Figures 41–44). Examination of a cross-section of the valley (Baker, 2004, Figure 15) illustrates why the LVC would not be expected to act as a groundwater boundary, except in shallow groundwater, with the continued decrease in surface elevation down to Valley Creek.

The initial contour shape in the vicinity of the Northwestern corner of General Warren Village appears unlikely, and there are no wells in that corner of the Village to confirm or deny the

prior modeling (Baker, 2004, Figures 41–52) that projected contamination beneath that corner. The RIR also lacks any figures showing future modeled contours, except for the interpretation of the plume extent, so prevents evaluation of the modeling in that area.

8. Undetermined effect on the Little Valley Creek (LVC)

The LVC, treated as a line sink, was specified as gaining 75 gallons per minute along a 2,500 foot length (RIR, Appendix S, p7), despite the substantially higher measurements. These inflows along the northern boundary of the site imply influxes of TCE carried by those inflows. However, there is no accounting for the effect on concentrations in the LVC from those flows, so the RIR has failed to document the potential degradation of this stream, which is classified as being of exceptional value.

9. Undetermined evaluation of other volatile organic compound (VOC) contaminants

The RIR documents measurements of multiple volatile organic compounds (VOCs), but then models only the TCE plume. Other VOCs may have different plume characteristics because of their different transport and decay characteristics, and in any event should be explicitly evaluated. Of particular concern is the potent, established, human carcinogen, vinyl chloride (VC), which has a soil-water partition coefficient approximately 1/9 that of TCE, hence a retardation factor of about 2, so would move through the subsurface approximately 4 times faster than TCE. Actual concentrations would also depend on decay rates that differ for different VOCs. And since VC is a microbial degradation product of TCE, evaluation of plume characteristics requires a model such as the reactive multi-species transport in 3-dimensional groundwater systems model (RT3D) designed to account for degradation of contaminants.

10. Incomplete assessments of impacts to public health and the environment

The RIR performs limited human health risk assessments involving vapor inhalation and exposure to surface water based on recently measured concentrations at individual wells and in individual buildings (and implicitly for groundwater ingestion), but fails to evaluate the potential effects of future modeled concentrations throughout the whole plume. Indeed, it could not do so, in that it failed to model future concentrations of all contaminants, or any contaminants at all in the LVC. There are also no assessments of risk from other potential uses of groundwater, such as irrigation, or commercial and industrial uses.

Potential ecological effects were claimed to be evaluated in the tributary of the LVC near the Bishop Tube site, but the effect on the LVC of future potential concentrations was not evaluated (and, again, could not be evaluated through lack of evaluation of such concentrations). It is notable that the concentrations of hexavalent chromium in the tributary exceeded the PADEP Fish and Aquatic Life criteria (RIR Table 20) on the single occasion (in 2018) on which it was measured under low flow conditions; yet the Ecological Risk Assessment (RIR, Appendix R) passes over hexavalent chromium because "hexavalent chromium, thallium and vanadium did not have TRVs that could be located in the published literature commonly used to conduct ecological risk assessments, therefore the potential for ecological risk to benthic invertebrates ***cannot be estimated***" (emphasis added). Clearly, however, what can be

"estimated" is that the current conditions exceed PADEP criteria. Moreover, it appears that hexavalent chromium has never been measured any further downstream than SW-5, despite the exceedance of criteria at SW-5. Clearly again, therefore "the potential for ecological risk to benthic invertebrates cannot be estimated" any further downstream into the LVC.

11. Inadequacy of the Feasibility Study Report (FSR)

The Feasibility Study Report necessarily relies upon the RIR for site evaluation, and in particular must account for the future condition of the site under various alternative scenarios. As documented above, however, the RIR fails to adequately evaluate future site conditions in the plume. The Feasibility Study Report is thus necessarily inadequate, since evaluation of future changes due to potential remedial technologies necessarily require an accurate baseline. This is particularly true for "Monitored Natural Attenuation" (MNA), since the only clean-up mechanisms in such circumstances are decay, dilution, and containment (if the latter two can be considered "clean-up"). The RIR, however, provides an inaccurate estimate of decay rate and dilution for TCE only, since it uses a methodology that fails to account for multiple effects. Production, decay, and dilution of the other VOCs is, inappropriately, ignored entirely.

In addition, the FSR considers that the DNAPL phase of TCE in deep bedrock is "a) below the water table, b) contained in rock, and c) at depth," so that "there is no direct exposure pathway from DNAPL in bedrock" (FSR, p6). However, this is an argument made without any apparent analysis whatsoever. The RIR assumes the absence of DNAPL and fails to evaluate multiple depth ranges separately, so cannot examine whether there is a "direct exposure pathway." Such a pathway is certainly plausible, since the deep DNAPL will certainly act as a source to groundwater, and that groundwater may be directly tapped, or may flow into surface water. The current RIR does not (and could not) evaluate either possibility; clearly, it should.

Concluding remarks

Overall, then, the analyses presented in the 2019 Remedial Investigation Report and Feasibility Study Report for this site are inadequate, particularly with respect to evaluation of the future plume conditions and associated risks: these reports could and should be improved. Such improvements should include full acknowledgement and use of previous analyses. The substantial quantities of TCE, other volatile organic compounds, and inorganic contaminants apparently remaining in soils at the site create a potentially significant risk to public health and the environment, due to exposures via soil, ambient air, surface water, and groundwater. It appears that prevention of continuing contamination of the LVC tributary, if not the LVC itself, above PADEP criteria requires removal (or other mitigation) of the site soil sources. And further downgradient contamination with TCE and other VOCs would also likely be substantially ameliorated by removal (or other mitigation) of site soil sources; and given the likely higher cost and requirement for off-site action to achieve the same amelioration later, the sooner the better.

Acknowledgements
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Appendix: The one-dimensional advection-dispersion groundwater solute transport model

1. **Analytic solution for specific boundary conditions**

The one-dimensional version of the advection-dispersion groundwater solute transport model of the Aquifer^{Win32} model (ESI 2011) as used in the RIR is a solution of the differential equation:

$$D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} = \varphi R\frac{\partial C}{\partial t} + \lambda\varphi RC$$

where the terms are:

$C = C(x,t)$	the solute concentration at distance x, time t,
$V = -iK$	the Darcy velocity of the groundwater, the product of hydraulic gradient i and hydraulic conductivity K,
$D = \alpha V$	the dispersion coefficient, the product of the dispersivity α and the Darcy velocity V (ignoring molecular diffusivity, which is small enough to ignore in this context),
φ	the porosity of the soil or rock,
R	the retardation coefficient of the solute, and
λ	the first-order decay coefficient of the solute.

This formulation assumes that all the terms except C are constant in time and space (as assumed in the RIR), and for this analysis the required solution has boundary conditions of a zero concentration everywhere prior to $t = 0$, with a constant concentration C_0 for all $t > 0$ at $x = 0$ (maintained, for example, by dissolving DNAPL), and with $C(x,t) \to 0$ as $x \to \infty$ for all t.

The unique analytical solution satisfying the differential equation with these boundary conditions is:

$$C(x,t) = \frac{C_0}{2}\exp(-\lambda t - [X - B]^2)\{\mathrm{M}(X + \gamma) + \mathrm{M}(X - \gamma)\}$$

where:

$$a = {}^{D}/_{\varphi R};\ \ b = {}^{V}/_{\varphi R};\ \ d = 2\sqrt{at};\ \ X = {}^{x}/_{d};\ \ B = {}^{bt}/_{d};\ \ \gamma = \sqrt{\lambda t + B^2};\ \text{and}$$

$$\mathrm{M}(z) = \exp(z^2)\mathrm{erfc}(z)\ \text{for arbitrary}\ z\ \text{is a modified Mills ratio}$$

This solution was used in the text to produce the curves shown. The linearity in concentration of the differential equation shows that the effect of multiple sources can be obtained independently and added to obtain the effect of all sources combined; and negative sources at later times can be used to obtain the effect of arbitrary step function sources.

2. Unique unphysical solution for similar exponential decay at all locations and times.

If it is assumed, as in the RIR, that the concentration at all locations falls exponentially with the same decay rate λ at all times, then the right hand side of the defining equation above

vanishes, and the solution factorizes into a product of a term exp($-\lambda t$) and an x-dependent term $H(x)$, which is the solution of the equation

$$D\frac{d^2H}{dx^2} - V\frac{dH}{dx} = 0$$

which has the general solution

$$H = K_1 + K_2 \exp\left({}^{Vx}/_{D}\right)$$

where K_1, K_2 are constants, corresponding to a concentration everywhere constant or exponentially increasing with x everywhere, which is physically impossible.

Appendix Reference

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EDUCATION

1972. B.A., University of Cambridge, England, Natural Sciences (Theoretical Physics).

1975. Ph.D., University of Cambridge, England, High Energy Physics, (Thesis: "The Algebraic Structure of Some Dual Resonance Models").

OVERVIEW

Dr. Edmund Crouch is Vice President and Senior Scientist at Green Toxicology LLC. He specializes in all aspects of exposure assessment and risk assessment, but particularly the analysis of experimental and observational data and the application of such analyses to those fields. His original research, publications, and consultant work includes quantitative evaluation of uncertainties in rodent cancer bioassays and in interspecies extrapolations of carcinogenicity; meta-analysis of cancer bioassay results, epidemiological observations, experimental bacterial growth rate data, and observable effects of ethanol in humans; and construction and application of Monte Carlo analyses in exposure and risk assessments. He has applied these skills to numerous quantitative risk assessment projects involving air emissions, groundwater contamination, consumer exposures, worker exposures, indoor air, food safety, and others. Dr. Crouch (with Professor Richard Wilson) "wrote the book" in 1982 on Risk-Benefit analysis, and his work since then has been recognized by his 2008 designation as a National Associate of the National Research Council of the National Academies and in the Society for Risk Analysis Outstanding Practitioner award in 2013.

PROFESSIONAL EXPERIENCE

2015–Present	Vice President and Senior Scientist, Green Toxicology LLC.
2015-Present	Senior Risk Assessor, Part-time, ARM Group Inc.
1987–2016	Associate of the Department of Physics, Harvard University, Cambridge, Massachusetts.
2013–2015	Principal, CDM Smith Inc., Cambridge, MA.
1989–2012	Senior Scientist, Cambridge Environmental Inc., Cambridge, MA.
1992–1994	Lecturer in the Department of Epidemiology, Harvard University School of Public Health.

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1990–1992	Assistant Professor of Community Health, Tufts University School of Medicine, Boston, Massachusetts.
1987–1989	Senior Scientist, Environmental Health and Toxicology Group, Meta Systems Inc., Cambridge, Massachusetts.
1984–1986	Consulting Associate in Risk Assessment, Meta Systems Inc., Cambridge, Massachusetts.
1979–1986	Research Associate In Physics, Jefferson Physical Laboratory, Harvard University, Cambridge, Massachusetts.
1977–1979	Research Fellow in Physics, Jefferson Physical Laboratory, Harvard University, Cambridge, Massachusetts.
1974–1977	Research Fellow in the Energy Research Group, Cavendish Laboratory, University of Cambridge, Cambridge, England.

NATIONAL ACADEMIES OF SCIENCE COMMITTEES

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SELECTED PROJECT EXPERIENCE

- Evaluated diffusive emissions of PCBS from contaminated concrete floors, through uncontaminated floors, and through topping layers applied to contaminated floors.

- Designed, wrote, and implemented the probabilistic (Monte Carlo) risk assessment for FSIS, USDA, on the risk of *C. Perfringens* in Ready-to-Eat and Partially Cooked Foods.

- Derived and used in risk assessments and in support of various litigations many quantitative exposure assessments involving transport and fate of chemicals in the

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natural (for example: air, soil, groundwater, surface water) and man-made (for example: indoor and outdoor air) environment.

- Performed quantitative risk assessments to demonstrate compliance with California Proposition 65 "safe harbor" limits for various consumer items, including dishwasher liquid, guitar strings, and baby shoes.

- Analyzed original human experimental data on exposure to sulfur dioxide to derived uncertainty estimates for the dose-response relationship. Applied this analysis to EPA's justification for the 1-hr NAAQS for sulfur dioxide.

- Designed the theory and implemented in computer code a site assessment tool (called RISK-ON-SITE™) that uses Voronoi diagrams to assist in estimating risks from soil and groundwater on a site. Provided suitable color displays to allow rapid evaluation of the available data on a site. Extended the methodology to give risk-based estimates of required clean-up levels.

- Wrote and still maintains a software program (MSTAGE) to evaluate the results of carcinogenesis bioassays in laboratory animals. This program is flexible enough to incorporate the standard EPA methodologies, but may also be used with more advanced methodologies to correctly incorporate uncertainties.

- Managed and wrote several site risk assessments for Massachusetts and Federal Superfund sites.

- Managed and wrote several risk assessments for Waste-to-Energy plants.

- Performed full uncertainty analyses of cancer risk assessments for several chemicals and in several defined situations, incorporating all the known uncertainties in a consistent fashion.

- Provided expert technical comments on proposed EPA rules in such areas as exposure assessment (for example: for landfill leachate and landfill gas), and risk assessment methodology (for example, as applied to the Hazard Ranking System).

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Technical Memorandum

January 24, 2020

Subject: Bishop Tube 2019 Remedial Investigation Report and Feasibility Study

Prepared for: Delaware Riverkeeper Network

Summary of Findings

Roux Associates (Roux) prepared a Remedial Investigation Report (RIR) for the Bishop Tube Site using false assumptions. First, Roux assumed the property would be developed for nonresidential uses but, the property has since been rezoned for residential use and the plans appear to be for residential development. Second, the analysis assumes that the soils, meaning unsaturated materials above the water table in the overburden, will be removed, so that analysis assumes there is no contaminant source leaching into the groundwater long term. This assumption affects all analyses of groundwater quality and remediation strategies presented in the Feasibility Study (FS). If the assumption is incorrect, all analyses and remediation strategies presented in the RIR and FS are inaccurate and inappropriate. Additionally, the RIR/FS presents no reasons that could explain why the source areas have not been remediated during the period the site has been under investigation. The hot spots existing in the soils will continue to be sources of contaminants into the future, as indicated by analysis of groundwater monitoring wells, if they are not removed.

Trichloroethene (TCE) concentrations vary substantially with both location around the area and with time at all levels. A plume map represents conditions at a point in time. The short-term variability in TCE concentration at some wells indicates that the source is variable, which is probably due to recharge events, and the mass is moving. This causes concentrations within a plume to vary substantially over the short term. The TCE contour map as presented in the RIR has errors and uncertainties as represented by the rapid fluctuation of TCE concentrations in various wells and the lack of a single consistent date for sampling events. Continuing recharge of TCE causes the concentrations within the plume to vary over the short term. The steep gradient in the concentration contours on the east side shows plume has a sharp boundary. However, the lack of monitor wells in the General Warren Village east of Bishop Tube means there is no evidence to support the sharp plume boundary.

Variations with depth and between the overburden and bedrock indicate that a single map does not adequately represent the plume. The RIR should include TCE contours for overburden and shallow bedrock, because the data show clearly the plume differs between the aquifer media and both are targets for remediation.

The TCE contour maps should also be specific to a single date or at least a shorter period than used in the RIR (2012 to 2014). Such a time series of concentration contours would provide an assessment of changing conditions in the past. The RIR should also show the modeled variation in future by a sequence of proposed contours.

TCE contours on the east show a narrow boundary but there are no wells within General Warren Village to justify such steep concentration contour gradients. Some data and prior modeling suggest that TCE flows beneath the subdivision at some depths. Additional monitoring wells in the General Warren Village are necessary to verify whether TCE currently or has in the past entered groundwater beneath the subdivision.

The mapped plume extends northeast from the source at Bishop Tube at all aquifer levels. Concentrations at onsite wells, both shallow and deep, have remained stable but with distance from the source, TCE concentrations have decreased with time. An exception is along a narrow track northeast from the site from wells MW-51 and MW-79 through wells MW-44 and MW-47 at all levels. These trends indicate the source leaches sufficient TCE to keep TCE under the site high. The source is not sufficient to sustain the level of load leaving the site as has been observed in the past, therefore attenuation has decreased concentrations far from the site. However, some TCE continues to move further from the site while concentrations within portions of the plume decrease. In deep bedrock, TCE concentrations near the site are very high due to dissolution of DNAPL being bound in the deep bedrock fractures. However, TCE drops rapidly with distance at depth because of the few fractures. It is possible the TCE moves through narrow fractures and reaches unknown discharge points.

The northeast trend of the plume counters the regional flow gradient which is due north. The plume cuts northeast which would occur only if it follows a fracture trace rather than the flow gradient. This demonstrates the preferential flow caused by the trend of fractures being to the northeast. Preferential flow occurs when conditions are more favorable for flow in a given direction that may differ from the slope of the groundwater table.

Groundwater at the Bishop Tube site eventually discharges to surface water. Most critically, shallow groundwater discharges to and supports the Little Valley Creek (LVC) tributary just east of the site and intermittently to a ditch that bounds the north side of the site and flows east. The highest TCE concentrations are near the site, but they are detectable as far as a site beyond

Conestoga Ave although they decrease going downstream. The decrease with distance is misleading because of dilution and it would be more appropriate to analyze the load, or total mass, at points to determine if groundwater discharging to the stream at various points contains TCE. The RIR should analyze load in the creek rather than simply concentration to attain a better assessment of the location TCE-laden groundwater enters the creek. Moreover, the LVC is gaining and losing at various points, so may act as both a sink and source for groundwater contamination at various points along it.

The time series of data at SW-4 and SW-5 shows concentrations have substantially decreased since 2003, but the data is not controlled for flow which could cause the concentrations to fluctuate due to the amount of dilution. The most recent dry season value, September 2018, is the lowest compared to previous samples (the November 2018 value is a wet period and therefore more diluted). Five observations show a consistent downward trend at two locations most likely to be affected by groundwater discharge from the site, however, analyzing the load would be a better assessment.

TCE and other contaminant concentrations in surface and groundwater at and near the site continue to represent a potential threat to human health and the environment. The FS provides seven alternatives for remediation, including no action (1), monitored natural attenuation (MNA, 2), in-situ chemical reduction (ICR, 3), in-situ chemical oxidation (4), enhanced reductive chlorination (5), two-part in-situ chemical oxidation (6), and hydraulic control (HC, 7). MNA is basically just monitoring the on-going natural attenuation.

The FS determined that removal of DNAPL is technically impracticable. Due to the depth and inability to even sample it, this may be correct. However, it is essential the FS determine whether the DNAPL could be a substantial source of TCE in fractures that move from the site and discharge to surface water or publicly used groundwater.

Alternatives 3 through 6 involve injection of various chemicals to cause the TCE and other contaminants to degrade or decay. Alternative 3, ICR is the most promising because it would remove both VOCs and inorganics; the other alternatives would not remove inorganics. Alternative 7, HC, would create a line of wells to prevent the offsite movement of contaminants. The injection alternatives would substantially speed remediation as compared to MNA because it would hasten the breakdown. For this reason, they have substantial advantages. It is possible that more than one alternative could be used together to attain a faster remediation, as discussed below.

However, there are implementability issues with injection of material into shallow groundwater. Injection in shallow groundwater, either overburden or shallow bedrock, could

dissolve adsorbed contaminants so that they would discharge to surface water. Too much injection could cause the groundwater table to rise and daylight to the ground surface. Either problem could be mitigated by capturing the contaminants before they reach the stream, possibly with shallow, horizontal collection wells. Also, the layout of the injection systems could be changed to avoid short flow paths to surface water.

Alternative 7, HC, involves creating a line of low water level or potentiometric surface levels which would create a capture zone for groundwater flowing from the site. However, it could deplete stream flow or dry groundwater dependent wetlands which would be an unacceptable effect, therefore HC should not be used by itself. HC could be used in conjunction with an injection alternative to capture any liberated contaminants as long as pumpage does not exceed injection to protect the streamflow. Establishing a line of collection wells downgradient of a system of injection wells could prevent the unwanted products of injection from reaching the streams or wetlands. Implementing injection wells downgradient of collection (extraction) wells would do the same

The fate and transport model used to partially delineate the TCE plume is over simplified and has many errors, some of which are listed here. The modeling section of this memorandum discusses the errors in more specificity. The model simplifications and errors render its predictions inaccurate. Among the concerns are the following:

- assumes the aquifer is homogeneous which ignores the fact the aquifer is fractured bedrock in which the conductivity decreases with depth
- no consideration of aquifer layers
- no consideration of horizontal anisotropy which controls the direction of flow
- failure to consider vertical gradients which are essential for understanding flux to streams
- no consideration of preferential flow pathways
- the model simulates decay as happening too quickly because the estimated decay rate does not adjust for dilution and advection of the material
- the decay rate estimated by Roux is inaccurate because it was based on observed changes at wells which is affected by much more than simple decay.
- the model does not simulate a source of contaminant, either from the soil or the DNAPL deep in the bedrock, so the simulation with time simply moves the existing, or initial, concentrations from the model domain either by advection or decay
- the flow model calibration has a large range of residuals, or errors in how the model simulates the measured water level

- The boundary condition used for LVC is incorrect, since the LVC is both gaining and losing along various parts of its length. LVC can transport contaminants and be a source of contaminants to groundwater downstream.

Introduction

Roux Associates (Roux) completed a Remedial Investigation Report (RIR) and Feasibility Study (FS) for the Bishop Tube site in 2019. The RIR supplemented earlier reports completed in 2015 and 2010 (RIR, p 1). RIR Appendix A presents raw soil contaminant concentrations and Appendix B presents a time series of groundwater concentrations for all monitoring wells. RIR Appendix S partially documents a groundwater fate and transport model used to develop the plume map. The FS identifies potential remedial activities, as identified by Roux. This memorandum reviews aspects of the RIR and FS, concentrating on the 2019 versions.

Analysis of Site Conditions

The RIR does not quantitatively describe the hydrogeologic properties of the site, which should be the first step to developing a site conceptual model. The 2015 RIR provided a cursory description of slug-test results but left out significant important information. The 2019 RIR essentially sets conductivity equal to 1.1 ft/d for the entire aquifer consisting of both overburden and fractured bedrock, the geometric mean of a few slug tests discussed in the 2015 RIR (conductivity is specified only in RIR Appendix S). A mid-range estimate such as the mean ignores the high and low values which control most flow. Reported values (in the 2015 RIR) are as much as an order of magnitude higher than the geometric mean. Higher conductivity zones are often preferential flow zones. Flow and contaminant transport through such a zone occur much faster than expected from the (unweighted geometric) average values. Contaminants could flow much faster and have a higher load than expected using averages.

The geometric mean conductivity also provides no data on anisotropy, the tendency for flow to be greater in one direction over another. As will be discussed, flow at this site is at an angle to the primary gradient, south to north, which means there are preferential flow zones in the bedrock that controls the flow direction.

Contaminants in groundwater at the site (chlorinated volatile organic compounds (CVOCs)) discharge to local tributaries of Little Valley Creek (LVC). Stream trichloroethene (TCE) concentrations have decreased for six consecutive sampling events, but those events may not be comparable, because they may have been collected during differing wet or dry periods,

when flow rates were not similar. (Groundwater is the source, and surface runoff will mostly dilute the concentrations, because the contaminants are not lying on the ground surface where they can be washed into runoff).

- Roux should analyze the flow rates for the sampling events to assess changes with time. Roux should consider the change in load with time, rather than concentration.

There has been no data collected or tests performed to obtain evidence describing groundwater flow, dissolved contaminant transport, and DNAPL (undissolved TCE and other COCs) flow among aquifer levels, although it clearly occurs. This would be important to understand how fast contaminants settle into the aquifer and from how deep they could discharge to LVC.

Soil Concentrations

RIR Appendix A compiles soil contaminant masses from 1988 through 2018, but Roux does not analyze soils contaminant concentrations or consider them as a source. It presents figures of concentration in soils by well of TCE and other contaminants including heavy metals; the figures color code wells by contamination categories. Soil samples have identified CVOCs including TCE, 1,1,1-trichloroethane (TCA), cis-1,2-dichloroethene (cDCE), and tetrachloroethene (PCE) (Id.). An earlier figure presented by Baker includes contours of TCE (Figure 1). Contaminants occur in at least three hot spots, but there is no evidence of how they vary with time. Neither the RIR figures nor Appendix A present data that can be analyzed for trend because samples are spot measures, not monitoring points, meaning they extract soil at distinct locations rather than measure concentrations in place.

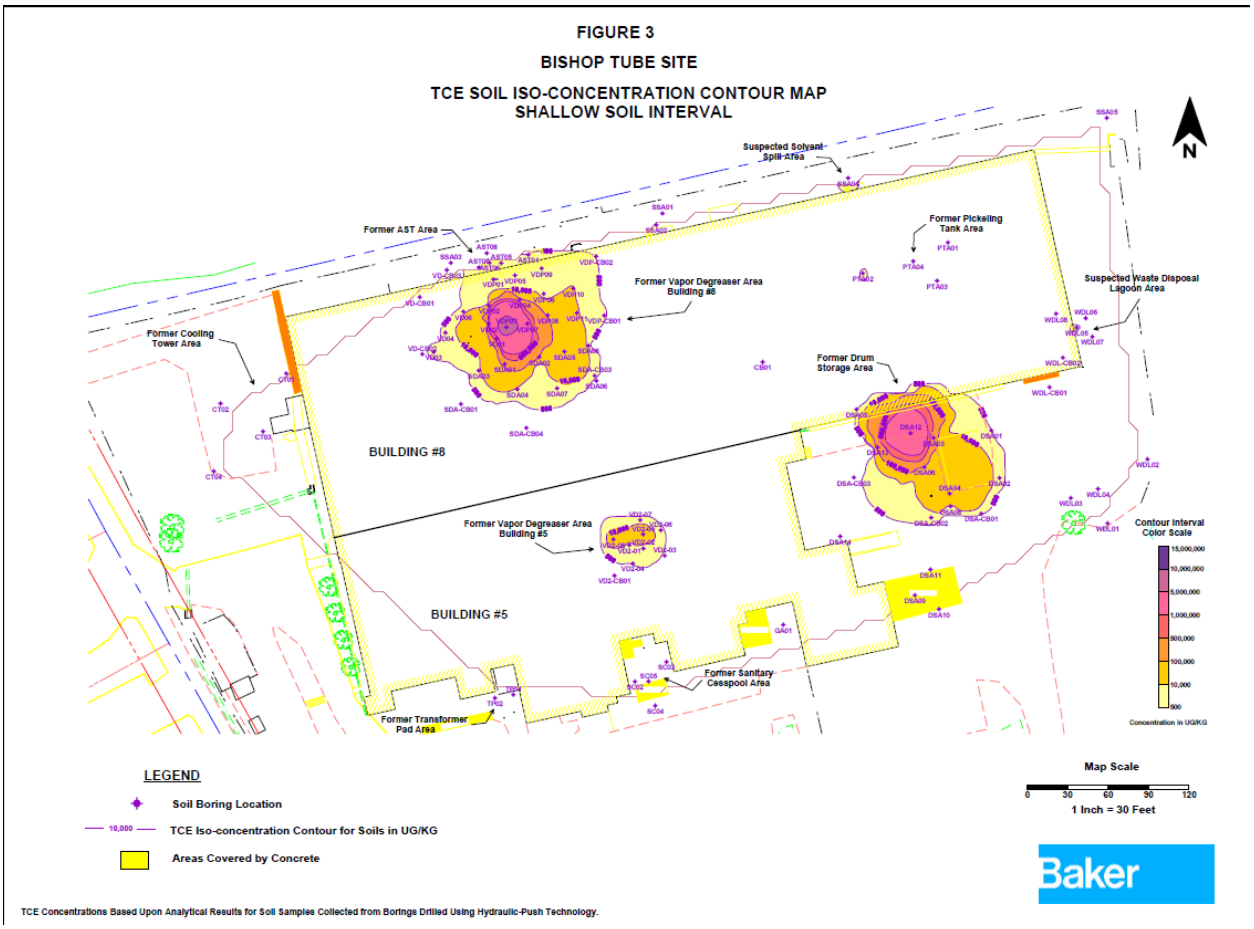

Figure 1: Concentration map for TCE prepared by Baker 2003).

- The RIR should develop concentration contours for the hot spots for as many points in time as possible. This would create a time series of mass in the soil and provide an assessment of how much of the contaminants degrade or leach into the groundwater with time.
- Roux should sample soils as part of this RIR and provide a current estimate of contaminant mass at each hot spot.

Roux collected additional data from known hotspots and PADEP investigated reports of other potential hot spots, with Roux analyzing split samples, but did not find any. There does not appear to have been a systematic sampling of soil beneath the site.

- As part of the sampling of hot spots, Roux should sample on a grid around the site to find hot spots that have not been reported.

As presented, it is not possible to assess whether the mass in soils is decreasing, as might be expected as precipitation leaches mass from the original sources. Prior to making assumptions regarding soil as a source and whether various treatments that include natural attenuation would be successful, it is essential to understand the fate of the sources.

- The RIR should contain time series plots of the mass of TCE and other constituents in the soil at each hotspot.

The analysis assumes that the soils, meaning unsaturated materials above the water table in the overburden, will be removed (FS p 4). This means **the analysis assumes there is no contaminant source in the unsaturated zone leaching into the groundwater long term**. The FS notes that this assumption may make the analysis of clean-up options in the groundwater easier. For example, it could "obviate the need to consider complex remedies for inorganics in groundwater" (FS p 4).

- Assuming total removal of the source renders predictions of the evolution of the plume inaccurate and renders the use of the model, discussed below, to assess remediation useless. Modeling should be redone to include the continuing source.
- All assessments of remediation, also discussed above, should include the potential for any sources in the soil and bedrock not being fully removed (there is no indication even for removal of bedrock sources).

Groundwater TCE Concentration Contour Mapping and Errors

A contaminant plume in groundwater resulting from a constant load discharging into an aquifer eventually reaches a steady state wherein it no longer expands. Load equals attenuation based on dilution, dispersion, and reactivity. The rate of attenuation with distance from the source equals the rate of mass entering the plume from the source. An expanding plume means that equilibrium has not been reached or that the factors of attenuation have been eliminated. Contraction of the plume means that rate of mass leaving the source is decreasing.

Concentrations decrease with distance from the source due to natural attenuation and dilution. The change in isotopes for TCE and other COCs and the increase in daughter products documented in the RIR is evidence of the breakdown of the contaminants. Although breakdown contributes to the decrease in concentration, dispersion and dilution also occur.

The RIR presents TCE concentration contours in two figures, Figures 45 and 46. These figures were developed in the groundwater model discussion presented in RIR Appendix S (the model is reviewed below). Roux hand-contoured contours from 10 to 100,000 ug/l (logarithmic

spacing) based on 2012 to 2014 groundwater quality data for both figures. The figures claim they used the maximum concentration from that period, therefore the figures do not represent a point in time. The description of the contours indicates the contouring was for just shallow bedrock (RIR, App S, p 11), although the figures show both overburden and bedrock wells. For nested bedrock wells, Roux used the highest concentration regardless of depth, so the plume map cannot be said to represent a given level in the bedrock. Some wells have higher TCE at depth, so the map would be representing deep bedrock at those wells. The 5 ug/l contour, developed in part using the groundwater model, is the only difference between Figure 46 and Figure 45.

Concentrations in overburden wells SMP-2 through SMP-5, adjacent to the LVC tributary east of the site, far exceed the mapped contours. For example, TCE concentrations at SMP-2 is 245 ug/l although it outside of the 5 ug/l contour. The concentration at SMP-1 on the same date is 802 ug/l although it is between the 5 and 10 ug/l contour. The SMP wells are shallow, with screens from 5 to 10 or 6 to 11 ft bgs. These observations show the TCE has certainly expanded further east toward General Warren Village in the overburden than Roux estimates in the bedrock, although the basis for the 5 ug/l contour is unclear since Roux does not present any contoured model outputs, and these results contradict earlier multi-level modeling (Baker, 2004). There are insufficient wells east of LVC to accurately identify the extent that TCE has reached within the subdivision.

TCE concentrations vary substantially with both location around the area and with time at all levels. This indicates that plume maps represent conditions at a point in time[1]. The short-term

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[1] MW-07 is east of building 5 and west of LVC. It is screened in overburden from 9.8 to 19.8 ft bgs. In 2010 and 2014, its TCE was 3.6 and 1.8 ug/l, respectively, so it is properly outside of the 5 ug/l contour. Four of five observations from 1987 to 1990 exceeded 100 ug/l, but since then all observations were decreasing from 62 to below the lab reporting limit in 2018. MW-05 is an overburden well, screened from 10 to 20 ft bgs, east of Building 8 and plotted between the 10 and 100 ug/l contour. However, its 2014 TCE concentrations was nondetect, suggesting the contours are too expansive in that area. However, the contours are very closely spaced and in 2018 TCE at this well increased to 14 ug/l (one of few on the east side that increased).

MW-04 is east of the southeast corner of Building 8 and screened in bedrock from 7 to 20 ft bgs. By 2014, its TCE concentration was 2 ug/l, so it is properly outside the 5 ug/l contour. The concentration was 2.1 ug/l in 2018, but prior to 2004 had exceeded 100 ug/l and even exceeded 1000 ug/l twice prior to 1991. MW-09 is screened in bedrock from 46 to 63 ft bgs just east of the northeast corner of Building 8. Its 2014 TCE concentration is 314 ug/l, so it is properly between the 100 and 1000 ug/l contour. TCE concentrations at this point have been as high as 100,000 ug/l in 1990. Several wells under the AOC in the NW portion of Building 8 have very high TCE. MW-77, screened in bedrock from 40 to 50 feet, had TCE increase from 3010 to 218,000 ug/l from 2017 to 2018. Because it is shallow, it could be evidence of a recent recharge/leaching event.

MW-75 is a deep bedrock well just west of MW-8 east of building 8. MW-75A is screened from 345 to 360 and MW-75B from 374 to 419 ft bgs, respectively. It has high readings, all over 310,000 ug/l since 2014 without a

variability in TCE at some wells indicates that the source is variable which is probably due to recharge events[2]. Therefore, the TCE contour map as presented in the RIR has errors and uncertainties as represented by the rapid fluctuation of TCE concentrations in various wells and the lack of a single consistent date for a sampling event. Continuing recharge of TCE is one cause. The steep gradient in the concentration contours on the east side shows plume has a sharp boundary. However, the lack of monitor wells in the General Warren Village east of Bishop Tube means there is no evidence to support the sharp plume boundary.

- The RIR should include TCE contours for overburden and shallow groundwater. This is because the data show clearly the plume differs between the aquifer media. Because each are targets for remediation, there is a reason to include both.
- The TCE contour maps should also be specific to a date and to depth or at least a shorter period than used in the RIR (2012 to 2014). Such a time series of concentration contours would provide an assessment of changing conditions
- The contours on the east should be verified with additional monitoring wells in the General Warren Village. This is necessary to verify whether TCE currently does or has in the past contaminated groundwater beneath subdivision.
- TCE extends far from the original site, as demonstrated by the plume shown in the RIR and by the changes in the mapping suggested here and represents a potential threat to human health and the environment.

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trend. It was not used for contouring and suggests that deep bedrock has higher TCE concentrations than shallow bedrock. MW-26 is adjacent to MW-75 but screened in bedrock from 90 to100 (A), 176 to 186 (B), and 222 to 232 ft (C) bgs, respectively. MW-26A had TCE equal to 1720 and 1580 in 2014 but MW-26B was 178,000 ug/l in 2014. MW-26C was 418,000 and 457,000 ug/l in 2014 but has increased to 898,000 ug/l in 2018. In the same vicinity, MW-31, an overburden well, TCE equaled 175 ug/l in 2014. These three wells illustrate the substantial increase with depth that has occurred all over the site.

[2] MW-78, also not used for contouring, demonstrates the short-term variability of TCE concentrations in shallow bedrock and that the AOC continues to be a source. This well is located near the center of the AOC in NW building 8. The well has three screens in bedrock from 85 to 110 (A), 262 to 287 (B) and 340 to 400 (C) ft bgs, respectively. In just two years, the shallow well decreased from 10,000 ug/l to non-detect and then increased back to 15,600 ug/l; this demonstrates a slug of TCE transported through the well, probably with a significant downward gradient based on the much higher concentrations at depth. MW-78B fluctuated between 21,500 and 93,600 ug/l and MW-78C between 147,000 and 233,000 ug/l. The proportional fluctuations at depth are probably less than higher up because the K at depth is lower so groundwater and TCE moves slower and thereby accumulates.

Some shallow wells near the sources showed significant increases in the 2018 observation that could coincide with wet conditions and leaching. The observed fluctuations demonstrate that it is inappropriate to claim a trend with a couple of wells. The trends at the monitoring wells indicate that loading continues at least intermittently but may suggest the average load has decreased. Spikes in shallow wells and wells near the sources show intermittent loading. That the extent of the plume extent is marginally shrinking shows the loading is likely decreasing but with spikes during events.

Analysis of Groundwater TCE Trends

The trend of TCE plume in the groundwater at all depths indicates the source of TCE in soil in the Former Degreaser Area in the northwest portion of Building 8 is still active (RIR Figure 30). This is the location of the highest soil mass concentrations. High TCE in the overburden groundwater clusters directly under the source but decreases rapidly with distance to the northeast, the direction the plume extends[3]. TCE emanating from the site is highest in the overburden and in the deep bedrock, although it has traveled further in the overburden. LVC is not gaining north of Lancaster Blvd, so the TCE must pass beneath the creek.

A conceptual transport model (CTM) from the Former Degreaser Area source in the northwest portion of Building 8 is that TCE leaches from the soil into the overburden at the site. Some TCE transports downgradient to and past the creek, but a large amount flows deeply into the bedrock. Also, DNAPL has settled into deep fractures and provides a source of TCE to deeper bedrock.

Rather than indicating TCE did not reach bedrock downgradient from the site, between Lancaster and Conestoga Blvd, the trends observed in the data tables (RIR, Table B-1) are that TCE has decreased with time, with some monitoring wells having had much higher values within the last 15 years[4].

The groundwater gradient suggests regional flow should be due north. Flow should advect TCE north from the site. However, Figure 30 shows that in the overburden (MW-49A and MW-60) and the shallow bedrock (MW-7, MW-14D, MW-49B and MW-50A, B), little TCE moves in that direction. The plume cuts northeast almost parallel to the groundwater level contours, which would occur only if contaminants follow a fracture trace rather than the flow gradient (also discussed below the review of the groundwater model). Concentration time series at overburden wells MW-61, MW-37, MW-63, MW-38, MW-47 and MW-40 and shallow bedrock wells MW-51B, MW-53A, MW-45A, MW -43A, MW-54, and MW-44A do not show the downward trend apparent in other parts of the plume possibly because of their presence on a fracture trace which could be a contaminant pathway. No monitoring wells defines the

[3] Based on Figure 30A, TCE exceeds the 5ug/l but generally not 5000 ug/l under the source in Building 8. TCE up to 5000 ug/l occurs across the lot north of Lancaster in the overburden. The plume shape is similar but with lower TCE in the shallow bedrock. MW-51B northeast of the site at Lancaster Blvd is an exception with TCE equal to 156,000 ug/l. TCE in the intermediate and deep bedrock is very high away from the source but in the near portions of the lot north of Lancaster Blvd. Further from the site in the vacant lot, TCE at depth is highest at 694 ug/l in MW-44c.

[4] MW-44C dropped from 1860 to 646 ug/l between 2010 and 2017. MW-58C dropped from 390 ug/l in 2012 to 16.5 in 2014 before increasing to 70.1 ug/l in 2017. Although as noted overburden TCE is still high, most wells with sufficient data to analyze have had TCE decreased by about half in ten years.

downgradient end of that pathway, so it remains poorly defined. There are fewer monitoring wells deeper in the bedrock, but the higher concentrations there suggest the pathway occurs at depth as well. TCE is almost nondetect north of Lancaster Blvd at shallow levels suggesting the source does not contribute to flow in that direction.

DNAPL is probably the source of very high TCE in wells under the northwest and northeastern portions of Building 8 (RIR Figure 30B). This high TCE deep in the bedrock is isolated, being several orders of magnitude higher than in other nearby deep bedrock wells. It is probably bound in the bedrock and slowly dissolving into the groundwater. The slow movement of groundwater at depth allows the concentration to become very high. There is insufficient well density, however, to know whether preferential flow causes some TCE to move substantially from the source, however it could be part of the fracture trace discussed in the previous paragraph. For example, MW44C had TCE 694 and 646 ug/ in 2017, but it appears to be downgradient of MW43C which had TCE equal to 27 ug/l; this suggests there could be very narrow pathways for TCE to move from DNAPL sources downgradient.

The summary is that onsite wells, both shallow and deep, have remained stable but with distance from the source, TCE has been decreasing with time. The exception is the apparent preferential pathway heading northeast from the site. The soil source continues to leach sufficient TCE to keep TCE under the site high. The source is not sufficient to sustain the level of load leaving the site as has been observed in the past and natural attenuation is decreasing concentrations far from the site. At depth, DNAPL continues to dissolve supporting very high TCE concentrations at the site and a continuing source for transport downgradient. However, some TCE continues to move further from the site, so while concentrations within the plume decrease, TCE continues to flow further downstream.

- The trends in TCE and other contaminants continue to be a potential threat to human health and the environment.
- Additional monitoring wells should be constructed along a apparent pathway northeast of the site, as discussed in this section, to more fully identify the plume and its trend with time.

Surface Water Trends

Groundwater at the Bishop Tube site eventually discharges to surface water. Most critically, shallow groundwater discharges to and supports the LVC tributary just east of the site and to a ditch that bounds the north side of the site and flows east. Figure 40 in the RIR shows 2014 sampling results for the stream and a few nearby springs. The highest TCE concentrations are near the site, but they are detectable as far as a site beyond Conestoga Ave (SW-11).

Concentrations decrease going downstream, as noted in the RIR (p 77), but this reflects the dilution that comes with flow from unaffected areas. The TCE mass could have increased if there are TCE discharges into the stream below the site. Springs along the creek to as far as SP-5, east of South Morehall Road, have positive concentrations which indicates that TCE in the groundwater contaminate the creek for a long distance from the site. The groundwater TCE contours do not extend as far as this spring.

- Concentrations of TCE and other contaminants remain sufficiently high to constitute a potential threat to human health and the environment.
- The RIR should analyze load in the creek rather than simply concentration. Load would allow a better assessment of the location TCE-laden groundwater enters the creek.

The 2015 RIR presents a time series of data at SW-4 and SW-5 through 2014 and the current RIR adds more recent data that shows concentrations have substantially decreased since 2003. The data is not controlled for flow which could cause the concentrations to fluctuate due to the amount of dilution. However, the trend is for decreasing values. The most recent dry season value, September 2018, is the lowest compared to previous samples (the November 2018 value is a wet period and therefore more diluted). With five observations showing a consistent downward trend at two locations most likely to be affected by groundwater discharge from the site, the surface water concentrations reflect the observed groundwater concentrations with a general downward trend. However, analyzing the load would be a better assessment.

Remediation

Roux assumes the property would be developed for nonresidential uses only (RIR p 3, FS p 2), even though it has been rezoned for residential use and current development plans are for residential development (FS p 10). This means the clean-up standards are different. The analysis uses the nonresidential use assumption to claim that “current exposure pathways” (FS p 4) do not cause a risk to “any existing receptors or the LVC tributary” (Id.). The no residential use standard therefore allows the analysis to consider less remediation. The RIR therefore fails to describe the extent of the needed remediation and the FS fails to identify strategies based on the actual site requirements.

The only pathway discussed for future residential development is vapor intrusion, for which there is an assumption that “pathway elimination measures” will protect the residents (FS 39); there is no analysis of these practices, and no analysis of the current residential plans to determine whether they incorporate any such measures. Groundwater exposure would be minimized by institutional controls rather than by treatment to residential standards.

- The FS should analyze the pathways from the nonresidential groundwater to surface water or downgradient residential water.

Because the site is abandoned and not being used, the analysis identifies "no current unacceptable human health or ecological risk" (FS p 5). The FS then implies that remedial actions could make the site worse (Id.) which allows Roux to imply current conditions are better than conditions that could occur due to remedial actions. Antidegradation standards could be violated if treatment of shallow groundwater near the creeks could contaminate the creeks (Id.).

- The FS should identify actions to prevent degradation of the streams. This could include shallow groundwater interception systems, such as horizontal wells, to prevent liberated constituents from reaching the streams.

DNAPL has been designated as technically impractical to remove due to its depth in fractured bedrock (FS p 6). Specifically, its high specific gravity (it is heavier than water so it sinks), the reduction in fracture frequency and connectivity, decreasing fracture transmissivity, and matrix diffusion limits the vertical movement of DNAPL (Id.). Matrix diffusion would mean that DNAPL has entered the pore spaces of the rock including the bulk media, from which it could diffuse into groundwater for as long as it remains. Because it is below the water table, in rock and at depth, the analysis assumes there is no direct exposure pathway for DNAPL from bedrock, the analysis declares it is technically impractical to remove it.

- If DNAPL remains in place, it will remain a source of TCE to deep groundwater. The FS should analyze the discharge point for the deep groundwater and assess the effects of that TCE on the discharge point.

The FS considers seven alternatives for remediation, including no action (1), monitored natural attenuation (MNA, 2), in-situ chemical reduction (ICR, 3), in-situ chemical oxidation (4), enhanced reductive chlorination (5), two-part in-situ chemical oxidation (6), and hydraulic control (HC, 7). MNA is basically just monitoring the on-going natural attenuation. It depends on the continuing decrease of TCE concentrations. It also relies on the source in the soils decreasing or being eliminated, although it could also allow for the source to totally leach out. Roux predicts it would require more than 30 years.

Alternatives 3 through 6 involve injection of various chemicals to cause the TCE and other contaminants to degrade or decay. Alternative 7, HC, would prevent the offsite movement of contaminants and will be discussed below. The injection alternatives would substantially speed

remediation as compared to MNA because it would hasten the breakdown. For this reason, they have substantial advantages.

Alternatives 3 through 6 involve injection and have implementability issues, as described in the FS:

> Injection of large quantities of amendments in immediate proximity to the LVC tributary (and its related wetlands) also poses significant implementability concerns (e.g., human health and/or ecological risks that do not currently exist). Other implementation concerns include a) dissolution of adsorbed-phase COCs and an increase in the rate of discharge or migration of these COCs, b) discharge of the amendments themselves into the adjacent stream, c) injection measures could modify the groundwater flow (and COC transport) conditions and cause undesirable conditions such as creation of VI exposure routes that do not currently exist, d) injection measures could cause COCs or the amendments themselves to discharge at land surface (i.e., "day-lighting"), e) ineffective delivery of the amendment to the desired treatment intervals, f) loss of amendment to less-impacted but more transmissive bedrock fractures (i.e., not the desired fracture network where high CVOCs are located), g) loss of amendment to subsurface infrastructure (e.g., the abandoned AS/SVE piping network), h) rebound effects after treatment including anticipated matrix back diffusion, and i) amendments meant to treat inorganic COCs in groundwater will not treat fluoride. A pre-design injection testing program and associated monitoring would be required to ensure implementability and to optimize the potential injection program design. (FS, p 137)

The first four implementability issues are legitimate from a hydrogeologic perspective. Because the remediation strategies would hasten recovery, the FS should consider strategies for mitigating the implementability issues.

- Injection in shallow groundwater, either overburden or shallow bedrock, could dissolve adsorbed COCs and increase their movement in the groundwater in a way that causes them to discharge to LVC. However, the FS should consider ways to capture the liberated COCs before they reach the stream. Shallow, horizontal collection wells would be one means.
- Too much injection could cause the groundwater table to rise and daylight to the ground surface, including to the wetlands between the site and LVC tributary east of the site. Shallow collection wells, possibly horizontal, could prevent the surfacing of groundwater.

- Alternative 3, ICR, could be used but with a different layout of injection. The primary concern could possibly be eliminated by removing the easternmost portion of the GW-1A treatment area. This area is closest to the LVC tributary and would be most likely to cause discharge to the creek. ICR in the western portion of the site conceivably could cause discharge to the drainage ditch just north of the site, but close monitoring of groundwater levels should prevent that. Groundwater would flow beneath the ditch and to the northeast as currently occurs. Decreasing the injection flow rate could prevent such discharge. Thus, an alternative should be considered that has less ICR to avoid discharge to surface water and still get much of the advantage of enhanced attenuation.

Alternative 7, HC, attempts to prevent the offsite movement of contaminants by creating a line of low water levels which would create a capture zone for groundwater flowing from the site. Wells implementing HC should be developed in various aquifer levels because there appears to be little flow among aquifer levels. For example, there is no evidence that pumping in the shallow bedrock would draw groundwater from the overburden or from all levels of shallow bedrock. Intercepting groundwater flowing to LVC would cause stream baseflow to be less and could dry up the stream. Lowering water levels in the overburden could also dry groundwater dependent wetlands.

- Roux should consider an additional alternative that would combine an injection alternative with an HC alternative. A line of collection wells downgradient of a system of injection wells could prevent the unwanted products of injection from reaching the streams or wetlands. Detailed monitoring of stream flows and water quality changes during the treatment process would also be necessary to prevent impacts to LVC.
- HC should also be considered to intercept the preferential flow moving through the fracture zone northeast from the site from about wells MW-51 and MW-79 through wells MW-44 and MW-47. HC should be considered at all levels, including deep bedrock. Intercepting transport in the deep bedrock could be the best means of capturing TCE that may be emanating from DNAPL trapped deep in the bedrock.

Groundwater Fate and Transport Model

Roux complete a simple, two-dimensional groundwater flow and transport model to generally fill in the 5 ug/l contour in the plume mapping; the discussion is included in RIR Appendix S. The description is incomplete, and assumptions are necessary to understand how the modeling was completed. The page references in this section are to the model report in Appendix S unless otherwise stated.

Roux used the WinFlow/WinTran code to simulate a two-dimensional model of the shallow groundwater. The flow model WinFlow is analytic which means it relies on solutions of the differential equations so can accommodate only very simplified representations of the domain. WinFlow describes a flow field based on a grid over the domain. The model outputs water level and flow rates for any chosen point in the flow field. Roux's description is confusing because it can be confused with models that use a grid-based finite difference solution.

- Roux should provide a better description of how the flow field is developed and how the grid was chosen. In particular, the exact location and specifications for the grid should be explicitly provided.

The flow field is steady state which means that seasonal changes in the water level due to recharge events cannot be considered. Wet and dry season discharges to the streams cannot be considered, for example.

The transport model uses a finite element solution based on the steady state flow solution on the grid. The transport model is transient for contaminant but cannot consider temporal changes in recharge rates. In Roux's modeling, it only considers the movement of a plume described with initial conditions through the domain. No sources can be incorporated.

Roux calibrated the model to the 2014 observed TCE concentrations and simulated four years to 2018 for verification. Roux claims the verification shows that simulated concentrations match observed concentrations, but there is little evidence of this in the report. However, the parameters, other than decay rate, used are not the primary problem with the modeling.

Roux hypothesized a model thickness to be 500 feet (p 6) but the actual simulated thickness is less than that (and very poorly described by Roux). The model top and bottom were set equal to 500 and -100 feet (p 7), but the constant head boundary at the upgradient end was set equal to 390 feet. At this boundary, the thickness would be 490 feet. Water level at the downgradient end is not specified, but the report sets a gradient equal to 0.019 ft/ft (p 8), so with an aquifer length of 6000 feet, the groundwater level would be 276 feet, so the thickness reduces to 376 feet, assuming the aquifer bottom elevations are constant throughout the domain. The reducing thickness means the transmissivity decreases with length along the flow paths, but the flow velocity may not change because groundwater would discharge to the line sink boundary on the north of the domain.

- There is no justification for the model to simulate a 390-foot aquifer because the fractures at depth prevent most flow below 200 to 250 feet below ground surface.

The model assumes the aquifer is homogeneous, so the same parameters describe its entire thickness, which is as much as 390 feet. Roux provides substantial evidence that this is poor conceptual modeling but does it regardless. Specifically, the pores and permeability decrease with depth in bedrock, so conductivity also decreases as noted by Roux (p 3). The parameters were based on shallow bedrock, so at depth the parameters describe media that is more porous than reality and therefore cause the model to simulate more flow at depth than really occurs. Second, Roux notes that high TCE concentrations at depth do not represent a flow path because the fractures are discontinuous and do not represent a long-range flow path (p 3). There is "no expectation that the deep bedrock interval will produce higher groundwater velocities or a longer CVOC plume when compared with the shallow interval" (p 3, 4).

Roux claims it is conservative to treat the entire aquifer thickness with the parameters as described for shallow bedrock:

> Therefore, the fate and transport analysis focuses (sic) on the shallow bedrock conditions, thereby presenting a conservative/protective evaluation for all depth intervals. The entire vertical thickness of the affected bedrock aquifer was assigned the characteristics of the shallow bedrock interval as a conservative measure regarding TCE fate and transport analysis. (p 4)

This is not conservative because, being 2-d, the model assumes that concentration is the same throughout the layer thickness. As contaminants enter a section of the domain, the model assumes that the concentration is spread evenly through the layer. TCE load that would otherwise be near the surface would be simulated at depth. The monitoring wells with multiple sampling portals show substantial variation with depth, so this is not correct. In some areas, TCE is higher in the overburden and other areas the higher concentrations occur at depth, so the model is an oversimplification.

Also, the higher flow velocities modeled at depth would allow the model to move contaminant load away from the project domain faster than occurs in reality. Predictions would be for faster attenuation as a result. Roux does not calibrate for changing TCE with time.

Roux cites the Sloto (1990) analysis as justification for using a 2-d analysis. There are two problems with this. First, Sloto's analysis occurred in 1992 when the ability for models to simulate two or more layers was much less than it is currently because of the lesser computer power. Second, and more important, Sloto described a regional model where the details of local flow were less important. And, Sloto's model was for flow only; the effect of vertical gradients on transport was less. Furthermore, there was already available a model for the site using multiple layers (Baker, 2004) that Roux could readily have adapted.

Vertical gradients are ignored in a one-layer model. Roux dismisses this by stating that vertical gradients are local (p 3), but this is exactly the point. The model cannot simulate the variable vertical flow which would affect the distribution of contaminants. This assumption is most problematic near the stream where there is evidence for upward gradients and flow into the stream. This could cause the model to underestimate discharge of contaminants into the stream.

- Roux should complete a three-dimensional flow/transport model to accommodate the issues regarding homogeneity and the lack of vertical flow. Calibration data should not be limiting because many of the wells have multiple ports
- If the choice was made to continue with just a 2-d model, the thickness should be no more than about 120 feet because of the lower permeability at depth. A common rule of thumb in numerical modeling is that the flow in a media with conductivity two orders of magnitude lower is sufficiently small that it can be considered a no flow boundary.

The model ignores recharge that occurs across the site by assuming all flow enters at the constant head boundary (p 7). The model does not consider that about 15 in/y enters the top of the domain and therefore ignores a source of dilution. Rather than making the model conservative, the failure to consider recharge causes the calibration to adjust other parameters to match the observed conditions.

- The model should be redesigned to consider dilution from natural recharge

Boundaries provide flow sources and sinks to the model and partially control the groundwater level, but Roux describes them poorly. At the upgradient end, the boundary is a constant head set at 390 feet. Roux states the 390 feet is at a point, but a CH boundary is along the edge of the model domain so is actually a line. Roux should improve the description. Roux describes a CH as an infinite source of water, which is correct, but the flow rate is controlled by the gradient in the model and the conductivity of the media (based on Darcy's law).

The other described boundary is a line sink for LVC and its tributaries, which Roux describes as representing "a portion of LVC and its tributaries that has gaining conditions between Conestoga Road and Morehall Road" (p 7). This indicates that the model does not simulate discharge to the LVC tributary on the east side of the site or the gaining reaches upstream of Conestoga Road. Although this allows TCE to pass further in the model, it fails to simulate the concentrating effect of having TCE-laden groundwater converge on the creek.

A line-sink boundary simply accepts groundwater discharge from the domain. The boundary would have an elevation which would control the downgradient elevation and hence the

gradient through the model. Roux claims that LVC and tributaries are simulated with line-sink boundaries and Figure S-1 shows the stream and tributaries which could receive groundwater discharge, the description appears to allow only discharge downgradient of Conestoga Road (p 7). With the constant head boundary at the upgradient end, the boundaries impose a simplistic control on the flow through the aquifer, preventing flow from converging to the streams within the domain, such as the tributary just east of the site. This may prevent the stream from simulating hot spots of TCE concentration.

LVC has reaches from which water discharges into the groundwater, so a boundary that can act only as a sink is not appropriate. The proper boundary for this simulation would be one that both receives and provides groundwater and contaminants to the aquifer. This would be similar to a STREAM boundary in MODFLOW/MT3DMS.

Also, Roux considers it "conservative" to simulate the line-sink as receiving "discharge from shallow bedrock to LVC and its tributaries of approximately 75 gallons per minute over a length of approximately 2,500 feet" as compared to measured 237 and 171 gpm during previous surveys (p 7). Since this is the only outflow from the model domain, it causes flow and advection to occur slower, but it also allows more TCE to decay before it reaches downgradient portions of the domain. It would cause the model to simulate less TCE transmission off the site and constrain simulated future TCE contours.

Transmissivity changes through the model domain as the saturated thickness decreases. Because the line sink boundary borders the northern portion of the domain, the decreasing transmissivity would direct groundwater toward the boundary. However, decreasing the transmissivity must also increase the gradient to allow groundwater to flow through the domain cross-section. This means the Darcy flow velocity (flow rate over the entire cross-sectional area) must increase. This would increase the rate that contaminants transport by advection through the domain and from the model.

The model simulates flow that cuts across the regional potentiometric surface contours, which run generally east-west and show a north-south gradient of 0.05 to 0.04 ft/ft. Roux shifted the grid 32 degrees north of east to align with the flow/transport axis surmised from the TCE contour maps, and create a gradient of about 0.023 ft/ft, later calibrated to 0.019 ft/ft based on matching groundwater levels at various wells. That groundwater flow does not follow the steeper regional gradient demonstrates the control exhibited by fractured rock. The horizontal conductivity is highly anisotropic, which means the conductivity along the flow path (at a 0.019 ft/ft gradient) is much higher than the conductivity in another direction. This is a major reason that the simplifying assumptions used in this model are inappropriate.

Many of the simplifications critiqued above led to an absolutely horrid calibration for the model. Roux used just 14 monitoring wells for calibration (p 8) and the statistics show the fit is very poor. The standard deviations and sum of squares are very high for a domain with such a small elevation range. The maximum absolute residual is about 28% of the total potentiometric head difference, a very high number (p 9). Although there is no "standard" for an acceptable model, 10% is often considered a decent fit. The reason for the high scatter of residuals is the model effectively tried to fit a flat surface (a plane based on one parameter set) through a curvilinear surface (the reality of a nonhomogeneous aquifer).

The model simulates concentration in three ways. It starts with an initial concentration, which is the observed concentrations from the 2012-14 contour mapping. Contaminants flow with the steady state groundwater flow and undergo dispersion, degradation, and retardation.

The model does not simulate TCE sources to the model domain. The mass initially present (as initial concentrations) is the only mass simulated as flowing through the system. It is effectively a slug of contaminant present throughout the aquifer at a given initial time. The model then advects and disperses contaminants through the aquifer and removes contaminants either by degradation processes or by discharging them into a boundary sink. For any future predictions, the model assumption is that sources in the unsaturated soils have been removed, and no leaching occurs from TCE adsorbed to soil or from non-aqueous phase TCE. The simulated graphs of monitoring well concentration show the movement of a slug of TCE passing through the system rather than a source providing TCE to the system.

There are two ways that TCE mass is removed from the model domain. One is for it to discharge into the line sinks that simulate LVC and its tributaries. Roux does not report the amount that leaves the domain through the boundaries but should so it can be compared to measured values for calibration. Most of the TCE likely does not discharge in this way and therefore remains within the domain after adsorbing or disappears after decaying, the second way TCE is removed from the domain.

- The report should include a hydrograph of mass simulated as leaving the domain through the boundaries, the mass adsorbed to aquifer media, and the mass that decays.

A half-life controls the rate that TCE decays within the domain. This means that half of the mass disappears in that time period (the model does not consider its fate, so "disappears" is the proper descriptor). Even without advective transport removing mass from the domain, the simulated concentrations would decrease by half over that period. Roux used a decay half-life of 2200 days based on decay rate constants of 30 site monitoring wells. The wells chosen to estimate half-life had a minimum of 4 observations over at least 4 years and a decreasing

concentration which shows evidence of attenuating TCE (p 10, 11). Numerous factors cause the TCE concentration to decrease at a site which, in addition to degradation, include mass transport from the area, dilution and retardation. Not accounting for these factors could lead to estimating a faster decay than really occurs. Treating mass transport, dilution, and retardation as decay biases the decay calculations.

- The RIR should account for other factors controlling the apparent decrease in TCE at a well.

Retardation is the process that the contaminant moves much slower it would if controlled simply by advection, or transport with the flow of groundwater. Dispersion through pore spaces and adsorption to aquifer particles contributes to retardation (Fetter 1999). Roux notes that retardation varies with depth at Bishop Tube because in fractured rock retardation increases in areas with lower fracture density (p 13). Adsorption and the process of a contaminant being bound in fractures would also contribute to estimated decay, so Roux's model double counts the effects of retardation; it withdraws mass from the plume inappropriately fast. Roux calibrated the model by adjusting the retardation coefficient and comparing the evolution of concentration with time. Degradation affects the observed concentrations, so calibration also causes the model to double count retardation.

- Calibration using the retardation coefficient must be redone to remove the effects of degradation so that the model does not double count some of the contaminant removal.

Calibration of the transport parameters by adjusting parameters so that simulated concentrations approximate the observed concentrations yields parameters based on there being no source of TCE to the groundwater, which is simply incorrect. Observed TCE concentration graphs show temporally variable values that reflect recharge events contributing TCE to the groundwater. The simulated concentrations often rise and fall in a steady pattern, but the observed concentrations appear mostly random in comparison. An obvious reason is that the sources continue to leach TCE which affects the observed TCE concentrations; observed TCE increases rapidly in response to a TCE recharge event. Without simulating the sources leaching contaminant into the groundwater, the calibrated parameters are meaningless.

- Calibration of the model should occur only if the rate and location that TCE is added to the domain can be estimated. Otherwise the calibrated parameters are meaningless.

The graphs of simulated concentration at various monitoring wells and hypothetical monitoring points demonstrate that the model simply advects TCE from the domain into the boundaries. For example, TCE at MW-51, which lies about 500 feet northeast of Building 8, starts at near 100,000 ug/l, which is about 70% of the actual observed value, decreases rapidly to about 12,000 ug/l by 2025 and approaches zero by 2035. Considering that this monitoring well has had high values for a couple decades, Figure S-3 demonstrates what would occur only if the sources are removed. A similar trend occurs for MW-15, which lies about 150 feet north of Building 8; a difference is that TCE increases in the simulation for the first few years from its initial (currently observed) values. Advection of the higher concentrations under the building causes the initial increase; after the mass passes, TCE concentration decreases rapidly because there is no source adding TCE to the system.

- The model should be redone to include TCE sources so that predicted future concentrations will be more accurate. This would allow a comparison of future remediation strategies with varying source clean-up.

Not surprisingly, the model was most sensitive to hydraulic conductivity. Multiplying the 1.1 ft/d value by 5 caused the model to move the plume faster which allows more mass to flush faster. It also causes higher downgradient concentrations (p 17). Higher conductivity would allow TCE to move from the site faster, before it decays or has the chance to be retarded. It could cause more contamination further offsite and faster than currently simulated or assumed. This is another reason to better understand the conductivity including the horizontal anisotropy.

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Curriculum Vitae

Objective: To provide diverse research and consulting services to nonprofit, government, legal and industry clients focusing on hydrogeology specializing in mine dewatering, contaminant transport, natural gas development, groundwater modeling, NEPA analysis, federal and state regulatory review, and fluvial morphology.

Education

Years	Degree	University
1992-96	Ph.D. Hydrology/Hydrogeology	University of Nevada, Reno Dissertation: Stochastic Structure of Rangeland Streams
1990-92		University of Arizona, Tucson AZ Classes in pursuit of Ph.D. in Hydrology.
1988-90	M.S. Hydrology/Hydrogeology	University of Nevada, Reno Thesis: Stream Morphology, Stability and Habitat in Northern Nevada
1981-83		University of Colorado, Denver, CO Graduate level water resources engineering classes.
1977-81	B.S., Civil Engineering	University of Colorado, Boulder, CO

Professional Experience

Years	Position	Duties
1993-Pr.	Hydrologic Consultant	Completion of hydrogeology studies and testimony focusing on mine dewatering, groundwater modeling, natural gas development, contaminant transport, NEPA review, and water rights for nonprofit groups and government agencies.
1999-2004	Great Basin Mine Watch, Exec Director	Responsible for reviewing and commenting on mining projects with a focus on groundwater and surface water resources, preparing appeals and litigation, organizational development and personnel management.
1992-1997	Univ of NV, Reno, Res. Assoc.	Research on riparian area and watershed management including stream morphology, aquatic habitat, cattle grazing and low-flow and flood hydrology.
1990-1992	U of AZ, Res. and Teach. Assistant	Research on rainfall/runoff processes and climate models. Taught lab sections for sophomore level "Principles of Hydrology". Received 1992 Outstanding Graduate Teaching Assistant Award in the College of Engineering
1988-1990	U of NV, Reno Res. Asst	Research on aquatic habitat, stream morphology and livestock management.
1983-1988	US Bureau of Reclamation Hydraulic Eng.	Performed hydrology planning studies on topics including floodplains, water supply, flood control, salt balance, irrigation efficiencies, sediment transport, rainfall-runoff modeling and groundwater balances.

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Special Coursework

Years	Course	Sponsor
2011	Hydraulic Fracturing of the Marcellus Shale	National Groundwater Association
2008	Fractured Rock Analysis	MidWest Geoscience
2005	Groundwater Sampling Field Course	Nielson Environmental Field School
2004	Environmental Forensics	National Groundwater Association
2004 and -5	Groundwater and Environmental Law	National Groundwater Association