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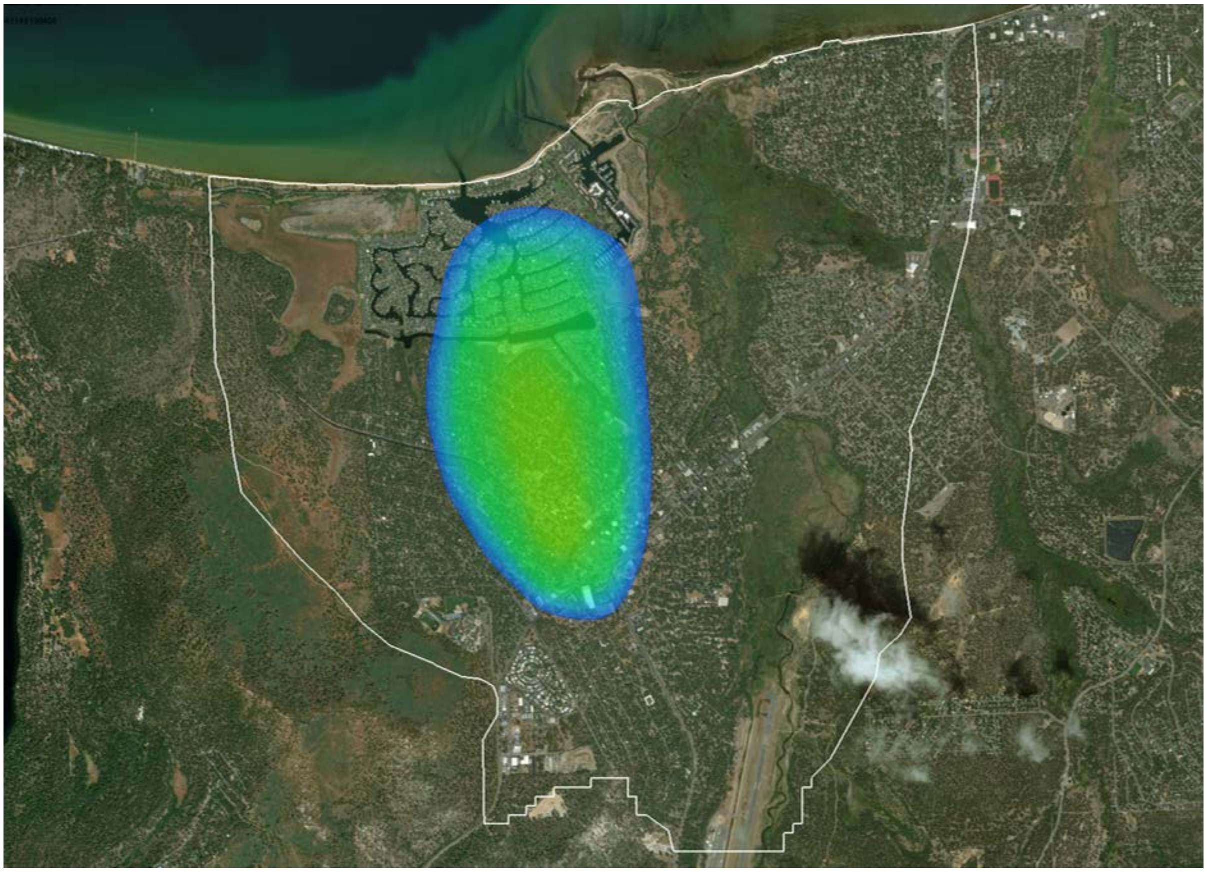
Fate and Transport Modeling of the South Y PCE Groundwater Contamination Plume - Addendum



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Introduction

The South "Y" Area is named for the intersection of California State Highway 89 and U.S. Highway 50, located within the north-central part of the Tahoe Valley South Sub-basin (TVS Basin). Chlorinated hydrocarbons (tetrachloroethylene or PCE) have been detected in water supply wells north and south of the South Y Area since 1989, when these compounds were first required to be tested in regulated drinking water sources. Many of the supply wells have since ceased operating due to PCE concentrations exceeding the drinking water standard of 5 micrograms per liter (µg/L).

In partnership with Lukins Brothers Water Company (LBWC) and Tahoe Keys Water Company (TKWC), South Tahoe Public Utility District (STPUD) contracted with Kennedy Jenks Consultants (KJC) to conduct a feasibility study of remedial alternatives to continue to provide clean water supplies while removing the PCE groundwater contamination plume from the South Y Area. To aid in this effort, a series of potential management scenarios were tested in a calibrated numerical flow and transport model. The results of these simulations were published in Rybarski et al., 2019. Based on the response of stakeholders, two additional management scenarios have since been proposed for simulation. This report details the results of these simulations, as well as assessing the potential placement of six sentinel well locations intended to act as an early warning system for plume encroachment on key production wells in the area. Additionally, this addendum provides a response to questions posed by stakeholders following the publication of the initial report.

Management Scenarios

Following a review of the simulation results presented in Rybarski et al., 2019 and after receiving feedback from stakeholders, two additional management scenarios were proposed based on the Targeted Pumping (Alternative 2) scenario described in the initial report. Though the intent of these scenarios is the same as in the Targeted Pumping scenario, pumping rates have been adjusted to reduce the role of TKWC 2 in PCE mass removal and plume migration control.

1) Alternative 2, Option 1 – this alternative serves to identify the benefit of using LBWC 5 as the lead well for hydraulic control and PCE mass removal, as this well is positioned near the simulated center of mass of the plume. Increased pumping at this well is intended to remove mass from the system as well as limit potential plume migration towards TKWC 1, TKWC 3, and LBWC 1. Produced water from LBWC 5 is planned to be treated via a granular activated carbon (GAC) system. Simulation is run 50 years into the future (2068 WY).
2) Alternative 2, Option 2 – this alternative serves to identify the benefit of adding a new extraction well at 843 Hazel Drive (LBWC 4 site) for plume control and PCE mass removal. Aside from the addition of this extraction well, all other pumping rates are identical to Option 1. Simulation is run 50 years into the future (2068 WY).

For both of the proposed alternatives, two simulations were run – one using all calibrated model properties, and one conservative simulation. The calibrated scenario, details of which are provided by Rybarski et al. (2019) is based on a best fit between simulated and observed PCE concentrations at a range of locations, whereas the conservative simulations are intended to simulate a worst-case scenario. For the conservative simulations, the PCE source term is maintained at a recharge concentration of 10 mg/l for the duration of the model (as opposed to returning to zero in the calibrated simulations) and no biogenic decay is simulated (as opposed to half-lives of 17 years in layers 1 and 2, and 2 years in layers 3 and 4 in the calibrated simulations). Pumping rates, PCE source term definition, and biogenic decay rates by layer for each alternative and hypothetical scenario are listed in Table 1 and Table 2. For comparison, the Base Treatment scenario (Alternative 1) described in Rybarski et al., 2019 is included in these tables, as well as in all results summaries, though this scenario is not described in detail in this addendum.

Sentinel Wells

Six sites have been proposed for construction of sentinel wells, located generally between active production wells and the inferred extent of the PCE plume, with the exception of SW6, which was situated within the plume, upgradient of TKWC1. The sentinel wells are proposed to provide early detection of increasing concentrations and monitor potential movement of the contaminant plume towards these active wells. A combination of reverse and forward particle tracking was used to assess the capture area of the four production wells under observation (Bayview, TKWC 1, TKWC 3, and LBWC 1) and the travel time between each sentinel well and their respective production wells.

Particle tracking simulations were run using MODPATH, a particle-tracking post-processing program designed to work with MODFLOW (Pollock, 2016). Reverse particle tracking was assessed at each of the four production wells in question over a 20 year period. Forward tracking was assessed from each of the sentinel well locations from the beginning of the 2019 water year through the end of the 2068 water year, or until particles reached the associated production well.

Results

Described here in detail, results for both alternative options are tabulated in Table 3 and Table 4 (mass removed by well and alternative, and years to PCE concentrations less than 4 µg/l, respectively).

Alternative 2A, Option 1

Transport model results for the 2068 WY indicate that the majority of mass will have either decayed or exited across the northern boundary of the model domain towards Lake Tahoe. While a small area at the northern boundary of the model domain show detectable (greater than 0.5 µg/l) concentrations of PCE in layers 1 and 2 (Figure 1-Figure 2), no concentrations exceed detection limits in layers 3 and 4. Concentrations for this stress period do not exceed the maximum contaminant level (MCL) anywhere within the model domain.

Prior to the 2068 WY, concentrations of PCE at TKWC 2 (Figure 4) and LBWC 5 (Figure 7) meet or exceed the MCL of 5 µg/l for 32 and 36 years, respectively, while concentrations at LBWC 1 (Figure 6) and TKWC 3 (Figure 5) never exceed the detection limit of 0.5 µg/l. This represents a minor but notable change relative to the Base Treatment scenario described in Rybarski et al. (2019), where concentrations at TKWC 3 were seen to slightly exceed the detection limit of 0.5 ug/l. Concentrations at TKWC 1 exceed the detection limit for 57 years, but never exceed the MCL (Figure 3). LBWC 5 reaches a maximum concentration of 22.3 µg/l in 2019, and declines to below 4 µg/l in 2038. TKWC 1 reaches a maximum concentration of 4.5 µg/l in 2034, and declines to below 4 µg/l in 2041. TKWC 2 reaches a maximum concentration of 13.2 µg/l in 2021, and declines to below 4 µg/l in 2039. These results indicate that given the pumping rates assigned in this scenario, concentrations are unlikely to increase substantially in the near future, though they could remain above the MCL for the next 20-25 years. At no time during this simulation did the prescribed pumping rate exceed the design flow of the GAC water treatment system for PCE removal at TKWC 2 (550 gpm). The simulated PCE concentrations and pumping rate did not exceed the engineering design flow (1,000 gpm) and maximum influent concentration (PCE = 300 µg/l) used to size the planned GAC water treatment system for PCE removal at LBWC5 (RCI, 2015).

Alternative 2B, Option 1 (Conservative)

Transport model results for the 2068 WY indicate that a large quantity of mass will remain in the system at this time. Simulated concentrations exceed 100 µg/l at the simulated source in layer 1, and exceed 50 µg/l near the northern model boundary in layers 1 and 2 (Figure 8-Figure 9). Likewise, simulated concentrations exceed 10 µg/l in layers 3 and 4 (Figure 10-Figure 11) at the northern model boundary. It should be emphasized that this scenario was simulated for the purpose of creating a worst-case result, with a constant input from the source continuing for the duration of the model and with no biogenic decay, and that the results of this simulation are not consistent with observed concentrations, with the exception of LBWC 1 and TKWC 3 where simulated concentrations remain below detection limits through the present.

Like Alternative 2A, Option 1, simulated concentrations at LBWC 1 (Figure 15) and TKWC 3 (Figure 14) remain below detection limits for the duration of the simulation. Concentrations at TKWC 1 (Figure 12) and TKWC 2 (Figure 13) remain greater than 4 µg/l for the duration of the simulation, reaching maximum concentrations of 44.9 µg/l in 2038 and 106.4 µg/l in 2022, respectively. LBWC 5 (Figure 16) reaches a maximum concentration of 94.0 µg/l in 2019, declining to below 4 µg/l in 2058. At no time during this simulation did the prescribed pumping rate exceed the design flow of the GAC water treatment system for PCE removal at TKWC 2 (550 gpm). The simulated PCE concentrations and pumping rate did not exceed the engineering design flow (1,000 gpm) and maximum influent concentration (PCE = 300 µg/l) used to size the planned GAC water treatment system for PCE removal at LBWC5 (RCI, 2015).

Alternative 2A, Option 2

Transport model results for the 2068 WY indicate that the majority of mass will have either decayed or exited across the northern boundary of the model domain towards Lake Tahoe. While a small area at the northern boundary of the model domain show detectable (greater than 0.5 µg/l) concentrations of PCE in layers 1 and 2 (Figure 17-Figure 18), no concentrations exceed detection limits in layers 3 and 4. Concentrations for this stress period do not exceed the MCL anywhere within the model domain.

Prior to the 2068 WY, concentrations of PCE at TKWC 2 (Figure 20) and LBWC 5 (Figure 23) meet or exceed the MCL of 5 µg/l for 29 and 31 years, respectively, while concentrations at LBWC 1 (Figure 22) and TKWC 3 (Figure 21) never exceed the detection limit of 0.5 µg/l. Concentrations at TKWC 1 exceed the detection limit for 52 years, but never exceed the MCL (Figure 19). LBWC 5 reaches a maximum concentration of 21.1 µg/l in 2016, and declines to below 4 µg/l in 2033. TKWC 1 reaches a maximum concentration of 3.7 µg/l in 2029. TKWC 2 reaches a maximum concentration of 13.1 µg/l in 2021, and declines to below 4 µg/l in 2036. These results indicate that given the pumping rates assigned in this scenario, concentrations are unlikely to increase substantially in the near future, though they could remain above the MCL for the next 20-25 years. At no time during this simulation did the prescribed pumping rate exceed the design flow of the GAC water treatment system for PCE removal at TKWC 2 (550 gpm). The simulated PCE concentrations and pumping rate did not exceed the engineering design flow (1,000 gpm) and maximum influent concentration (PCE = 300 µg/l) used to size the planned GAC water treatment system for PCE removal at LBWC5 (RCI, 2015).

Alternative 2B, Option 2 (Conservative)

Transport model results for the 2068 WY indicate that a large quantity of mass will remain in the system at this time. Simulated concentrations exceed 100 µg/l at the source in layer 1, and exceed 50 µg/l near the northern model boundary in layers 1 and 2 (Figure 24-Figure 25). Likewise, simulated concentrations exceed 10 µg/l in layers 3 and 4 (Figure 26-Figure 27) at the northern model boundary. It should be emphasized that this scenario was simulated for the purpose of creating a worst-case result, with a constant input from the source continuing for the duration of the model and with no biogenic decay, and that the results of this simulation are not consistent with observed concentrations, with the exception of LBWC 1 and TKWC 3 where simulated concentrations remain below detection limits through the present.

As in all three previously described scenarios, simulated concentrations at LBWC 1 (Figure 31) and TKWC 3 (Figure 30) remain below detection limits for the duration of the model. Concentrations at TKWC 1 (Figure 28) remain greater than 4 µg/l for the duration of the model, reaching a maximum concentration of 37.9 µg/l in 2035. TKWC 2 (Figure 29) reaches a maximum concentration of 103.2 µg/l in 2021, declining to below 4 µg/l in 2062. LBWC 5 (Figure 32) reaches a maximum concentration of 89.4 µg/l in 2018, declining to below 4 µg/l in 2046. At no time during this simulation did the prescribed pumping rate exceed the design flow of the GAC water treatment system for PCE removal at TKWC 2 (550 gpm). The simulated PCE concentrations and pumping rate did not exceed the engineering design flow (1,000 gpm) and maximum influent concentration (PCE = 300 µg/l) used to size the planned GAC water treatment system for PCE removal at LBWC5 (RCI, 2015).

Sentinel Wells

Reverse particle tracking results over a 20 year time period are shown in Figure 35, with pathlines marked at 5-year intervals. Of the six potential sentinel well sites, three fell outside the capture zone of their respective production wells – SW 4 and SW 5 (LBWC 1) and SW 2 (Bayview). Simulated travel times from the remaining three sentinel wells to their respective production wells ranged from 176 to 1871 days (0.48 to 5.1 years) and are detailed in Table 5. Forward particle tracking pathlines for all six sentinel wells are shown in Figure 36.

It is important to note that the particle tracking results presented here are derived from the MODFLOW simulation results only, and do not include transport effects simulated by MT3DMS (sorption, decay, and dispersion). Because dispersion can result in more rapid transport than would be indicated by the average flow velocity of an aquifer, particle tracking results may underestimate arrival times. This is of particular relevance in the area of LBWC 1, where results show a capture zone to the southwest (Figure 35). Likewise, forward particle tracking at SW 4 and SW 5 shows flow generally to the north/northeast and away from LBWC 1 (Figure 36). However, MT3DMS simulations show westward spreading of detectable levels of PCE terminating at the approximate location of SW 4 and SW 5 (Rybarski et al, 2019) – counter to the direction of simulated flow. Here, transport to the west is a result of dispersion rather than flow velocity. Thus, although SW 4 and SW 5 do not fall within the capture zone of LBWC 1, they would likely still serve as effective locations for sentinel wells.

Implications

Assuming the validity of the non-conservative model calibration, aquifers within the simulated area can be expected to maintain concentrations of PCE greater than 4 µg/l in localized areas for the next 20-25 years, given the pumping rates assigned in Alternative 2, Options 1 and 2. The addition of an extraction well in the area of the simulated EW-1 used in Option 2 could serve to remove mass more rapidly. Simulation results indicate concentrations at downgradient wells in this scenario drop below 4 µg/l 3-5 years sooner than in Option 1, or 4-7 years sooner than in the Base Treatment scenario (Alternative 1) (Table 4) (Figure 33). Extraction at the EW-1 site also relieves some of the mass removal burden from downgradient wells – while the total mass removed from the system is much greater in Alternative 2A, Option 2, the total mass removed by TKWC 1, TKWC 2, and LBWC 5 is reduced by 53 kg relative to Option 1 (Table 3) (Figure 34).

This study serves only to assess potential future concentrations of PCE within the aquifer system, and makes no effort to analyze the costs (of operating, infrastructure, or remediation) and stakeholder input that may be associated with the management scenarios described here.

Response to Comments

Following the distribution of the Rybarski et al, 2019 report, a number of questions and comments were submitted by stakeholders. These comments and their responses are explored below. It should be noted that these comments were directed towards a draft version of the report, and minor changes were made between the reviewed version and the final version. These changes were not substantive, but may affect page or figure numbers called out in the comments below.

Comment: Some of the numerical aquifer properties used to estimate fate and transport parameters appear to be inconsistent with the same set of properties used to develop the groundwater flow model in 2016. For example, on the top of page 7 it is stated that porosity values of 10% in layer 1 and 8% in layers 2-4 were used to estimate PCE retardation factors. The basis for these porosity values is not explained. They are, in general, very inconsistent with empirical porosity values for typical sand and gravel aquifers (e.g., 20%-35%, as referred to by GEI in its June 29, 2016 study for STPUD) and inconsistent with the specific yield values used by DRI (December 2016) for the transient groundwater flow model.

Response: Porosity values in a transport model represent effective porosity, which is typically smaller than the total porosity of a porous medium. This is not a parameter that can be readily measured in the field due to the complexity of pore structures, and must instead be estimated in model calibration to provide the closest representation of plume movement (Zheng and Wang, 1999).

Comment: The initial PCE recharge concentration of 700 mg/L described on pages 5-6 seems to be inconsistent with the most predominantly reported solubilities for PCE, which are in the range of 150 mg/L (Montgomery, 1996; SERC-Carleton College) to 200 mg/L (State Water Resources Control Board, Division of Water Quality, Groundwater Information Sheet: PCE). In other words, the fate and transport model assumes PCE concentrations in water that are several times greater than the actual solubility of PCE. Use of such a high initial concentration needs to be defended with either site-specific data or other studies that would indicate that the preponderance of literature is incorrect regarding PCE solubility as it applies to the South Y area.

Response: While the influx of PCE is simulated as a recharge concentration, it is not necessary for PCE to be dissolved in water in order to enter an aquifer. The recharge concentration of PCE in the model represents the annual mass flux of PCE into the groundwater, which occurs both at the source and in flow paths. As the non-aqueous phase liquid PCE moves through the aquifer along with water, it continues to dissolve into the groundwater. This continued dissolution is incorporated into the recharge concentration. Like porosity, the recharge concentration is a model parameter that incorporates multiple physical processes and is calibrated to match in situ observations of PCE in the system.

Comment: The analysis of PCE degradation assumes a mass loss from the groundwater system, with no accounting made for PCE degradation products. However, it is well documented that PCE degrades first to TCE, then to cis- and trans-1,2-DCE, then to vinyl chloride. These compounds have MCLs and toxicities that are comparable to or in some cases worse than PCE. The model appears to assume that once PCE degrades, that mass is lost and no longer remains in the aquifer. This is a very unprotective assumption and one that could lead to substantial errors for planning purposes in terms of estimating clean up times and costs to treat contaminated groundwater.

Response: Multiple field/in-situ studies have indicated that TCE degrades only slightly more slowly than PCE under anaerobic conditions, with a mean half-life of 277 days for TCE compared to 239 days for PCE (though these half-lives have extended to years in laboratory studies) (Lawrence, 2006). It would therefore be expected to accumulate slowly as it continually degrades, and would also be transported similarly to PCE. Additionally, these rates are applicable only to anaerobic degradation, and sampling has indicated the presence of dissolved oxygen concentrations greater than 1.5 mg/l within the upper 150 feet of the model domain (Rybarski et al, 2019). Studies have shown that degradation of PCE is extremely slow in the presence of dissolved oxygen, and may not be possible when DO is greater than 1.5 mg/l. However, TCE, DCE, and VC may all degrade readily in the presence of oxygen. Furthermore, while the PCE -> TCE -> DCE -> VC degradation chain is well documented for anaerobic conditions, multiple studies have shown that under aerobic conditions TCE will not decay to DCE, and will instead follow one of several alternate decay paths, terminating in carbon dioxide, oxalate, or glyoxylate (Lawrence, 2006). Therefore, under aerobic conditions, PCE would be expected to slowly decay to TCE, which would then decay more rapidly. Finally, though sampling for TCE, DCE, and VC within the model domain has been extremely limited, results have shown very low or ND concentrations for all samples, with the exception of the area near LTLW where PCE concentrations have historically been the highest. These results imply that either PCE degradation in the basin is extremely slow, or that any degradation byproducts are rapidly decaying – or both. In either case, simulation of TCE with very few calibration points would be an unnecessary complication, especially given the bookended results created by the conservative, no-decay simulations.

Comment: On page 7, the PCE half-life used in the fate and transport model is stated to be 17 years in layers 1 and 2 and 2 years in layers 3 and 4. The assumed PCE half-lives in the model are not supported by, and in fact are contrary to, plume-specific data. For example, a 2-year half-life means that 97.5 percent of the PCE present in that layer would degrade in five half-lives, or 10 years. Even with a 17-year half-life, in the 45+ years since the release occurred, over 85 percent of the original PCE mass would have degraded. If these half-lives were correct, only 15 percent of the originally-released volatile organic compound (VOC) mass in layers 1 and 2 should be PCE and 85 percent should be degradation products. In layers 3 and 4, there should be virtually no detectable PCE (there have been over 25 half-lives) and any detectable VOCs should consist of the PCE degradation products. This is substantially inconsistent with the existing monitoring information. Specifically, very little TCE and almost no 1,2-DCE and vinyl chloride are reported in any of the monitoring data.

Response: The calculation of remaining mass described in the comment is incorrect, as it assumes a static, no-flow system where all mass within the model was initially present beginning in the early 1970s, and furthermore that all mass present in the deeper layers (up to 280 meters below land surface) began in those layers. Instead, the simulations describe a system where mass is continuously released into layer 1 until 2011. This mass is then allowed to migrate between layers as defined by advection and dispersion. See the above comment for additional response related to degradation byproducts.

Comment: The Y-axis scale units appear to be incorrect on Figure 13. This should likely be meters above mean sea level as opposed to feet.

Response: Yes, the units are in meters. A corrected version is presented in this addendum in Figure 37.

Comment: The statement on the top of page 8 that "simulated trends are generally excellent" is not borne out by the actual model output charts. For example:

a. Figure 21 indicates that only moderate PCE concentrations, in the range of 50 to 70 ug/L, should have passed through the Clement well. However, the peak concentrations observed at that location reached 200 ug/L in the mid-1990s.
b. Figure 24 suggests that some of the highest concentrations observed in the downgradient plume (over 200 ug/L) should have passed through the LBWC #4 well. To date, the highest PCE concentration observed at that well is only a little over 50 ug/L.
c. Figure 25 shows a predicted gradual increase of PCE up to about 25 ug/L in LBWC #5. However, over the past five to six years, concentrations have increased exponentially to almost 70 ug/L. (The exponential trend versus gradual increase is more concerning here than the differences in the predicted and actual concentrations.)
d. Figure 28 predicts that the PCE concentrations in the Tahoe Valley Elementary School well should have increased quickly over the last decade, from about 25 ug/L to 40 ug/L. Over that period, the actual PCE concentrations in this well have been stable and less than 2 ug/L.

Response: In general, the calibration of a transient model is determined by its ability to predict trends rather than specific concentrations, and is limited by the resolution of the model. The purpose of this model is not to predict exact concentrations at wells, but to assess the relative effectiveness of potential management scenarios. In response to the specific examples presented:

a. While peak concentrations are not correctly simulated, the arrival time of the plume and subsequent decline in concentrations at Clement Well are well represented.
b. The validity of the model at LBWC 4 is unclear given the 25 year (1990-2015) data gap.
c. Numerical groundwater models are generally unable to simulate exponential trends without significant numerical instability. As this trend has not yet been observed at any other well, it may be anomalous. However, simulated concentrations are at the same order of magnitude as observed concentrations, and observations are well below those seen in the conservative simulations.

d. The model is poorly constrained to the east. As the nearest sampling points (LBWC 4 and MW-4) both show much higher concentrations, this well may simply be an anomaly. However, the Tahoe Valley Elementary School is a relatively shallow well, reported to have partially collapsed in 2013, and recent sampling in progress (LRWQCB, written communication, 2019) appears to show the plume to be descending in elevation as it migrates to the north. It is then possible that the plume exists spatially in the area of the well, but is below the screened interval. Pending sampling in this area may clarify the validity of the simulation at this well.

Data Sources

Publicly available PCE, TCE, and DCE concentrations collected by STPUD, TKWC, LBWC, the Lahontan Regional Water Quality Control Board (LRWQC), and other stakeholders were used in both the pre-design investigation and in the development of the model presented in this report. A more detailed list of these sources can be seen in Table 6.

Limitations and Disclaimer

The South Y Fate and Transport Model is intended to be used as a decision support tool for the Technical Advisory Committee for the South Y Feasibility Study of Remedial Alternatives. The goal of that program is to determine a path forward that will continue to provide clean public water supplies to all residents of South Lake Tahoe while addressing the PCE contamination in the South Y area. The intended use of the numerical model is to facilitate comparisons between remedial options (i.e., the management scenarios described above).

The available data on PCE concentrations throughout the model domain are relatively sparse in both space and time. When data are available, the uncertainties are relatively high. While the calibrated model matches the trends seen in the available data, the uncertainties in the simulated concentrations of PCE are necessarily greater than the uncertainties in observed concentrations over the last thirty years.

Although the South Y Fate and Transport Model has been verified, DRI makes no representations or warranties of any kind as to its accuracy. DRI additionally makes no warranties of merchantability or fitness for a particular use, nor are such warranties to be implied, with respect to the South Y Fate and Transport Model. Any person utilizing the South Y Fate and Transport Model is responsible for understanding its accuracy and limitations. In particular, alterations and/or manipulation of the original data may adversely affect their accuracy, meaning, and design integrity. Any person utilizing the South Y Fate and Transport Model assumes all responsibility for its correct use and for its interpretation.

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Tables

Table 1. Pumping rates used for the three alternatives and two hypothetical scenarios.

Alternative	Description	Pumping Rates (m^3/d)										
		LBWC 1	LBWC 5	TKWC 1	TKWC 2	TKWC 3	Sunset	Paloma	Helen 2	Bayview	Al Tahoe 2	EW-1
1A	Base Treatment	872.19	199.66	532.54	1,219.49	1,316.98	1,735.79	195.74	713.22	8,997.45	1,462.21	0
1B	Base Treatment Conservative	872.19	199.66	532.54	1,219.49	1,316.98	1,735.79	195.74	713.22	8,997.45	1,462.21	0
2A, Option 1	Targeted Pumping	199.66	872.19	532.54	1,219.49	1,316.98	1,735.79	195.74	713.22	8,997.45	1,462.21	0
2B, Option 1	Targeted Pumping Conservative	199.66	872.19	532.54	1,219.49	1,316.98	1,735.79	195.74	713.22	8,997.45	1,462.21	0
2A, Option 2	SW Conversion	199.66	872.19	532.54	1,219.49	1,316.98	1,735.79	195.74	713.22	8,997.45	1,462.21	872.17
2B, Option 2	SW Conversion Conservative	199.66	872.19	532.54	1,219.49	1,316.98	1,735.79	195.74	713.22	8,997.45	1,462.21	872.17

Note: To convert pumping rates from cubic meter per day (m^3/d) into gallons per minute (gpm) multiply by 0.1835

Table 2. PCE recharge concentration for predictive simulations and biodegradation half-lives by layer.

Alternative	Description	Source Term – Future Recharge PCE	Source Term – Future Recharge PCE	Biodegradation Half-life (years)			
		(mg/l)	(kg/yr)	Layer 1	Layer 2	Layer 3	Layer 4
1A	Base Treatment	0	0	17	17	2	2
1B	Base Treatment Conservative	10	4.45	0	0	0	0
2A, Option 1	LBWC 5 Lead	0	0	17	17	2	2
2B, Option 1	LBWC 5 Lead Conservative	10	4.45	0	0	0	0
2A, Option 2	LBWC 5 Lead / EW-1	0	0	17	17	2	2
2B, Option 2	LBWC 5 Lead / EW-1 Conservative	10	4.45	0	0	0	0

Table 3. Mass removed and removal rate by well for all alternatives.

Alternative	Description	PCE Mass Removed (0.4536 kg) or (lbs); WY 2019-2068					Total Extracted Groundwater Volume; WY 2019-2068	Average PCE Mass Removal Rate
		LBWC 5	TKWC 1	TKWC 2	EW-1	Total	(3785 m^3) or (MG)	(lb/MG)
1A	Baseline	54.1	68.8	224.1	N/A	347.0	9416.1	0.04
1B	Conservative Baseline	260.4	763.8	1548.3	N/A	2572.5	9416.1	0.27
2A, Option 1	LBWC 5 Lead	205.9	61.8	217.5	N/A	485.2	12660.7	0.04
2B, Option 1	LBWC 5 Lead Conservative	979.5	692.1	1519.1	N/A	3190.7	12660.7	0.25
2A, Option 2	LBWC 5 Lead / EW-1	140.0	47.8	181.5	449.0	818.3	16868.6	0.05
2B, Option 2	LBWC 5 Lead / EW-1 Conservative	698.7	568.9	1364.9	1503.6	4136.1	16868.6	0.24

Table 4. Simulated year PCE concentrations drop below 4 ug/l, by well, and the number of years after 2018 each well drops below 4 ug/l for all alternatives. N.E. = Never Exceeds 4 ug/l.

Alternative	Description	Year PCE < 4 µg/l					Years after 2018 (PCE < 4 µg/l)				
		LBWC 1	LBWC 5	TKWC 1	TKWC 2	TKWC 3	LBWC 1	LBWC 5	TKWC 1	TKWC 2	TKWC 3
1A	Baseline	N.E.	2040	2045	2040	N.E.	N.E.	22	27	22	N.E.
1B	Conservative Baseline	N.E.	2058	>2068	>2068	N.E.	N.E.	40	>50	>50	N.E.
2A, Option 1	LBWC 5 Lead	N.E.	2038	2041	2039	N.E.	N.E.	20	23	21	N.E.
2B, Option 1	LBWC 5 Lead Conservative	N.E.	2054	>2068	>2068	N.E.	N.E.	36	>50	>50	N.E.
2A, Option 2	LBWC 5 Lead / EW-1	N.E.	2033	N.E.	2036	N.E.	N.E.	15	N.E.	18	N.E.
2B, Option 2	LBWC 5 Lead / EW-1 Conservative	N.E.	2046	>2068	2062	N.E.	N.E.	28	>50	44	N.E.

Table 5. Simulated travel times from sentinel wells to the associated production well.

Production Well	Sentinel Well	Travel Time (days)	Travel Time (years)
Bayview	SW1	156-355	0.42-0.97
Bayview	SW2	N/A	N/A
TKWC 3	SW3	1156-1408	3.1-3.8
LBWC 1	SW4	N/A	N/A
LBWC 1	SW5	N/A	N/A
TKWC 1	SW6	1769-1871	4.8-5.1

Table 6. Data sources for pre-design investigation/model design and calibration.

Data Type	Location	Description	Source
PCE	Bel Pac South	Off-site/alternative source investigation	APEX, 2000
PCE	Big O Tire	Off-site/alternative source investigation	Harding ESE, 2001
PCE	Big O Tire	Off-site/alternative source investigation	LFR, 2006
PCE	Hurzel Properties	Off-site/alternative source investigation	Harding ESE, 2001
PCE	Hurzel Properties	Off-site/alternative source investigation	SECOR, 2008
PCE	Lakeside Napa	Off-site/alternative source investigation	SECOR, 2002/2004
PCE	NorCal Beverage	Off-site/alternative source investigation	WKA, 2001
PCE	TCI Building	Off-site/alternative source investigation	GHH Engineering, Inc, 2001
PCE	Multiple South Y area sites	Off-site/alternative source investigation	EKI, 2017
PCE	All STPUD, TKWC, and LBWC production wells; South Y area monitoring wells	Historical plume delineation	GEI, 2016
PCE/Lithology/Aquifer properties	EW-1 boreholes	Extraction test well/ aquifer property assessment	STPUD, 2018
PCE/TCE/DCE/VC	LTLW Site	Source/clean-up monitoring	LTLW, 2003-2005; 2010-2016
PCE/TCE/DCE	Eloise Area monitoring wells downgradient of source	Source/migration monitoring/ plume delineation	LRWQCB, 2015-2019
PCE/TCE/DCE/DCA/VC	South Y area production wells	Monitoring	STPUD, 1989-2015
Water Quality	South Y area production wells	Monitoring	STPUD, 1989-2012
Lithology	South of South Y; Clement, Julie, South Y, Tata 1-3 area	Clay lens assessment	IT Corp./USA Gasoline, 1999
Lithology	LBWC 4 area extending north to TKWC 1 and TKWC 3	Clay lens assessment	STPUD, 2019

Figures

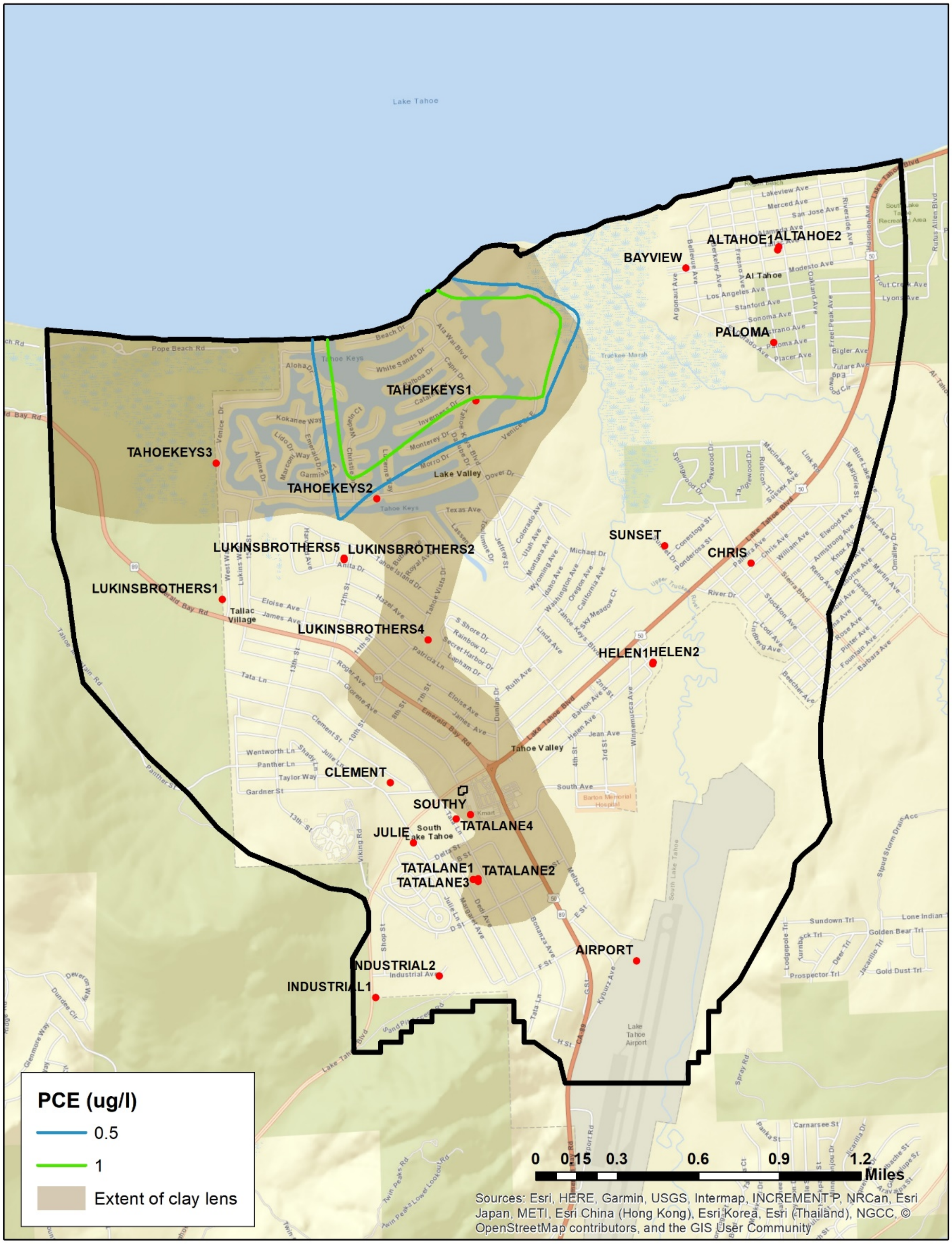

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Figure 1. Alternative 2A, Option 1. Simulated PCE plume in model layer 1 at the end of the 2068 water year. All concentrations are below the MCL for this stress period.

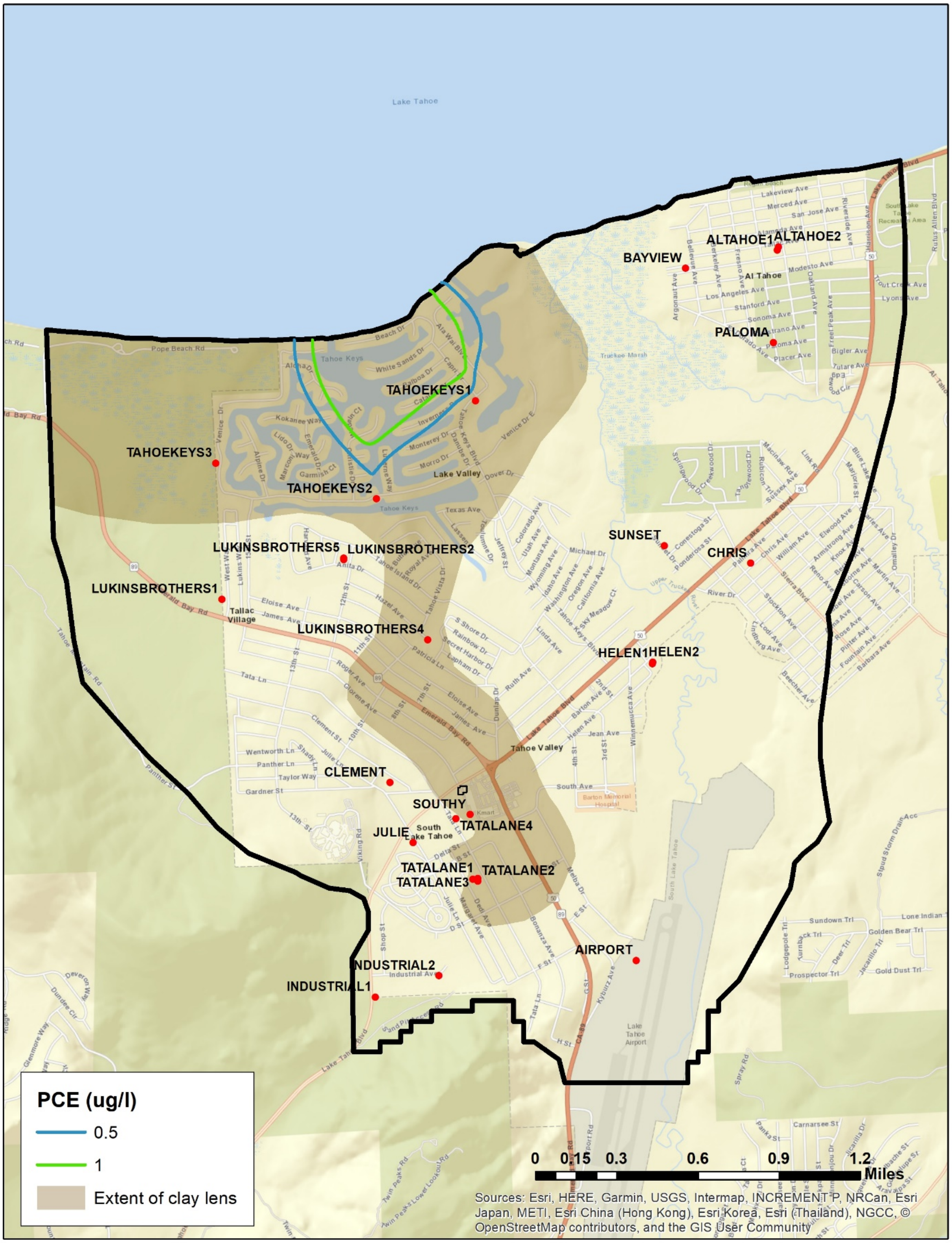

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Figure 2. Alternative 2A, Option 1. Simulated PCE plume in model layer 2 at the end of the 2068 water year. All concentrations are below the MCL for this stress period.

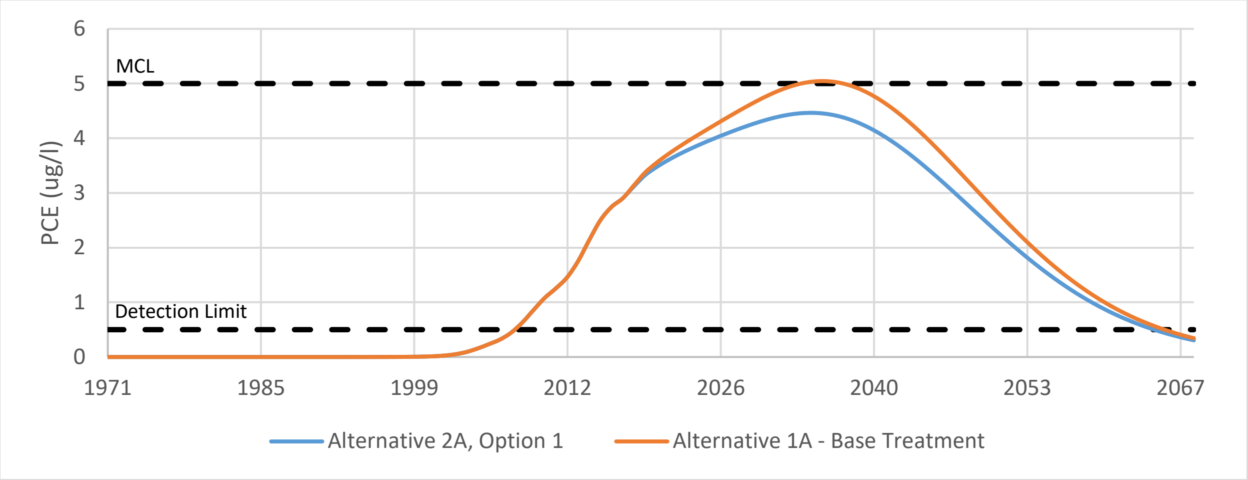

Figure 3. Breakthrough curve for TKWC 1 for Alternatives 2A, Option 1 (blue) and 1A (orange).

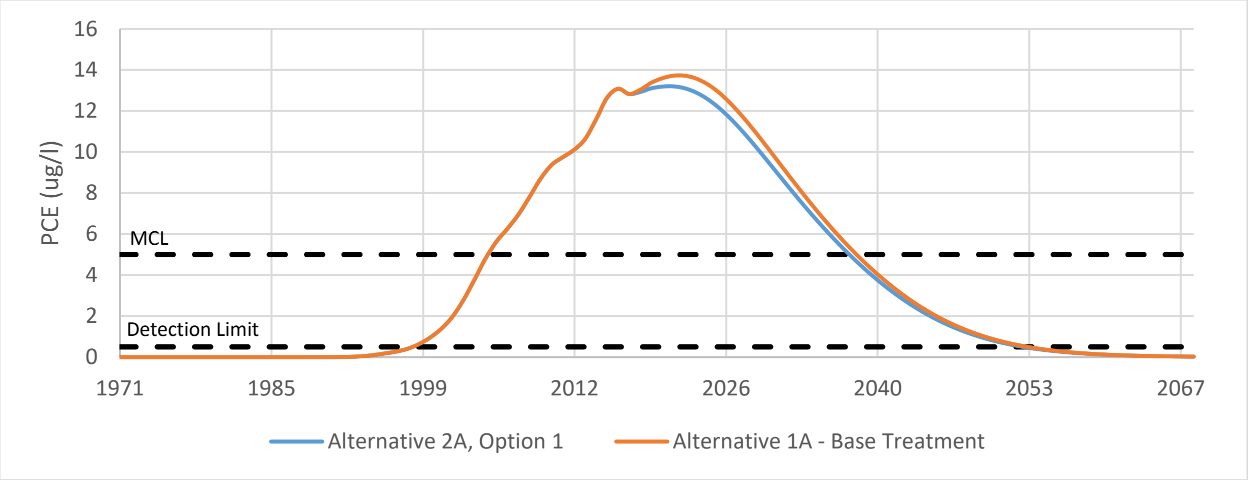

Figure 4. Breakthrough curve for TKWC 2 for Alternatives 2A, Option 1 (blue) and 1A (orange).

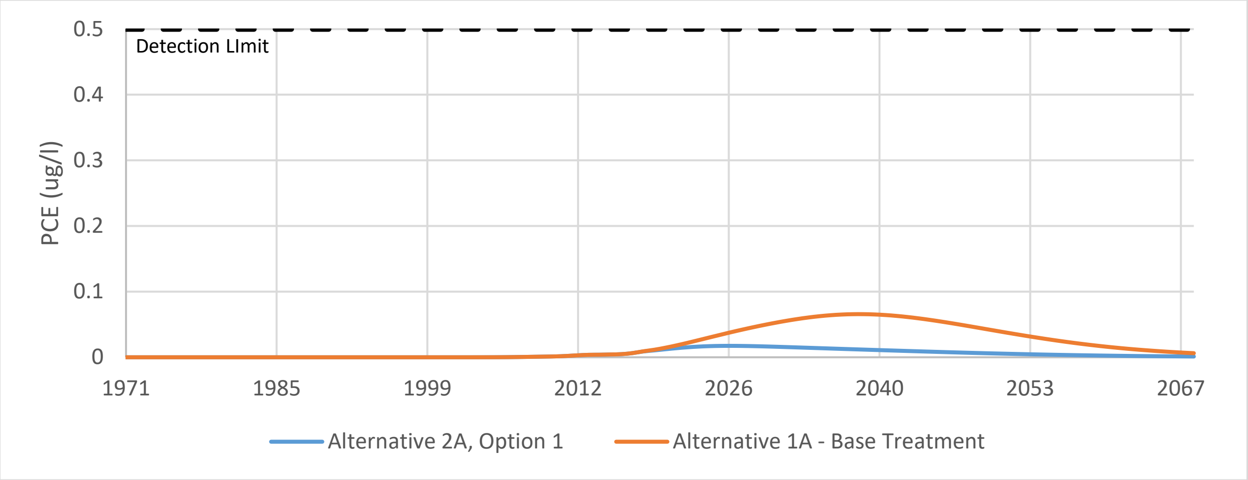

Figure 5. Breakthrough curve for TKWC 3 for Alternatives 2A, Option 1 (blue) and 1A (orange).

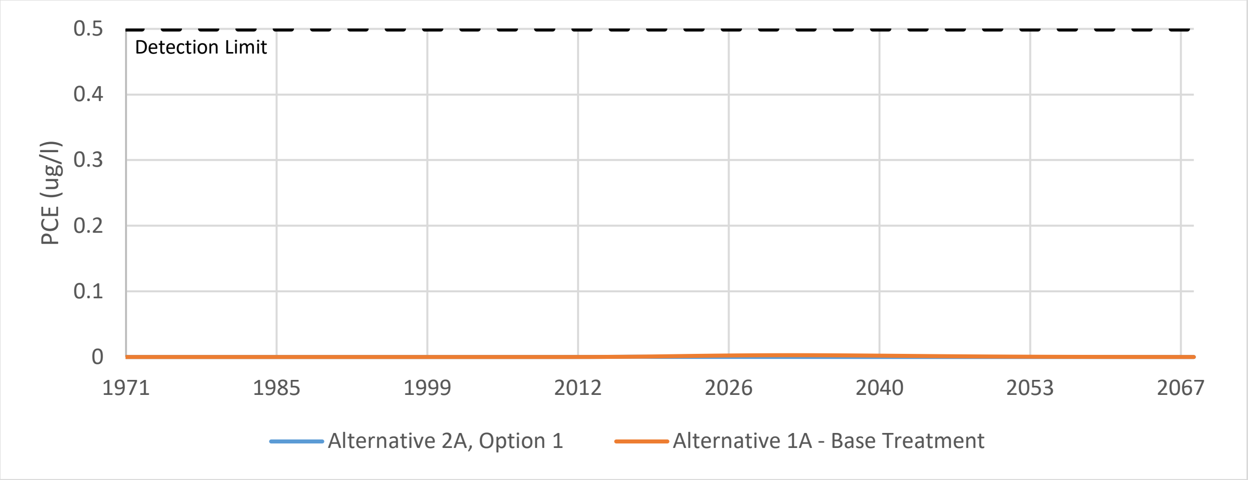

Figure 6. Breakthrough curve for LBWC 1 for Alternatives 2A, Option 1 (blue) and 1A (orange).

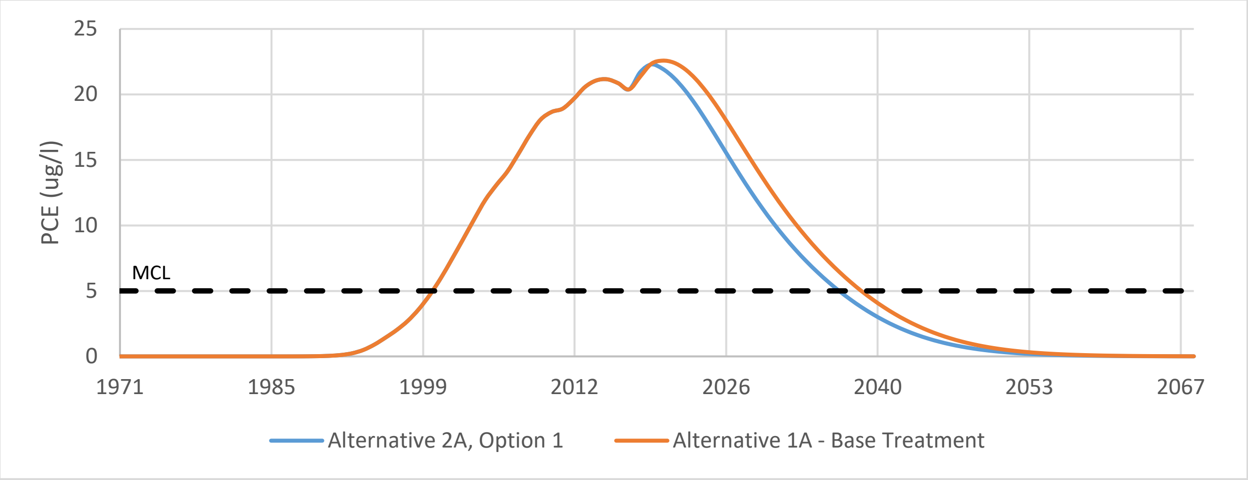

Figure 7. Breakthrough curve for LBWC 5 for Alternatives 2A, Option 1 (blue) and 1A (orange).

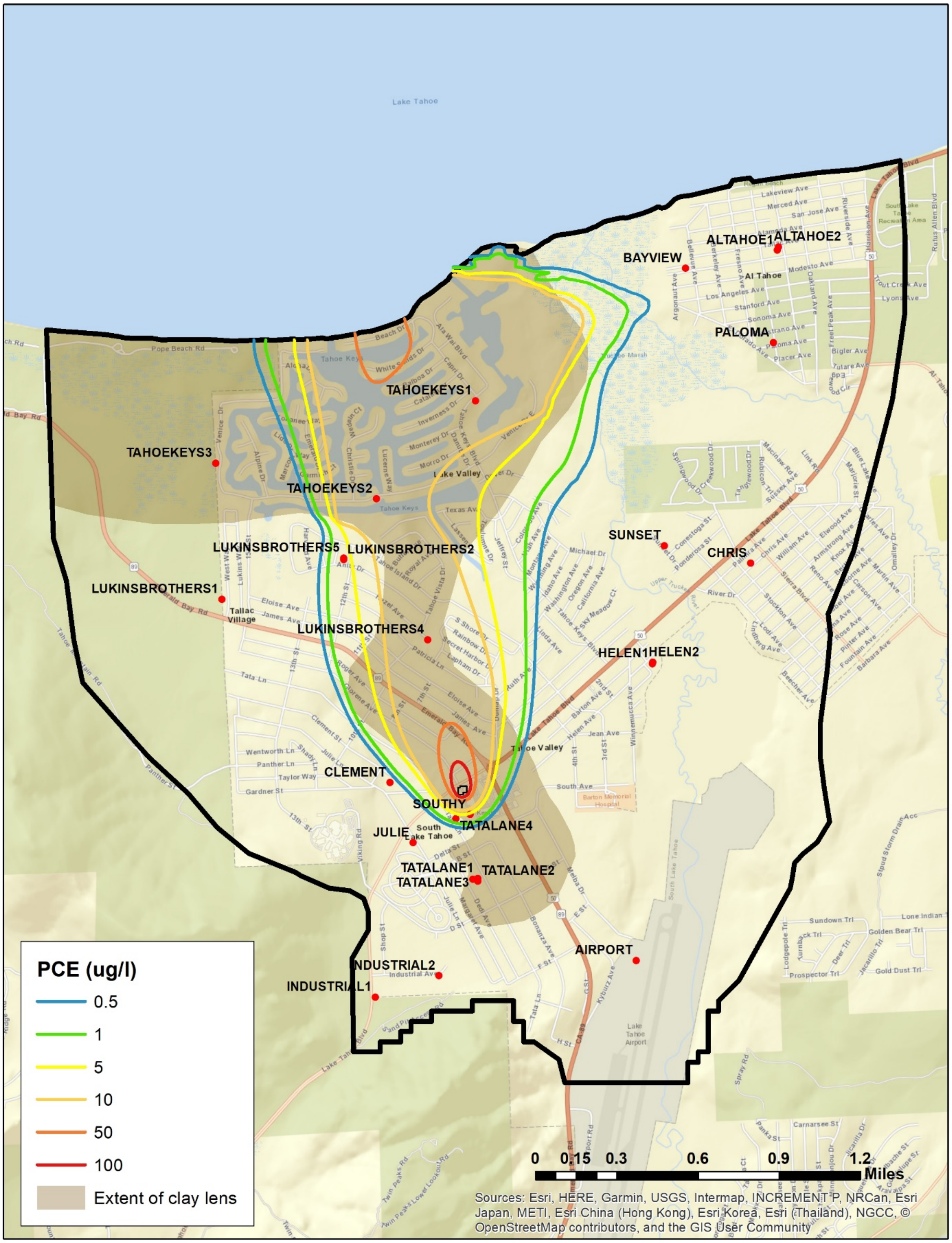

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Figure 8. Alternative 2B, Option 1 (Conservative). Simulated PCE plume in model layer 1 at the end of the 2068 water year.

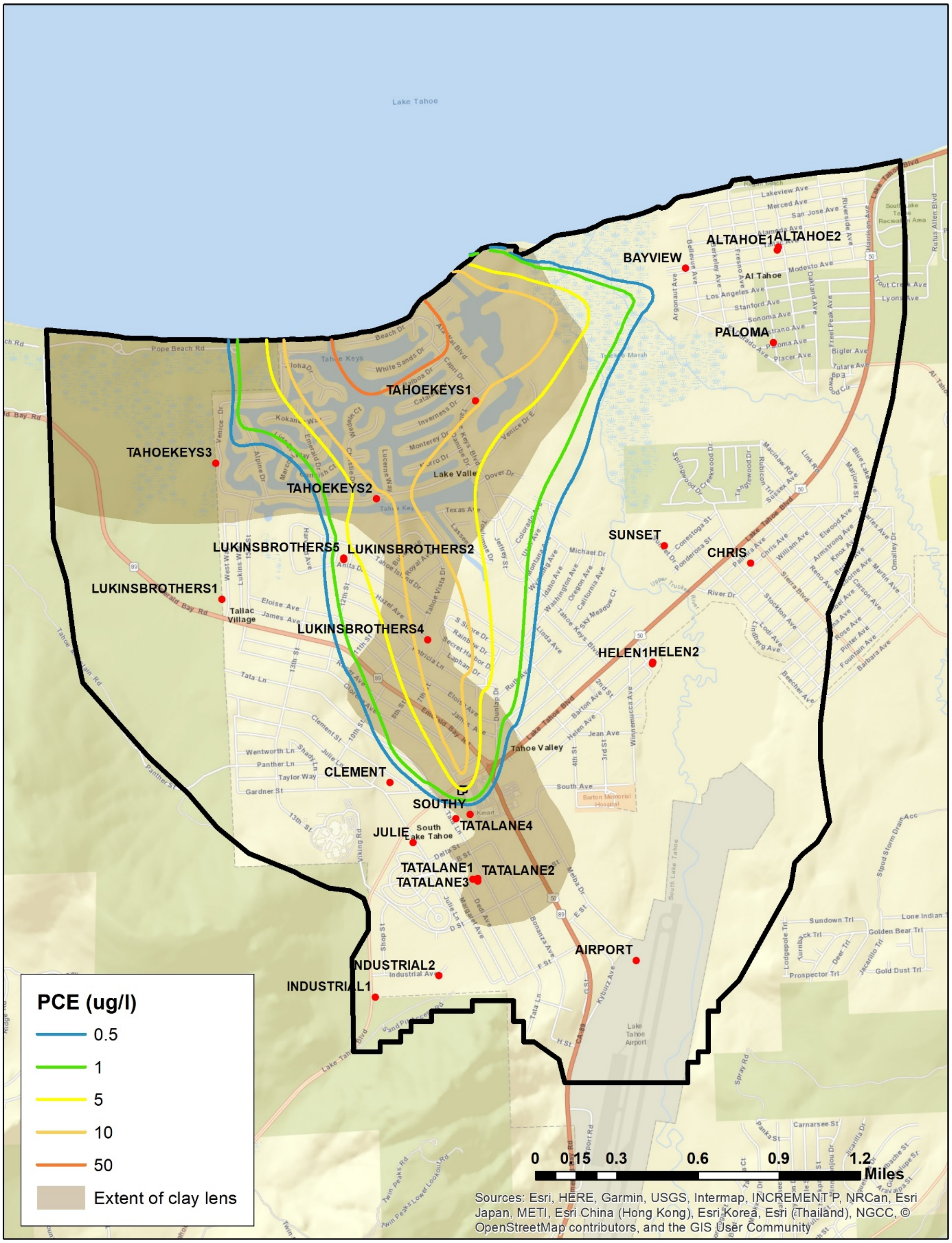

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Figure 9. Alternative 2B, Option 1 (Conservative). Simulated PCE plume in model layer 2 at the end of the 2068 water year.

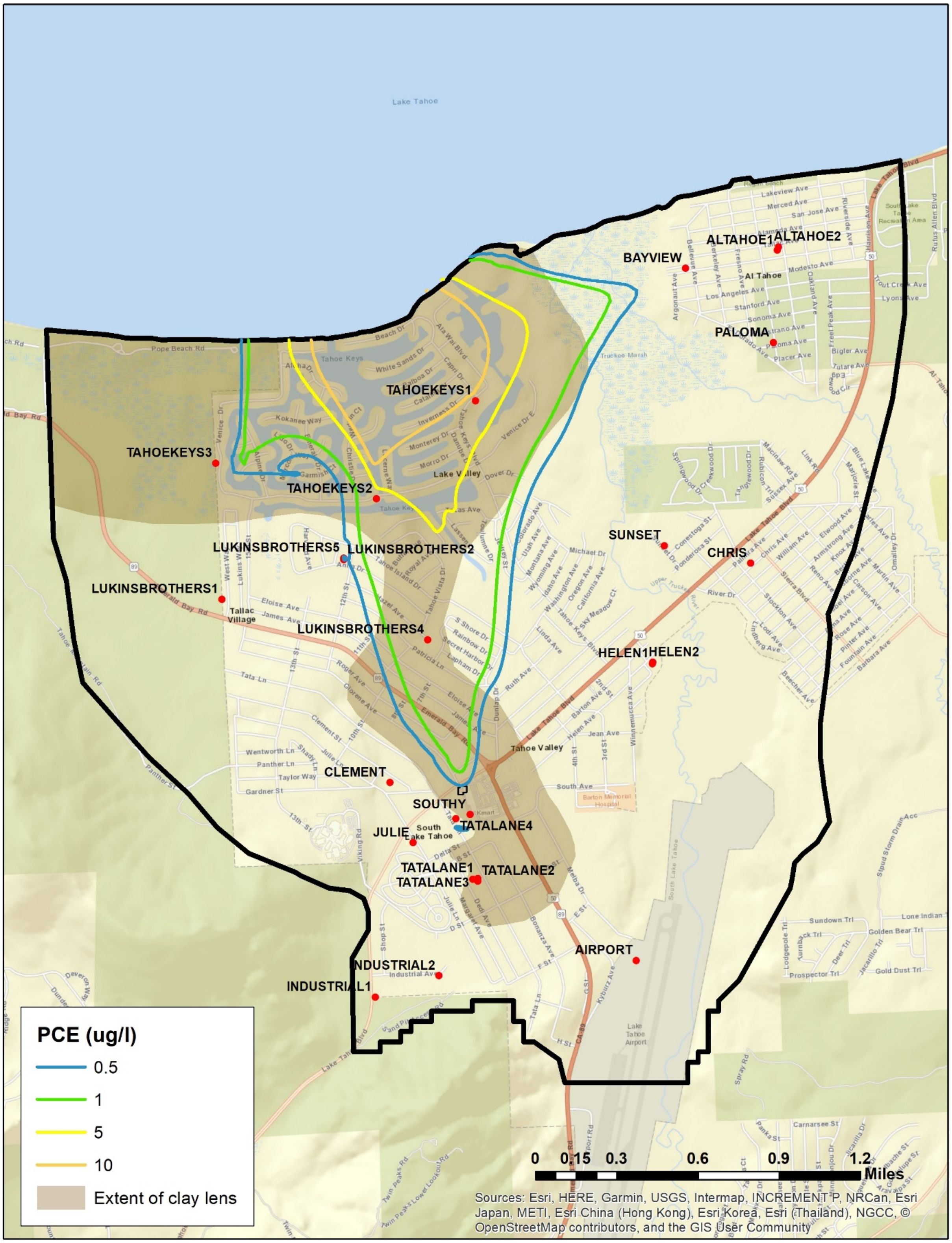

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Figure 10. Alternative 2B, Option 1 (Conservative). Simulated PCE plume in model layer 3 at the end of the 2068 water year.

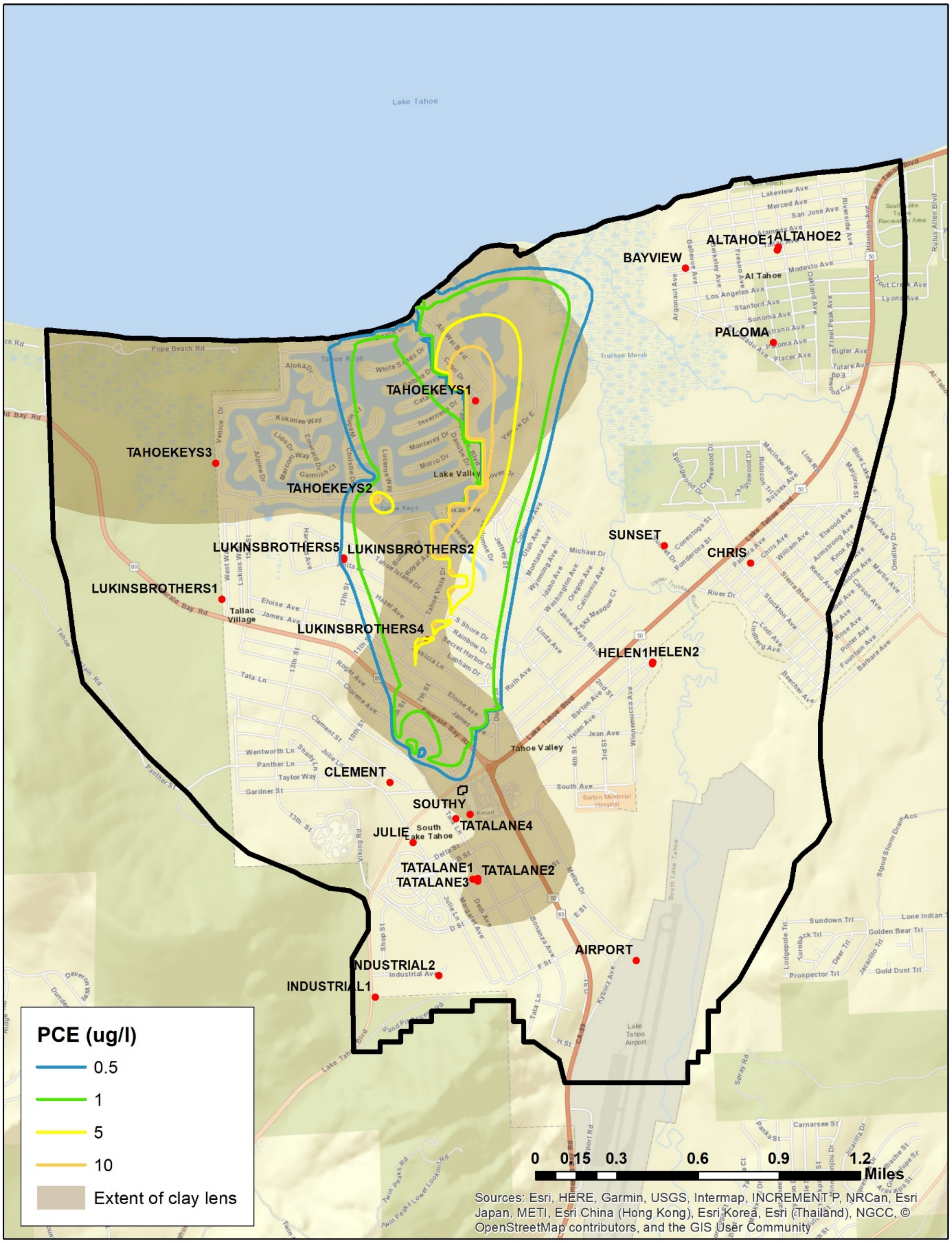

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Figure 11. Alternative 2B, Option 1 (Conservative). Simulated PCE plume in model layer 4 at the end of the 2068 water year.

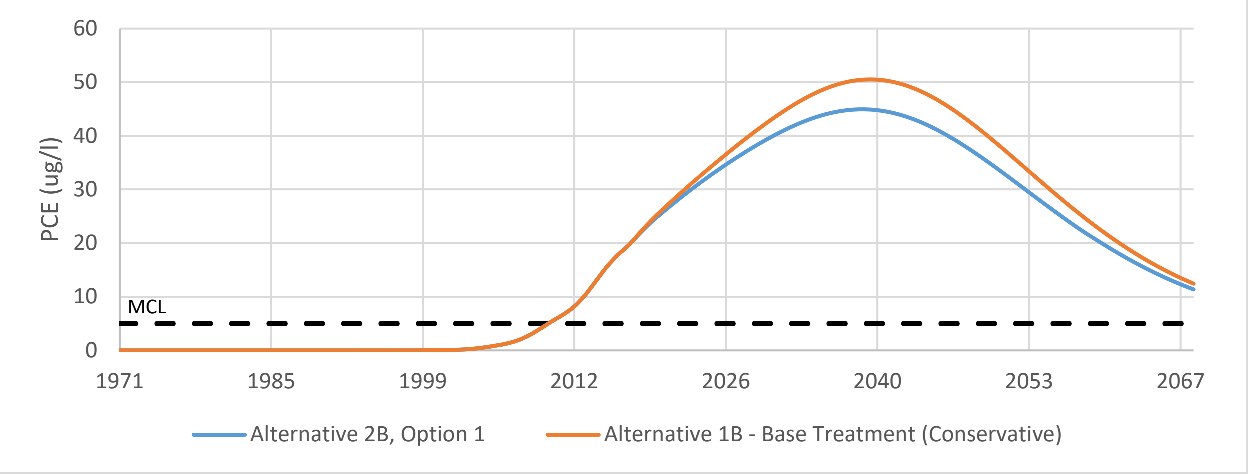

Figure 12. Breakthrough curve for TKWC 1 for Alternatives 2B, Option 1 (Conservative) (blue), and 1B – Base Treatment (Conservative) (orange).

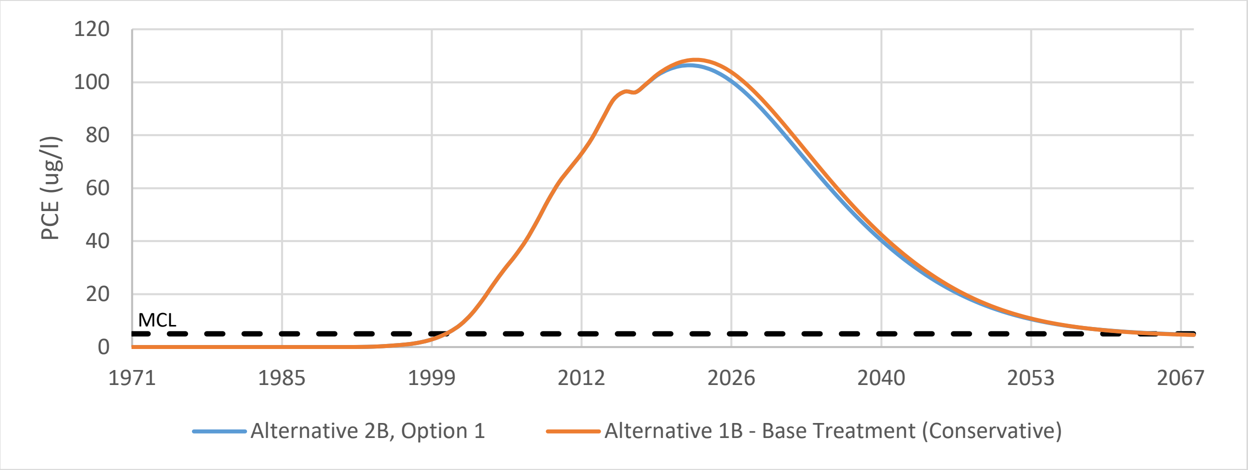

Figure 13. Breakthrough curve for TKWC 2 for Alternatives 2B, Option 1 (Conservative) (blue), and 1B – Base Treatment (Conservative) (orange).

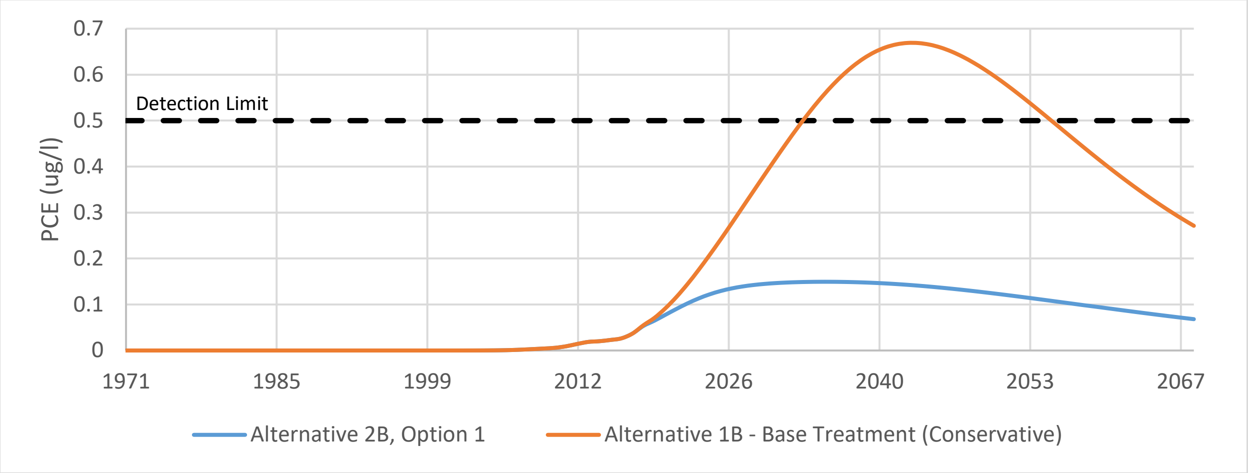

Figure 14. Breakthrough curve for TKWC 3 for Alternatives 2B, Option 1 (Conservative) (blue) and 1B – Base Treatment (Conservative) (orange).

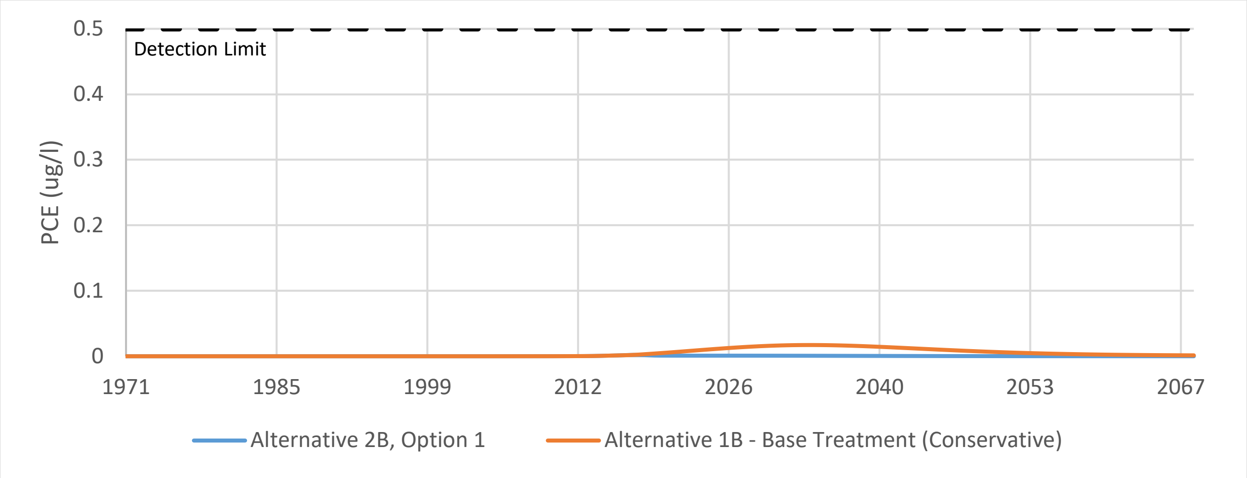

Figure 15. Breakthrough curve for LBWC 1 for Alternatives 2B, Option 1 (Conservative) (blue), and 1B – Base Treatment (Conservative) (orange).

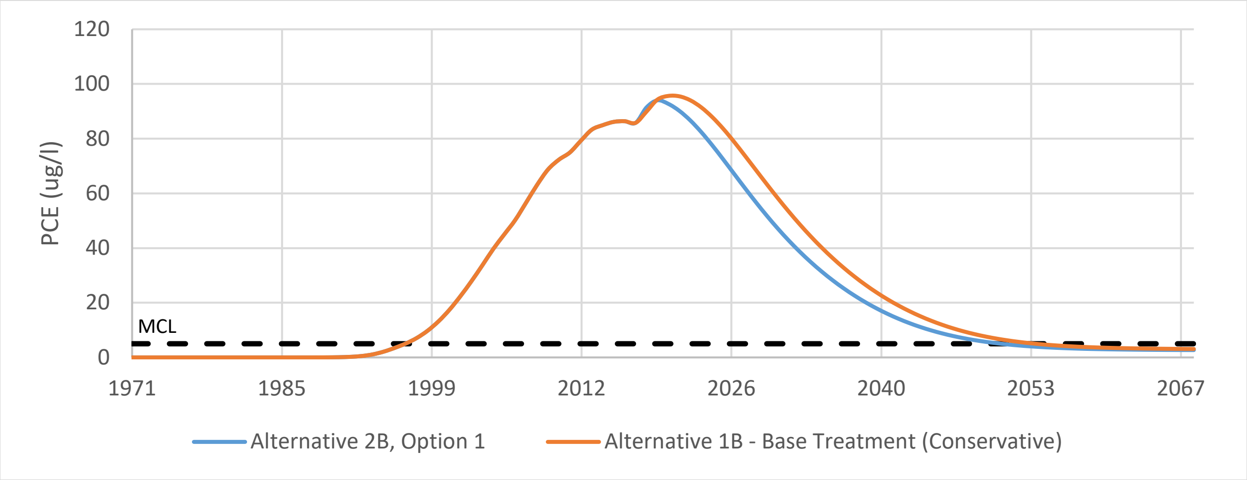

Figure 16. Breakthrough curve for LBWC 5 for Alternatives 2B, Option 1 (Conservative) (blue), and 1B – Base Treatment (Conservative) (orange).

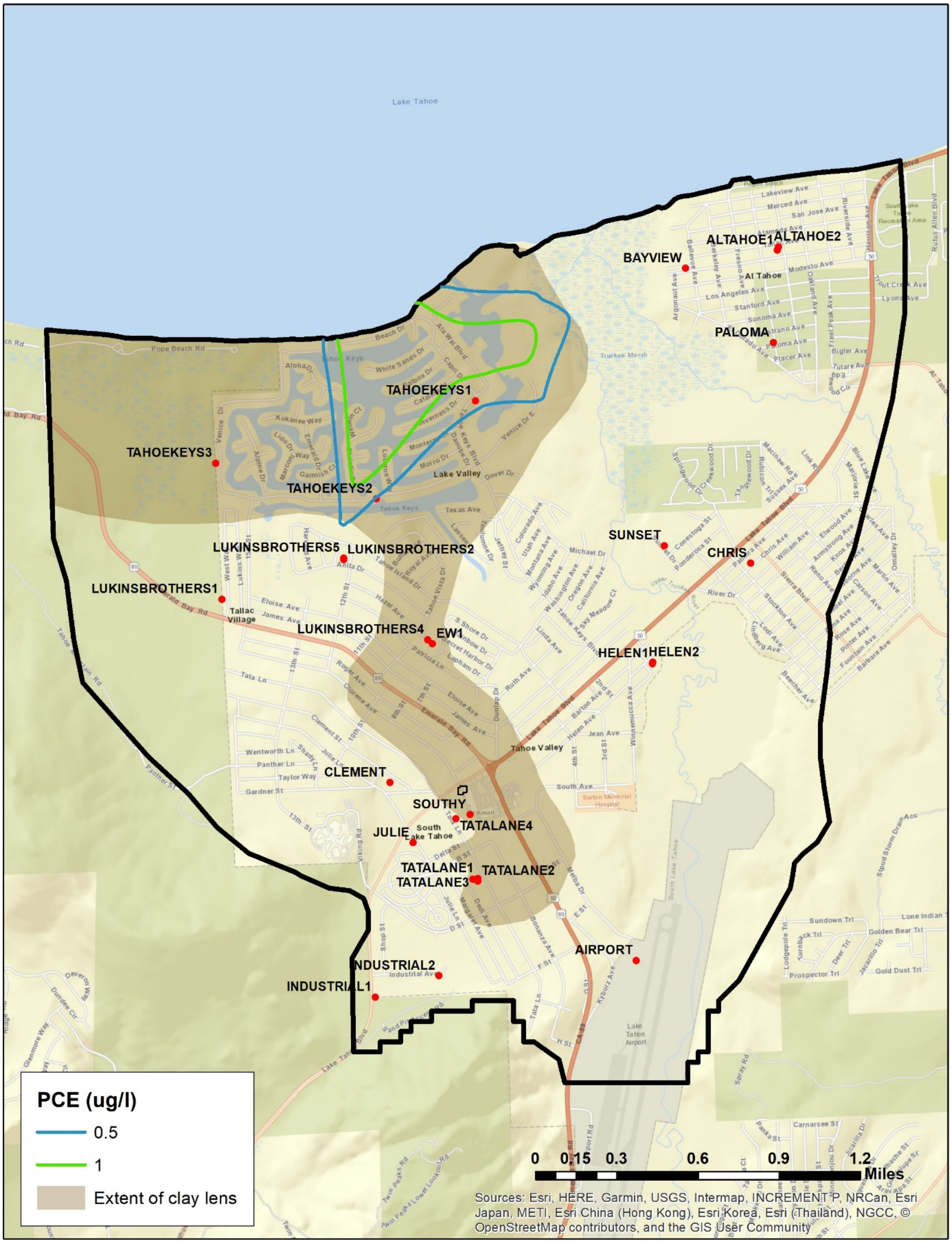

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Figure 17. Alternative 2A, Option 2. Simulated PCE plume in model layer 1 at the end of the 2068 water year.

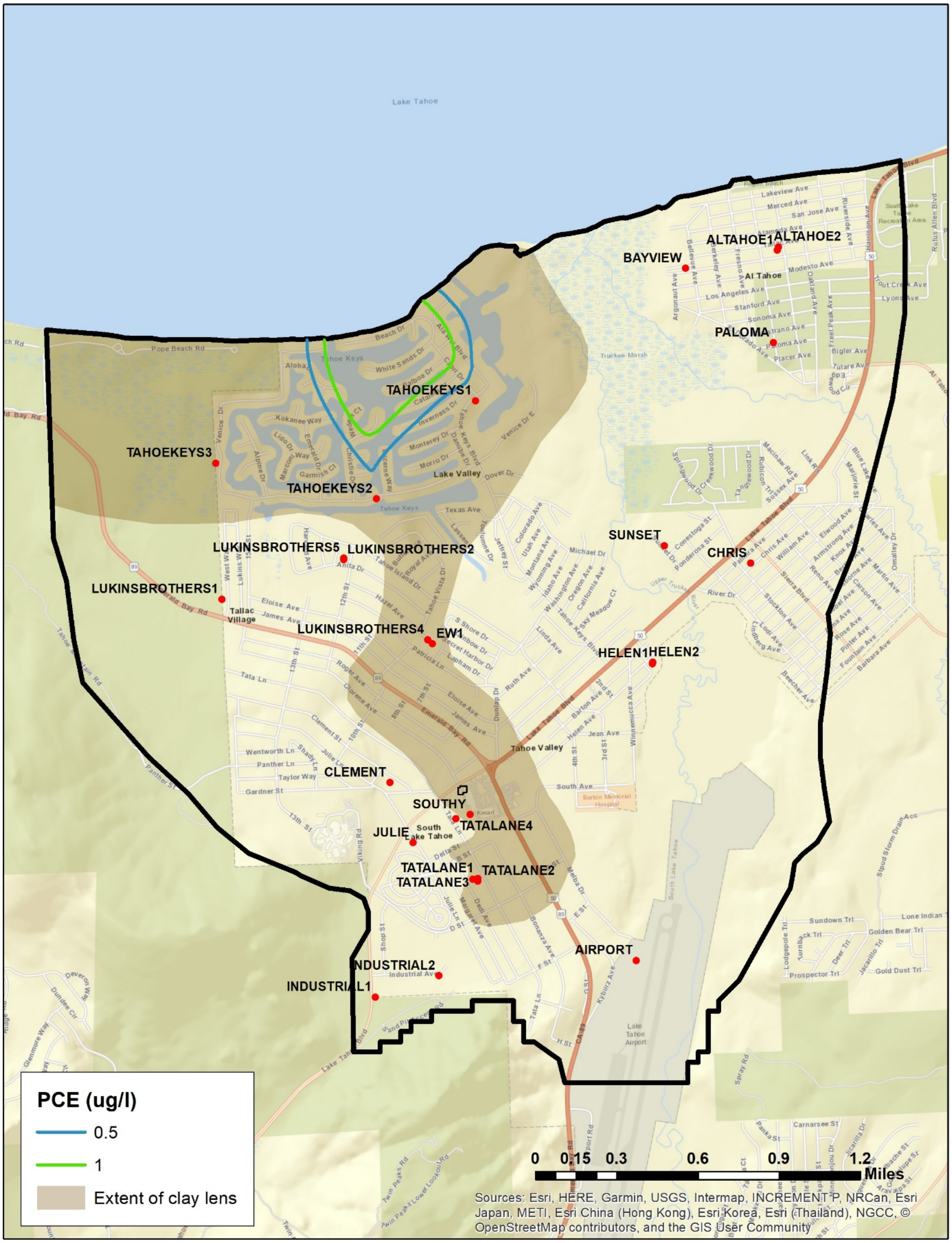

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Figure 18. Alternative 2A, Option 2. Simulated PCE plume in model layer 2 at the end of the 2068 water year.

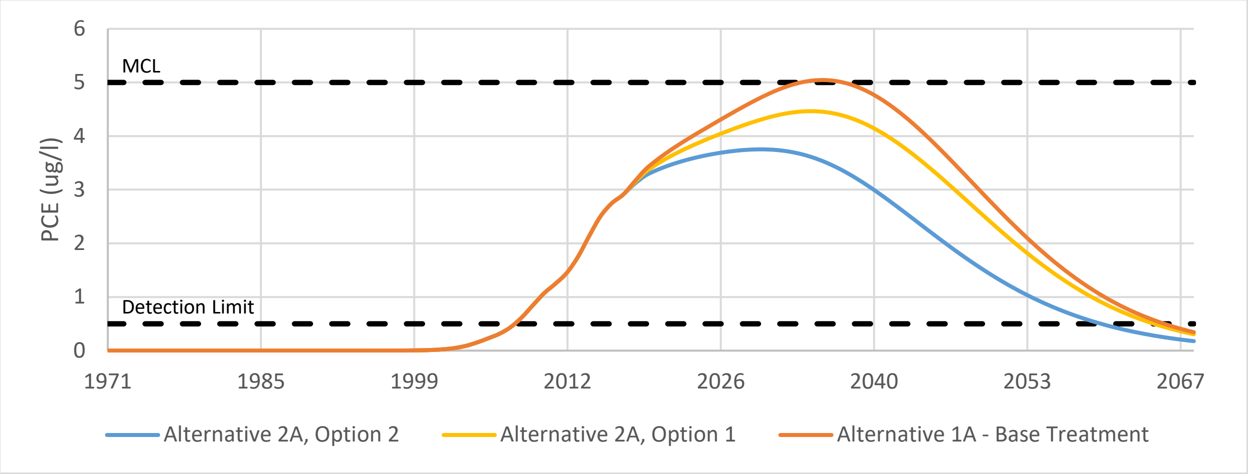

Figure 19. Breakthrough curves for TKWC 1 for Alternatives 2A, Option 2 (blue), 2A, Option 1 (yellow), and 1A – Base Treatment (orange).

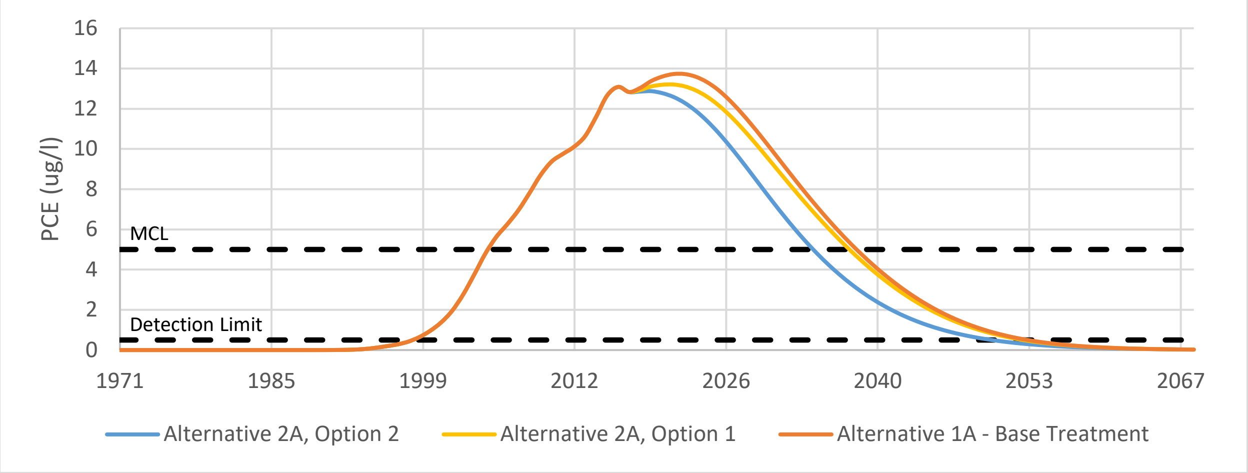

Figure 20. Breakthrough curve for TKWC 2 for Alternatives 2A, Option 2 (blue), 2A, Option 1 (yellow), and 1A – Base Treatment (orange).

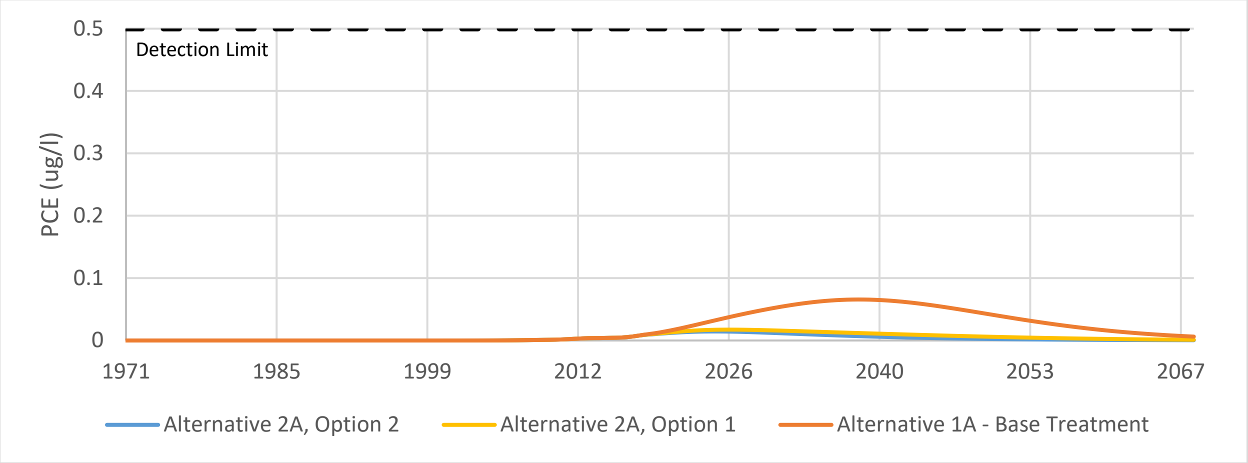

Figure 21. Breakthrough curve for TKWC 3 for Alternatives 2A, Option 2 (blue), 2A, Option 1 (yellow), and 1A – Base Treatment (orange).

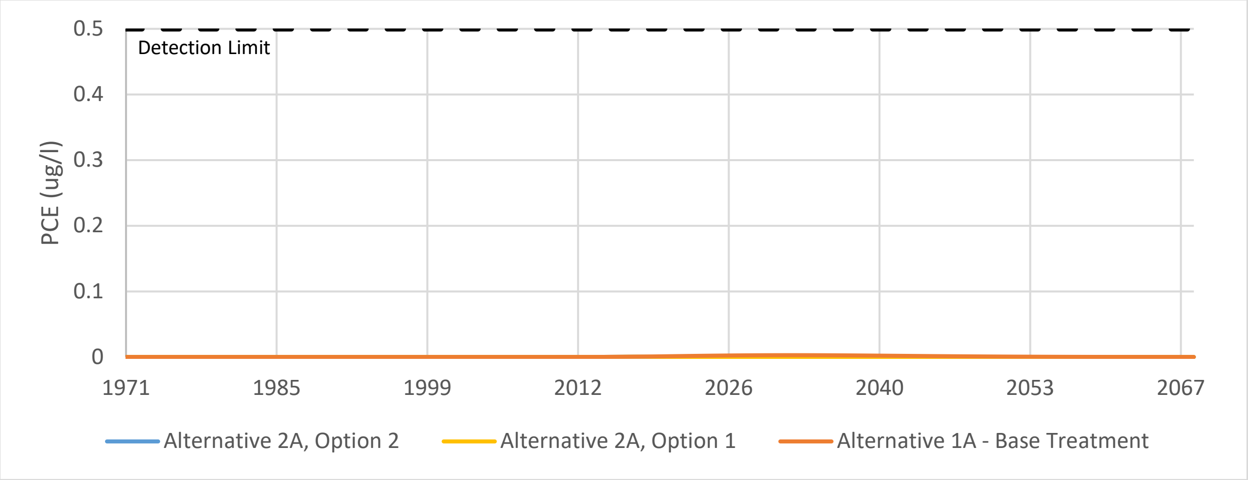

Figure 22. Breakthrough curve for LBWC 1 for Alternatives 2A, Option 2 (blue), 2A, Option 1 (yellow), and 1A – Base Treatment (orange).

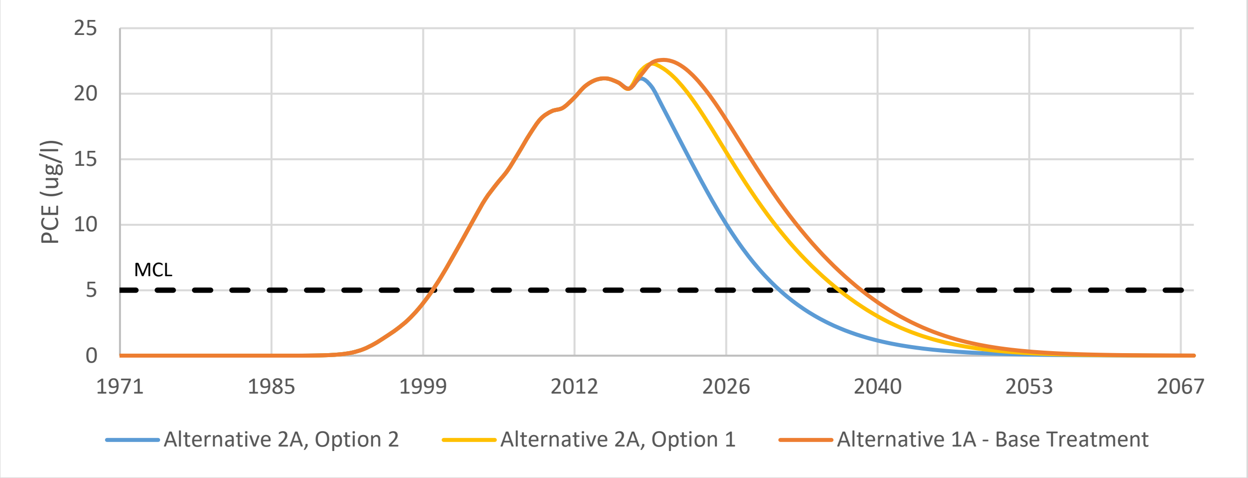

Figure 23. Breakthrough curve for LBWC 5 for Alternatives 2A, Option 2 (blue), 2A, Option 1 (yellow), and 1A – Base Treatment (orange).

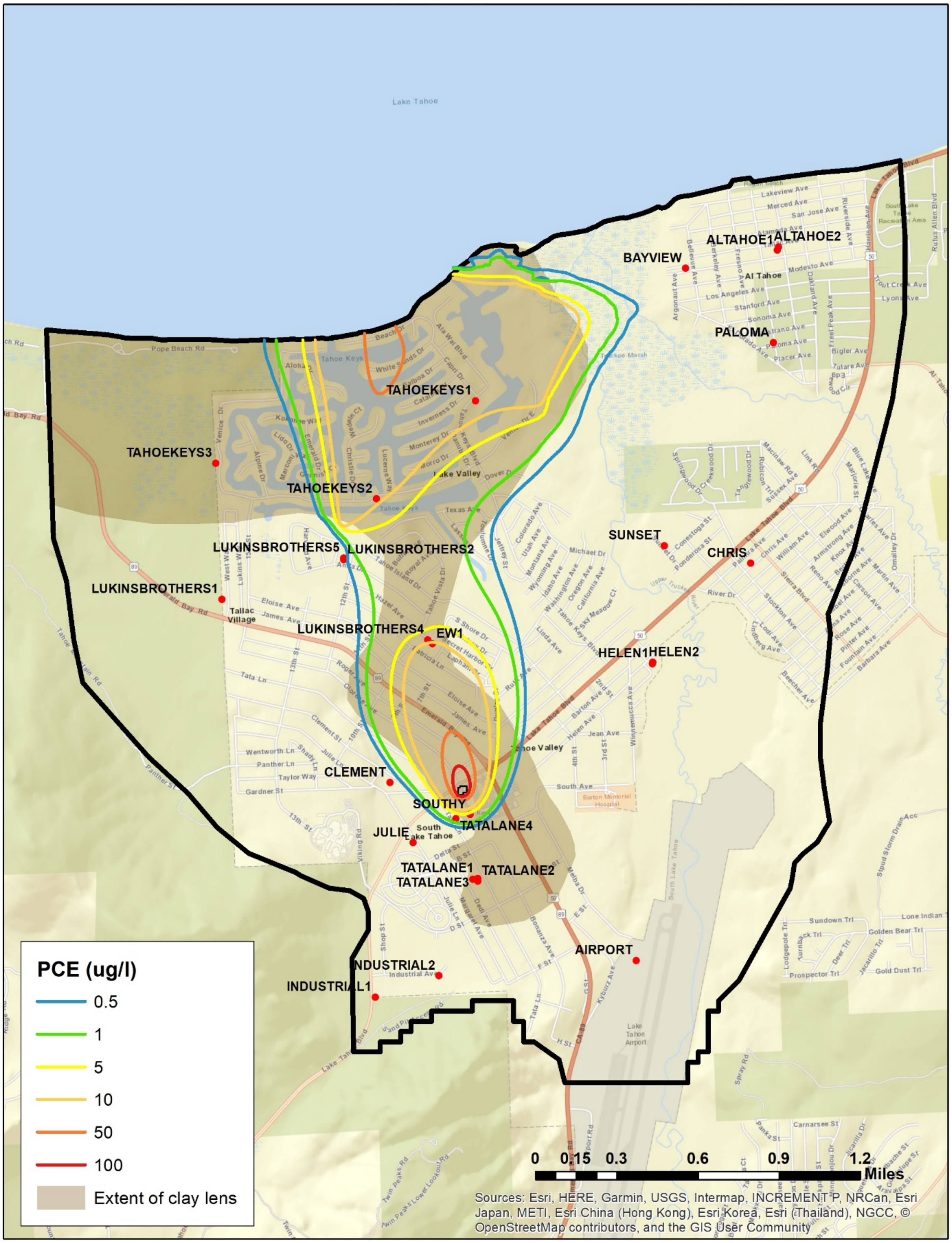

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Figure 24. Alternative 2B, Option 2 (Conservative). Simulated PCE plume in model layer 1 at the end of the 2068 water year.

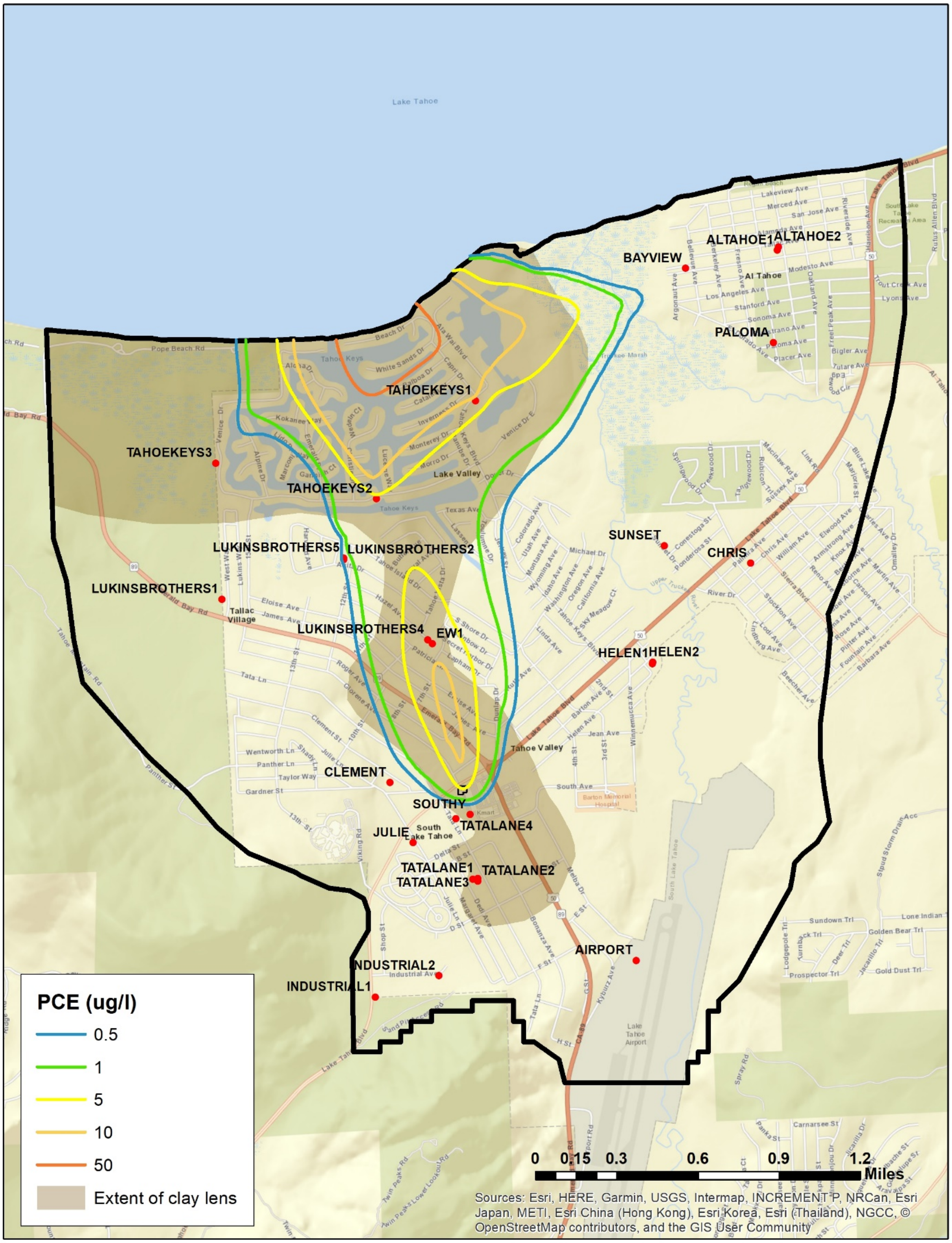

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Figure 25. Alternative 2B, Option 2 (Conservative). Simulated PCE plume in model layer 2 at the end of the 2068 water year.

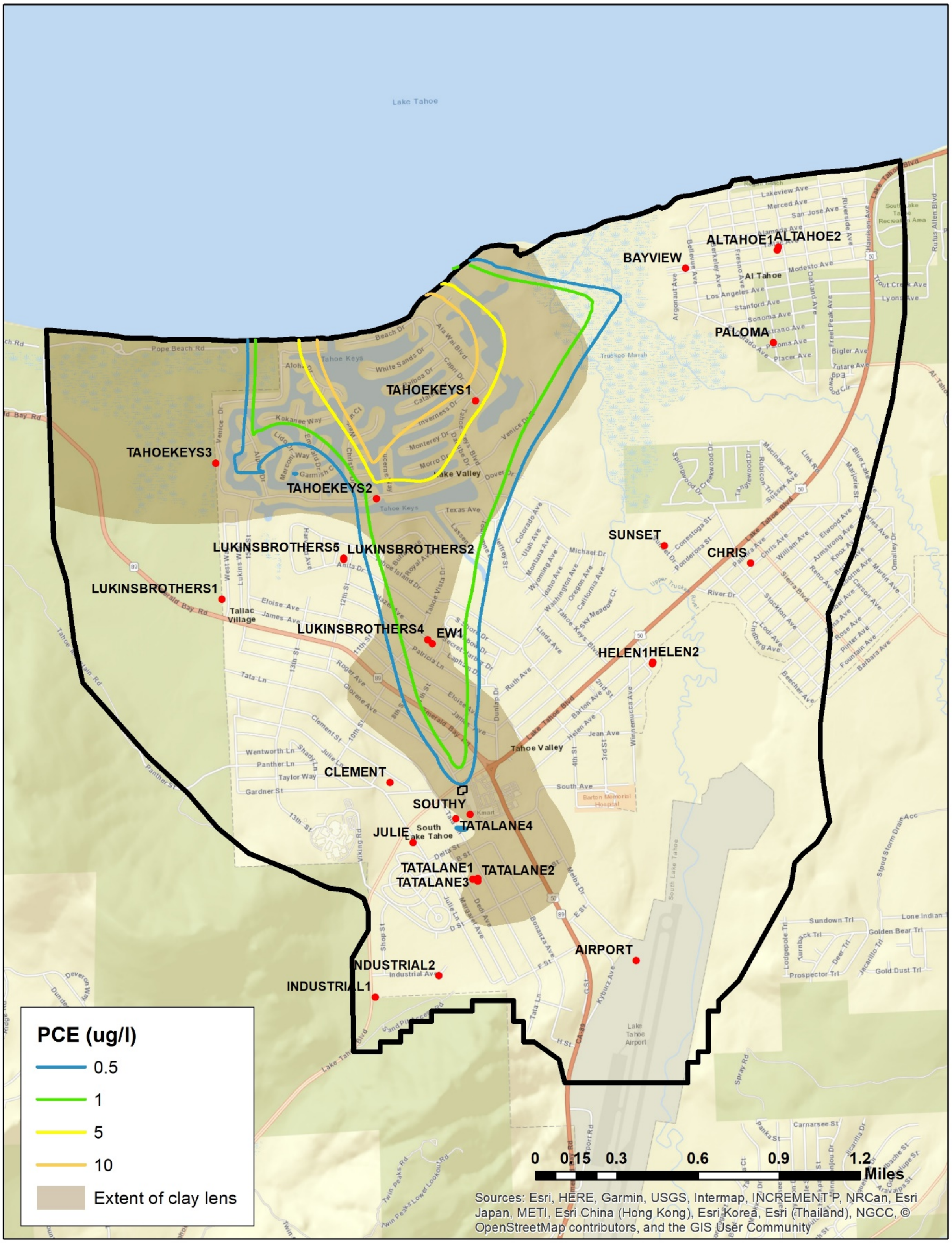

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Figure 26. Alternative 2B, Option 2 (Conservative). Simulated PCE plume in model layer 3 at the end of the 2068 water year.

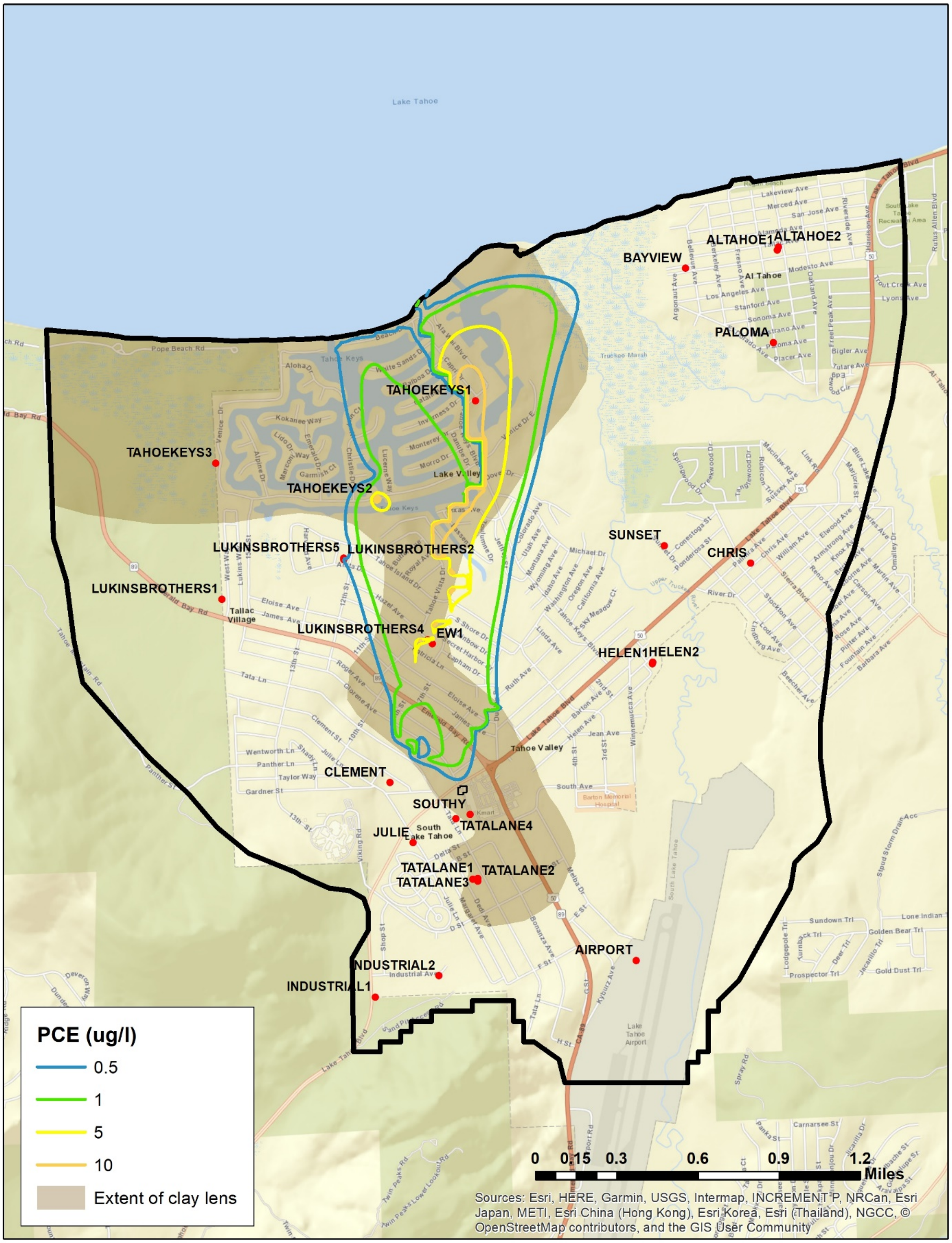

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Figure 27. Alternative 2B, Option 2 (Conservative). Simulated PCE plume in model layer 4 at the end of the 2068 water year.

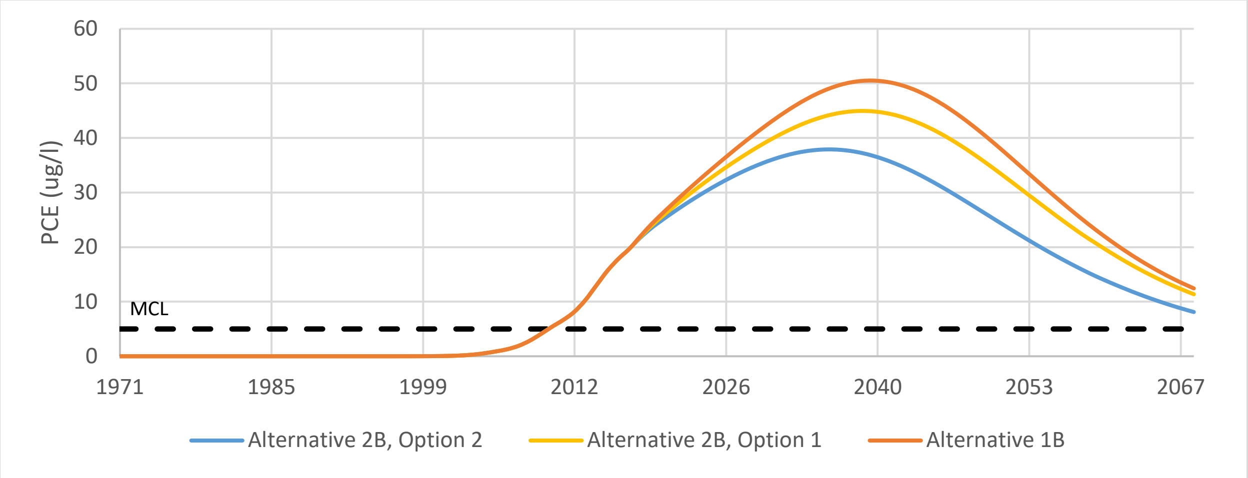

Figure 28. Breakthrough curve for TKWC 1 for Alternatives 2B, Option 2 (blue), 2B, Option 1 (yellow), and 1B – Base Treatment (orange).

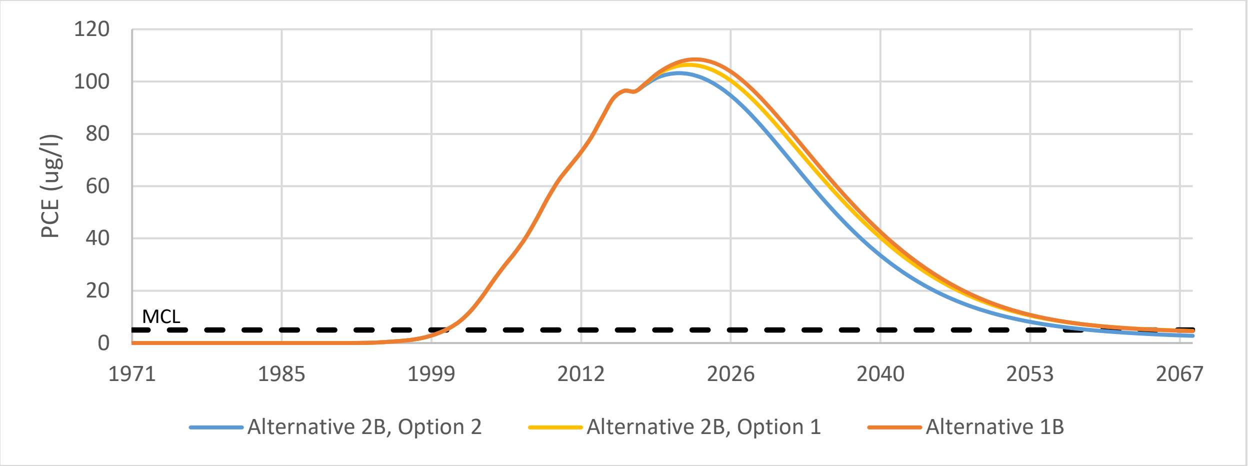

Figure 29. Breakthrough curve for TKWC 2 for Alternatives 2B, Option 2 (blue), 2B, Option 1 (yellow), and 1B – Base Treatment (orange).

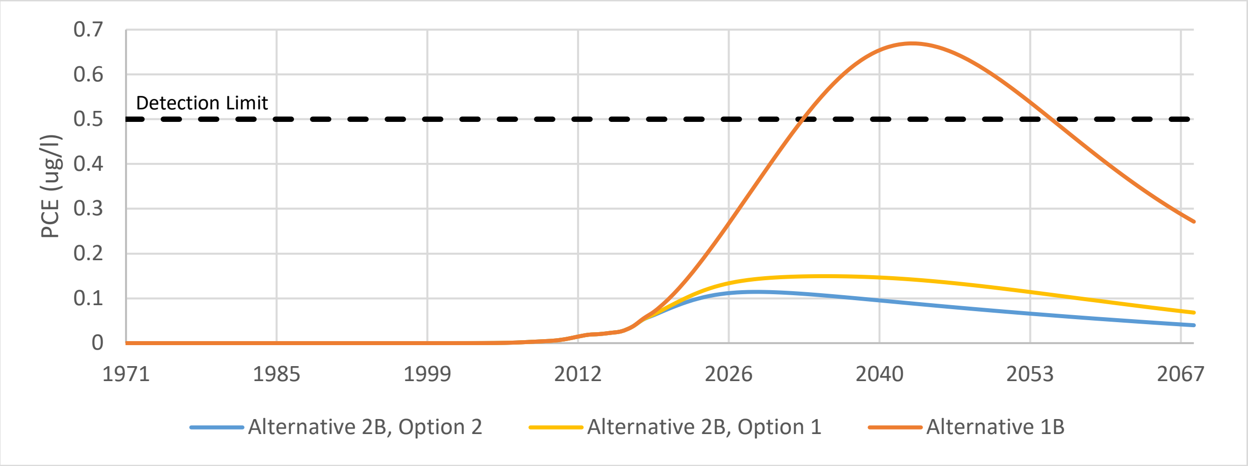

Figure 30. Breakthrough curve for TKWC 3 for Alternatives 2B, Option 2 (blue), 2B, Option 1 (yellow), and 1B – Base Treatment (orange).

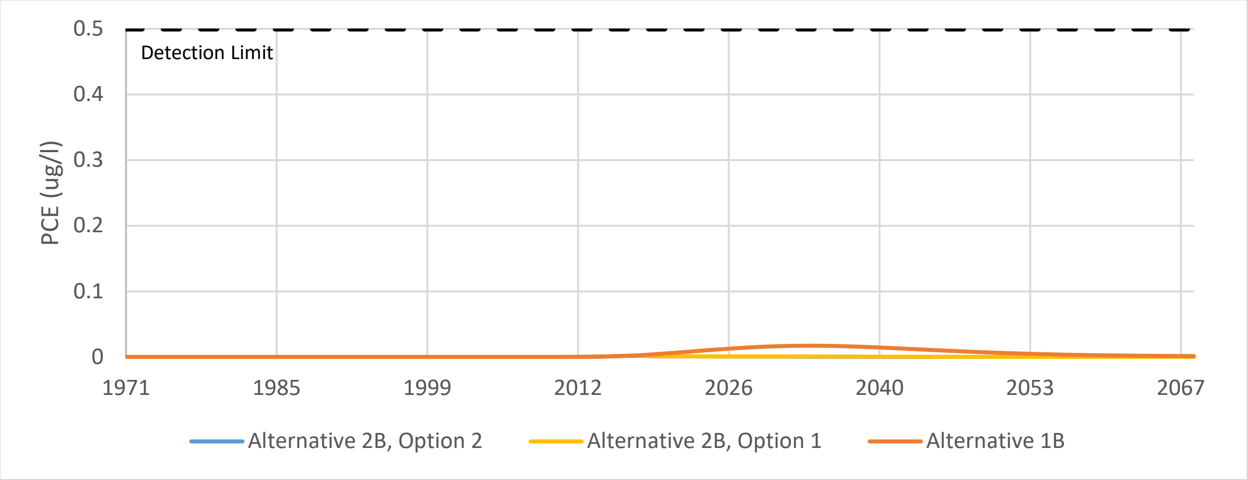

Figure 31. Breakthrough curve for LBWC 1 for Alternatives 2B, Option 2 (blue), 2B, Option 1 (yellow), and 1B – Base Treatment (orange).

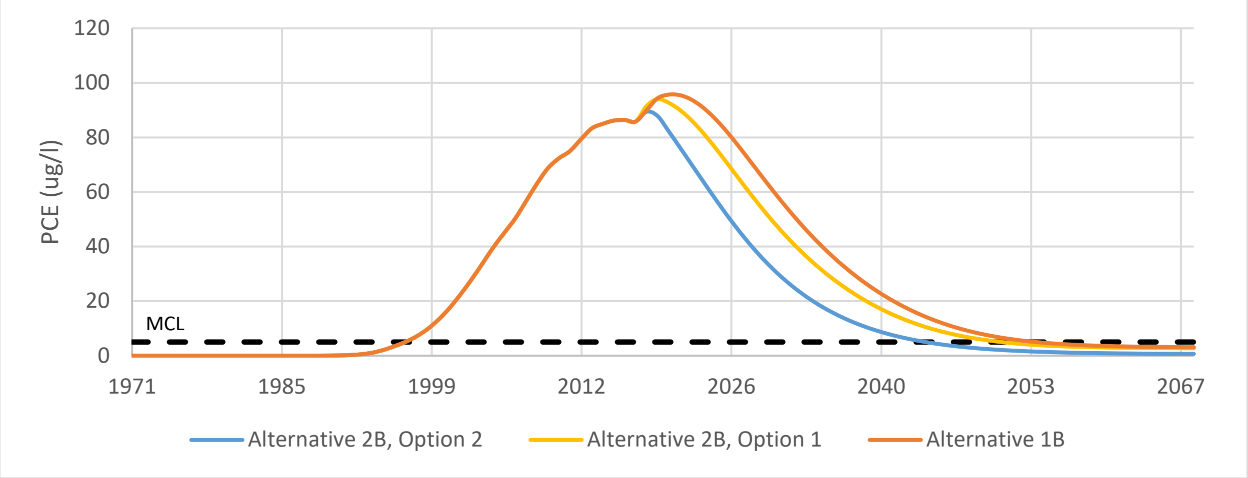

Figure 32. Breakthrough curve for LBWC 5 for Alternatives 2B, Option 2 (blue), 2B, Option 1 (yellow), and 1B – Base Treatment (orange).

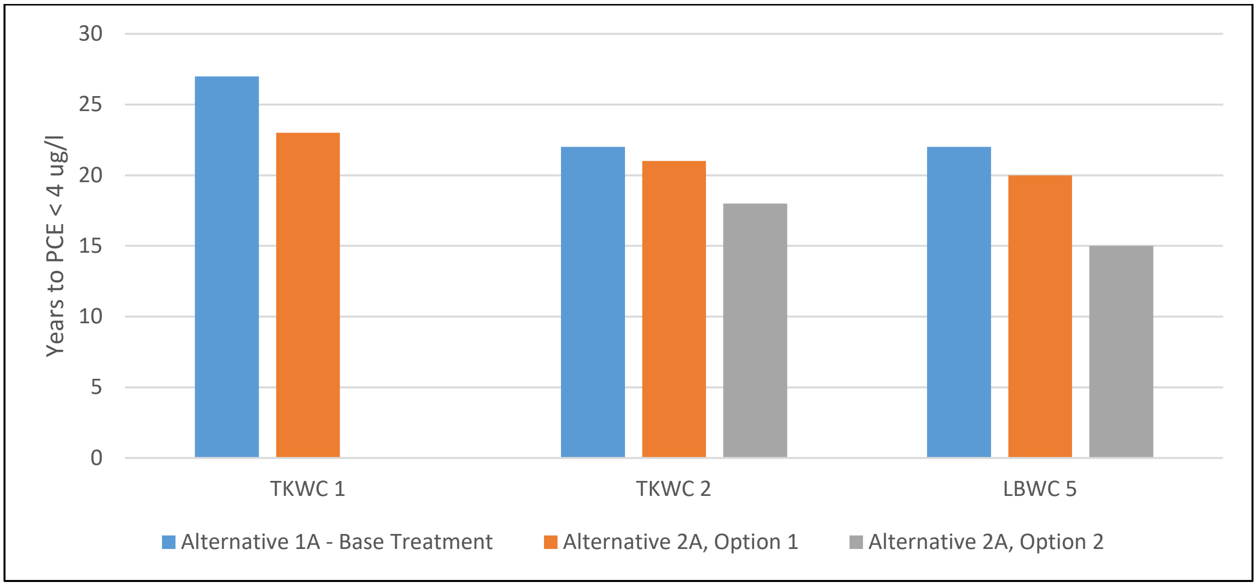

Figure 33. Years after 2018 until simulated PCE concentrations drop below 4 ug/l, by alternative and well. Concentrations at TKWC 1 never exceed 4 ug/l in Alternative 2A, Option 2.

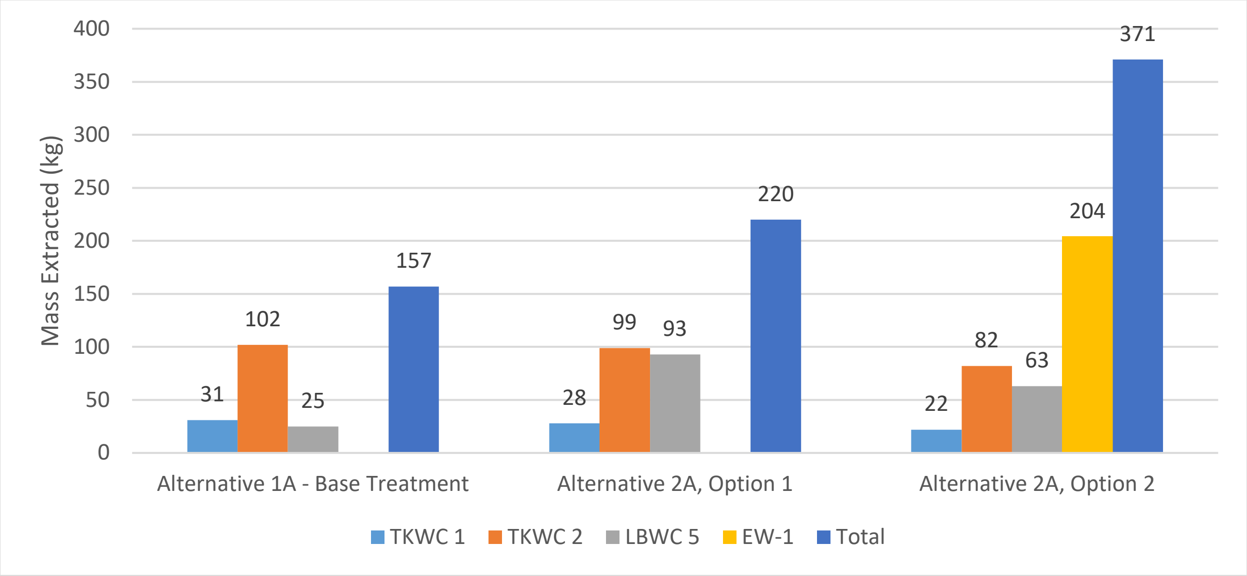

Figure 34. Mass extracted (in kilograms) by alternative and well. Note EW-1 does not pump in Alternative 1A or Alternative 2A, Option 1 and mass extraction at that well is therefore zero.

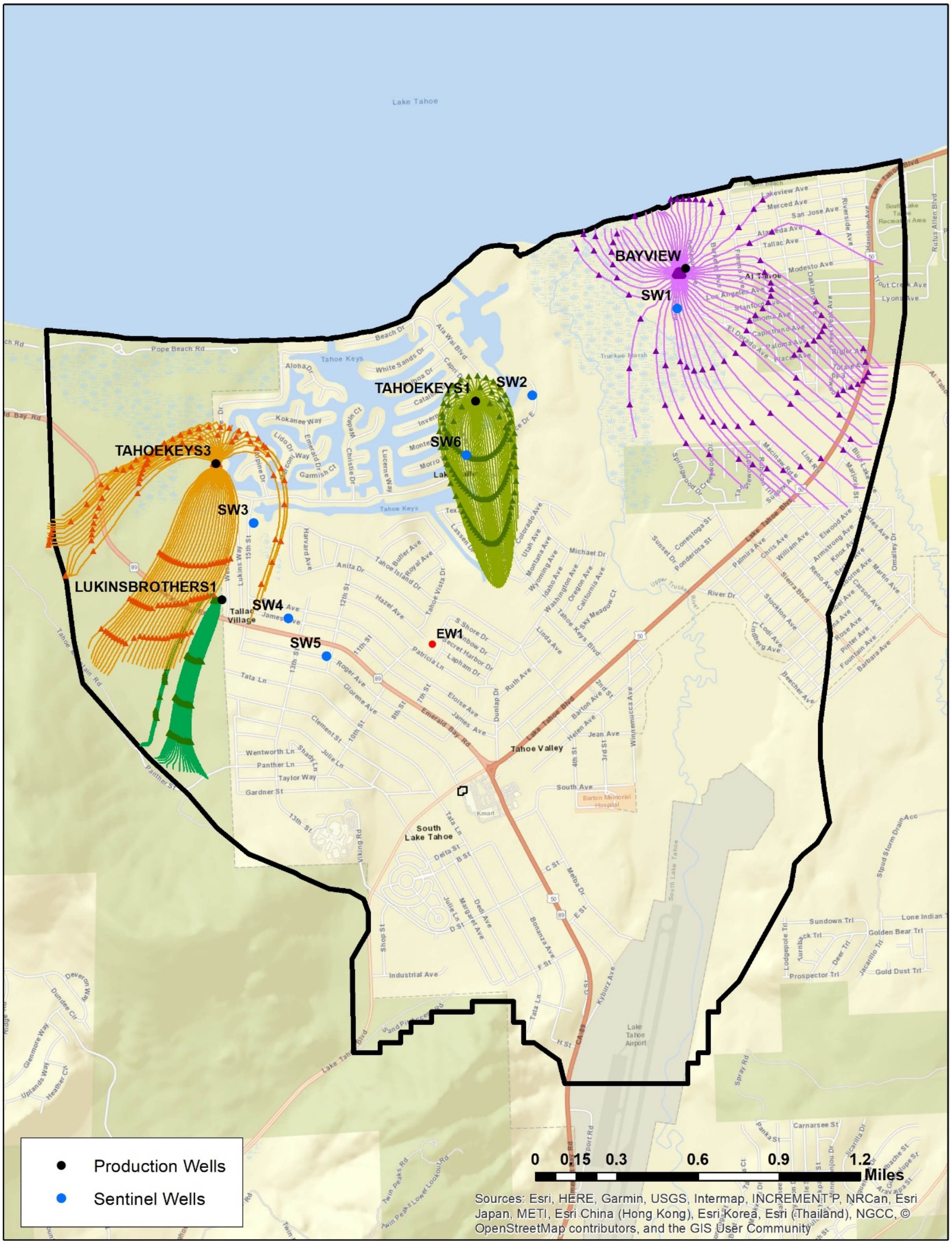

Figure 35. Reverse particle tracking results at four production wells (Bayview, TKWC 1, TKWC 3, and LBWC 1) for a 20 year time period. Triangle markers indicate 5 year intervals.

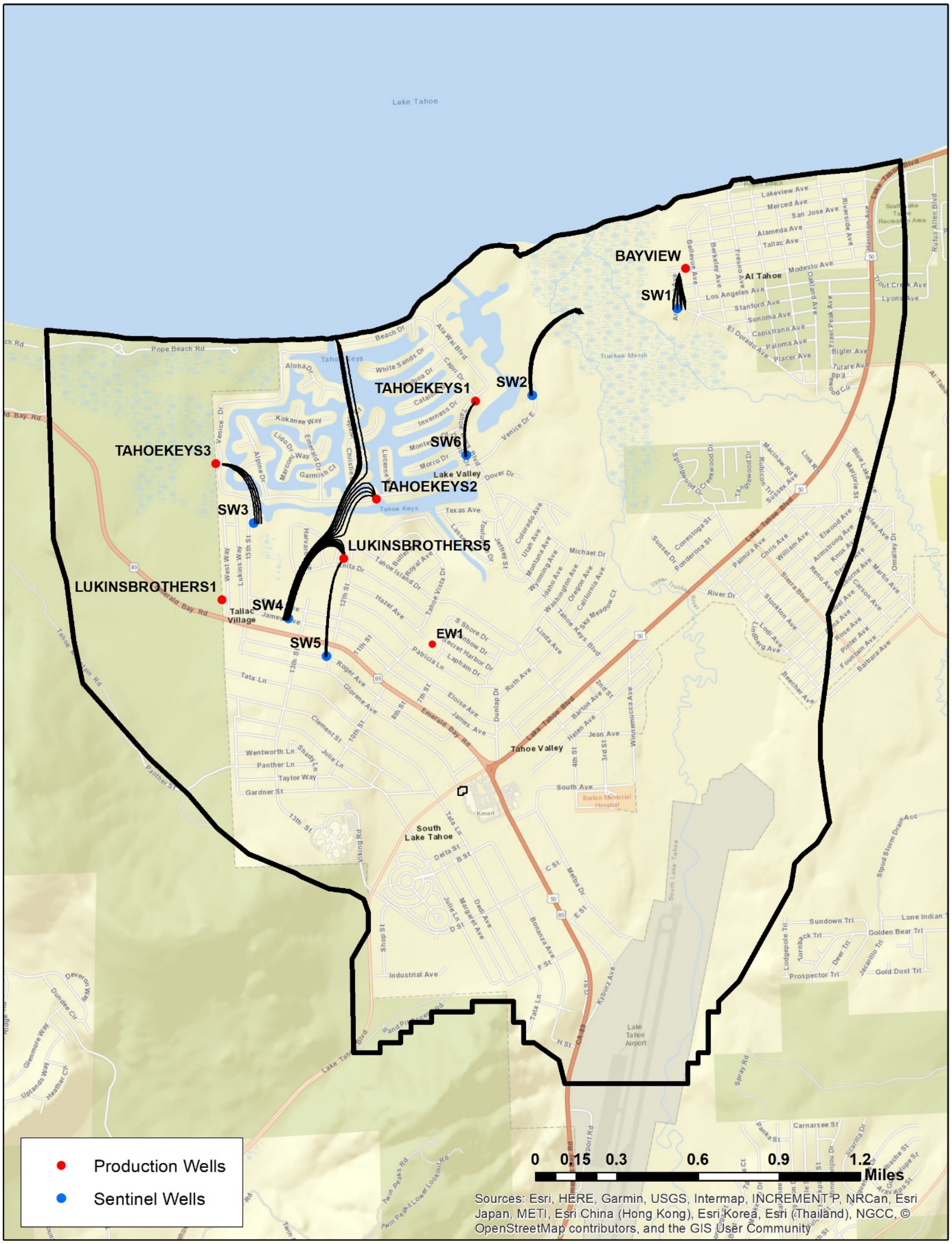

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Figure 36. Particle pathways from each prospective sentinel well location through the end of the model, or until the particle reaches a sink.

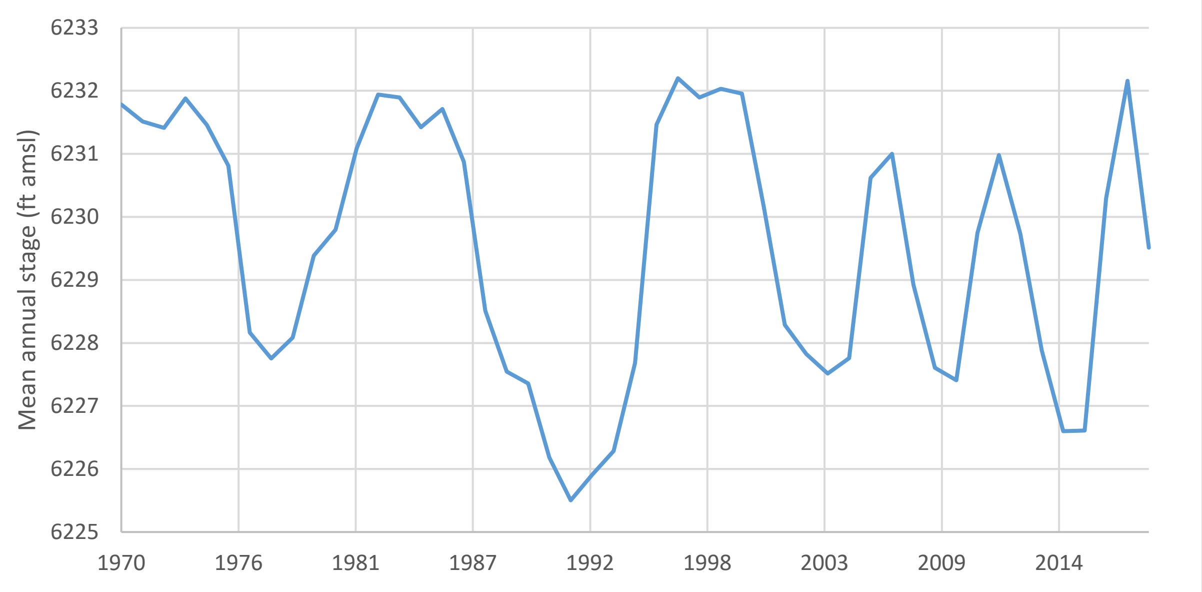

Figure 37. Mean annual stage by water year at Lake Tahoe used to define heads in the General Head Boundary along the northern boundary of the model.