14 September 2022

Technical Memorandum

To: Lillian Xie, Zone 7 Water Agency

Reviewed by: Jean Debroux, PhD; Melanie Tan, P.E.

From: Walt McNab, PHG; Cayla Whiteside

Subject: Analysis of PFAS Mobilization Under Various Pumping Scenarios
K/J 2168016*00

Zone 7 Water Agency (Zone 7) manages the Livermore Valley Groundwater Basin and is evaluating groundwater management options including artificial recharge with purified reclaimed water as well as contaminant mobilization and management under various pumping scenarios to meet water supply needs during droughts. These groundwater management options may potentially affect groundwater quality through chemical reactions between recharged water and the native aquifer mineralogy, or through changes in distributions of dissolved natural elements and anthropogenic compounds in response to altered groundwater flow pathways and gradients. The latter category includes the existing per- and polyfluoroalkyl substances (PFAS) plume present in both the upper and lower aquifer portions of the Livermore Valley Groundwater Basin.

This memorandum summarizes a groundwater modeling analysis of potential changes in the distribution of the PFAS plume under different drought management pumping scenarios, as compared to baseline conditions, using an existing MODFLOW groundwater flow model for the basin. The purpose of this memorandum is to provide background and supporting information for the Summary of PFAS Management Model Results (included in Appendix A). Pumping scenario definitions, modeling assumptions and limitations, and screening-level model results are described below.

1. Technical Approach

1.1 Pumping Scenarios

There was a total of five scenarios that modeled varied pumping rates for Zone 7's production wells. They consisted of one baseline scenario reflecting average pumping conditions (Scenario 1), and four other scenarios entailing increased pumping rates in selected wells in response to supply needs during drought. All scenarios span a 20-year simulation period and begin with a three-year drought. Three of the non-baseline scenarios (Scenarios 2, 3 and 5) include increased pumping only during this three-year drought period. A fourth scenario (Scenario 4) maintains an increased pumping rate over the full 20 years of simulation, including continuous injection at one location to maintain a sustainable water balance and to mitigate the downgradient migration of the PFAS plume. The baseline scenario and four other pumping scenarios are described in Table 1 below. One set of coordinates was selected to compare the four scenarios against the baseline.

Table 1. Summary of Pumping Scenarios

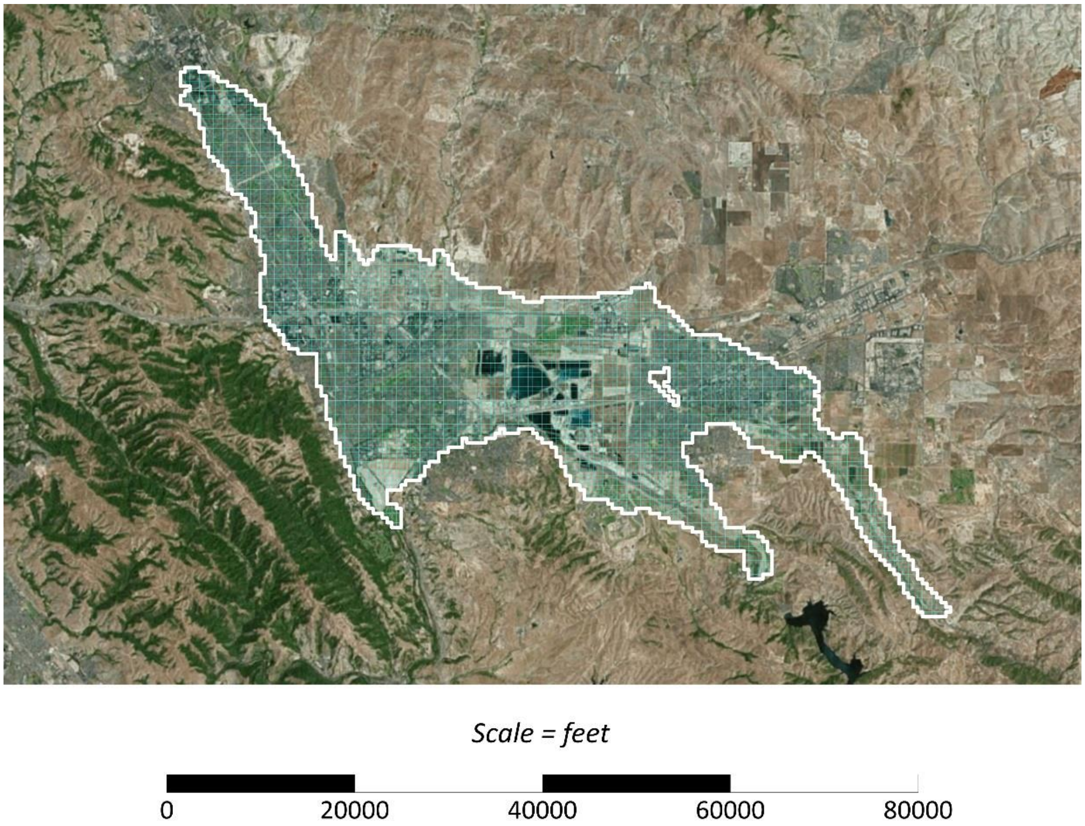
Scenario	Title	Description	Recharge	Zone 7 Production Wells Pumping Rates (AFY)										Zone 7 Pumping Rate
				Hopyard 6	Hopyard 9	Mocho 1	Mocho 2	Mocho 3	Mocho 4	Stoneridge	COL 1	COL 2	COL 5	
1	Baseline	Uses Zone 7's 5-year average well production (2016-2020)	-	670	70	-	1,060	1,660	760	930	520	1,070	160	20 years of average pumping rate (6,900 AFY)
2	Low State Water Project Allocation (No PFAS treatment)	Operations during a year with ~5% State Water Project allocation and no PFAS treatment.	-	5,140	1,540	-	-	630	1,980	4,850	-	-	-	3 years higher rate (14,140 AFY) + 17 years average (6,900 AFY)
3	Pump Clean Wells (No PFAS treatment)	Max production of wells currently unaffected by PFAS.	-	5,280	1,680	-	-	-	5,400	6,480	-	-	-	3 years higher rate (18,840 AFY) + 17 years average (6,900 AFY)
4	Pump and Treat PFAS Wells (PFAS treatment at COL, reinjection at Mocho 1)	Treatment of PFAS at the planned new facilities at Chain of Lakes and injection of water from Mocho 4 into Mocho 1.	5,400 AFY at Mocho 1	-	-	-	-	-	5,400	-	3,000	4,800	2,160	20 years of higher pumping rate (15,360 AFY)
5	Pump and Treat PFAS Wells (PFAS treatment at COL and MGDP)	Treatment of PFAS at the planned new facilities at Chain of Lakes and at the Mocho Groundwater Demineralization Plant.	-	-	-	-	3,360	5,280	5,400	-	3,000	4,800	2,160	3 years higher rate (24,000 AFY) + 17 years average (6,900 AFY)

1.2 Groundwater Flow Model

The groundwater flow model used for the PFAS mobilization simulations is a regional-scale MODFLOW model (McDonald and Harbaugh, 1988) for the Livermore Valley (Hydrometrics, 2017). This model (2014 Revised Baseline 10-Layer Model), which is based upon the NWT version of MODFLOW (Niswonger et al., 2011) consists of a uniform 500-foot x 500-foot grid (Figure 1) extending across 10 layers that represent the underlying aquifer-aquitard structure of the basin. The white boundary shown in Figure 1 represents the extents of the model. The small area in the eastern portion represents a rock outcropping where groundwater flow is not present; this area is not included in the model. A cross-section diagram showing the model layers within the groundwater basin is included in Appendix B. Supporting MODFLOW packages include:

- Recharge (RCH): for percolating precipitation extending beneath the root zone, in addition to irrigation;
- Lake (LAK): to simulate groundwater-surface water interactions, along with evaporation and direct precipitation, with respect to the Chain of Lakes (a series of lakes in the Livermore Valley);
- Stream Flow Routing (SFR): to simulate groundwater-surface water exchanges and stream flows along the arroyos;
- Multi-node Well (MNW): to simulate extraction from wells screened across multiple layers/aquifers, including interlayer groundwater through wellbores;
- Horizontal Flow Barrier (HFB): to simulate the impacts of faults on horizontal groundwater flow.

Figure 1. Livermore Valley Groundwater Model Spatial Extent and Grid



The version of the Livermore Valley groundwater model used in the PFAS modeling is characterized by cyclical wet and dry seasons that represent average hydrology extending over a ten-year period. This ten-year period is implemented twice in a row to create the 20-year simulation period. Each season corresponds to a model stress period, and each model stress period is broken into three timesteps. The wet and dry seasons were established on an annual basis and the pumping and recharge conditions in each season were scaled to reflect expected pumping and recharge during each season, while still meeting the annual pumping and recharge rate. An initial two-year equilibration phase, which entails time-averaged pumping and recharge, precedes the 20-year simulation period. The 20-year simulation period is comprised of a 3-year drought followed by 17 years of wet and dry seasons.

Figure 2 compares water inputs and outputs modeled in the baseline pumping scenario (noted as "MODFLOW") against the basin's long-term sustainable average as calculated by Zone 7 (noted as "Sustainable Average[1]"). Model results correspond to water budget summaries listed at the end of each stress period with respect to external sources (recharge package, lake package, stream package, etc.), averaged between wet and dry conditions. Differences between input and output fluxes represent the net water budget terms, expressed as volumetric water per unit time. In Figure 2, net inputs are shown as positive fluxes (in acre-feet per year (AFY)) and net outputs are shown as negative fluxes.

- The storage is very close to zero for the model, representing that the inflows and outflows are approximately in balance.

- Underflow is the estimated flux of groundwater from adjacent basins into the main groundwater basin in the valley. There is no equivalent flux to represent underflow in the model. There are other external and internal fluxes present (recharge, stream leakage, lakes, etc.), but the model does not have a way to represent underflow.

- As shown in Figure 2, there is general agreement between the modeled and estimated sustainable average water budget components; minor differences with respect to underflow and recharge are largely attributable to spatial coverage differences between the model and the sustainable average data set.

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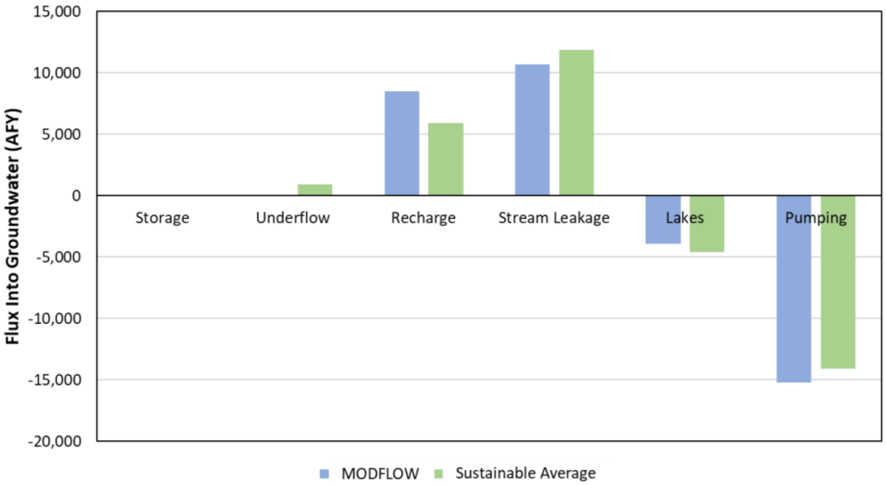
[1] The sustainable average calculation is described in the Alternative Groundwater Sustainability Plan 2021 Update for the Livermore Valley Groundwater Basin, dated December 2021.

Figure 2. Comparison of Water Balances: Baseline Pumping Scenario and Sustainable Average



The MT3D-USGS solute transport model (Bedekar et al., 2016) for MODFLOW was used to simulate PFAS mobilization through groundwater under the influence of both ambient groundwater movement and the hydraulic influences of the different pumping scenarios. Implementation of MT3D-USGS for this application included the Lake Transport (LKT) package and the Stream Flow Transport (SFT) package additions. To simulate both flow and transport over a period of 20 years, the 10-year groundwater model was run twice (after the initial two-year equilibration period), with final conditions for both groundwater flow and PFAS concentrations used as initial conditions for the second model run. For each pumping scenario, drought conditions, which entailed reduction of recharge by 30 percent for three consecutive years, follow the initial two-year equilibration period.

Solute transport modeling across all scenarios assumed the following:

(1) PFAS behaves as a conservative solute and is not affected by adsorption or desorption to/from the soil.

(2) Degradation or breakdown of PFAS over time is not modeled since PFAS is persistent in the environment.

(3) The sources of the existing PFAS plume are no longer active such that there is no ongoing PFAS discharge to the system. This assumption was relaxed in the context of setting initial conditions, as described in the next section.

(4) The longitudinal, transverse, and vertical dispersivities were assigned values of 1,000 feet, 100 feet, and 10 feet, respectively, across the model domain in each model scenario. Porosity was assumed to be equal to 0.25.

1.3 Initial Conditions for Solute Transport

PFAS concentration data from approximately 100 monitoring locations in the Livermore Valley Groundwater Basin, including multi-screened or nested monitoring wells, were used to posit initial distributions of dissolved-phase PFAS. Perfluorooctane sulfonate (PFOS), a type of PFAS, was used as a surrogate to represent all PFAS compounds in the basin. PFOS was chosen because it was detected most frequently and was characterized by the highest concentrations in the monitoring well data set. Only data collected since 2018 were used, with the maximum value chosen when data from multiple sampling events was available at the same individual well or for screened intervals within an individual well. Appendix C includes the PFOS sample data used to establish the initial concentrations in the model.

Initial concentrations were assigned to model grid cells in accordance with the following procedure:

1. Observed PFOS concentrations were parsed by model layer, with a concentration assigned to a particular monitoring well location only if the screened interval for that well partially or fully crosses the layer.

2. PFOS concentrations within each layer were then distributed using a simple linear interpolation scheme with triangulation between the locations identified in Step 1.

3. For the initial two-year hydrologic equilibration period noted in the previous section, the interpolated starting PFOS concentrations were subject to advective and dispersive transport under baseline conditions, resulting in a more diffuse plume with an accompanying reduction in the sharp concentration gradients introduced as an artifact of the interpolation in Step 2. At the same time, the concentrations of PFOS at comparative “hot spots”, such as Well 10B, Pleasanton 8, or the Mocho well cluster, were maintained as constant concentration grid cells during this time. The resultant initial conditions are shown on Figure 3 through Figure 4 for two model layers: Layer 4 and Layer 8. Layer 4 was selected to represent the upper aquifer because it is above the confining layer in the

aquifer but is less influenced by lake infiltration than Layer 2. Layer 8 was selected to represent the lower aquifer because most of the wells in the Groundwater Basin are screened within this layer. A coordinate, symbolized with a pink star, was chosen to compare the modeling results across the five pumping scenarios (refer to Section 2: Model Results). <u>With limited three-dimensional monitoring data resolution and a short sampling history for PFOS for most of the wells in the data set, these starting concentrations should be considered highly provisional and are intended for comparison at a scenario screening level.</u>

4. After the two-year initial hydrologic equilibration period, the constant-concentration conditions at selected “hot spots” were relaxed and the plume was subjected to continued simulated advection and dispersion. In the absence of additional constraining data or investigation insights, neglecting additional source inputs will significantly impact the overall accuracy of the model results with time. <u>Consequently, solute transport results should be viewed as comparative for purposes of evaluating proposed pumping scheme impacts against the baseline scenario, rather than as absolute predictions.</u>

To complement the groundwater PFOS data sets, limited surface water PFOS concentration measurements from Lakes H, I, and Cope Lake from the Chain of Lakes during the same time period were reviewed. Maximum concentrations from these data were chosen to represent initial concentrations for the LKT package.

The lakes modeled by the LAK (MODFLOW) and LKT (MT3D-USGS) packages extend down to model Layer 4, at most. Within Layer 4, only seven PFOS groundwater concentration data points exist (Wells 10B8, 11G1, 13P5, 19D7, 19N3, 4J6, and 9J7), with only four of these characterized by detections. This implies that Layer 4 is poorly characterized with respect to PFOS concentration distributions and, by extension, so are the modeled lake concentrations. Consequently, PFOS concentration for the remaining lakes lacking observational data were simply assigned a fictious starting value of 1 nanogram/liter. In Figure 3 below, the PFOS concentrations in the Chain of Lakes is not shown in Layer 4; the lakes are simply represented by a grey outline.

It should also be recognized that lake solute behavior in MT3D-USGS packages is highly idealized and assumes perfect mixing. Wind effects and seasonal turnover are not considered. Moreover, the neglect of possible continuing sources of PFOS as well as adsorption used in the groundwater model is extended to the lakes and thus contributions of surface runoff and transport retardation through the lake sediments are not modeled. Finally, the lake bottom leakance terms are also based on the flow model calibration but not solute transport. Consequently, the simulated lake concentrations over time are unconstrained/untested. These are included in the model for purposes of maintaining process continuity but otherwise are not a focus of this assessment.

Figure 3. PFOS Concentration Distribution in Layer 4 (Upper Aquifer) after Initial Two-year Equilibration Period

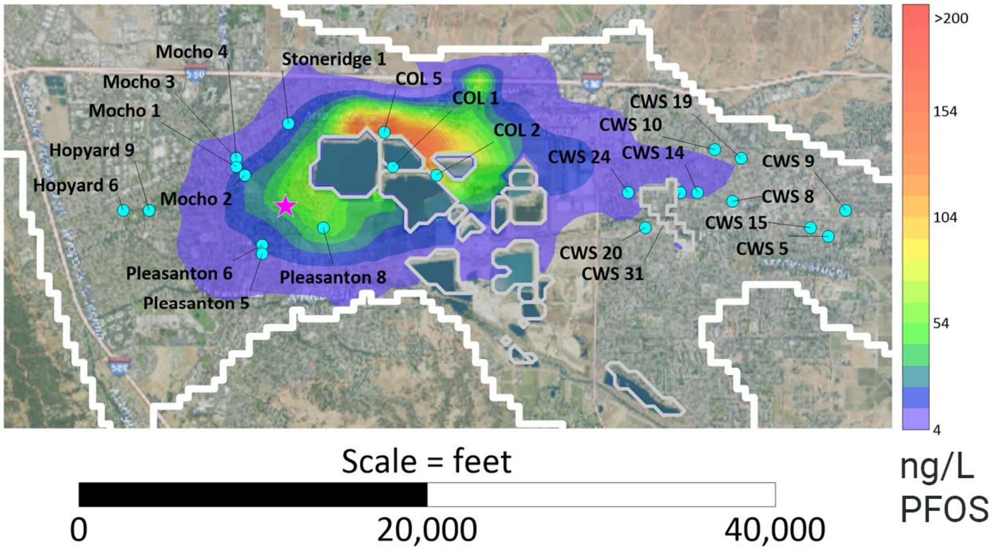
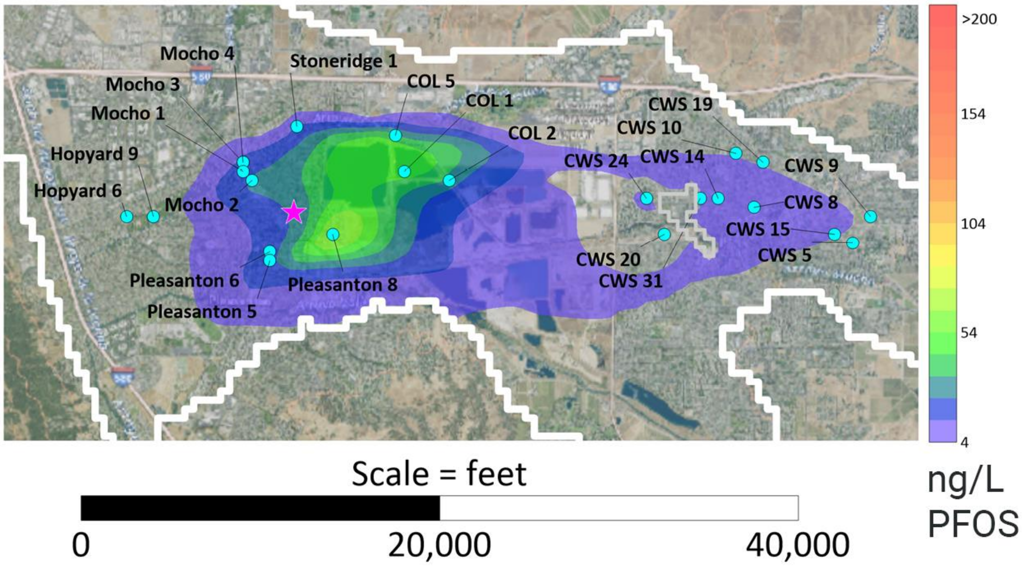


Figure 4. PFOS Concentration Distribution in Layer 8 (Lower Aquifer) after Initial Two-year Equilibration Period



2. Model Results

The distributions of modeled PFOS concentrations from Layers 4 (Upper Aquifer) and 8 (Lower Aquifer) – representing the upper and lower portions of the Livermore Valley groundwater basin aquifer system, respectively – are summarized at the end of the three-year drought period and at the end of 20 years in Figure 5 and Figure 6. Figure 7 plots simulated PFOS concentrations as a time series at the location indicated by the pink star symbol on each of the plume maps (Figures 3 – 6).

- In the short-term (i.e., end of the three-year drought), the PFOS plume is subject to spreading, dilution, and some downgradient movement, primarily evident in Layer 8. The additional short-term pumping associated with Scenarios 2, 3, and 5 exerts only very minor spreading impacts relative to Scenario 1.

- In the longer-term (i.e., 20 years), some additional simulated plume spreading and downgradient movement occurs. Because Scenarios 2, 3, and 5 revert to baseline pumping conditions after three years, no additional changes in these plumes is evident.

In contrast, Scenario 4, which entails both re-injection and continuous operation over the full 20-year period, results in some blunting of downgradient PFOS movement relative to the other scenarios. This result is evident in both Layers 4 and 8.

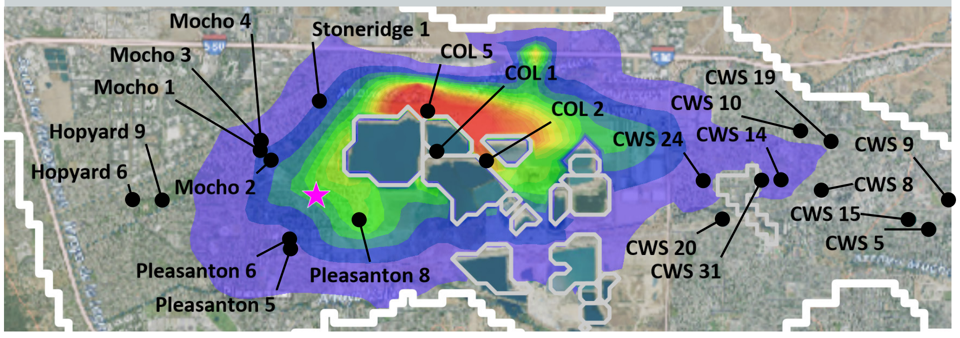
- The pink star location was selected for comparison due to its proximity to the Mocho wellfield and Pleasanton 8 well and because it is on the western edge of the plume. At this location, Scenarios 2, 3, and 5, which have increased pumping rates during the three-year drought, experience a higher PFOS concentration compared to Scenario 1 in the short-term. However, once Scenarios 2, 3, and 5 revert to baseline pumping for the remaining 17 years, their PFOS concentrations converge closely with Scenario 1 at the end of 20 years. Scenario 4 involves injection into Mocho 1, which does not occur in the other scenarios. The injection affects the movement of groundwater and could cause initial higher concentrations of PFOS that have not experienced significant mixing and dilution to move toward the pink star location in the short-term in the upper aquifer. However, in the longer-term, the PFOS concentration decreases at the pink star location in the upper aquifer due to long-term mixing and dilution combined with the altered groundwater flow from injection. The short-term increase in PFOS concentration at the pink star location in the upper aquifer is likely due to the model representing initial PFOS concentrations as localized hotspots that have not been well mixed at the start of the simulation. In the lower aquifer, Scenario 4 experiences lower PFOS concentration throughout the whole 20 years.

In summary, the hypothesized pumping scenarios (particularly scenarios 2, 3, 5) – which are intended to address drought management - do not appear to appreciably worsen the PFOS groundwater impact by significantly expanding the plume footprint. A strategy of increased pumping coupled with reinjection (i.e., Scenario 4) indicates promise for more directly preventing westerly plume expansion and should be explored further. Note that the nearby Mocho 4 well serves as an important production well for Zone 7.

As noted, all modeled PFOS plume comparisons are relative and should not be used to predict exact future values of PFAS. The model results indicate general patterns of PFAS mobilization under various pumping stresses. A water quality monitoring program to detect PFAS concentration in sentry locations to track actual movement of the PFAS plume will be helpful for future model analyses.

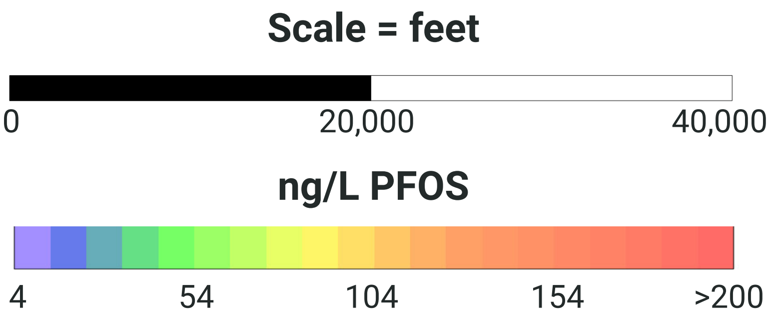
Figure 5. PFOS Concentration Distributions in Layer 4 (Upper Aquifer) after 3-year Drought and after 20 years

PRE-DROUGHT CONDITIONS

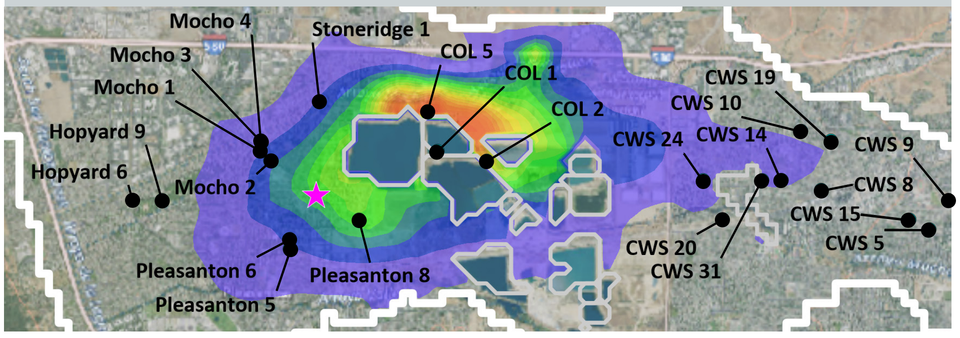


Modeled PFOS Levels (ng/L) in Upper Aquifer, Pre-Drought Conditions. (Same as Figure 3).

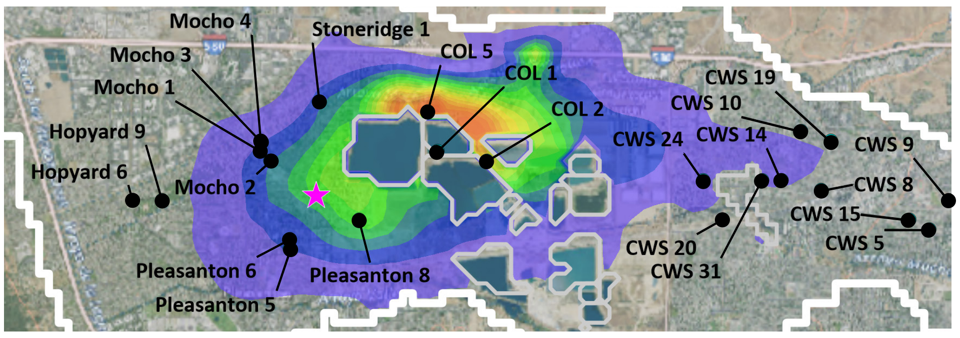
Note: CA PFOS Response Level = 40 ng/L



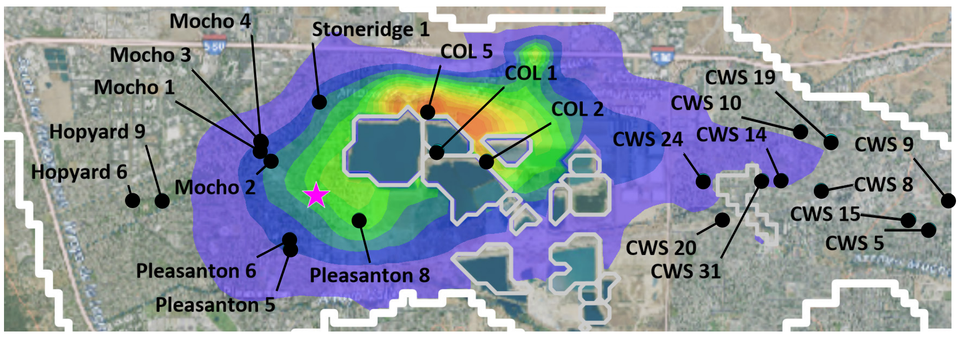
END OF 3-YEAR DROUGHT



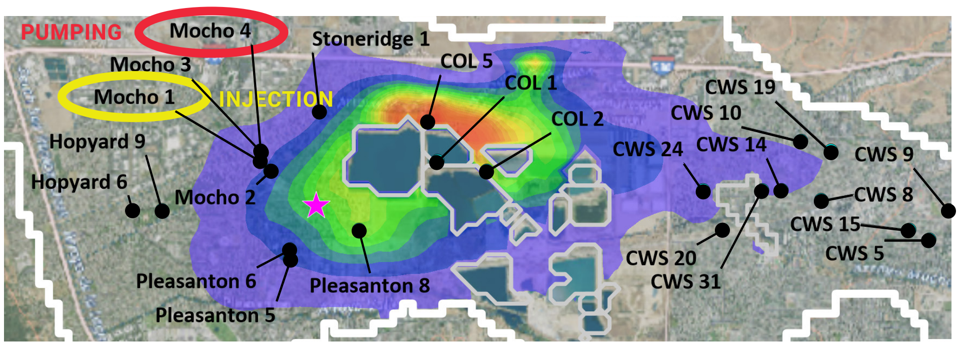
Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 1 – Baseline Condition.**



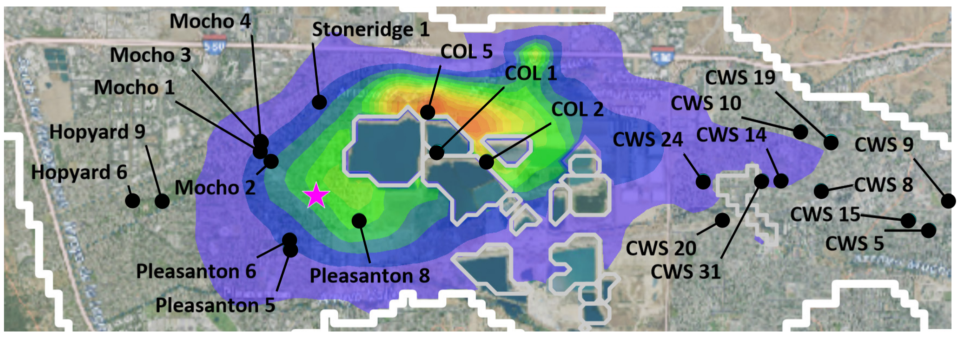
Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 2 – Low SWP Allocation (No PFAS Treatment).**



Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 3 – Pump Clean Wells (No PFAS Treatment).**

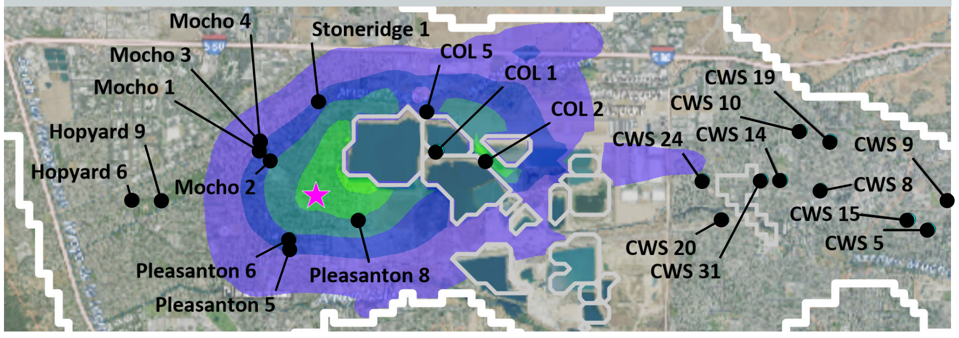


Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 4 – Pump & Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1).**

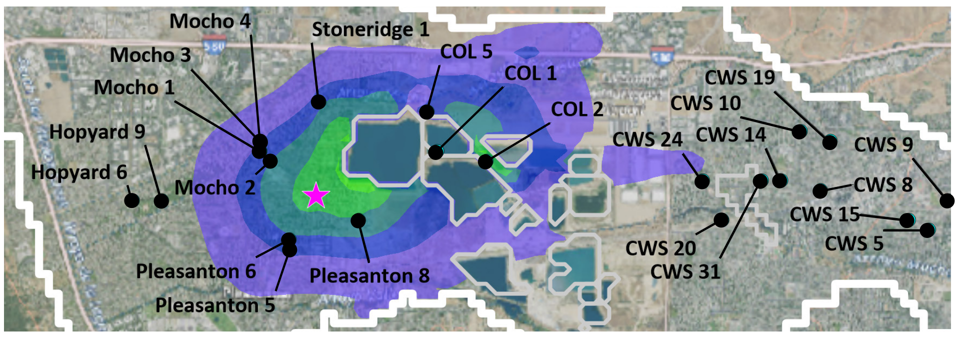


Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 5 – Pump & Treat PFAS Wells (PFAS Treatment at COL & MGDP)**.

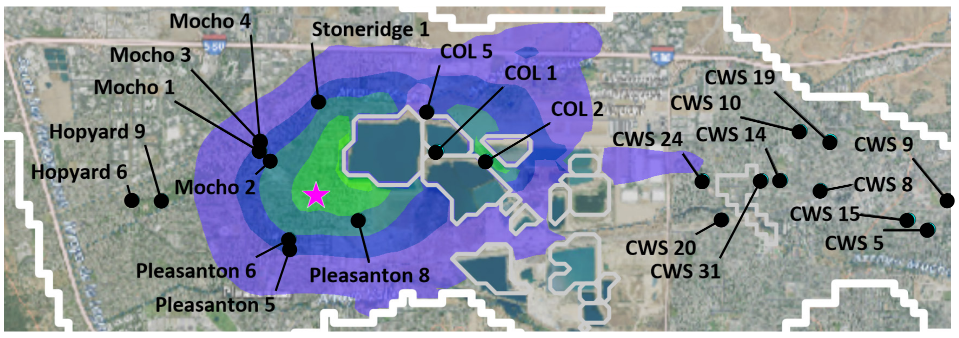
END OF 20 YEARS



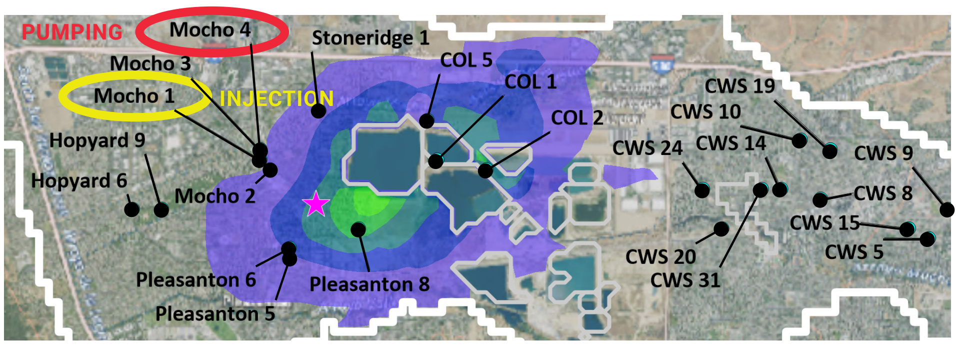
Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 1 – Baseline Condition.**



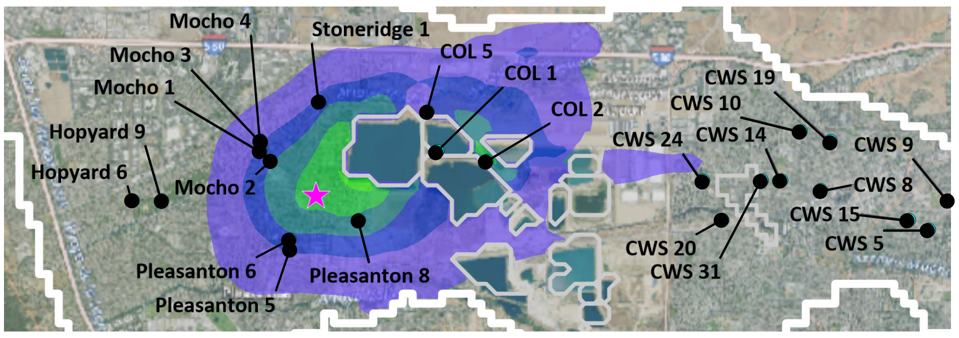
Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 2 – Low SWP Allocation (No PFAS Treatment).**



Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 3 – Pump Clean Wells (No PFAS Treatment)**.



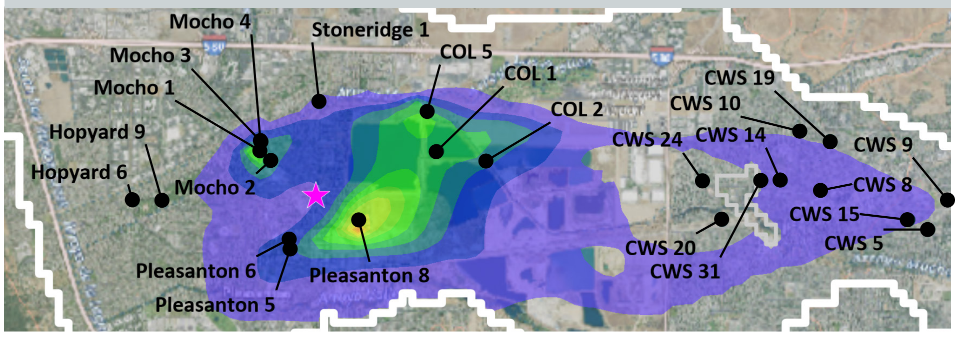
Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 4 – Pump & Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1).**



Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 5 – Pump & Treat PFAS Wells (PFAS Treatment at COL & MGDP)**.

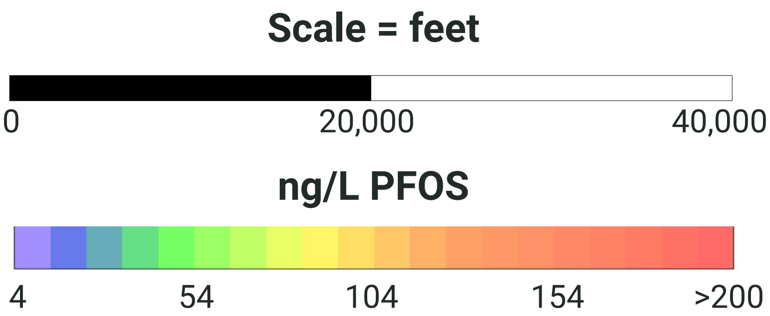
Figure 6. PFOS Concentration Distributions in Layer 8 (Lower Aquifer) after 3-year Drought and after 20 years

PRE-DROUGHT CONDITIONS



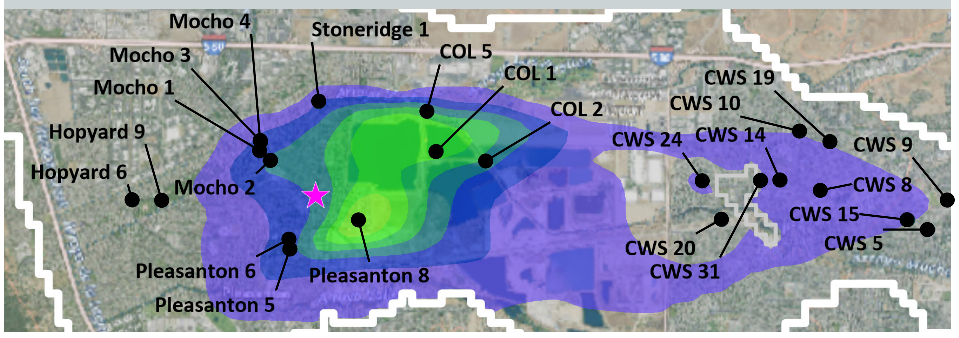
Modeled PFOS Levels (ng/L) in Lower Aquifer, Pre-Drought Conditions. (Same as Figure 5).

Note: CA PFOS Response Level = 40 ng/L

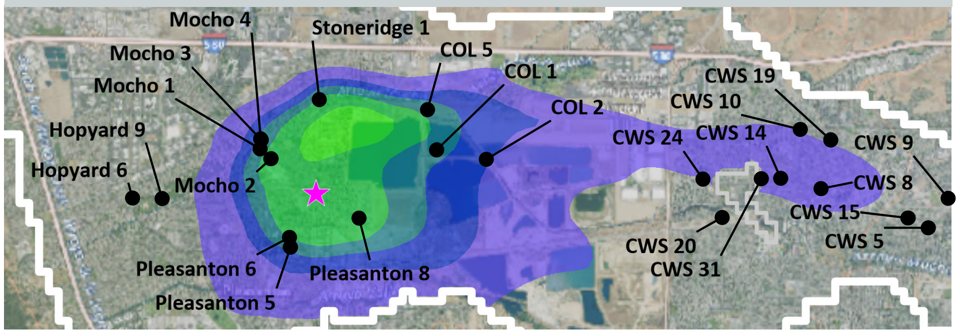


END OF 3-YEAR DROUGHT

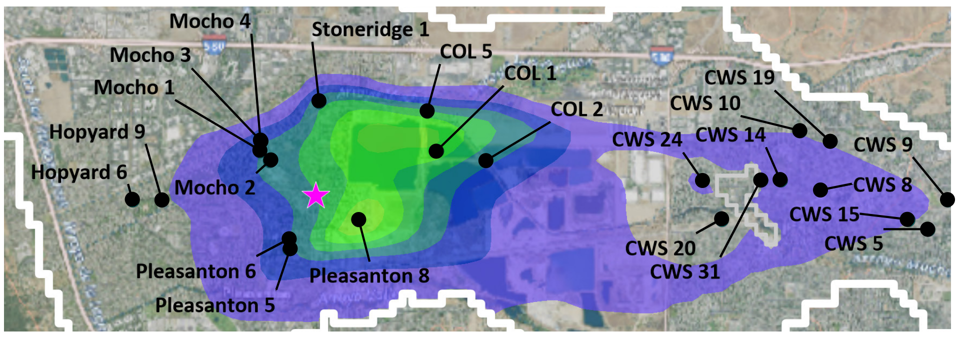
END OF 20 YEARS



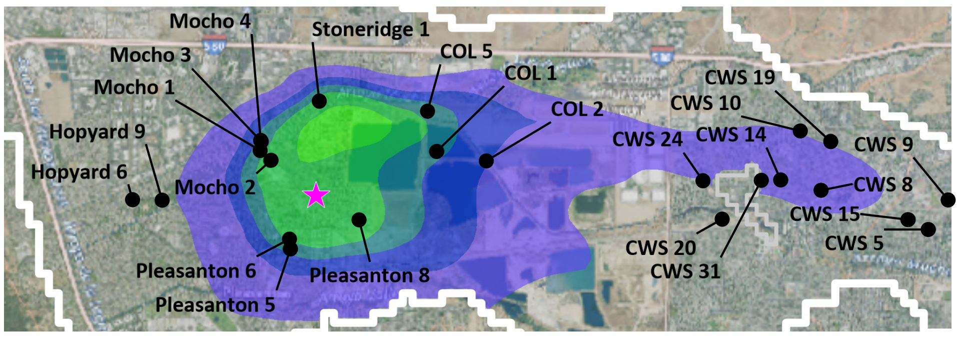
Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 1 – Baseline Condition.**



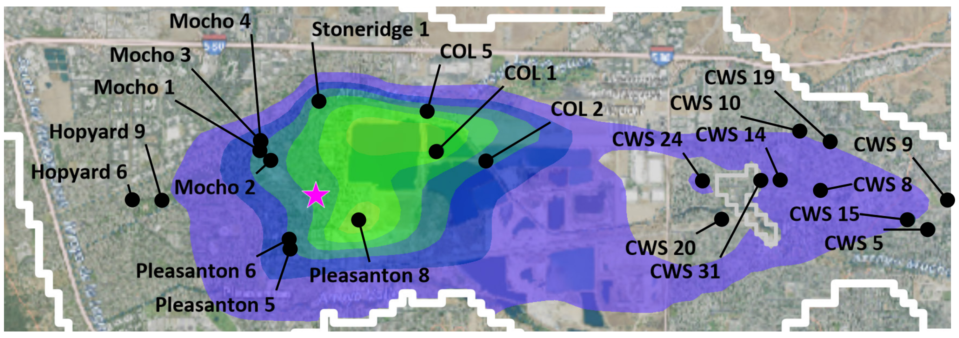
Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 1 – Baseline Condition.**



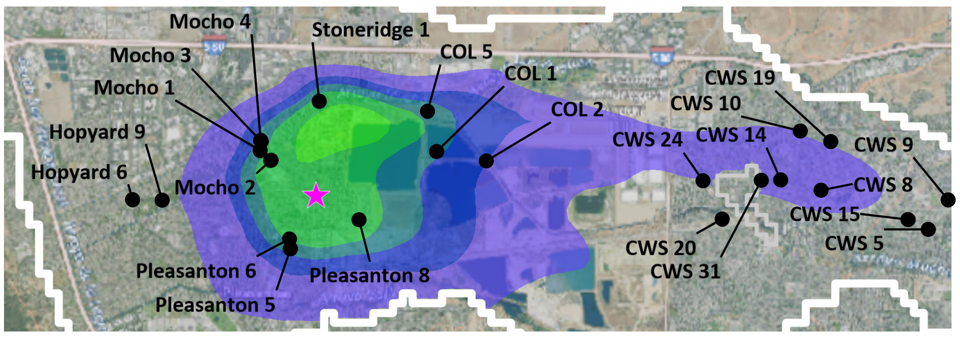
Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 2 – Low SWP Allocation (No PFAS Treatment).**



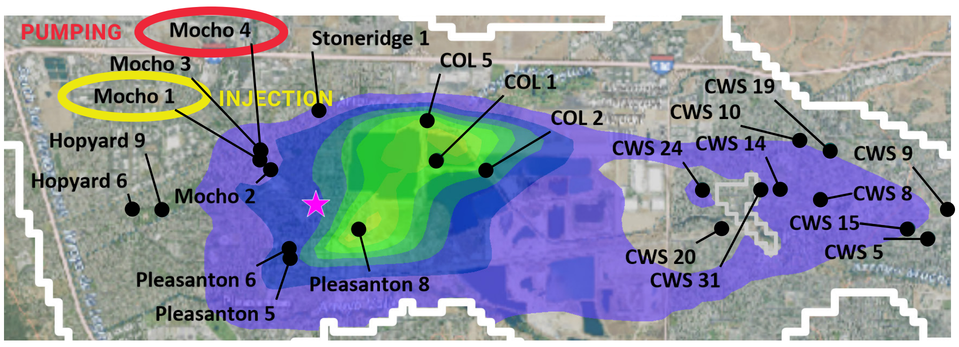
Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 2 – Low SWP Allocation (No PFAS Treatment)**.



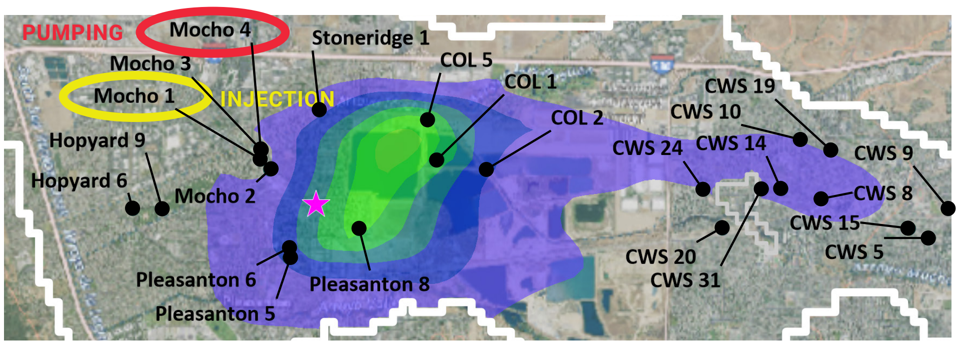
Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 3 – Pump Clean Wells (No PFAS Treatment).**



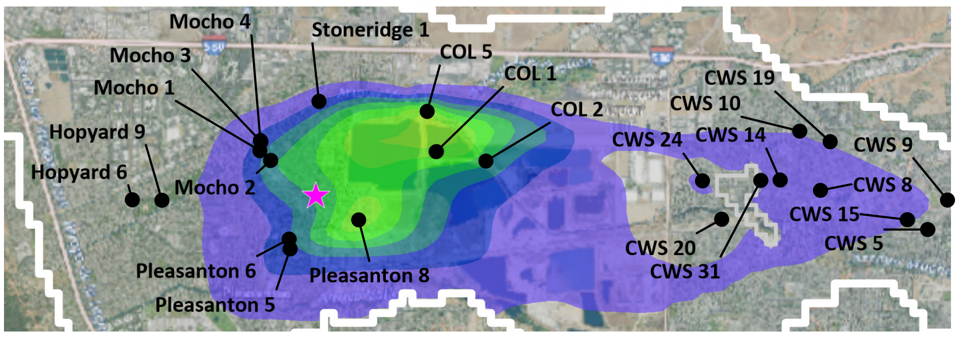
Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 3 – Pump Clean Wells (No PFAS Treatment).**



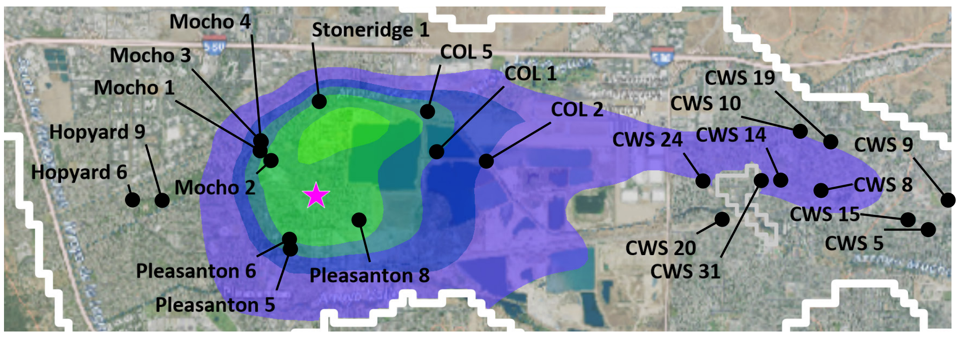
Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 4 – Pump & Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1).**



Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 4 – Pump & Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1).**

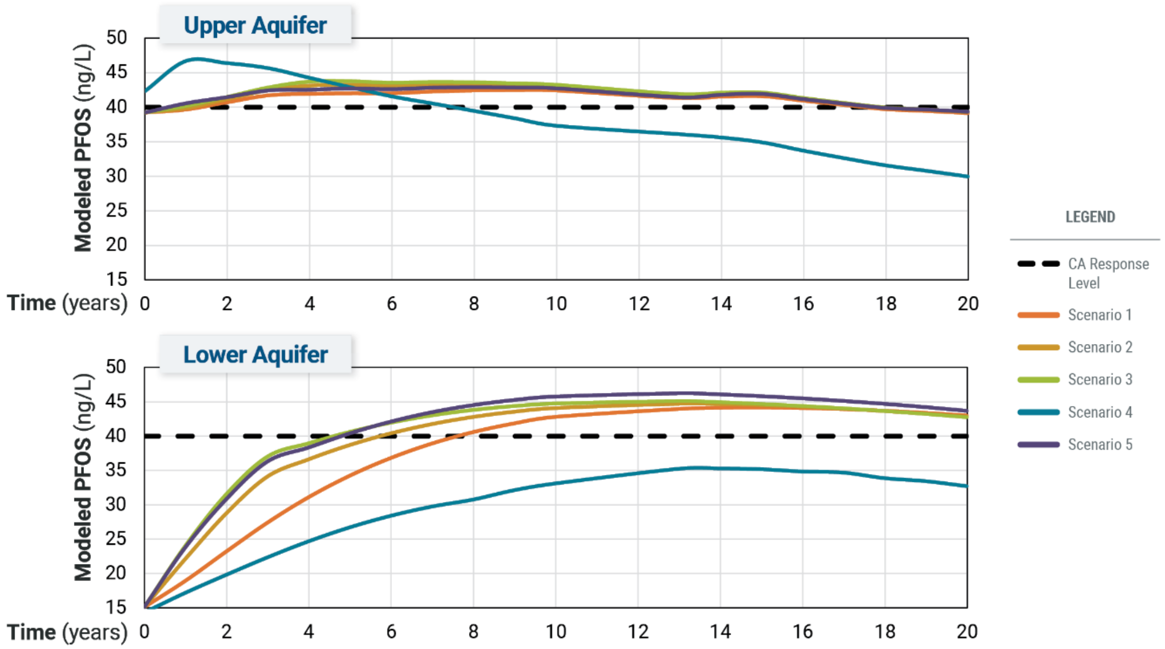


Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 5 – Pump & Treat PFAS Wells (PFAS Treatment at COL & MGDP).**



Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 5 – Pump & Treat PFAS Wells (PFAS Treatment at COL & MGDP).**

Figure 7. Change in PFOS Concentration Over Time at Selected Location (Pink Star)



3. Recommendations for Model Improvement

As noted, the model results described in this memorandum represent a screening level assessment for the purpose of comparison between scenarios. Each modeled scenario is subject to the same set of simplifications and approximations as noted in Section 1.2. To improve model fidelity and yield more accurate predictions, the following actions are recommended:

- Leverage future refinements to the Livermore Valley groundwater model so that an improved flow model can be used to directly inform subsequent solute transport simulations.
- The model grid should be refined across all three dimensions. Because of the added computational burden, we suggest updating the model to MODFLOW-USG or MODFLOW-6 so that an unstructured grid may be implemented.
- Recent literature studies pertaining to adsorption of PFAS compounds onto soil organic carbon should be reviewed, with resultant soil-water partitioning relationships used to model PFAS adsorption. This step may require collecting and analyzing representative site-specific soil organic carbon data for the Livermore Valley groundwater basin, or a review of literature values that may be applicable as default assumptions.
- Specific location- and time-dependent mass influx or concentration source terms for PFAS compounds across the Livermore Valley must be developed to inform refine solute transport modeling. This will require establishing a periodic monitoring program to sample both upper and lower aquifer units at key locations to track mobilization of the plume. This step is particularly important to address in some manner.
- Calibrate any future PFAS solute transport model to historic groundwater quality monitoring data. This may entail continued collection of observational data from existing monitoring wells to expand the calibration period, along with the possible addition of new monitoring points to address gaps in spatial sampling coverage.

Appendices

Appendix A. Summary of PFAS Management Model Results
Appendix B. Cross-Section of Groundwater Basin and Model Layers
Appendix C. PFOS Sample Results and Well Locations

References

Bedekar, V., Morway, E.D., Langevin, C.D., and Tonkin, M., 2016, MT3D-USGS version 1: A U.S. Geological Survey release of MT3DMS updated with new and expanded transport capabilities for use with MODFLOW: U.S. Geological Survey Techniques and Methods 6-A53, 69 p.

Hydrometrics, 2017. Groundwater Model for Groundwater and Salt Management in the Livermore Valley Groundwater Basin: Upgrades, Calibration, and Application, Prepared for Zone 7 Water Agency, 228 p.

McDonald, MG and AW Harbaugh, 1988. A modular three-dimensional finite-difference ground-water flow model. Techniques of Water-Resources Investigations, Book 6. U.S. Geological Survey.

Niswonger, RG, S Panday, and M Ibaraki, 2011. MODFLOW-NWT, A Newton formulation for MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6-A37.

Appendix A

Summary of PFAS Management Model Results

Summary of PFAS Management Model Results

For: Zone 7 Water Agency
Project: Tri-Valley Desktop Groundwater Contaminant Mobilization Study

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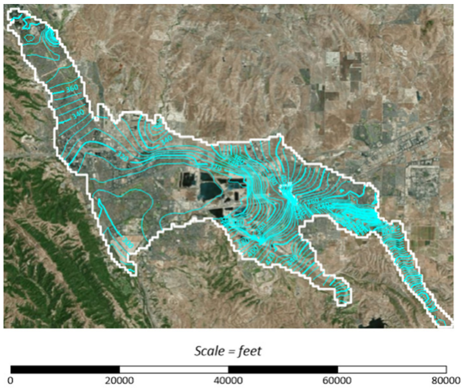
Main Questions

- How do concentrations and the plume footprint change over time under each pumping scenario?
- How does pumping mobilize the plume in each scenario?
- Is PFAS moving from the upper aquifer to the lower aquifer?

Model Purpose and Approach



This study analyzes and compares how the concentrations, movement, and size of the existing Per- and Polyfluoroalkyl Substances (PFAS) plume in the upper and lower aquifer units of the main groundwater basin would change over time under various pumping scenarios. The findings of this study will be used to formulate effective ways to manage (or contain) the plumes and minimize further migration.

This analysis was performed in Zone 7's existing Livermore Valley Groundwater model for a time period of 20 years. The impacts on the upper aquifer and lower aquifer were analyzed. Perfluorooctane Sulfonate (PFOS), a type of PFAS, was modeled as it is a good surrogate for all PFAS and Zone 7's PFOS dataset is the most complete available. The model assumed that the sources of the existing PFAS plume are no longer active and there is no ongoing PFAS discharge to the system. The baseline scenario and four different pumping scenarios represent different PFAS management strategies. These scenarios are described in the table below. One set of coordinates was selected to compare the four scenarios against the baseline.

PFAS Management Scenarios

Scenario	Title	Description	Recharge?	Zone 7 Pumping Rate
1	**Baseline**	Uses Zone 7's 5-year average well production (2016-2020)	-	20 years of average pumping rate (6,900 AFY)
2	**Low State Water Project Allocation (No PFAS Treatment)**	Operations during a year with ~5% State Water Project allocation and no PFAS treatment.	-	3 years higher rate (14,140 AFY) + 17 years average (6,900 AFY)
3	**Pump Clean Wells (No PFAS Treatment)**	Max production of wells currently unaffected by PFAS.	-	3 years higher rate (18,840 AFY) + 17 years average (6,900 AFY)
4	**Pump and Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1)**	Treatment of PFAS at the planned new facilities at Chain of Lakes and injection of water from Mocho 4 into Mocho 1.	5,400 AFY at Mocho 1	20 years of higher pumping rate (15,360 AFY)
5	**Pump and Treat PFAS Wells (PFAS Treatment at COL and MGDP)**	Treatment of PFAS at the planned new facilities at Chain of Lakes and at the Mocho Groundwater Demineralization Plant.	-	3 years higher rate (24,000 AFY) + 17 years average (6,900 AFY)

Drought: A 3-year drought was implemented for all scenarios to maintain consistency for comparison.

Recharge: Natural recharge and artificial recharge from Zone 7 is included in all scenarios. Natural recharge includes streams and rainfall and decreases during drought conditions.

Pumping: Increased pumping occurs for all scenarios compared to the baseline. For Scenarios 2, 3, and 5, the higher pumping rates only take place during the 3-year simulated drought period, after which pumping returns to baseline rates. In Scenario 4, the pumping rate is applied for the entire 20-year period. Water from Mocho Well 4 is also re-injected at Mocho Well 1 in Scenario 4.

Scenarios 1 through 5 – Upper Aquifer

- Upper Aquifer refers to an upper layer of the model and represents the upper aquifer in the groundwater basin.
- Scale is ng/L PFOS. 40 ng/L is the California Response Level for PFOS.
- High initial concentrations near COL 5 (approximately 850 ng/L).
- Starred point (★) was selected for comparison graphs of PFOS concentrations due to its proximity to Mocho 1 and Pleasanton 8 wells.

Scale = feet 0 20,000 40,000

ng/L PFOS 4 54 104 154 >200

PRE-DROUGHT CONDITIONS

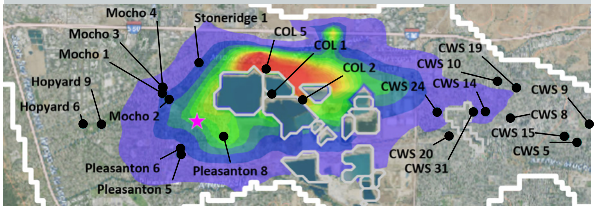


Figure 1: Modeled PFOS Levels (ng/L) in Upper Aquifer, Pre-Drought Conditions.

Note: CA PFOS Response Level = 40 ng/L

END OF 3-YEAR DROUGHT

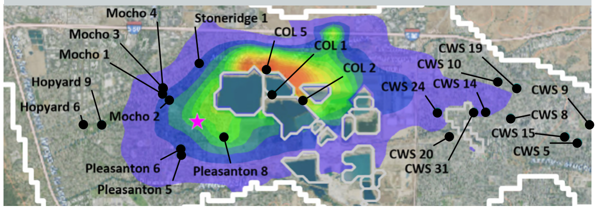


Figure 2: Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 1 – Baseline Condition.**

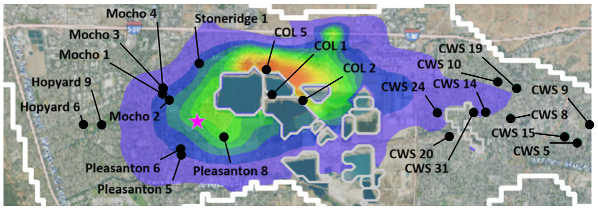


Figure 4: Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 2 – Low SWP Allocation (No PFAS Treatment).**

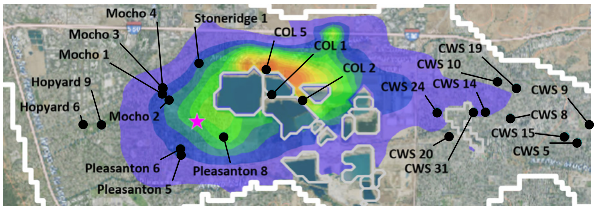


Figure 6: Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 3 – Pump Clean Wells (No PFAS Treatment).**

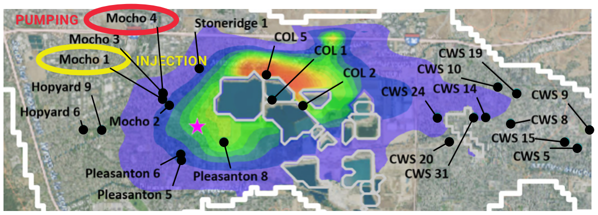


Figure 8: Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 4 – Pump & Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1).**

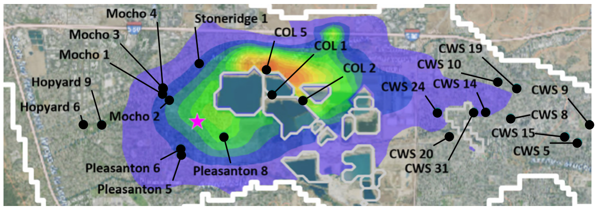


Figure 10: Modeled PFOS Levels (ng/L) in Upper Aquifer after 3-Year Drought, **Scenario 5 – Pump & Treat PFAS Wells (PFAS Treatment at COL & MGDP)**.

END OF 20 YEARS

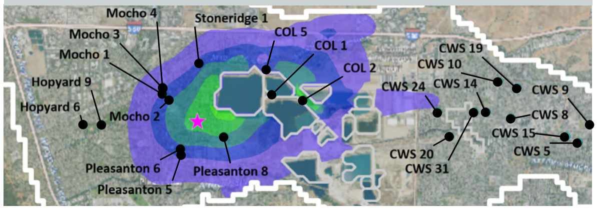


Figure 3: Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 1 – Baseline Condition.**

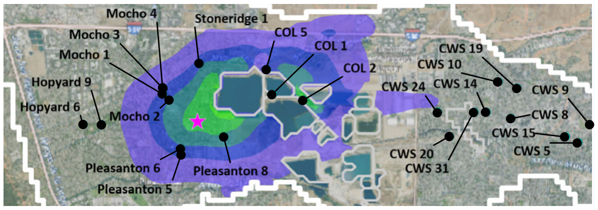


Figure 5: Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 2 – Low SWP Allocation (No PFAS Treatment).**

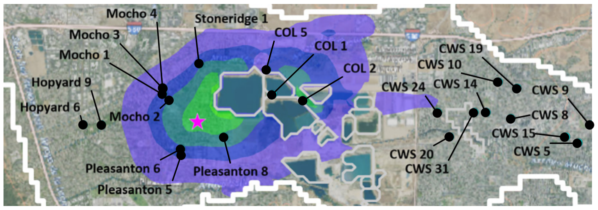


Figure 7: Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 3 – Pump Clean Wells (No PFAS Treatment)**.

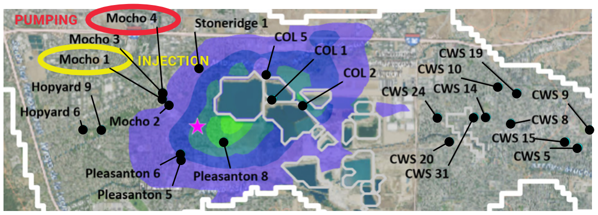


Figure 9: Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 4 – Pump & Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1).**

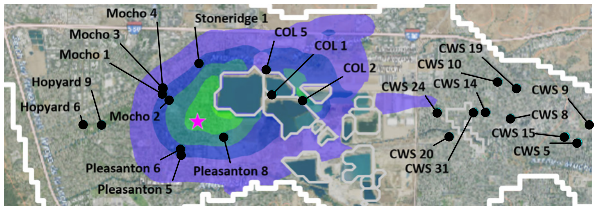


Figure 11: Modeled PFOS Levels (ng/L) in Upper Aquifer after 20-Years, **Scenario 5 – Pump & Treat PFAS Wells (PFAS Treatment at COL & MGDP)**.

Scenarios 1 through 5 – Lower Aquifer

PRE-DROUGHT CONDITIONS

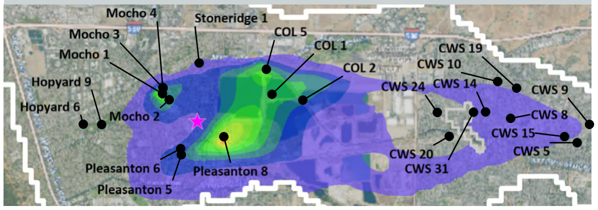


Figure 12: Modeled PFOS Levels (ng/L) in Lower Aquifer, Pre-Drought Conditions.
Note: CA PFOS Response Level = 40 ng/L

- Lower Aquifer refers to a lower layer of the model and represents the lower aquifer in the groundwater basin.
- Scale is ng/L PFOS. 40 ng/L is the California Response Level for PFOS.
- High initial concentrations near Mocho 1 (approximately 75 ng/L) and Pleasanton 8 (approximately 110 ng/L).
- Starred point (★) was selected for comparison graphs of PFOS concentrations due to its proximity to Mocho 1 and Pleasanton 8 wells.

Scale = feet 0 20,000 40,000

ng/L PFOS 4 54 104 154 >200

END OF 3-YEAR DROUGHT

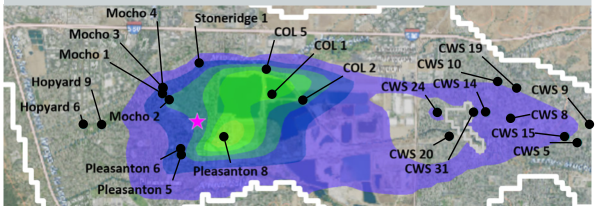


Figure 13: Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 1 – Baseline Condition.**

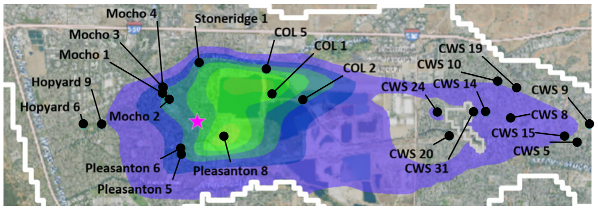


Figure 15: Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 2 – Low SWP Allocation (No PFAS Treatment).**

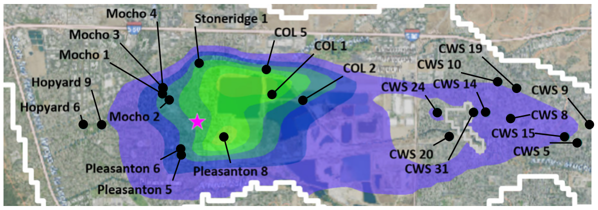


Figure 17: Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 3 – Pump Clean Wells (No PFAS Treatment).**

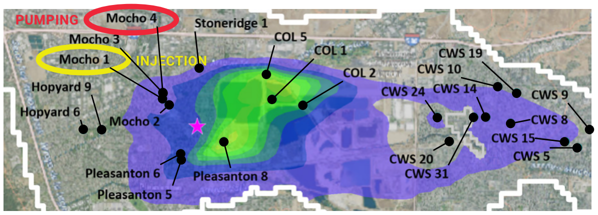


Figure 19: Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 4 – Pump & Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1).**

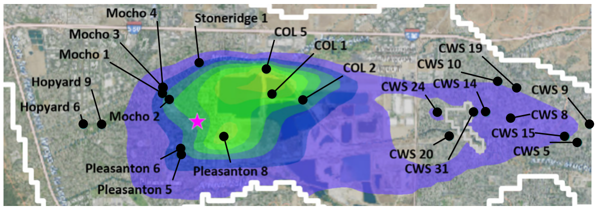


Figure 21: Modeled PFOS Levels (ng/L) in Lower Aquifer after 3-Year Drought, **Scenario 5 – Pump & Treat PFAS Wells (PFAS Treatment at COL & MGDP).**

END OF 20 YEARS

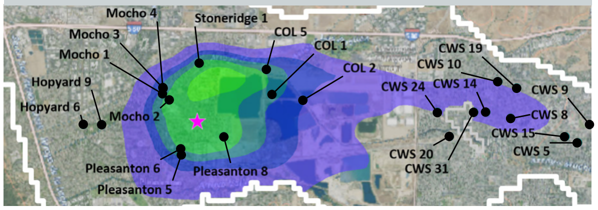


Figure 14: Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 1 – Baseline Condition.**

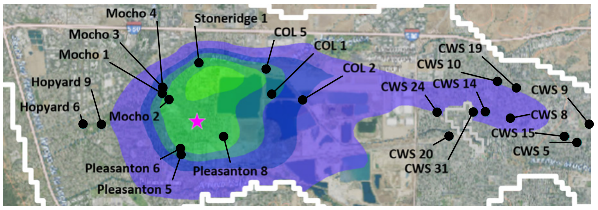


Figure 16: Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 2 – Low SWP Allocation (No PFAS Treatment)**.

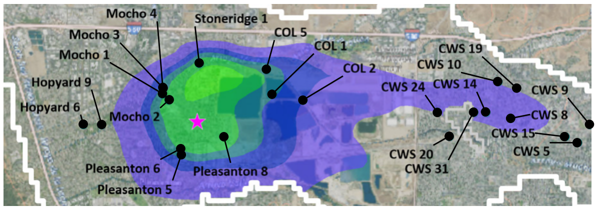


Figure 18: Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 3 – Pump Clean Wells (No PFAS Treatment).**

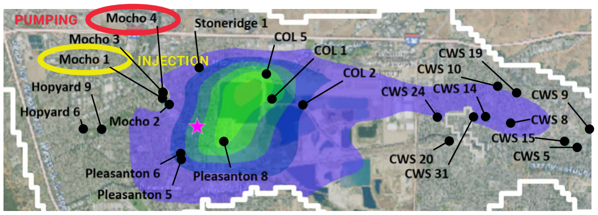


Figure 20: Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 4 – Pump & Treat PFAS Wells (PFAS Treatment at COL, reinjection at Mocho 1).**

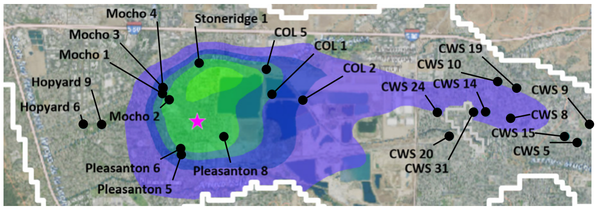
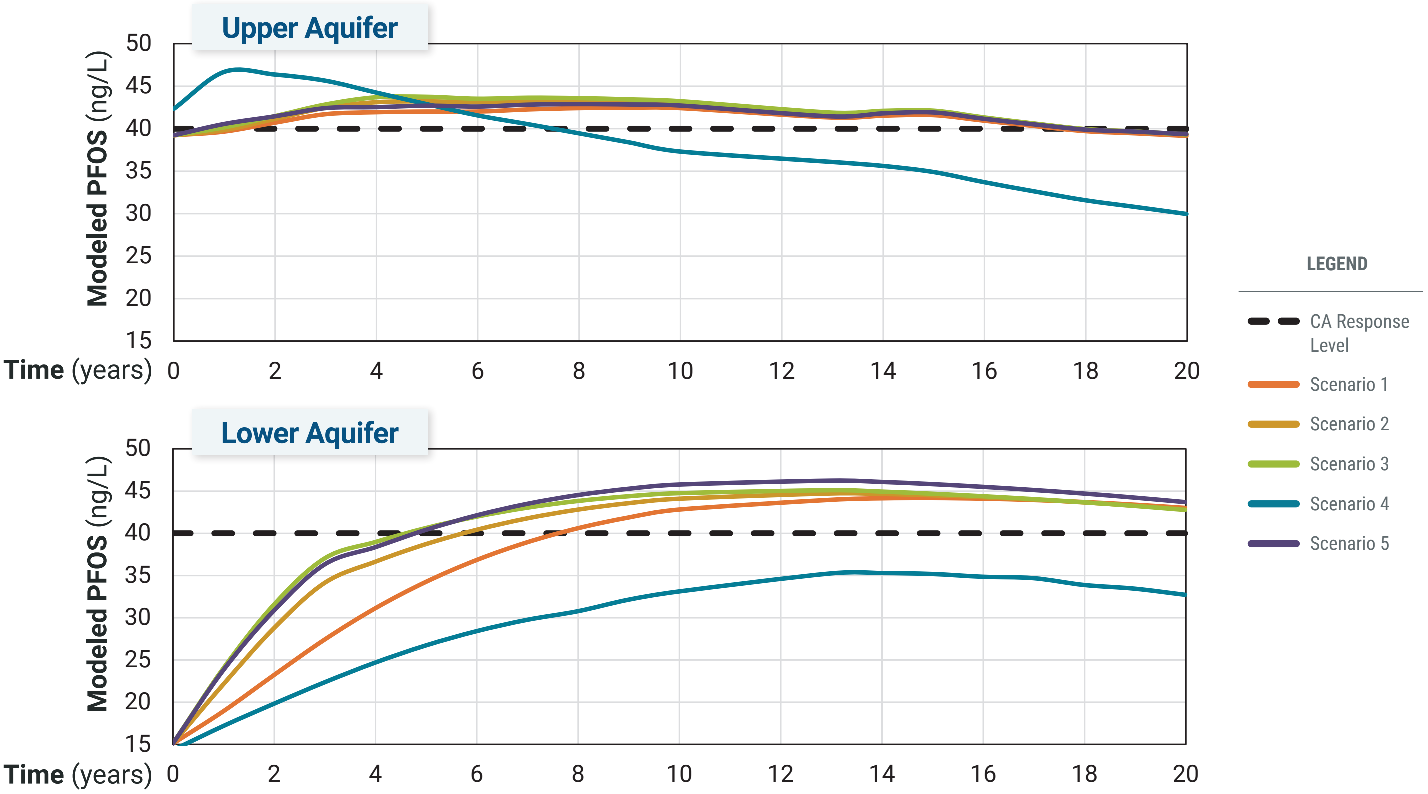


Figure 22: Modeled PFOS Levels (ng/L) in Lower Aquifer after 20-Years, **Scenario 5 – Pump & Treat PFAS Wells (PFAS Treatment at COL & MGDP).**

Graphs of Change of PFOS Concentration Over Time at Selected Location (★)



Summary of Model Results

To assess short-term impacts, Scenarios 2, 3, and 5 (higher pumping during the 3-year drought) can be compared to Scenario 1 (average pumping for 20 years) at the end of 3 years. These comparisons are relative only and should not be used to predict exact future values of PFAS. **At the starred location, Scenarios 2, 3, and 5 resulted in an approximate 2% increase in PFAS concentration in the upper aquifer and an approximate 25-35% increase in the lower aquifer compared to Scenario 1 at the end of 3 years.**

To assess long-term impacts, Scenario 4 (higher pumping for 20 years) can be compared to Scenario 1 (average pumping for 20 years). This comparison is relative only and should not be used to predict exact future values of PFAS. **At the starred location, Scenario 4 resulted in an approximate 24% reduction in PFAS concentration in the upper aquifer and an approximate 23% reduction in the lower aquifer compared to Scenario 1 at the end of 20 years.**

The long-term impacts of Scenarios 2, 3, and 5 are minimal since they only have increased pumping rates during the 3-year drought, after which they return to the baseline pumping rate for the remaining 17 years. **At the starred location, Scenarios 2, 3, and 5 have similar PFAS concentrations in the upper and lower aquifer compared to Scenario 1 at the end of 20 years.**

The model results do not show evidence of PFAS moving from the upper aquifer to the lower aquifer. **In both the upper and lower aquifer, the high concentrations shown in the initial conditions become spread across a larger area and the peak concentration is reduced over time.**

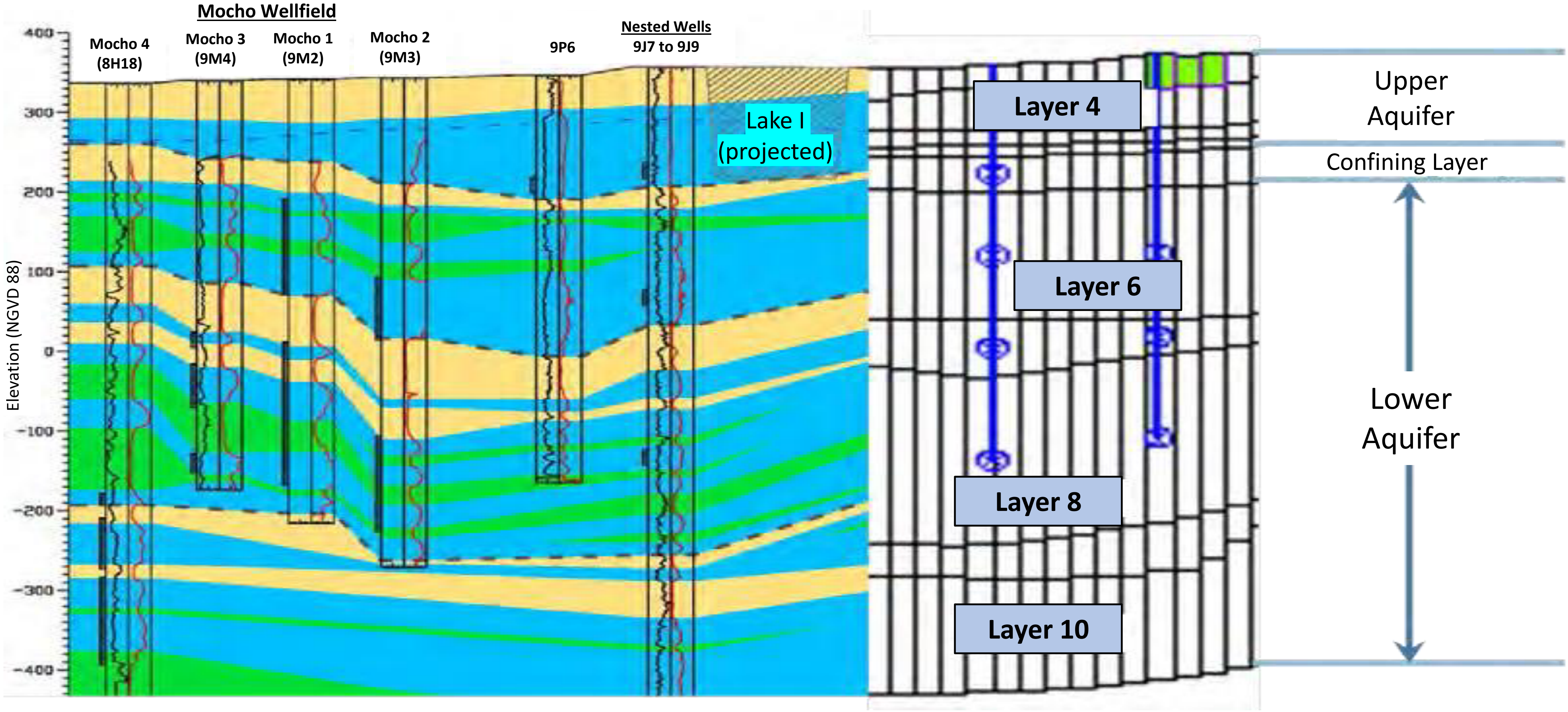
Overall Conclusions

- **Under all scenarios, the PFAS plume decreases in concentration over the 20-year period.** No active PFAS source was included in the model, resulting in natural attenuation over time.
- At the end of the 3-year drought, the initial concentrations have been reduced and the PFAS plume has spread over a larger area. At the end of the 20-year period, the initial concentrations have been further reduced and the PFAS plume has decreased in size.
- **The strategy of increased pumping and reinjection (Scenario 4) shows promise at preventing westerly plume expansion and should be explored further.** Note that Mocho 4 is a valuable production well for Zone 7.
- Similar trends are shown in both the upper and lower aquifer, although the lower aquifer has more reduced concentrations. **PFAS does not appear to move from the upper aquifer to the lower aquifer due to pumping.**

Appendix B

Cross-Section of Groundwater Basin and Model Layers

Appendix B: Cross-Section of Groundwater Basin and Model Layers



Legend:

🟧 Lacustrine Deposits (aquitard)
🟩 Overbank Deposits (aquitard)
🟦 Gravel/Sand Deposits (aquifer)

Source:
Figure 6.2 from the Joint Tri-Valley Potable Reuse Technical Feasibility Study (May 2018)

Appendix C

PFOS Sample Results and Well Locations

Appendix C: PFOS Sample Results and Well Locations

Well Name	Full Well Name	X-Coordinate	Y-Coordinate	PFOS Concentration (ng/L)	Top Model Layer	Bottom Model Layer
10A2	3S/1E 10A 2	6173303.181	2076901.018	450	2	3
10B10	3S/1E 10B10	6171163.028	2077870.113	24	8	10
10B11	3S/1E 10B11	6171163.028	2077870.113	54	10	11
10B8	3S/1E 10B 8	6171163.028	2077870.113	1400	4	5
10B9	3S/1E 10B 9	6171163.028	2077870.113	120	6	6
10D2	3S/1E 10D 2	6168495.132	2077931.182	1	6	6
10D3	3S/1E 10D 3	6168495.132	2077931.182	150	6	7
10D4	3S/1E 10D 4	6168495.132	2077931.182	4.1	8	10
10D5	3S/1E 10D 5	6168495.132	2077931.182	1	11	11
11C3	3S/1E 11C 3	6175652.771	2077487.113	360	2	2
11G1	3S/1E 11G 1	6176886.581	2076398.908	210	4	4
11G2	3S/1E 11G 2	6176886.581	2076398.908	160	6	8
11G3	3S/1E 11G 3	6176886.581	2076398.908	26	8	10
11G4	3S/1E 11G 4	6176886.581	2076398.908	170	10	11
12A2	3S/1E 12A 2	6182743.657	2077141.399	100	2	2
12D2	3S/1E 12D 2	6179799.102	2077224.584	100	2	2
12G1	3S/1E 12G 1	6181362.242	2075140.493	68	3	3
12H4	3S/1E 12H 4	6183225.629	2076300.142	5.3	6	6
12H5	3S/1E 12H 5	6183225.629	2076300.142	8.4	8	8
12H6	3S/1E 12H 6	6183225.629	2076300.142	1	8	8
12H7	3S/1E 12H 7	6183225.629	2076300.142	1	10	11
12K2	3S/1E 12K 2	6181274.37	2074395.861	6.9	6	6
12K3	3S/1E 12K 3	6181274.37	2074395.861	1	8	8
12K4	3S/1E 12K 4	6181274.37	2074395.861	1	10	10
13P5	3S/1E 13P 5	6180144.844	2068356.091	11	4	4
13P6	3S/1E 13P 6	6180140.32	2068351.849	1	6	6
13P7	3S/1E 13P 7	6180140.6	2068351.849	1	8	8
13P8	3S/1E 13P 8	6180143.43	2068350.153	73	10	11
16A4	3S/1E 16A 4	6167079	2071561.3	37	8	10
16C2	3S/1E 16C 2	6164483.459	2071607.676	9.6	6	6
16C3	3S/1E 16C 3	6164483.459	2071607.676	9.9	7	8
16C4	3S/1E 16C 4	6164483.459	2071607.676	8.6	8	8
18J2	3S/1E 18J 2	6156379.579	2069332.361	3.4	2	3
19C4	3S/1E 19C 4	6154770.963	2066754.734	6.9	5	5
19D10	3S/2E 19D10	6184048.982	2067396.101	10	10	10
19D7	3S/2E 19D 7	6184048.982	2067396.101	1	3	4
19D8	3S/2E 19D 8	6184048.982	2067396.101	2.9	6	6
19D9	3S/2E 19D 9	6184048.982	2067396.101	13	8	9
19N3	3S/2E 19N 3	6183936.84	2063337.737	1	4	5
19N4	3S/2E 19N 4	6183936.84	2063337.737	4	7	7
1B9	3S/1W 1B 9	6150745.265	2082737.343	1	6	6
1F2	3S/1E 1F 2	6181022.783	2080973.749	86	2	2
1H3	3S/1E 1H 3	6183649.625	2080700.619	1	2	2
1L1	3S/1E 1L 1	6180992.062	2080250.794	22	2	2
1P2	3S/1E 1P 2	6180951.339	2078621.584	26	2	2
20B2	3S/1E 20B 2	6161286.633	2066767.216	6.2	7	10
2J2	3S/1E 2J 2	6178550.708	2079749.442	35	2	2
2J3	3S/1E 2J 3	6178864.44	2080588.429	9.3	2	2
2K2	3S/1E 2K 2	6177307.064	2080571.802	970	2	2
2M3	3S/1E 2M 3	6174252.833	2080401.581	1	2	2
2N6	3S/1E 2N 6	6174218.831	2078394.766	47	2	2
2P3	3S/1E 2P 3	6176191.532	2079381.033	1	8	8
2Q1	3S/1E 2Q 1	6177087.461	2078442.091	37	2	2
2R1	3S/1E 2R 1	6178662.348	2078885.545	55	2	2
3G2	3S/1E 3G 2	6170996.197	2081542.369	1	2	2
3S1E18E004	3S/1E 18E 4	6153721.5	2071249.079	1	5	5
4A1	3S/1E 4A 1	6166818.03	2082027.032	16	1	2
4J5	3S/1E 4J 5	6166668.055	2080498.243	40	1	2

Appendix C: PFOS Sample Results and Well Locations

Well Name	Full Well Name	X-Coordinate	Y-Coordinate	PFOS Concentration (ng/L)	Top Model Layer	Bottom Model Layer
4J6	3S/1E 4J 6	6166667.294	2080490.273	1	3	6
4Q2	3S/1E 4Q 2	6166634.834	2078531.485	3.1	5	5
7C2	3S/2E 7C 2	6186317.771	2077489.523	60	2	2
8H10	3S/1E 8H10	6162783.651	2075995.68	13	7	8
8H11	3S/1E 8H11	6162783.651	2075995.68	20	9	10
8H9	3S/1E 8H 9	6162783.651	2075995.68	20	6	6
9J7	3S/1E 9J 7	6167442.38	2074675.087	26	4	4
9J8	3S/1E 9J 8	6167442.38	2074675.087	60	6	6
9J9	3S/1E 9J 9	6167442.38	2074675.087	7	8	8
9P10	3S/1E 9P10	6164985.417	2073596.33	19	7	7
9P11	3S/1E 9P11	6164985.417	2073596.33	3.1	8	8
9P5	3S/1E 9P 5	6165208.52	2073682.857	29	2	3
9P9	3S/1E 9P 9	6164985.417	2073596.33	46	6	6
COL1	3S/1E 10K 3	6172033.104	2074936.081	46	6	10
COL2	3S/1E 11M 3	6174538.723	2074894.642	22	8	11
COL5	3S/1E 10B16	6171549.855	2077069.559	52	8	11
CWS14	3S/2E 8N 2	6189598.62	2073626.798	5	6	10
CWS19	3S/2E 8G 1	6191878.97	2075426.884	21	5	10
CWS20	3S/2E 18B 1	6186763.578	2071520.858	3.6	6	10
CWS24	3S/2E 7P 3	6185537.573	2073763.917	1	7	10
CWS31	3S/2E 7R 3	6188433.556	2073764.012	5.4	10	10
CWS9	3S/2E 9Q 1	6197967.089	2072604.949	16	7	10
H6	3S/1E 18A 6	6156491.705	2072670.681	1	6	9
H9	3S/1E 17D12	6157986.431	2072573.888	1	8	8
M1	3S/1E 9M 2	6163305.214	2075348.073	110	6	8
M2	3S/1E 9M 3	6163379.017	2074830.044	50	6	9
M3	3S/1E 9M 4	6162931.903	2075510.438	56	8	9
M4	3S/1E 8H18	6162819.082	2076038.203	16	9	10
P5	3S/1E 16L 5	6164595.763	2070089.17	31	6	11
P6	3S/1E 16L 7	6164503.016	2070336.026	30	6	11
P8	3S/1E 16A 2	6167956.496	2071679.406	120	6	10
SF-A	3S/1E 19A11	6157188.962	2067506.375	1	6	8
SF-B	3S/1E 19A10	6157201.969	2066546.381	1	6	8
St1	3S/1E 9B 1	6166109.416	2077438.853	18	6	11