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Fate and Transport Analysis for the Groundwater Plume Remedies in the 200-ZP-1 and 200-UP-1 Operable Units Using the Central Plateau Groundwater Model

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

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Richland, Washington 99352

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J. Blainey
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Environmental Calculation File

Fate and Transport Analysis for the Groundwater Plume Remedies in the 200-ZP-1 and 200-UP-1 Operable Units Using the Central Plateau Groundwater Model

Contents

1 Purpose **1**

2 Methodology **3**

2.1 Groundwater Flow Modeling 3

2.2 Groundwater Transport Modeling 3

2.3 System Optimization 3

2.4 Post-processing of Transport Model Results 4

2.4.1 UCL95 Calculations on Mean Plume Concentration 4

3 Assumptions and Inputs **9**

3.1 Extraction and Injection Well Flow Rates 9

3.2 Initial Conditions for the Groundwater Transport Model 9

3.3 Transport Parameters 9

3.4 Treatment System Efficiency & Contaminant Treatment System Package 10

3.5 Source Concentrations 11

4 Software Applications **12**

4.1 Approved Software 12

4.1.1 Descriptions 12

4.1.2 Software Installation and Checkout 13

4.1.3 Statement of Valid Software Application 13

5 Calculations **14**

6 Results/Conclusions **15**

6.1 Forecast of Projected Baseline Operations 15

6.1.1 Carbon Tetrachloride – 41-year half-life 16

6.1.2 Carbon Tetrachloride – 100-year half-life 22

6.1.3 Carbon Tetrachloride – 630-year half-life 28

6.1.4 Chromium (VI) 34

6.1.5 Nitrate 38

6.1.6 Trichloroethene (TCE) 48

6.1.7 Technetium-99 (Tc-99) 53

6.1.8 Tritium 57

6.2 Forecast of Optimized Operations 60

6.2.1 Pumping Optimization Results 60
6.2.2 Carbon Tetrachloride – 41-year half-life 64
6.2.3 Carbon Tetrachloride – 100-year half-life 69
6.2.4 Chromium (VI) 75
6.2.5 Nitrate 79
6.2.6 Technetium-99 87
6.2.7 Trichloroethene 92
6.2.8 Tritium 95
6.3 Conclusions 98
7 References 102

Appendices

A. Appendix A Software Installation and Checkout 104
B. Appendix B Simulated Pumping Well Concentration Histories 107

Figures

Figure 1. 200 West Carbon Tetrachloride Plume, Pump and Treat Well Locations, and Piping Routes (DOE/RL-2016-20) 2
Figure 2. Schematic of the 200-ZP-1 Optimization Code (from SGW-50390) 4
Figure 3. Well Network for Carbon Tetrachloride UCL95 Calculation 7
Figure 4. Well Network for 200-ZP-1 Chromium, Nitrate, TCE, and Tc-99 UCL95 Calculation 8
Figure 5. Simulated Carbon Tetrachloride Distribution (41-year half-life) at the Ringold Unit E Water Table in 2037 after 25 years of baseline pumping 17
Figure 6. Simulated Carbon Tetrachloride Distribution (41-year half-life) at the base of Ringold Unit E in 2037 after 25 years of baseline pumping 17
Figure 7. Simulated Carbon Tetrachloride Distribution (41-year half-life) in the Ringold Unit A in 2037 after 25 years of baseline pumping 18
Figure 8. Simulated Carbon Tetrachloride (41-year half-life) Distribution at the Ringold Unit E Water Table in 2137 19
Figure 9. Simulated Carbon Tetrachloride (41-year half-life) Distribution at the base of Ringold Unit E in 2137 19
Figure 10. Simulated Carbon Tetrachloride (41-year half-life) Distribution in the Ringold Unit A in 2137. 20
Figure 11. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass – Baseline Pumping (bottom) 21
Figure 12. Simulated UCL95 Concentrations for Carbon Tetrachloride – Baseline Pumping - 41-yr half-life 22

Figure 13. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the water table in Ringold Unit E in 2037 after 25 years of baseline pumping 23

Figure 14. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the base of Ringold Unit E in 2037 after 25 years of baseline pumping 23

Figure 15. Simulated Carbon Tetrachloride Distribution (100-year half-life) in the Ringold Unit A in 2037 after 25 years of baseline pumping 24

Figure 16. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the water table in Ringold Unit E in 2137 25

Figure 17. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the base of Ringold Unit E in 2137 25

Figure 18. Simulated Carbon Tetrachloride Distribution (100-year half-life) in the Ringold Unit A in 2137 26

Figure 19. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass (bottom)– Baseline Pumping 27

Figure 20. Simulated UCL95 Concentrations for Carbon Tetrachloride – Baseline Pumping - 100-yr half-life 28

Figure 21. Simulated Carbon Tetrachloride Distribution (630-year half-life) at the water table in Ringold Unit E in 2037 after 25 years of baseline pumping 29

Figure 22. Simulated Carbon Tetrachloride Distribution (630-year half-life) at the base of the Ringold Unit E in 2037 after 25 years of baseline pumping 29

Figure 23. Simulated Carbon Tetrachloride Distribution (630-year half-life) in the Ringold Unit A in 2037 after 25 years of baseline pumping 30

Figure 24. Simulated Carbon Tetrachloride Distribution (630-year half-life) at the water table in Ringold Unit E in 2137 31

Figure 25. Simulated Carbon Tetrachloride Distribution (630-year half-life) at the base of the Ringold Unit E in 2137 31

Figure 26. Simulated Carbon Tetrachloride Distribution (630-year half-life) in the Ringold Unit A in 2137 32

Figure 27. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass (bottom) – Baseline Pumping 33

Figure 28. Simulated UCL95 Concentrations for Carbon Tetrachloride – Baseline Pumping - 630-yr half-life 34

Figure 29. Simulated Chromium(VI) Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping - Source 35

Figure 30. Simulated Chromium(VI) Distribution at the water table in the Ringold Unit E in 2137 - Source 35

Figure 31. Simulated Chromium(VI) Distribution at the base of the Ringold Unit E in 2137 - Source 36

Figure 32. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial Cr(VI) mass (bottom) – Baseline Pumping 37

Figure 33. Simulated UCL95 for Cr(VI) with and without sources – Baseline Pumping 38

Figure 34. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping – No Source 39

Figure 35. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2037 after 25 years of baseline pumping– No Source 39

Figure 36. Simulated Nitrate Distribution in the Ringold Unit A in 2037 after 25 years of baseline pumping– No Source 40
Figure 37. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2137 – No Source. 40
Figure 38. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2137 – No Source 41
Figure 39. Simulated Nitrate Distribution in the Ringold Unit A in 2137 – No Source 41
Figure 40. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping –Source 42
Figure 41. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2037 after 25 years of baseline pumping –Source 43
Figure 42. Simulated Nitrate Distribution in the Ringold Unit A in 2037 after 25 years of baseline pumping –Source 43
Figure 43. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2137–Source 44
Figure 44. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2137–Source 44
Figure 45. Simulated Nitrate Distribution in the Ringold Unit A in 2137–Source 45
Figure 46. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of nitrate initial mass (bottom) – Baseline Pumping 46
Figure 47. Simulated UCL95 for 200-ZP-1 Nitrate – Baseline Pumping 47
Figure 48. Simulated UCL95 for 200-UP-1 Nitrate – Baseline Pumping 48
Figure 49. Simulated TCE Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping 49
Figure 50. Simulated TCE Distribution at the base of the Ringold Unit E in 2037 after 25 years of baseline pumping 49
Figure 51. Simulated TCE Distribution in the Ringold Unit A in 2037 after 25 years of baseline pumping. 50
Figure 52. Simulated TCE Distribution at the water table in the Ringold Unit E in 2137 50
Figure 53. Simulated TCE Distribution at the base of the Ringold Unit E in 2137 51
Figure 54. Simulated TCE Distribution in the Ringold Unit A in 2137 51
Figure 55. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial TCE mass (bottom) – Baseline Pumping 52
Figure 56. Simulated UCL95 for TCE – Baseline Pumping 53
Figure 57. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping –Source 54
Figure 58. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2137 –Source 54
Figure 59. Simulated Tc-99 Distribution at the base of the Ringold Unit E in 2137 –Source 55
Figure 60. Simulated Tc-99 Distribution in the Ringold Unit A in 2137 –Source 55
Figure 61. Simulated Cumulative Mass Pumped in Curies (top) and fraction of initial Tc-99 mass (bottom) – Baseline Pumping 56
Figure 62. Simulated UCL95 for Tc-99 with and without sources – Baseline Pumping 57
Figure 63. Simulated Tritium Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping – No Source 58
Figure 64. Simulated Cumulative Mass Pumped in Curies (top) and fraction of initial tritium mass (bottom) – Baseline Pumping 59

Figure 65. Simulated UCL95 for Tritium with and without sources – Baseline Pumping 60
Figure 66. Summary of total extraction and in injection in the baseline pumping scenario 61
Figure 67. Summary of total extraction and in injection in the optimized pumping scenario 62
Figure 68. Pumping rates and simulated carbon tetrachloride concentrations for baseline and optimized pumping scenarios in the Ringold Unit E 63
Figure 69. Pumping rates and simulated carbon tetrachloride concentrations for baseline and optimized pumping scenarios in the Ringold Unit A 64
Figure 70. Simulated Carbon Tetrachloride Distribution (41-year half-life) at the Ringold Unit E Water Table in 2037 after 25 years of optimized pumping 65
Figure 71. Simulated Carbon Tetrachloride Distribution (41-year half-life) at the base of Ringold Unit E in 2037 after 25 years of optimized pumping 66
Figure 72. Simulated Carbon Tetrachloride Distribution (41-year half-life) in the Ringold Unit A in 2037 after 25 years of optimized pumping 66
Figure 73. Simulated Carbon Tetrachloride (41-year half-life) Distribution in the Ringold Unit A in 2137. 67
Figure 74. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass (bottom) – Optimized Pumping 68
Figure 75. Simulated UCL95 Concentrations for Carbon Tetrachloride – Optimized Pumping - 41-yr half-life 69
Figure 76. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the water table in Ringold Unit E in 2037 after 25 years of optimized pumping 70
Figure 77. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the base of Ringold Unit E in 2037 after 25 years of optimized pumping 70
Figure 78. Simulated Carbon Tetrachloride Distribution (100-year half-life) in the Ringold Unit A in 2037 after 25 years of optimized pumping 71
Figure 79. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the water table in Ringold Unit E in 2137 72
Figure 80. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the base of Ringold Unit E in 2137 72
Figure 81. Simulated Carbon Tetrachloride Distribution (100-year half-life) in the Ringold Unit A in 2137 73
Figure 82. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass (bottom) – Optimized Pumping 74
Figure 83. Simulated UCL95 Concentrations for Carbon Tetrachloride – Optimized Pumping - 100-yr half-life 75
Figure 84. Simulated Chromium(VI) Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping - Source 76
Figure 85. Simulated Chromium(VI) Distribution at the base of the Ringold Unit E in 2037 after 25 years of optimized pumping- Source 76
Figure 86. Simulated Chromium(VI) Distribution at the water table in the Ringold Unit E in 2137 - Source 77
Figure 87. Simulated Chromium(VI) Distribution at the base of the Ringold Unit E in 2137 - Source 77

Figure 88. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial Cr(VI) mass (bottom) – Optimized Pumping 78
Figure 89. Simulated UCL95 for Cr(VI) with and without sources – Optimized Pumping 79
Figure 90. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping – No Source 80
Figure 91. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2037 after 25 years of optimized pumping– No Source 80
Figure 92. Simulated Nitrate Distribution in the Ringold Unit A in 2037 after 25 years of optimized pumping– No Source 81
Figure 93. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping –Source 82
Figure 94. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2037 after 25 years of optimized pumping –Source 82
Figure 95. Simulated Nitrate Distribution in the Ringold Unit A in 2037 after 25 years of optimized pumping –Source 83
Figure 96. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2137–Source 83
Figure 97. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2137–Source 84
Figure 98. Simulated Nitrate Distribution in the Ringold Unit A in 2137 –Source 84
Figure 99. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of nitrate initial mass (bottom) – Optimized Pumping 85
Figure 100. Simulated UCL95 for 200-ZP-1 Nitrate with and without sources – Optimized Pumping 86
Figure 101. Simulated UCL95 for 200-UP-1 Nitrate with and without sources – Optimized Pumping 87
Figure 102. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping – No Source 88
Figure 103. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping –Source 89
Figure 104. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2137 –Source 89
Figure 105. Simulated Tc-99 Distribution at the base of the Ringold Unit E in 2137 –Source 90
Figure 106. Simulated Tc-99 Distribution at the water table in the Ringold Unit A in 2137 –Source 90
Figure 107. Simulated Cumulative Mass Pumped in Curies (top) and fraction of initial Tc-99 mass (bottom) – Optimized Pumping 91
Figure 108. Simulated UCL95 for Tc-99 with and without sources – Optimized Pumping 92
Figure 109. Simulated TCE Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping 93
Figure 110. Simulated TCE Distribution at the base of the Ringold Unit E in 2037 after 25 years of optimized pumping 93
Figure 111. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial TCE mass (bottom) – Optimized Pumping 94
Figure 112. Simulated UCL95 for TCE Baseline and Optimized Pumping 95
Figure 113. Simulated Tritium Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping – No Source 96
Figure 114. Simulated Cumulative Mass Pumped in Curies (top) and fraction of initial tritium mass (bottom) – Optimized Pumping 97

Figure 115. Simulated UCL95 for Tritium with and without sources – Optimized Pumping 98
Figure 116 Simulated Carbon Tetrachloride UCL95 for the pumping period - baseline and optimized pumping 99
Figure 117 Simulated Nitrate UCL95 for Baseline and Optimized Pumping, with and without sources. 100
Figure 118 Simulated Carbon Tetrachloride UCL95 for the MNA period - optimized pumping and 41-yr and 100-yr half-life 101

Tables

Table 3-1. Aquifer Properties for Fate and Transport Analysis 10
Table 3-2. COC Contaminant Transport Properties 10
Table 3-3. CTS Efficiency Percent Values Used for Transport Simulations (Percent) 11
Table 5-1. Time Intervals Used in 200-ZP-1 Optimization 14
Table 6-1. Phase I Masses (from ECF-200ZP1-16-0076) 15
Table 6-2. Final Cleanup Levels for the 200-ZP-1 Groundwater OU (from DOE/RL-2016-20) 16

Terms

CHPRC	CH2M Hill Plateau Remediation Company
COC	contaminant of concern
CP	Central Plateau
CPGWM	Central Plateau Groundwater Model
CTS	contaminant treatment system package
ECF	environmental calculation file
gpm	gallons per minute
HISI	Hanford Information Systems Inventory
MCL	maximum contaminant level
MNA	monitored natural attenuation
OU	operable unit
P&T	pump and treat
RLM	Ringold Lower Mud
SSM	Source sink mixing package
TCE	trichloroethene
UCL95	95th percentile upper confidence limit on the plume mean concentration
USGS	U.S. Geological Survey
WMA	Waste Management Area

1 Purpose

This Environmental Calculation File (ECF) documents the results of contaminant fate and transport simulations performed using the Central Plateau Groundwater Model (CPGWM) v. 8.4.5 for the 200-ZP-1 Groundwater Operable Unit (OU) pump and treat system (P&T) at the Hanford Site. Contaminants of concern (COCs) include carbon tetrachloride, total and hexavalent chromium [Cr(VI)], tritium, trichloroethene (TCE), technetium-99, and nitrate. Although an I-129 groundwater plume exists, but, as of August 2017, no remedy has been identified and I-129 is not considered in this ECF. This system began operating in July 2012 and currently consists of 26 extraction and 26 injection wells. Additionally, because of their extent, the tritium and nitrate plumes in the 200-UP-1 OU are also analyzed with the CPGWM; the Cr(VI) plume in southeastern 200-UP-1, which is still being characterized, is not considered in this analysis. More information regarding groundwater contamination at 200-ZP-1 and operation of the groundwater extraction system can be found in DOE/RL-2016-09, *Hanford Site Groundwater Monitoring Report for 2015*, and DOE/RL-2016-20, *Calendar Year 2015 Annual Summary Report for the 200-ZP-1 and 200-UP-1 Operable Unit Pump-and-Treat Operations*.

Specific objectives of this analysis are as follows:

1. Assess the performance of the current 200 West P&T system and projected operating rates in achieving the cleanup objectives (active remediation through the end of 2037, followed by monitored natural attenuation [MNA] through the end of 2137).
2. Determine if system performance can be improved via mathematical optimization.
3. Evaluate the effect that ongoing sources may have on remedy performance.

The remainder of this ECF documents construction of the transport model, system optimization, and predictions of future plume movement and remediation system performance.

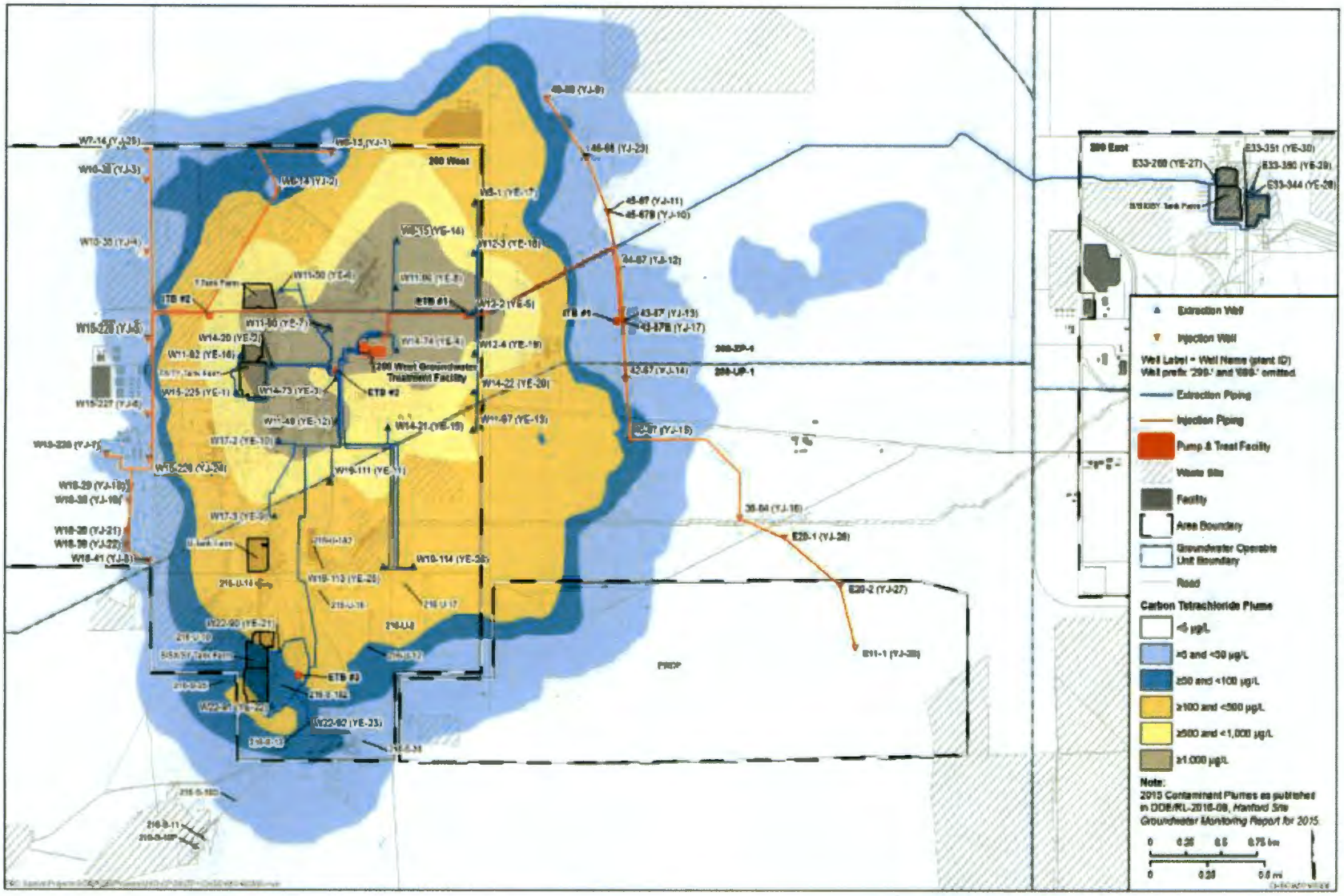


Figure 1. 200 West Carbon Tetrachloride Plume, Pump and Treat Well Locations, and Piping Routes (DOE/RL-2016-20)

2 Methodology

This section describes the construction of the transport model, mathematical optimization, and the post-processing of transport model results for various analysis products.

2.1 Groundwater Flow Modeling

The CPGWM was used perform the necessary flow modeling prerequisite to using MT3DMS (Modular Transport, 3-Dimensional, Multi-Species) for transport analysis. Only injection and extraction well flow rates were varied for this analysis.

2.2 Groundwater Transport Modeling

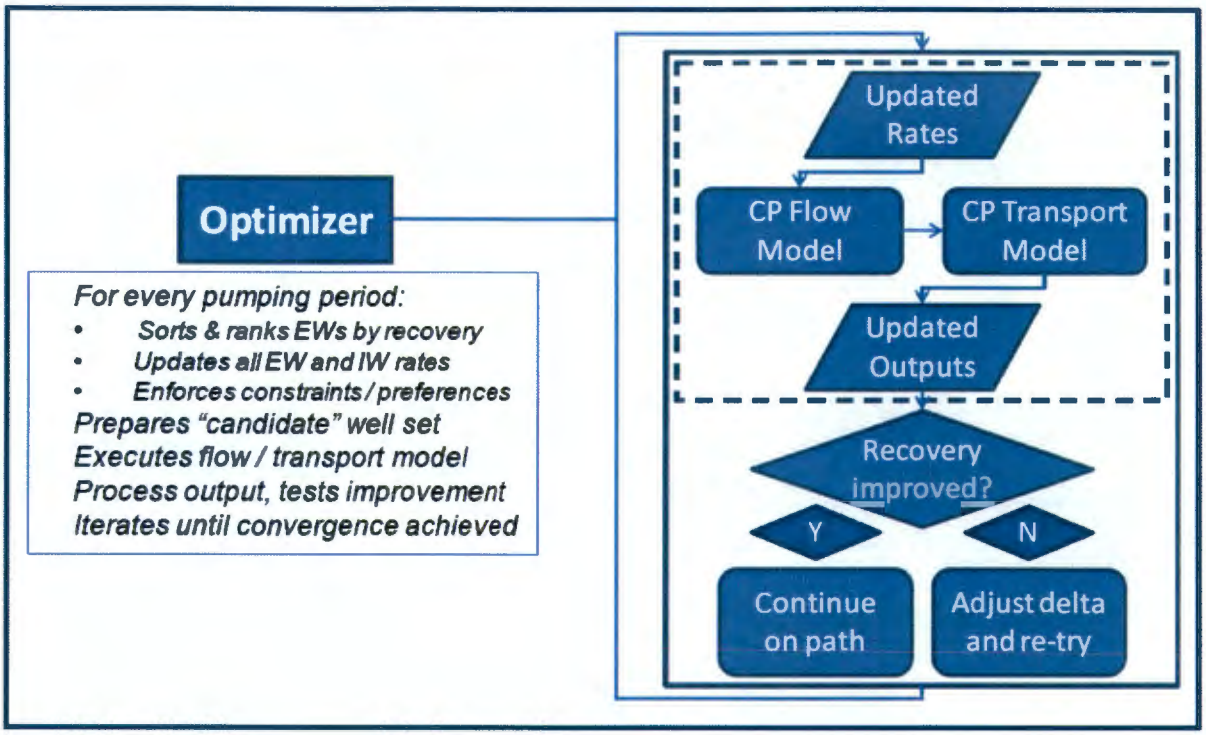
Contaminant transport simulations were performed using MT3DMS, a three-dimensional transport model which simulates advection, dispersion, source/sinks, and chemical reactions (Zheng and Wang, 1999). MT3DMS is designed for use with finite difference flow models, such as MODFLOW 2000 (Harbaugh et al., 2000). The flow model provides the velocity field needed for transport simulations. Contaminant transport simulations were conducted to approximate the recent and likely future movement and the fate of the 200-ZP-1 OU COCs and tritium and nitrate in the 200-UP-1 OU.

The approach to using MT3DMS was as follows:

1. Perform the necessary flow modeling prerequisite to using MT3DMS. The flow model is documented in ECF-200W-17-0043, *Capture-Zone and Particle-Tracking Analysis for the 200-UP-1/200-ZP-1 Areas Using the 2017 Updated Central Plateau Model*.
2. Generate the input files for MT3DMS. Input data are described in Chapter 3.
3. Execute the MT3DMS model simulations making use of the Transport Observation Package to gather output concentrations at specific times and locations needed for post-processing of the results.
4. Perform calculations of contaminant mass recovered by the extraction wells.
5. Perform the UCL95 calculations for each COC.

2.3 System Optimization

A mathematical optimization approach was used to determine the optimum pumping rates for the 200-ZP-1 injection and extraction wells. Mathematical optimization approaches are numerical methods that search for optimal designs based on specified objectives and constraints. These approaches can be coupled to groundwater flow and transport models to evaluate P&T designs. Optimization has been demonstrated at several field sites and shown to provide savings (in treatment costs and system infrastructure) over trial-and-error optimization (EPA/542/R-99/011B, *Hydraulic Optimization Demonstration for Groundwater Pump-and-Treat Systems, Volume II: Application of Hydraulic Optimization*). Pump and treat optimization was done using the code described in SGW-50390, *FY 2011 Simulation-Optimization of the 200-ZP-1 Remedy Using the Central Plateau Model*. The code adjusts individual well pumping rates to increase the mass recovered. Well location is not optimized in this approach; the potential (and existing) well locations are specified, and the algorithm assigns flow rates to achieve the best mass recovery and can suggest that certain wells be inactivated. A schematic of the code's function in shown in Figure 2.



EW = extraction well; IW = injection well

Figure 2. Schematic of the 200-ZP-1 Optimization Code (from SGW-50390)

2.4 Post-processing of Transport Model Results

Calculations were performed on the transport model results of concentration and mass to produce plots and maps including the following:

- Extent of contamination for each COC for the calendar years 2037 (end of 25 years of pumping) and 2137 (end of the 125-year cleanup period)
- Plots of cumulative mass recovery over time for each COC
- Plots of concentration over time at individual extraction wells for each COC
- The UCL95 of mean plume concentration for each COC based on simulated concentrations at specified monitoring well networks.

2.4.1 UCL95 Calculations on Mean Plume Concentration

Remediation performance was evaluated by calculating the 95th percentile upper confidence limit (UCL95) on mean plume concentrations. This is the same method recommended for calculating groundwater plume exposure point concentrations in superfund risk assessment guidance (OSWER 9285.6-10, *Calculating Upper Confidence Limits for Exposure Point Concentrations at Hazardous Waste Sites*). The advantage of the UCL95 is that it provides a comprehensive evaluation of plume concentrations in a single metric. It is calculated using sample results or simulated concentrations at monitoring wells.

The one-sided UCL95 was calculated using Student's *t* test assuming a normal distribution (OSWER 9285.6-10):

$$UCL_{95} = \bar{X} + t_{\alpha,n-1}\frac{s}{\sqrt{n}} \quad (1)$$

where

$\bar{X}$ = arithmetic mean of the sample results

$t_{\alpha,n-1}$ = the 1-α^{th} quantile of Student's *t* distribution with *n*-1 degrees of freedom; for the 95th percentile, $\alpha = 0.95$ (one-tailed)

s = standard deviation of the sample results

n = number of samples.

Well networks for tritium and nitrate UCL95 calculations in the 200-UP-1 OU are provided in DOE/RL-2015-14, *Performance Monitoring Plan for the 200-UP-1 Groundwater Operable Unit Remedial Action.* These networks are based on the current distribution of contamination. Well networks for UCL95 calculations in the 200-ZP-1 OU have not been formally established. For the calculations in this ECF, networks were chosen based on the wells identified for remedy performance monitoring in DOE/RL-2009-115, *Performance Monitoring Plan for the 200-ZP-1 Groundwater Operable Unit Remedial Action.* Locations identified in DOE/RL-2009-115 for future well drilling were also used, as appropriate. For transport simulations, additional wells needed to be added to the UCL95 networks as plumes migrated into regions outside of the monitoring networks identified in DOE/RL-2009-115 (no additional wells were needed for the tritium network in the 200-UP-1 OU; two additional wells, 299-W22-72 and 699-38-61, were added for nitrate in the 200-UP-1 OU). These additional locations were identified based on transport simulation results through the year 2137. Existing monitoring wells were used where available, but several additional monitoring locations were chosen to fill gaps in the well coverage. These locations are referred to herein as "synthetic" wells. When expanding the network, attempts were made to maintain a reasonably uniform spatial distribution of monitoring locations. Well networks for the 200-ZP-1 UCL95 calculations are shown in Figure 3 and Figure 4. Calculating the carbon tetrachloride UCL95 was done by segmenting the monitoring network into five zones based upon concentration and elapsed time. During active remediation as the plume reduces in size, the UCL95 is computed for three zones of the plume to more accurately evaluate the efficacy of remediation: low (5-100 µg/L), medium (>100-500 µg/L), and high (>500 µg/L) concentrations in the Ringold Unit E. A UCL95 is also computed for the Ringold Unit A because it is a separate hydrogeologic unit. After 25 years, when pumping has stopped, the entire network of Ringold Unit E wells is used to report one UCL95 value, and an updated UCL95 for the Ringold Unit A is computed.

Calculations of UCL95s for transport simulation results were performed as follows:

1. For a given constituent, the wells initially used for UCL95 calculations were those identified in DOE/RL-2015-14 for tritium and nitrate in the 200-UP-1 OU and those wells (or synthetic wells) in the 200-ZP-1 OU with concentrations above the cleanup level at the start of the simulations.

2. UCL95s were calculated annually beginning in 2012 (the first year of the transport simulations). The calculations used simulated concentrations at the end of each year. Three years of data were compiled for the calculations. For example, the data used for calculations of a 2014 UCL95 consisted of concentrations at the end of 2012, 2013, and 2014. This ensured that enough data

were available for representative calculation results. Note that only 1 year of data could be used for 2012 and 2 years for 2013.

3. As a plume moved into areas not covered by the UCL95 well network, additional wells were added to the calculation data set. This was done when concentrations at a nearby well, or a synthetic well, increased to above the cleanup level. When a new well was added, the convention of using 3 years of data was applied, i.e., if a well increased to above the cleanup level in 2030, concentrations for 2028, 2029, and 2030 were used in the calculation beginning in 2030.

4. When concentrations in a well declined to below one-tenth of the cleanup level that well was dropped from the calculation. This is the cutoff specified in DOE/RL-2015-14, and this was also applied to the 200-ZP-1 OU. However, if concentrations in that well later increased to above one-tenth the cleanup level, it was added back into the calculation. In other words, once a well is part of the UCL95 network, it is always used in the calculation if the concentration is above one-tenth the cleanup level.

5. Calculations were performed until the end of the simulation data set, or until there were less than two data points above one-tenth the cleanup level available for the calculation. The use of only two data points occurred in some of the simulations performed with no continuing sources when concentrations were very low and the mean was well below the cleanup level. Thus, the effect of using only a few data points in the calculation was considered insignificant.

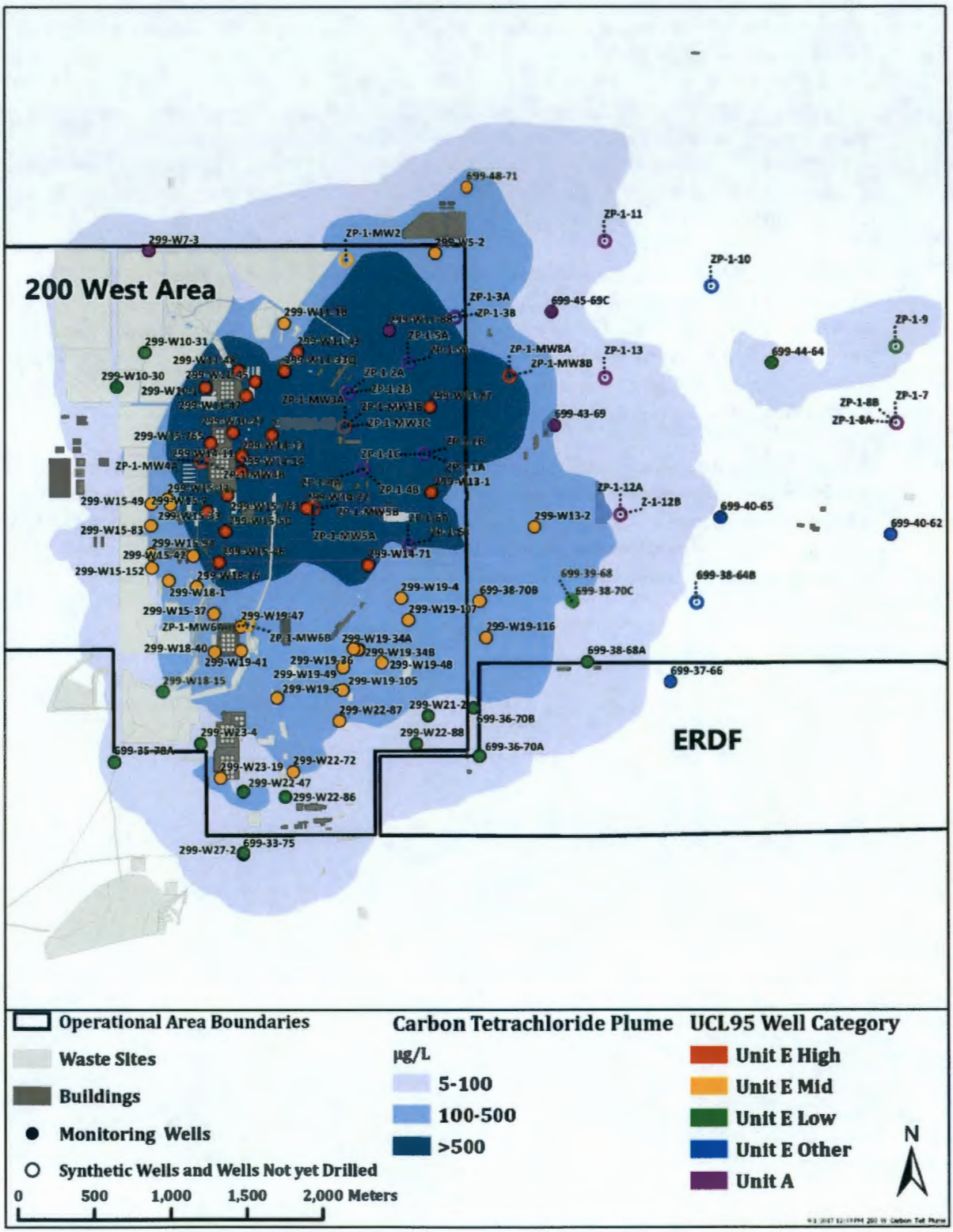


Figure 3. Well Network for Carbon Tetrachloride UCL95 Calculation

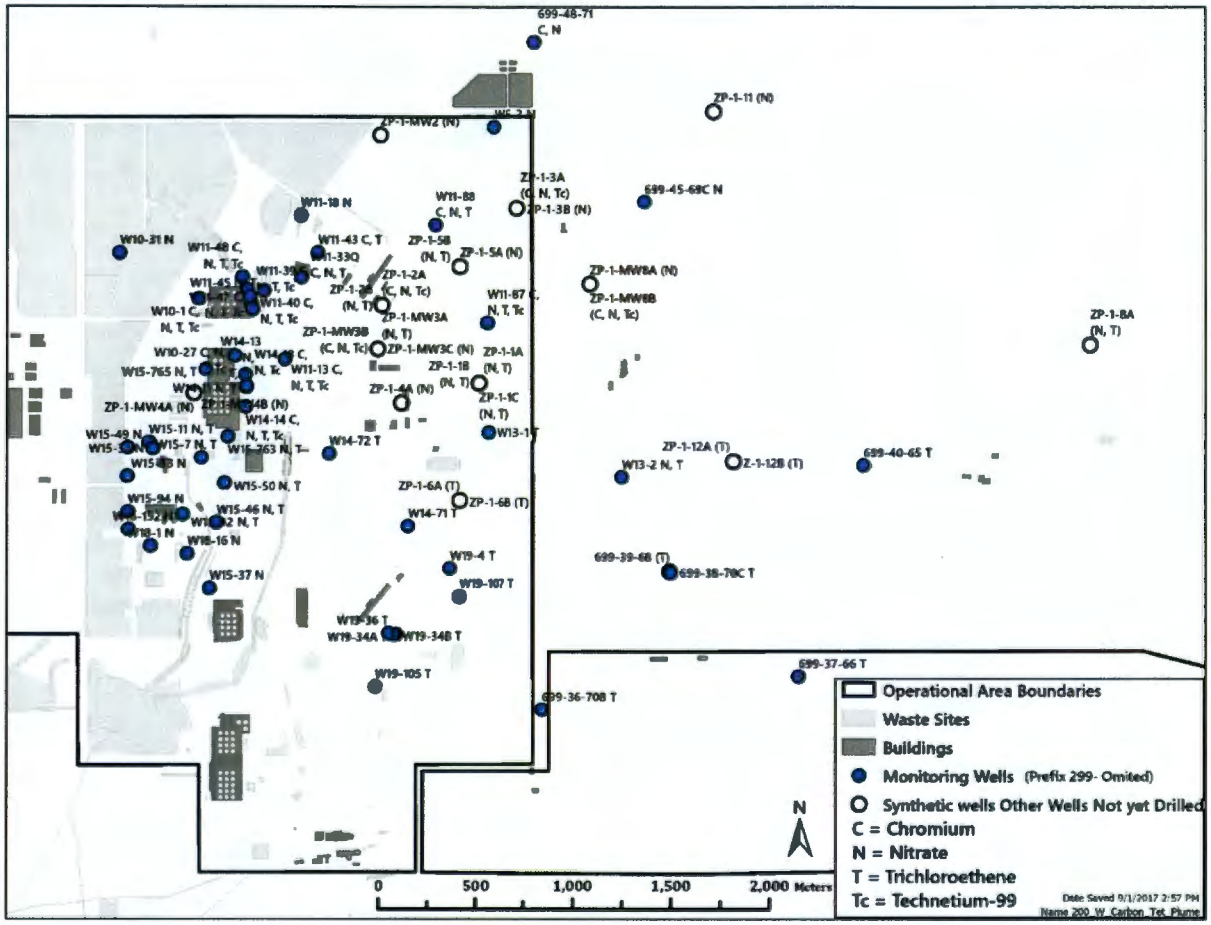


Figure 4. Well Network for 200-ZP-1 Chromium, Nitrate, TCE, and Tc-99 UCL95 Calculation

3 Assumptions and Inputs

This section summarizes the inputs that are specific to the calculations presented in this ECF. Features and inputs to the CPGWM that do not change for these calculations (e.g., the model layer elevations of the CPGWM) are not presented here. The principal inputs to the calculations are:

- Extraction and injection well flow rates
- Initial conditions for contaminant transport simulations (i.e., plumes)
- Input parameters for transport simulations
- Contaminant treatment system (CTS) package for transport simulations
- Source concentrations specified in the Sink & Source Mixing (SSM) package for transport simulations

These inputs are described in the following sections.

3.1 Extraction and Injection Well Flow Rates

Historical and recently projected pumping rates were used to forecast planned system operation (ECF-200W-17-0029, *Description of Groundwater Calculations and Assessments for the Calendar Year 2016 (CY 2016) 200 Areas Pump and Treat Report*). The optimization algorithm automatically changed the rates as part of its execution process.

3.2 Initial Conditions for the Groundwater Transport Model

For carbon tetrachloride and nitrate, the initial conditions in the transport model are specified concentrations that are identical to those used in the current version (8.4.5) of the CPGWM. The initial concentrations in the CPGWM were based on plumes derived from the 2012 initial conditions used in ECF-200ZP1-16-0076, *Description of Groundwater Calculations and Assessments for the Calendar Year 2015 (CY 2015) 200 Areas Pump and Treat Report*. Because the numerical grid for the current version of the CPGWM has different vertical discretization than previous versions of the CPGWM, the plumes were adjusted by volume-weighting the previous plume concentrations to ensure that the initial plume distribution produced plumes that conserved the mass from one version to another (CP-47631, *Model Package Report: Central Plateau Groundwater Model, Version 8.4.5*). The same procedure was used to create initial 2012 plume conditions for Cr(VI), Tc-99, TCE, and tritium.

3.3 Transport Parameters

The transport parameters, including effective porosity, longitudinal dispersivity, transverse horizontal dispersivity, and transverse vertical dispersivity, molecular diffusion constant and the bulk density, are the same as those documented in the most recent model package report for the CPGWM (CP-47631), and are reproduced in Table 3-1.

Table 3-1. Aquifer Properties for Fate and Transport Analysis

Property	Value
Effective porosity	0.15
Longitudinal dispersivity	3.5 m
Transverse horizontal dispersivity	0.7 m
Transverse vertical dispersivity	0.0 m
Molecular diffusion constant	0.0 m^2/day
Bulk density, Hanford, Cold Creek	1.93 g/cm^3
Bulk density, Ringold Taylor Flat, unit E, lower mud, unit A	1.90 g/cm^3

Transport parameters that are specific to a COC are the half-life and distribution coefficient (K_d) as shown in Table 3-2. Unless otherwise noted with a footnote, the source of the transport parameter values in Table 3-2 is DOE/RL-2009-122, *Remedial Investigation/Feasibility Study for the 200-UP-1 Groundwater Operable Unit.*

Table 3-2. COC Contaminant Transport Properties

Contaminant of Concern	Half-Life (yr)	Distribution Coefficient (mL/g)	Degradation Rate (1/day)
Carbon Tetrachloride	41.3[a]	0.011[a]	4.590E-05[a]
Chromium/Hexavalent Chromium	N/A	0	N/A
Nitrate	N/A	0	N/A
Technetium-99	210,000	0	8.9902E-09[a]
Trichloroethylene	N/A[a]	0.025[a]	N/A
Tritium	12.3	0	1.5403E-04[a]

Notes:

a. Source: ECF-200ZP1-16-0076, *Description of Groundwater Calculations and Assessments for the Calendar Year 2015 (CY 2015) 200 Areas Pump and Treat Report.*

N/A = not applicable, does not decay

3.4 Treatment System Efficiency & Contaminant Treatment System Package

In this ECF, the simulation of the performance of the P&T system accounts for the fact that the 200 West treatment system does not remove all COCs with 100% efficiency before water is injected back into the groundwater system. A removal efficiency can be calculated from influent and effluent concentrations measured at the 200 West P&T, and is listed in Table 3-3 (reproduced from Table 4-6 of ECF-200ZP1-16-0076). The removal efficiencies are the same as those documented in CP-47631. The transport model employs the CTS package, which simulates the removal of mass via a treatment system by incorporating extraction wells, mixing, treatment, and injection wells as part of an integrated P&T system. In this ECF, the CTS package represents the 200 West P&T system by removing COCs from extracted water prior to

injection. The removal efficiency of the treatment system is a time varying and COC specific parameter specified in the CTS package as per Table 3-3.

Table 3-3. CTS Efficiency Percent Values Used for Transport Simulations (Percent)

Month/Year	Carbon Tetrachloride	Hexavalent Chromium	Nitrate	Technetium-99	Trichloroethylene	Uranium	Tritium
2012	100	88	62	98	59	69	100
2013	100	77	64	97	96	38	100
2014	100	81	78	96	96	34	100
Jan. 2015	100	83	83	94	93	15	100
Feb. 2015	100	77	78	94	94	0	100
Mar. 2015	100	90	85	97	87	23	100
Apr. 2015	100	93	67	96	91	17	100
May 2015	100	86	76	98	92	20	100
June 2015	100	88	84	97	93	17	100
July 2015	100	83	73	96	92	8	100
Aug. 2015	100	94	74	95	92	28	100
Sept. 2015	100	86	74	95	93	8	100
Oct. 2015	100	89	95	91	90	6	100
Nov. 2015	100	82	76	93	90	15	100
Dec. 2015	100	76	72	91	91	68	100
2016 to 2037	100	86	78	95	91	36	100

3.5 Source Concentrations

The effects of potential continuing sources of groundwater contamination were evaluated by using the mass/activity fluxes specified in ECF-200W-17-0030, *Calculation of Source Terms for the 200 West Pump-and-Treat System Optimization Modeling, FY 2017*. The source terms were assigned to the blocks which contained the bulk of the estimated source release area. Source mass loadings were specified for hexavalent chromium, nitrate, technetium-99, and tritium.

4 Software Applications

MODFLOW-MST-2000, MT3DMS, Groundwater Vistas™[1], and Microsoft Excel®[2] software programs were used for this environmental calculation. MT3DMS is CH2M HILL Plateau Remediation Company (CHPRC) approved software, managed and used in compliance with the requirements of PRC-PRO-IRM-309, *Controlled Software Management*. Groundwater Vistas is support software managed under PRC-PRO-IRM-309 as described in CHPRC-00258, *MODFLOW and Related Codes Software Management Plan*. Microsoft Excel was used as a desktop calculator as defined in PRC-PRO-IRM-309.

4.1 Approved Software

Software use for this calculation was in accordance with PRC-PRO-IRM-309. Brief descriptions of the approved software used in this calculation are provided in the following discussion.

4.1.1 Descriptions

MODFLOW

- Software Title: MODFLOW-2000-MST
- Software Version: CHPRC Build 8 (Windows®[3] executable file mf2k-mst-chprc08dpv.exe)
- Hanford Information Systems Inventory (HISI) Identification Number: 2517 (Safety Software, Level C)
- Workstation type and property number: INTERA Laptop BLAINEY
- Authorized User: Joan Blainey
- CHPRC Software Control Documents:
    - CHPRC-00257, *MODFLOW and Related Codes Functional Requirements Document*
    - CHPRC-00258, *MODFLOW and Related Codes Software Management Plan*
    - CHPRC-00259, *MODFLOW and Related Codes Software Test Plan*
    - CHPRC-00260, *MODFLOW and Related Codes Requirements Traceability Matrix: CHPRC Build 8*
    - CHPRC-00261, *MODFLOW and Related Codes Acceptance Test Report: CHPRC Build 8*

MT3DMS

- Software Title: MT3DMS
- Software Version: CHPRC Build 8 (Windows® executable file mt3d-mst-chprc08dpv.exe)

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[1] Groundwater Vistas is a trademark of Environmental Simulations, Inc., Reinholds, PA.

[2] Microsoft Excel is a registered product of the Microsoft Corporation in the United States and in other countries.

[3] Windows is a registered trademark of the Microsoft Corporation in the United States and in other countries.

- HISI Identification Number: 2518 (Safety Software, Level C)
- Workstation type and property number: INTERA Laptop BLAINEY
- Authorized User: Joan Blainey
- CHPRC Software Control Documents:
    - CHPRC-00257 Rev 1, *MODFLOW and Related Codes Functional Requirements Document*
    - CHPRC-00258 Rev 4, *MODFLOW and Related Codes Software Management Plan*
    - CHPRC-00259 Rev 3, *MODFLOW and Related Codes Software Test Plan*
    - CHPRC-00260 Rev 8, *MODFLOW and Related Codes Requirements Traceability Matrix: CHPRC Build 8*
    - CHPRC-00261 Rev 8, *MODFLOW and Related Codes Acceptance Test Report: CHPRC Build 8*

MODFLOW Support Software

- **ArcGIS®**: Mitchell, 1999, *The ESRI Guide to GIS Analysis, Volume 1: Geographic Patterns and Relationships.* Provided visualization tool for assessing simulated plume distributions, identifying extraction/injection well coordinates, and mapping auxiliary data. Used version 10.3.1.
- **FloPy**: Bakker et al., 2016, Python package for creating, running, and post-processing MODFLOW-based models. FloPy includes support for MODFLOW-2000, MODFLOW-2005, MODFLOW-NWT, MODFLOW-USG, and MODFLOW-LGR. Other supported MODFLOW-based models include MODPATH (version 6), MT3D, MT3D-USGS, and SEAWAT. Provided a tool to extract binary concentrations from the MT3DMS output and write it as a shapefile within a Python script. Used FloPy version 3.2.7.

4.1.2 Software Installation and Checkout

The Approved Safety Software package (MODFLOW) was checked out in accordance with procedures specified in CHPRC-00258. Executable files were obtained from the Software Owner who maintains the configuration-managed copies in MKS Integrity™[4], installation tests identified in CHPRC-00259 were performed and successful installation confirmed, and Software Installation and Checkout Forms were completed and approved for installations used to perform model runs reported in this calculation. A copy of the Software Installation and Checkout Form is provided in Appendix A of this ECF.

4.1.3 Statement of Valid Software Application

The preparers of this calculation brief attest that the software identified above, and used for the calculations described in this calculation brief, are appropriate for the application and used within the range of intended uses for which they were tested and accepted by CHPRC.

Because MT3DMS is graded as Level C software, use of this software is required to be logged in the HISI. Accordingly, this environmental calculation has been logged by the software owner in the HISI under Identification Number 2518 (MT3DMS).

[4] MKS Integrity is a trademark of PTC, Incorporated.

5 Calculations

The baseline extraction and injection well flow rates from ECF-200W-17-0029 were used to simulate fate and transport of contaminants within the CPGWM domain. The optimization tool described in SGW-50390 was used to adjust the pumping rates at specified well locations in the baseline model to improve carbon tetrachloride recovery; no optimization of other COC remediation was performed. Pumping in the CPGWM was adjusted to optimize six pumping periods between 1/1/2017 and 12/31/2037, listed in Table 5-1, under the constraints and rules implemented in the optimizer to limit the overall treatment system and individual well pumping capacities, as well as to maximize carbon tetrachloride mass removal.

Table 5-1. Time Intervals Used in 200-ZP-1 Optimization

Start Date	End Date	Duration (Years)
1/1/2017	12/31/2017	1
1/1/2018	12/31/2019	2
1/1/2020	12/31/2022	3
1/1/2023	12/31/2027	5
1/1/2028	12/31/2032	5
1/1/2033	12/31/2037	5

The goal of the optimization was to reduce carbon tetrachloride concentration in the Ringold Formation Units A and E as much as possible by the end of 2037. The optimization process was carried out through a series of iterations where the pumping limits were modified and additional wells were included in the system to increase extraction in high concentration areas and to enhance flow circulation by additional injection. As part of the optimization process, the individual extraction rate limits and initial rates of existing wells included in the optimization were increased and the total pumping limit, after the addition of new wells, was also incrementally increased.

Transport simulations were performed through the year 2137, which is the end of the 125-year cleanup period for Central Plateau (CP) groundwater beginning in 2012, when the 200 West P&T began operating. Simulations were performed for carbon tetrachloride, chromium, nitrate, technetium-99, TCE, and tritium for both baseline and optimized extraction wells flow rates, and with and without including ongoing sources (as appropriate) of contamination to the aquifer. Estimates of the source terms are documented in ECF-200W-17-0030.

The results are described in Section 6.

6 Results/Conclusions

The figures produced as output from the calculations described in this ECF are provided in this section. The results of the extent of contamination are presented in a series of maps that depict groundwater concentration for model layers 3, 5, and 7 which represent the water table in Ringold Unit E, base of the Ringold Unit E, and Ringold Unit A, respectively. Calendar years 2037 and 2137 are shown, representing the end of pumping and the total cleanup period, respectively. Not all COCs were present above the cleanup level in all layers and years, and maps are omitted as appropriate. Concentration maps were truncated below the cleanup level to make the extent of contamination easier to identify. Plots of UCL95, and total mass removed from the aquifers are also included.

Cumulative mass plots were computed by adding the mass reported by the transport model as extracted, and adding the mass extracted during Phase I remediation activities to the total (Table 6-1).

Table 6-1. Phase I Masses (from ECF-200ZP1-16-0076)

COC	Mass Recorded as Recovered During Phase I
Carbon Tetrachloride (41-yr half-life)	2,305 kg
Carbon Tetrachloride (100-yr half-life)	2,305 kg
Chromium	14 kg
Nitrate [as NO_3]	84,693 kg
Technetium	0 Ci
Trichloroethene	3 kg
Tritium	0 Ci

Individual extraction well simulated concentration histories are shown in Appendix B.

6.1 Forecast of Projected Baseline Operations

Table 6-2 shows the final cleanup levels for the 200-ZP-1 OU (from Table 3-1 in DOE/RL-2016-20). Federal and State maximum contaminant levels (MCLs) are the COC cleanup levels for all COCs except TCE, which is 1 instead of 5 µg/L. These levels were used to display the following simulation results by removing lower values. Results are presented by COC.

Table 6-2. Final Cleanup Levels for the 200-ZP-1 Groundwater OU (from DOE/RL-2016-20)

Contaminant of Concern	90th Percentile Concentration	Federal MCL	State MCL	Model Toxics Control Act Method B Cleanup Levels		Final Cleanup Level
				Non-carcinogens	Carcinogens at 10^{-6} Risk Level	
Carbon Tetrachloride	2,900	5	5	5.6	3.4[a]	3.4[b]
Chromium (Total)	130	100	100	24,000	—	100
Hexavalent Chromium[c]	203	—[d]	—[d]	48	—	48
Iodine-129	1.2	1	1	—	—	1
Nitrate[e] (as NO_3)	359,052	45,000	45,000	113,408	—	45,000
Nitrate[e] (as N)	81,050	10,000	10,000	25,600	—	10,000
Technetium-99	1,442	900	900	—	—	900
Trichloroethene	10.9	5	5	2.4	1[a]	1[b]
Tritium	36,200	20,000	20,000	—	—	20,000

Reference: EPA et al., 2008, *Record of Decision Hanford 200 Area 200-ZP-1 Operable Unit Superfund Site, Benton County, Washington.*

Notes: Units are µg/L for nonradionuclides and pCi/L for radionuclides.

Federal MCL values are from 40 CFR 141, "National Primary Drinking Water Regulations," with iodine-129 and technetium-99 values from EPA 816-F-00-002, *Implementation Guidance for Radionuclides.*

State MCL values are from WAC 246-290, "Group A Public Water Supplies."

a. WAC 173-340-705, "Model Toxics Control Act—Cleanup," "Use of Method B," cleanup levels for carbon tetrachloride and trichloroethene are from the Cleanup Levels and Risk Calculations (CLARC) database table (Ecology, 2008).

b. DOE will clean up COCs for the 200-ZP-1 OU subject to WAC 173-340 (carbon tetrachloride and trichloroethene), so the excess lifetime cancer risk does not exceed 1×10^{-5} at the conclusion of the remedy.

c. The mobile form of chromium in Hanford Site groundwater is hexavalent chromium. Groundwater samples have been analyzed for chromium by the analytical laboratories as either total chromium or hexavalent chromium. Both methods yield similar results, although there can be differences caused by normal analytical variability or sample turbidity. Therefore, although total chromium and hexavalent chromium are listed as separate COCs, they represent the same constituent in Hanford Site groundwater. The effective cleanup level for chromium is the hexavalent chromium standard of 48 µg/L because it is more restrictive.

d. There is no MCL specific to hexavalent chromium.

e. Nitrate may be expressed as total nitrate (NO_3) or as total nitrogen (N). The MCL for nitrate as NO_3 is 45,000 µg/L, and the same concentration expressed as N is 10,000 µg/L. (Note that the EPA's drinking water regulations are published as 10,000 µg/L.)

— = not applicable

MCL = maximum contaminant level

6.1.1 Carbon Tetrachloride – 41-year half-life

Figure 5, Figure 6, and Figure 7 show the simulated extent of carbon tetrachloride at the end of pumping in 2037. Peak concentrations were 340, 490, and 852 µg/L at the water table, base of the Ringold Unit E, and Ringold Unit A, respectively. Areas above 100 µg/L persist in the Ringold Units E and A are present at the end of pumping. The highest concentrations are in the Ringold Unit A.

No source was estimated for carbon tetrachloride.

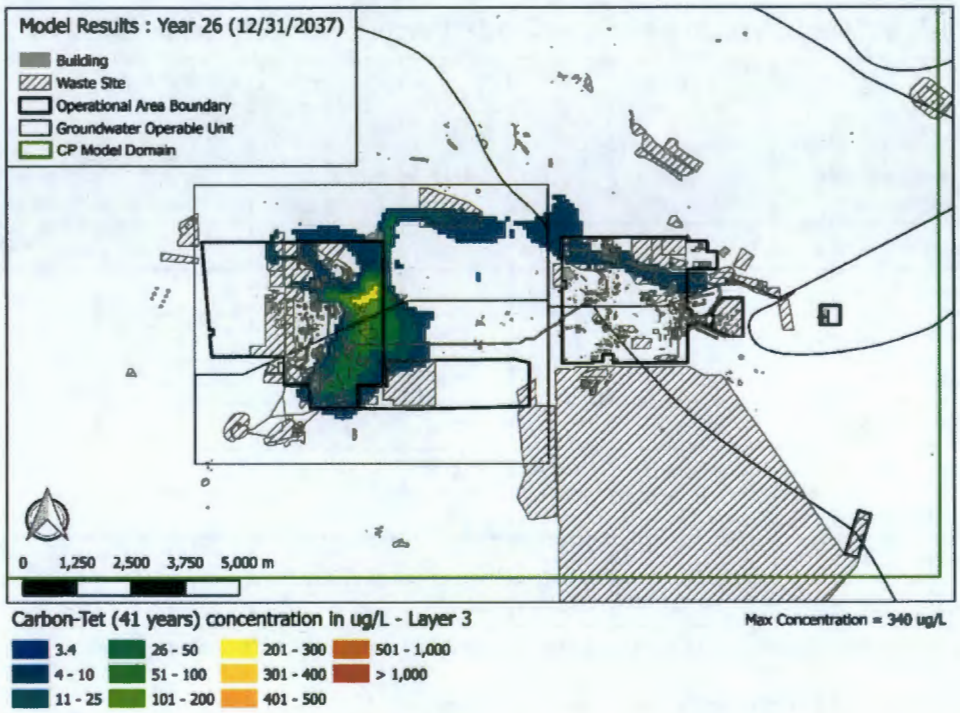


Figure 5. Simulated Carbon Tetrachloride Distribution (41-year half-life) at the Ringold Unit E Water Table in 2037 after 25 years of baseline pumping

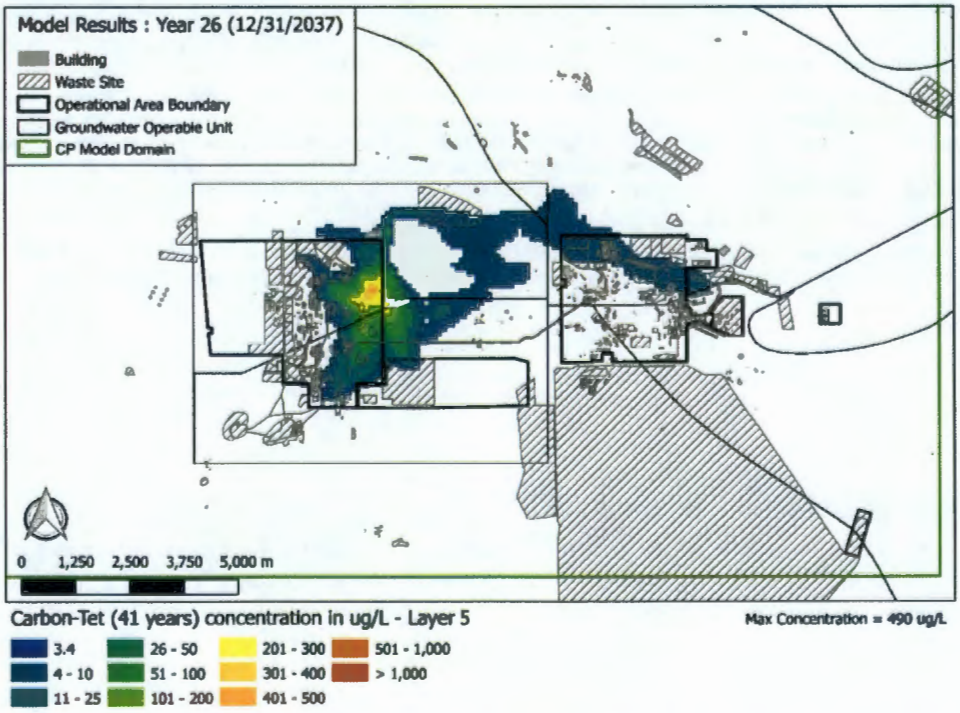


Figure 6. Simulated Carbon Tetrachloride Distribution (41-year half-life) at the base of Ringold Unit E in 2037 after 25 years of baseline pumping

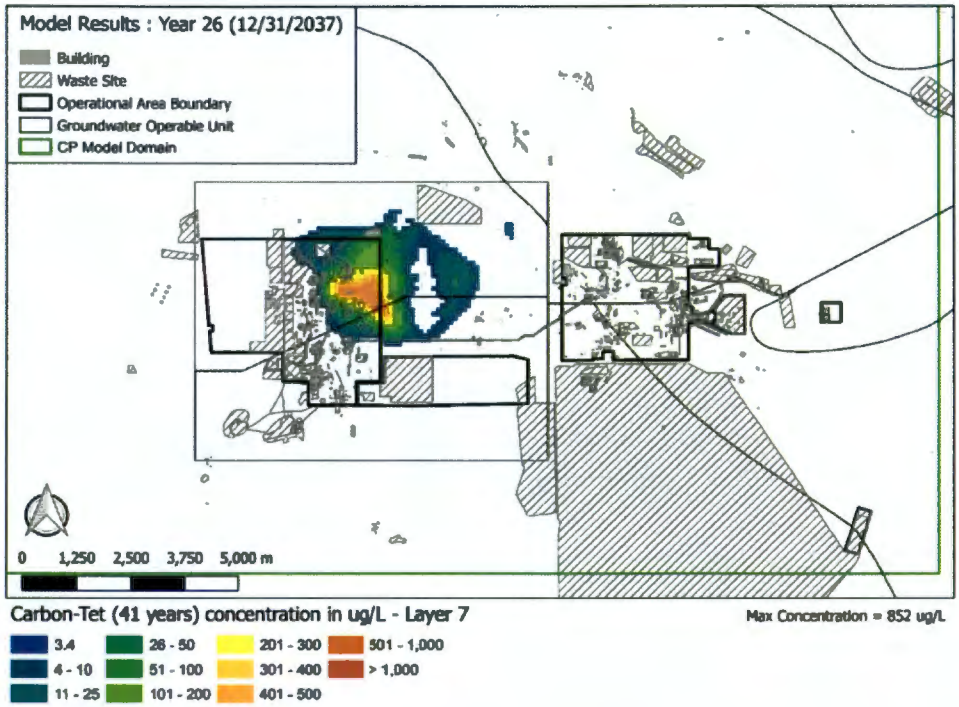


Figure 7. Simulated Carbon Tetrachloride Distribution (41-year half-life) in the Ringold Unit A in 2037 after 25 years of baseline pumping

Figure 8, Figure 9, and Figure 10 show the simulated extent of carbon tetrachloride at the end of 2137. Peak concentrations are above the MTCA cleanup level of 3.4 µg/L in the Ringold E and A; concentrations are highest in the Ringold A.

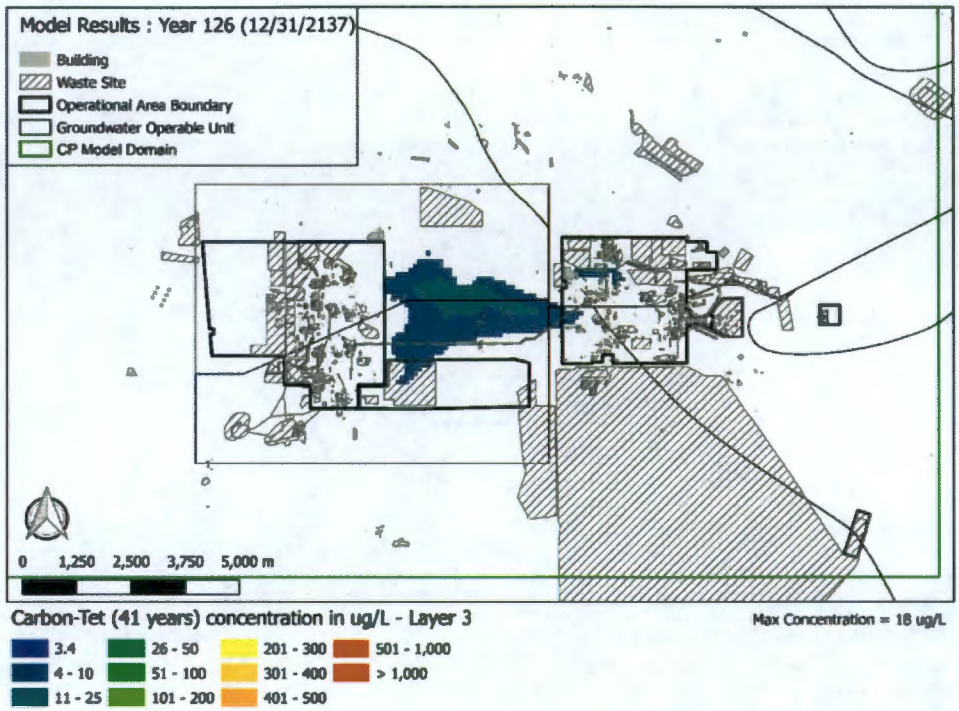


Figure 8. Simulated Carbon Tetrachloride (41-year half-life) Distribution at the Ringold Unit E Water Table in 2137

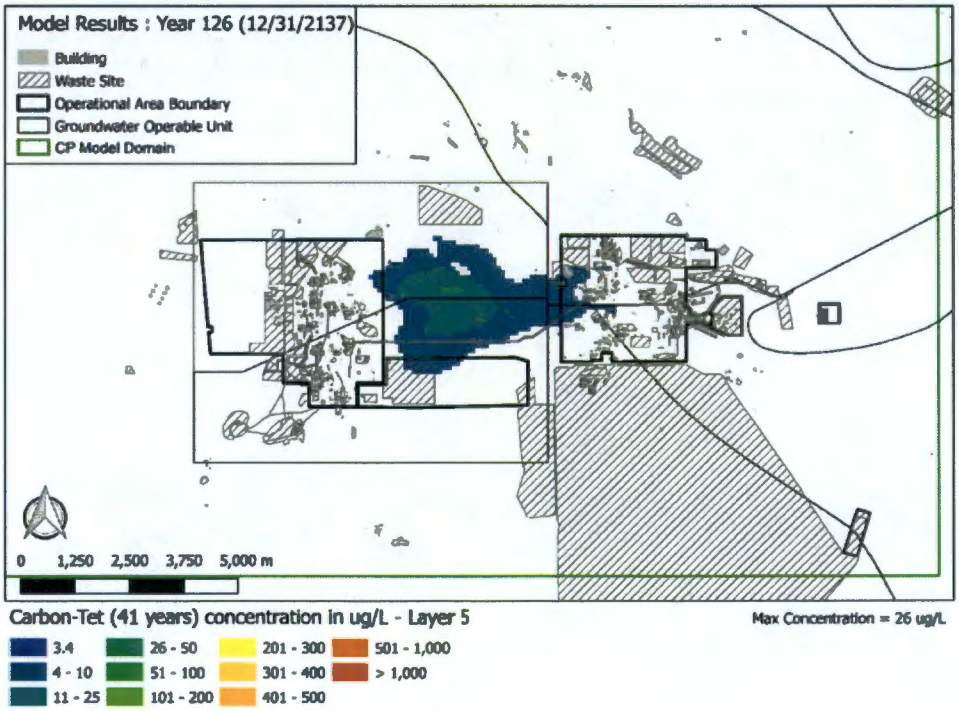


Figure 9. Simulated Carbon Tetrachloride (41-year half-life) Distribution at the base of Ringold Unit E in 2137

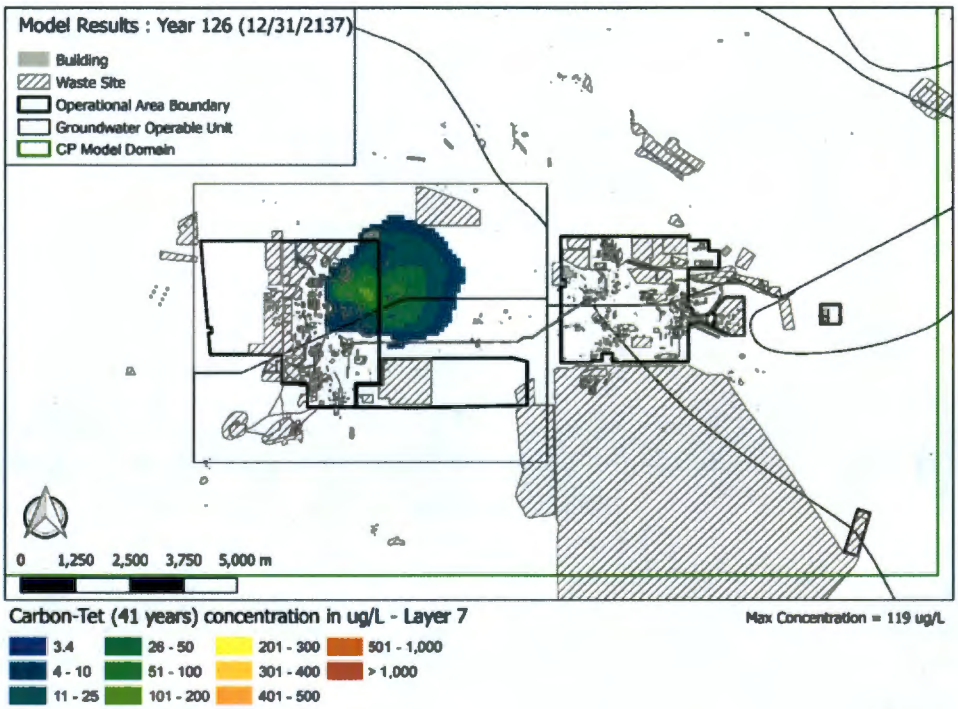


Figure 10. Simulated Carbon Tetrachloride (41-year half-life) Distribution in the Ringold Unit A in 2137

Simulated mass removed by pumping is shown as mass and fraction of initial mass in Figure 11.

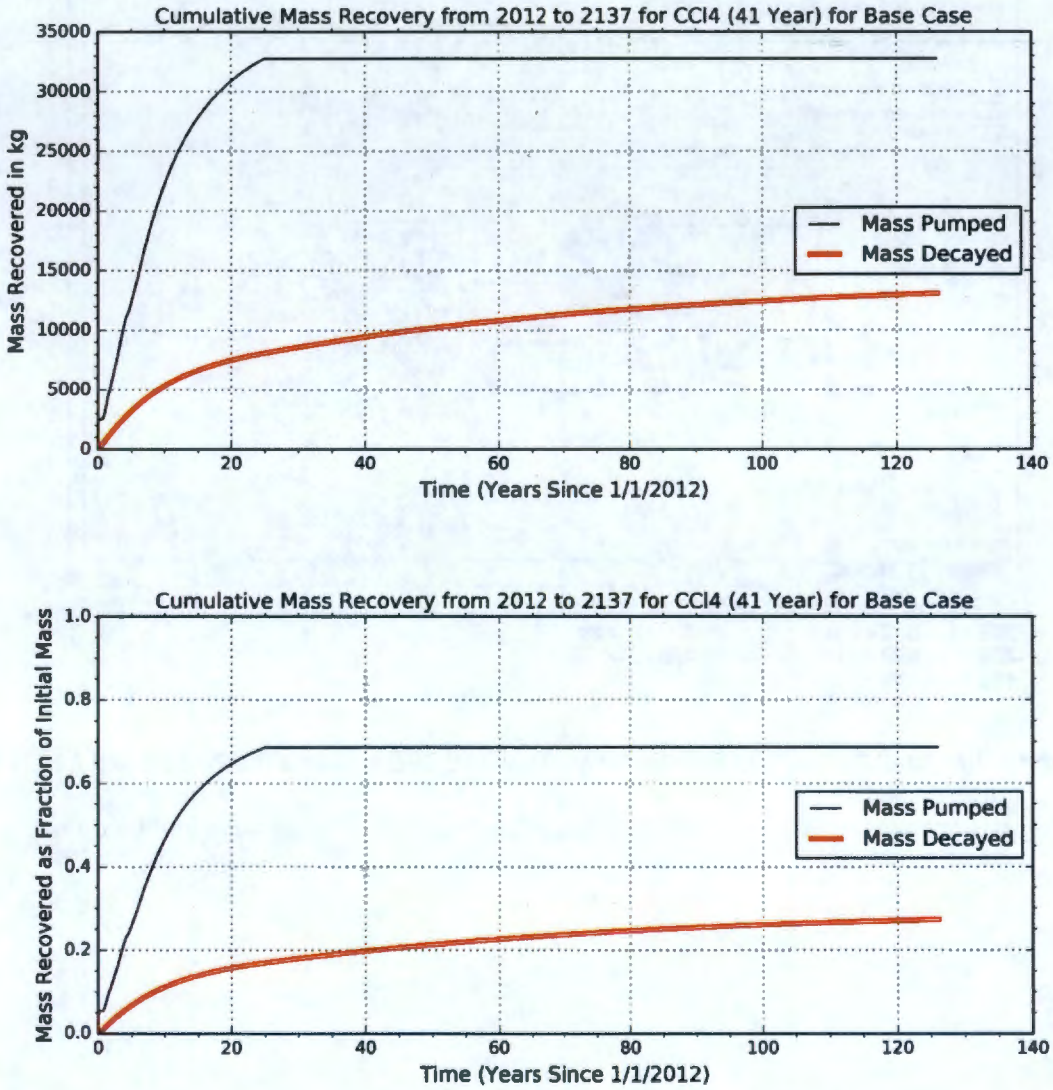


Figure 11. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass – Baseline Pumping (bottom)

Simulated UCL95 concentrations are shown in Figure 12. Four curves are shown for the pumping period representing the lower, medium, and upper Ringold Unit E concentration zones and the Ringold Unit A as described in Section 2.4.1. After pumping ceases, a single composite curve is used for the remaining carbon tetrachloride plume in the Ringold Unit E. The Ringold Unit E concentrations all decline at about the same rate for about the first 12 years of system operation, and then the low (5 to 100 µg/L) concentration zone rate of decline slows sharply, suggesting cleanup efficiency is dropping and the system needs to be adjusted. The Ringold Unit A shows a similar slope during and after pumping, suggesting that the pumping is not strongly affecting cleanup. At no time during the simulation did the UCL95 for Units E and A decline to below the 3.4 µg/L cleanup level.

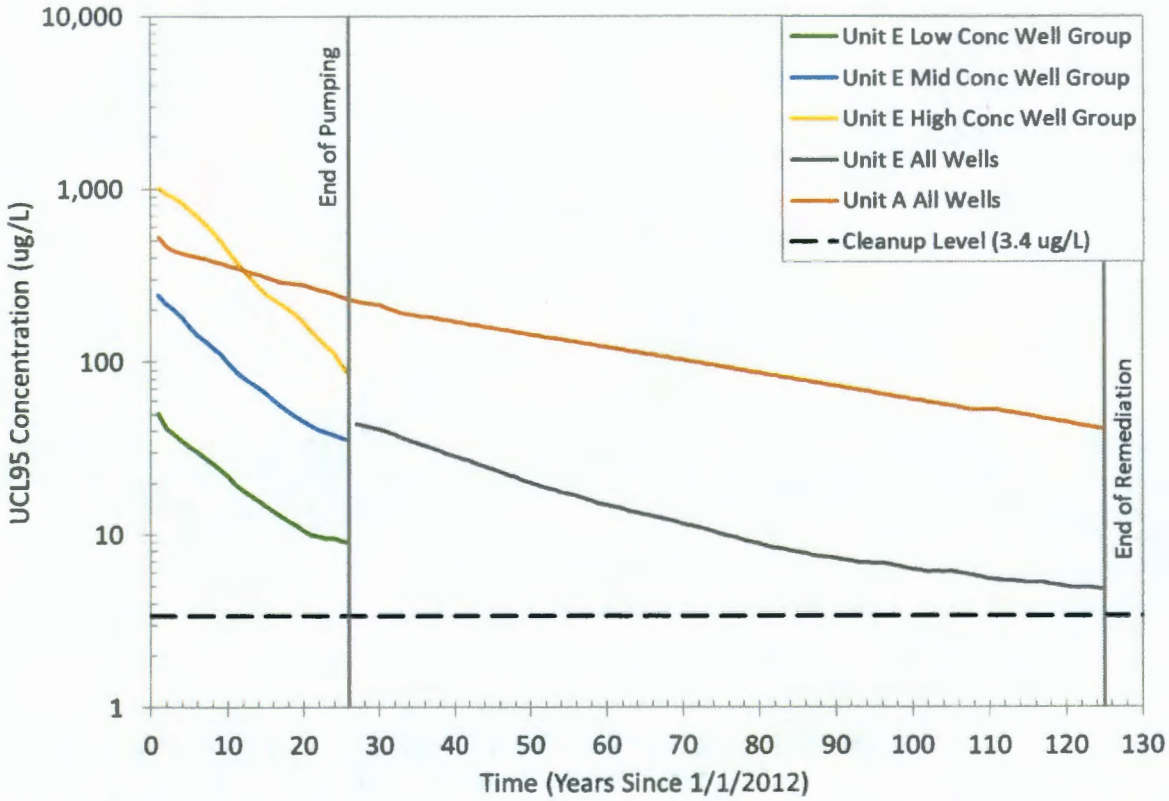


Figure 12. Simulated UCL95 Concentrations for Carbon Tetrachloride – Baseline Pumping - 41-yr half-life

6.1.2 Carbon Tetrachloride – 100-year half-life

Figure 13, Figure 14, and Figure 15 show the simulated extent of the carbon tetrachloride plume with a 100-year half-life at the end of 25 years of pumping in 2037. Peak concentrations are higher than those simulated with a 41-year half-life, and are above 100 µg/L. Simulated Ringold Unit A concentrations are the highest. Similarly, simulated concentrations in 2137 are greater than those with a 41-year half-life, and above the cleanup level.

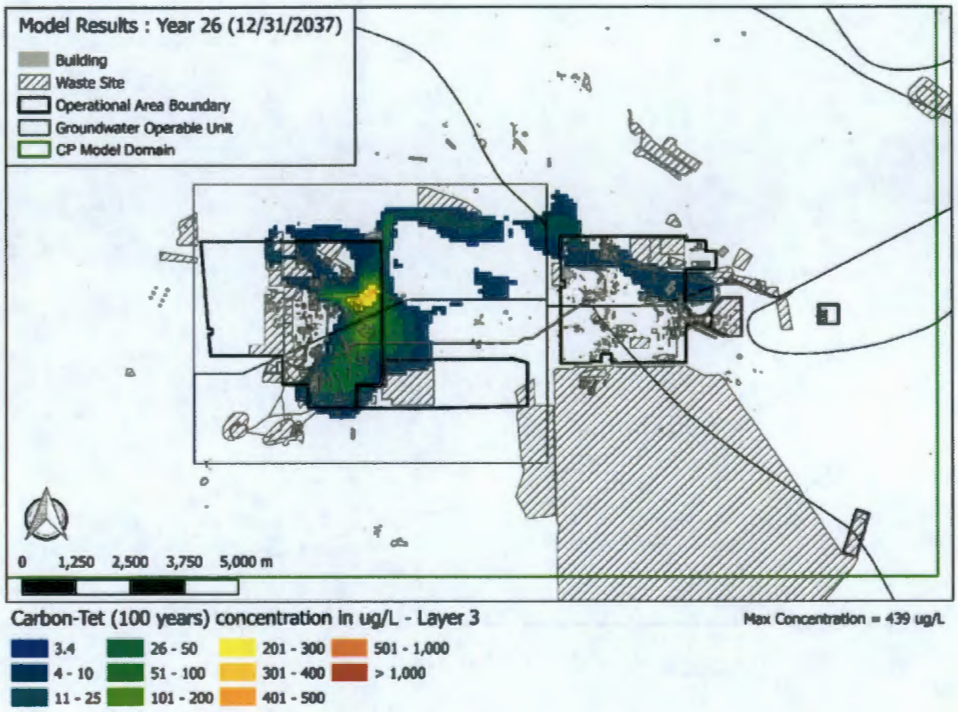


Figure 13. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the water table in Ringold Unit E in 2037 after 25 years of baseline pumping

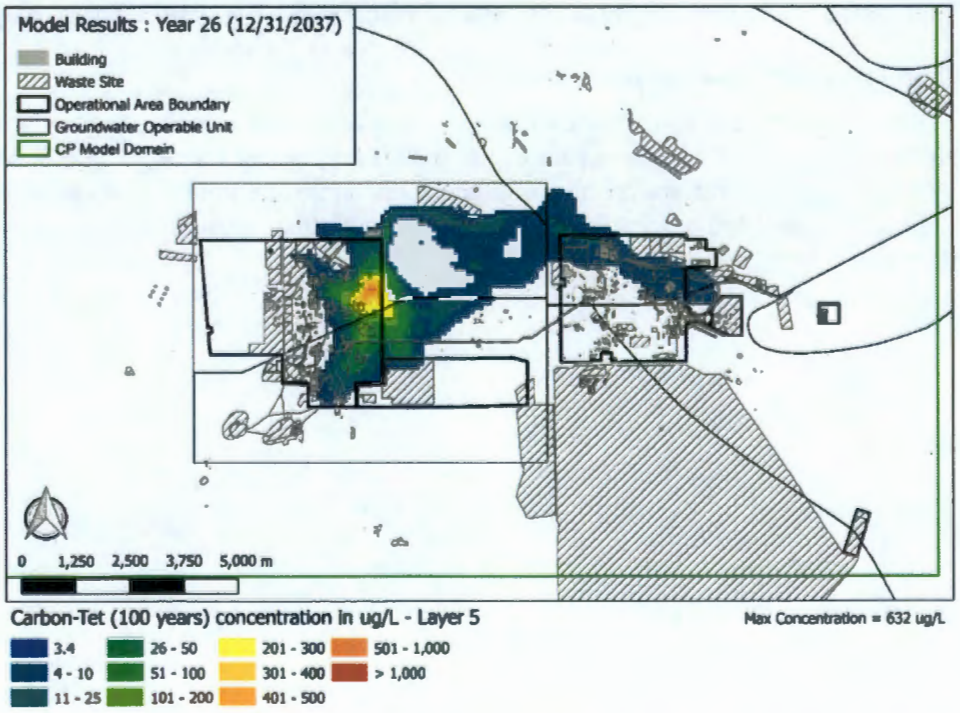


Figure 14. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the base of Ringold Unit E in 2037 after 25 years of baseline pumping

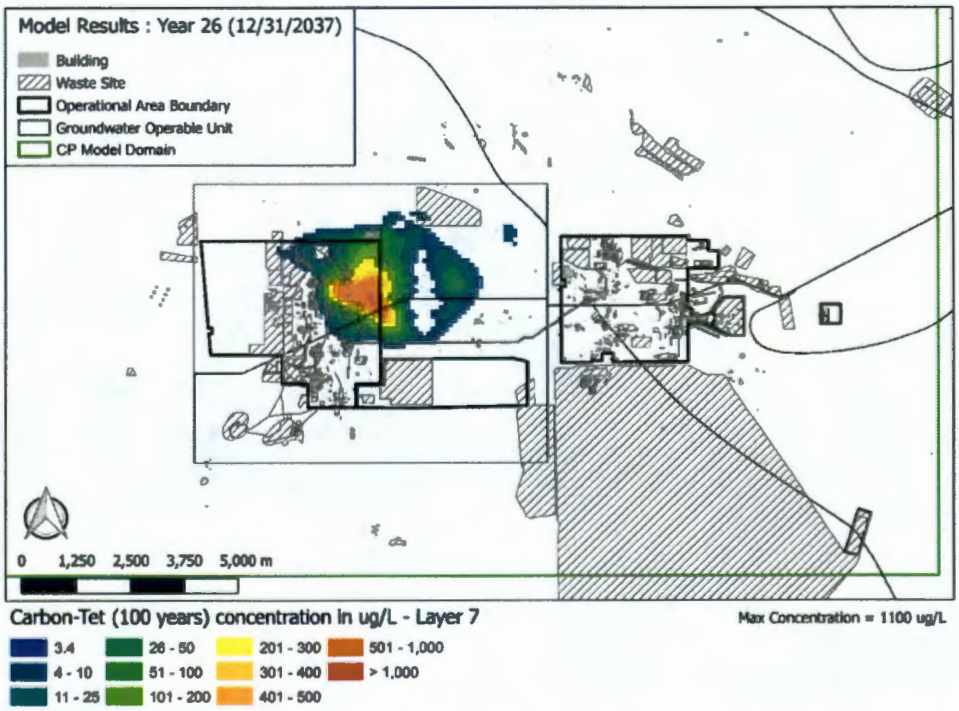


Figure 15. Simulated Carbon Tetrachloride Distribution (100-year half-life) in the Ringold Unit A in 2037 after 25 years of baseline pumping

Figure 16, Figure 17, and Figure 18 show the simulated extent of carbon tetrachloride in 2137. The plume area above 3.4 µg/L is greater than with a 41-year half-life because less mass is removed by decay.

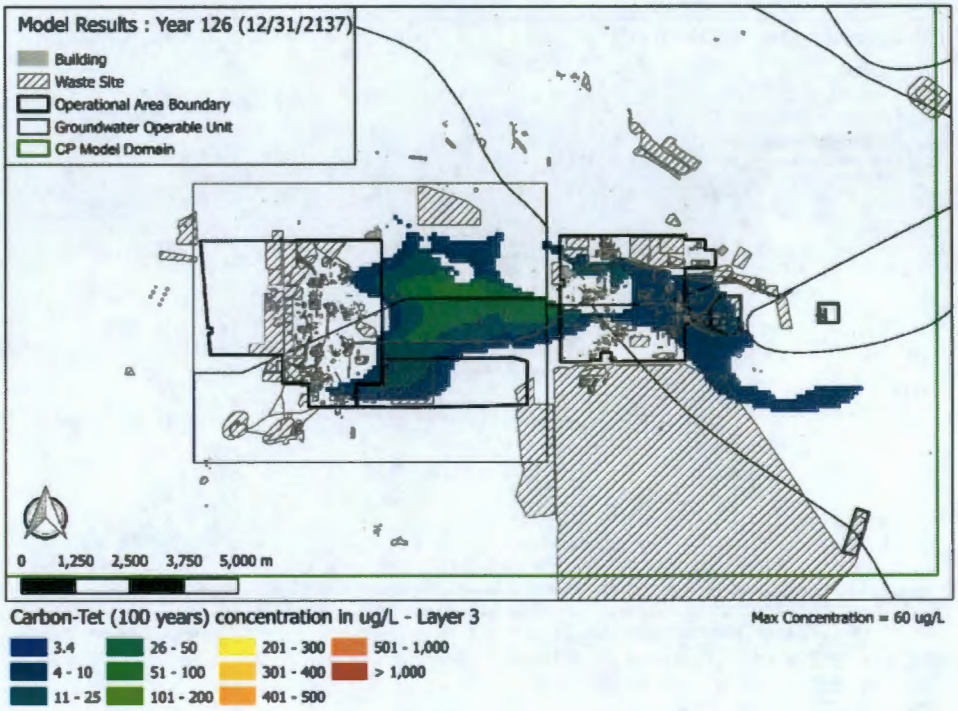


Figure 16. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the water table in Ringold Unit E in 2137

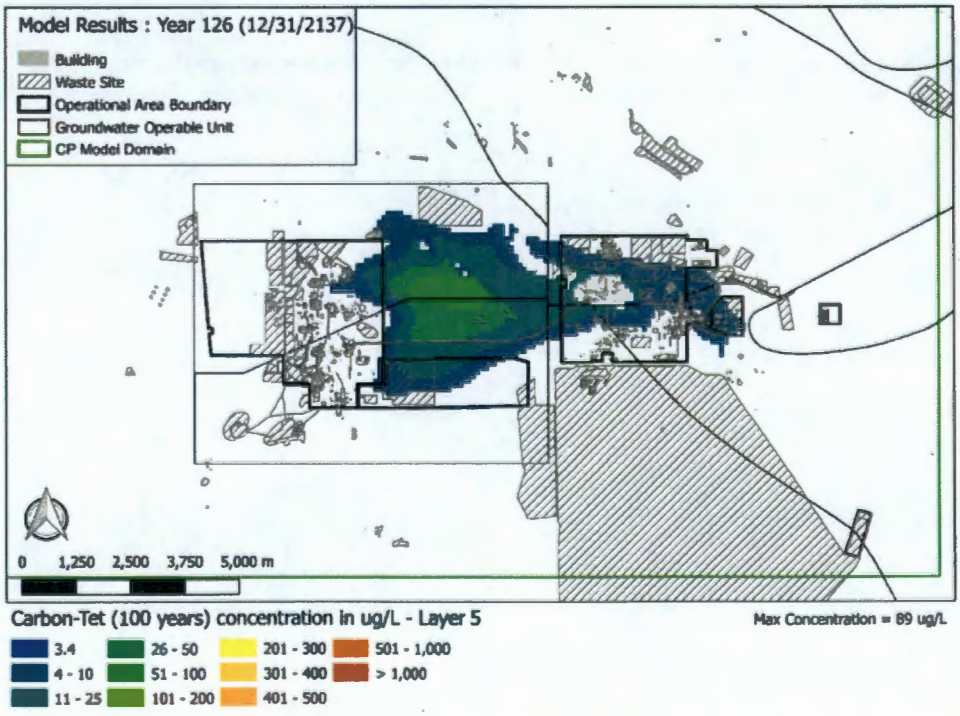


Figure 17. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the base of Ringold Unit E in 2137

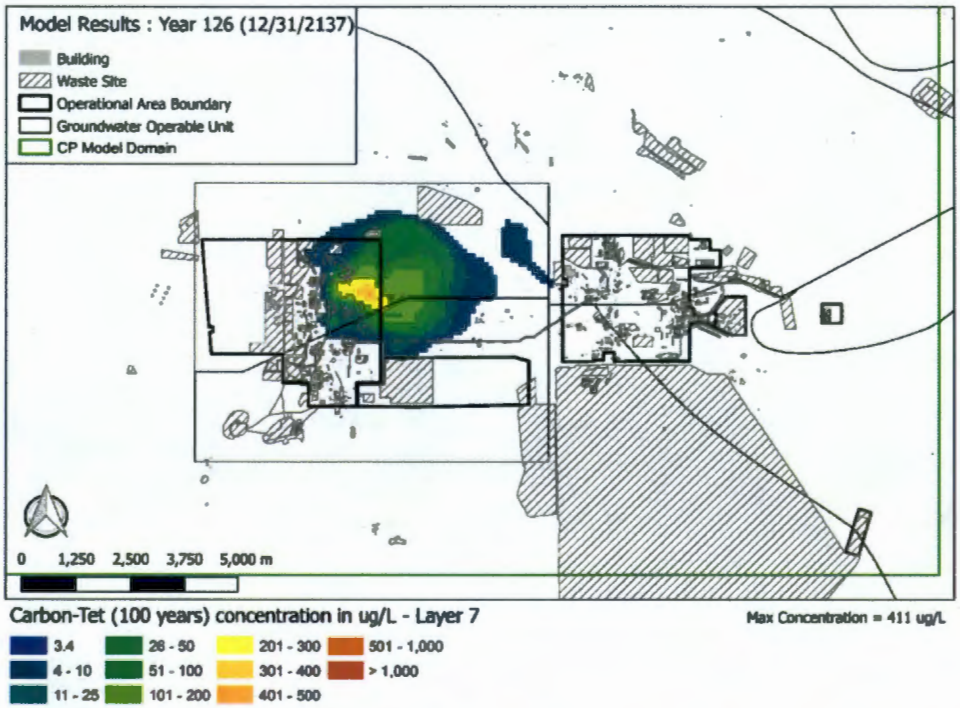
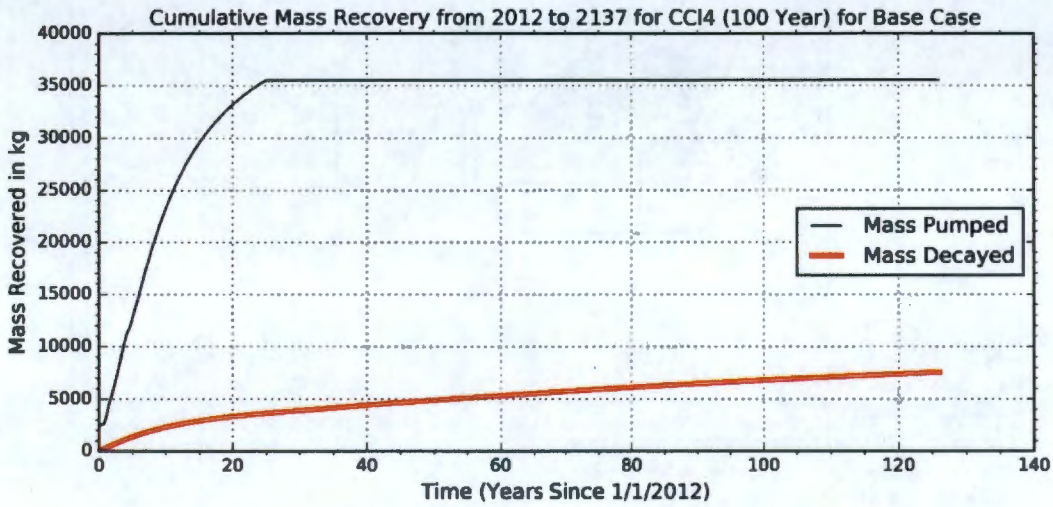


Figure 18. Simulated Carbon Tetrachloride Distribution (100-year half-life) in the Ringold Unit A in 2137

Simulated mass removed by pumping is shown as mass and fraction of initial mass (Figure 19); more mass is recovered by pumping assuming a 100-yr half-life than assuming a 41-yr half-life because less mass decays during pumping operations, i.e., higher concentrations are being pumped assuming a 100-yr half-life for carbon tetrachloride.



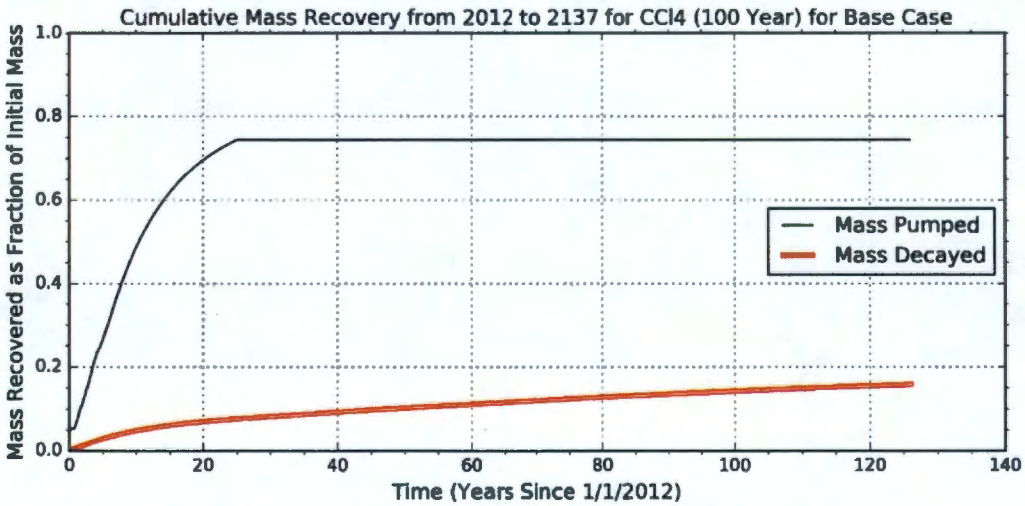


Figure 19. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass (bottom)– Baseline Pumping

Simulated UCL95 concentrations for carbon tetrachloride are shown in Figure 20. Four curves are shown for the pumping period representing the lower, medium, and upper Ringold Unit E concentration zones and the Ringold Unit A as described in Section 2.4.1. The overall pattern during pumping is similar to the UCL95 concentrations determined assuming a 41-yr half-life shown in Figure 12 earlier, but the concentrations at the end of remediation are higher; progress towards cleanup is less at the end of the 125-yr period because there is less mass removed by decay.

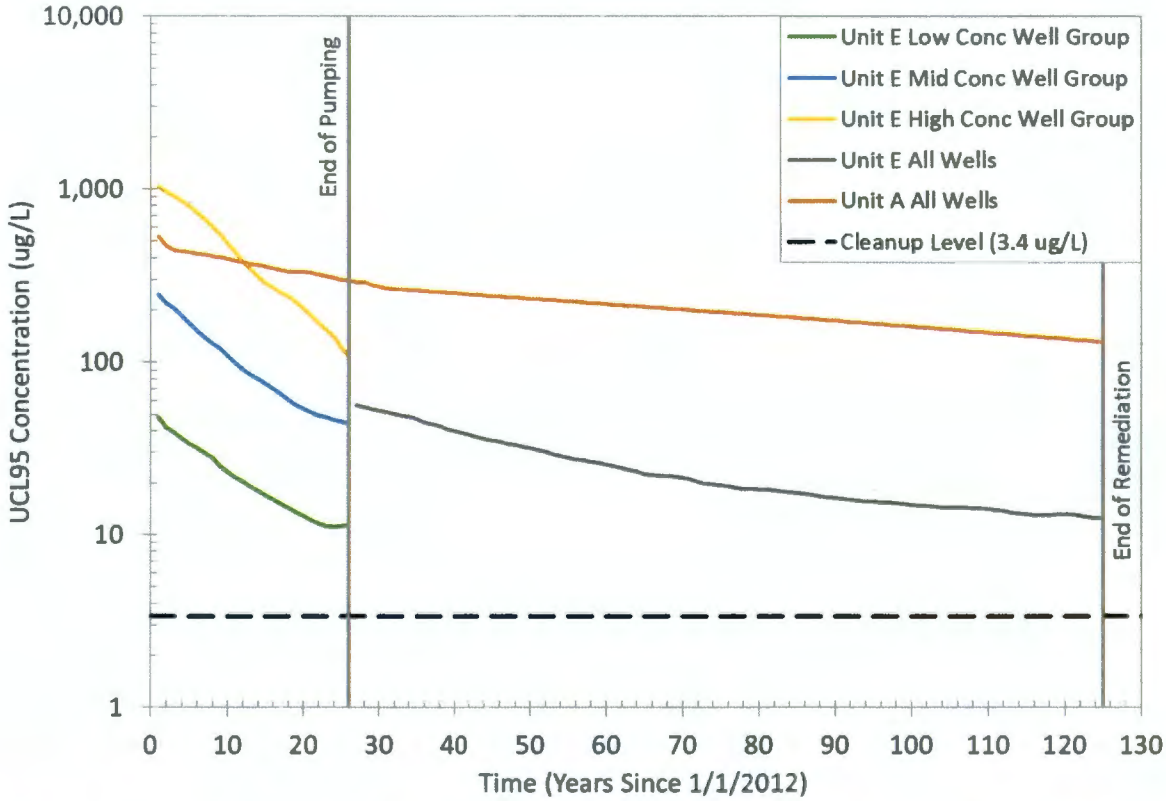


Figure 20. Simulated UCL95 Concentrations for Carbon Tetrachloride – Baseline Pumping - 100-yr half-life

6.1.3 Carbon Tetrachloride – 630-year half-life

A more recent, Hanford site-specific half-life for carbon tetrachloride was estimated in PNNL-22062, *Abiotic Degradation Rates for Carbon Tetrachloride and Chloroform: Final Report* at 630 years. Figure 21, Figure 22, and Figure 23 show the simulated extent of the carbon tetrachloride plume after 25 years of pumping (2037) using a 630-year half-life. Figure 24, Figure 25, and Figure 26 show the simulated extent of the carbon tetrachloride plume in 2137. Similar to the increases in concentrations that occurred assuming a 41-year half-life to a 100-yr half-life, the concentrations assuming a 630-yr half-life are notably higher at the end of pumping (2037) and at the end of the 125-year remediation period (2137) than concentrations computed using either of the lower half-lives. This analysis demonstrates the key role abiotic decay plays in carbon tetrachloride remediation.

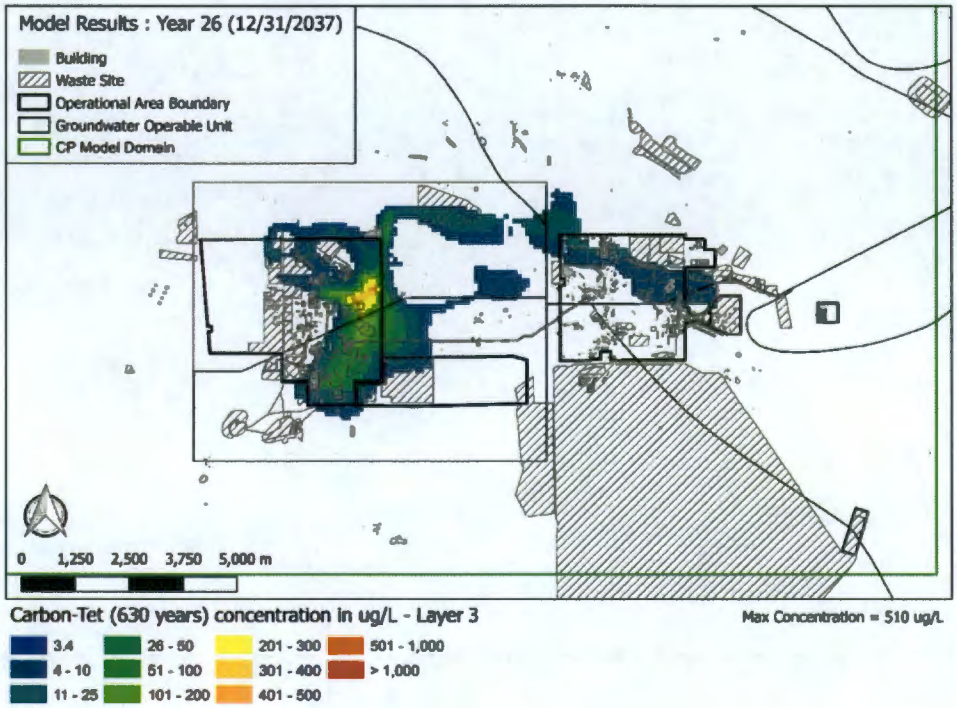


Figure 21. Simulated Carbon Tetrachloride Distribution (630-year half-life) at the water table in Ringold Unit E in 2037 after 25 years of baseline pumping

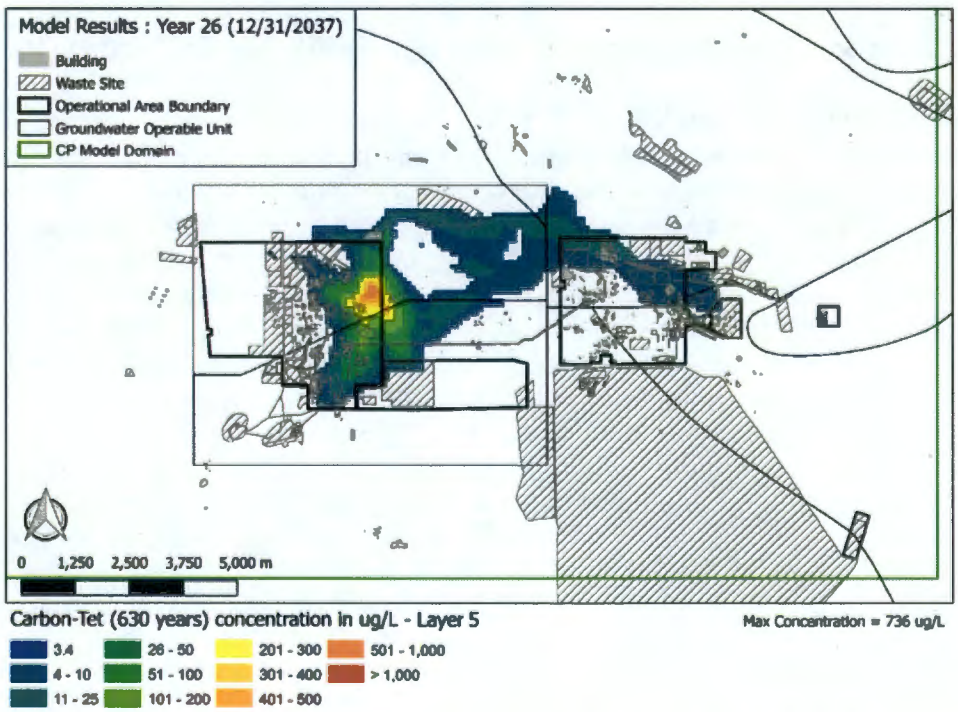


Figure 22. Simulated Carbon Tetrachloride Distribution (630-year half-life) at the base of the Ringold Unit E in 2037 after 25 years of baseline pumping

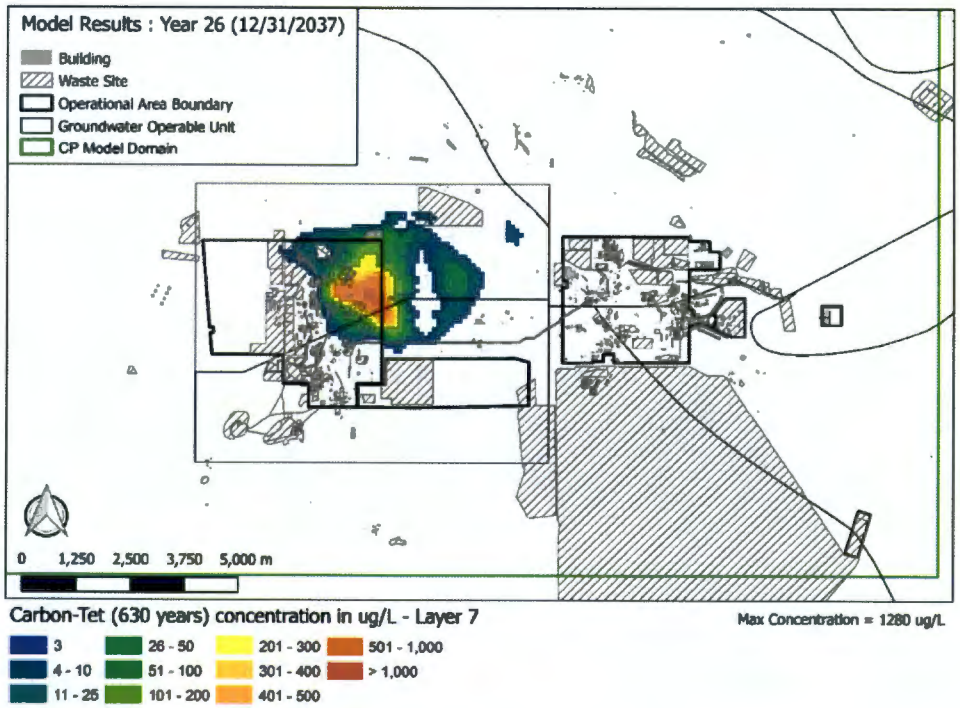


Figure 23. Simulated Carbon Tetrachloride Distribution (630-year half-life) in the Ringold Unit A in 2037 after 25 years of baseline pumping

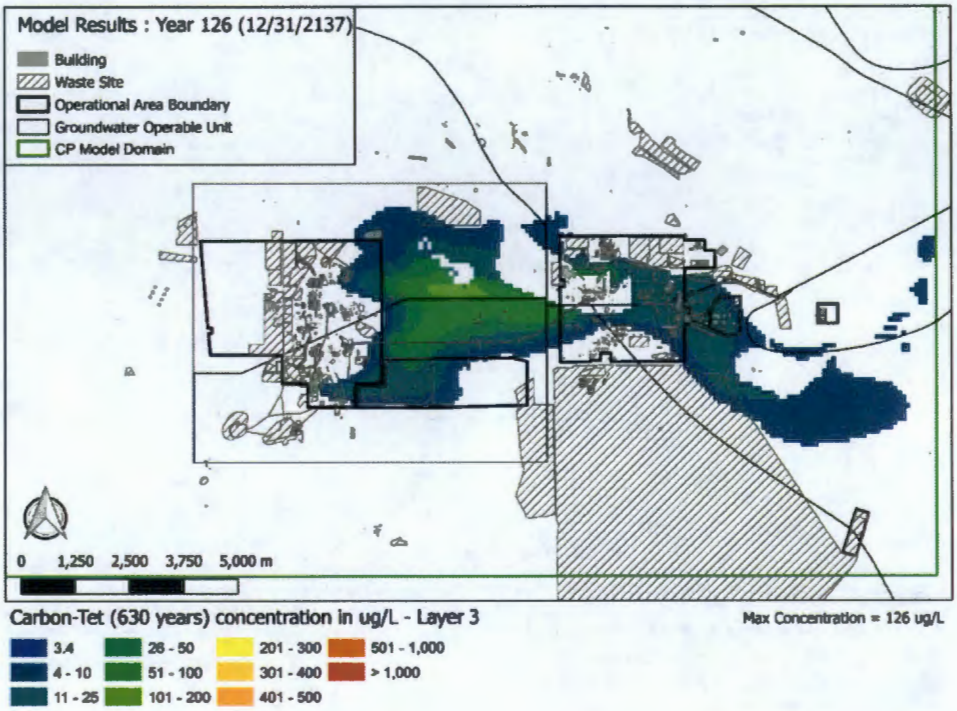


Figure 24. Simulated Carbon Tetrachloride Distribution (630-year half-life) at the water table in Ringold Unit E in 2137

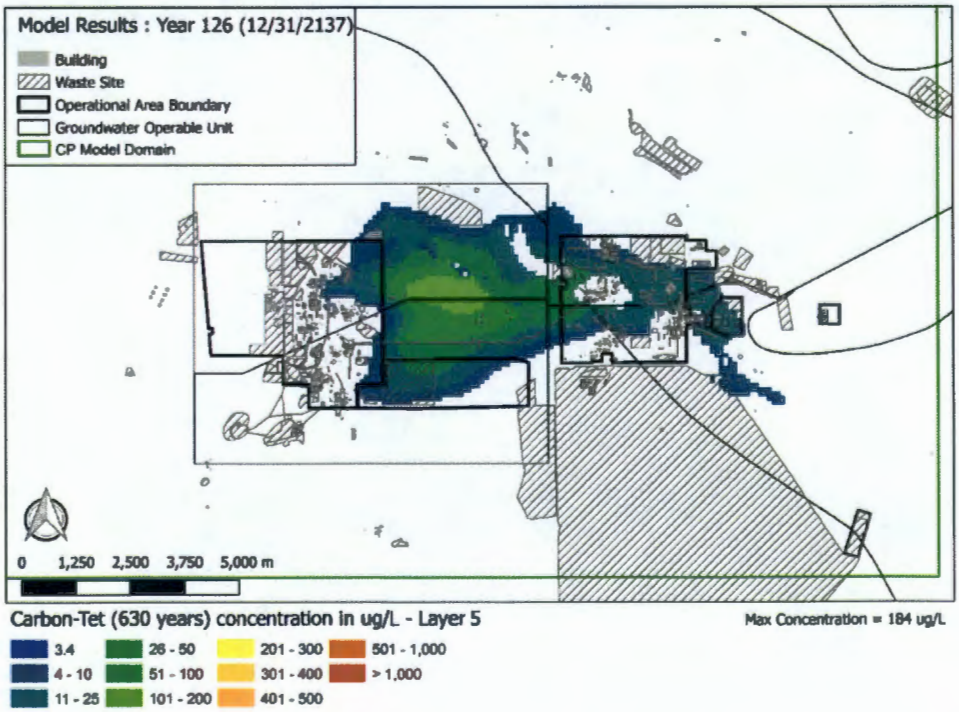


Figure 25. Simulated Carbon Tetrachloride Distribution (630-year half-life) at the base of the Ringold Unit E in 2137

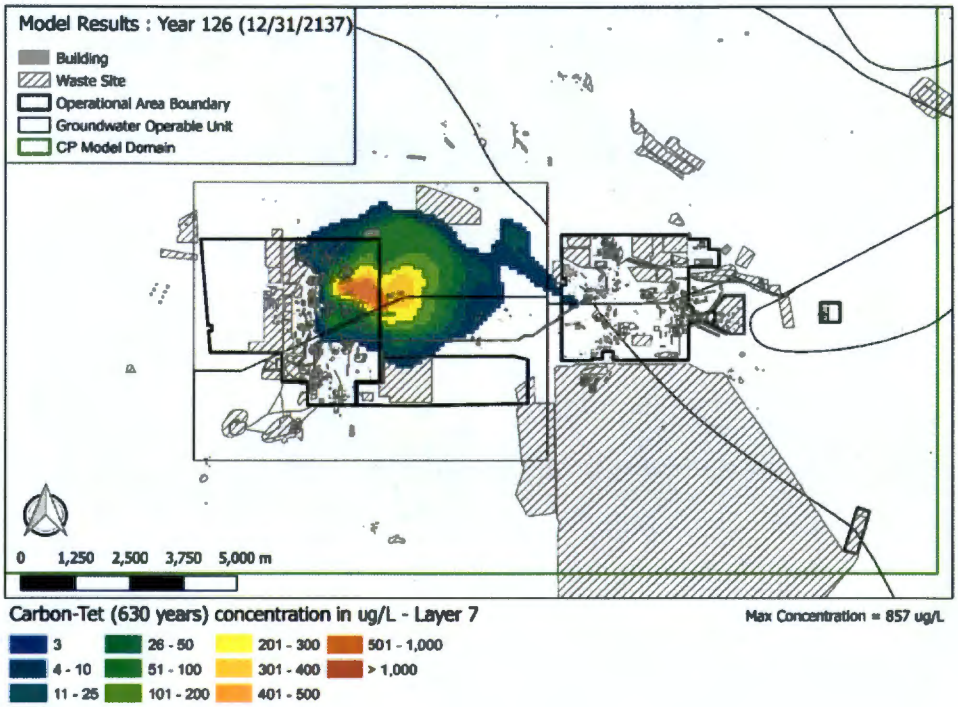


Figure 26. Simulated Carbon Tetrachloride Distribution (630-year half-life) in the Ringold Unit A in 2137

Simulated mass recovery is shown in Figure 27; more mass is recovered than in the 41- and 100-yr half-life calculations; concentrations in the pumped water are higher because less mass is removed by decay.

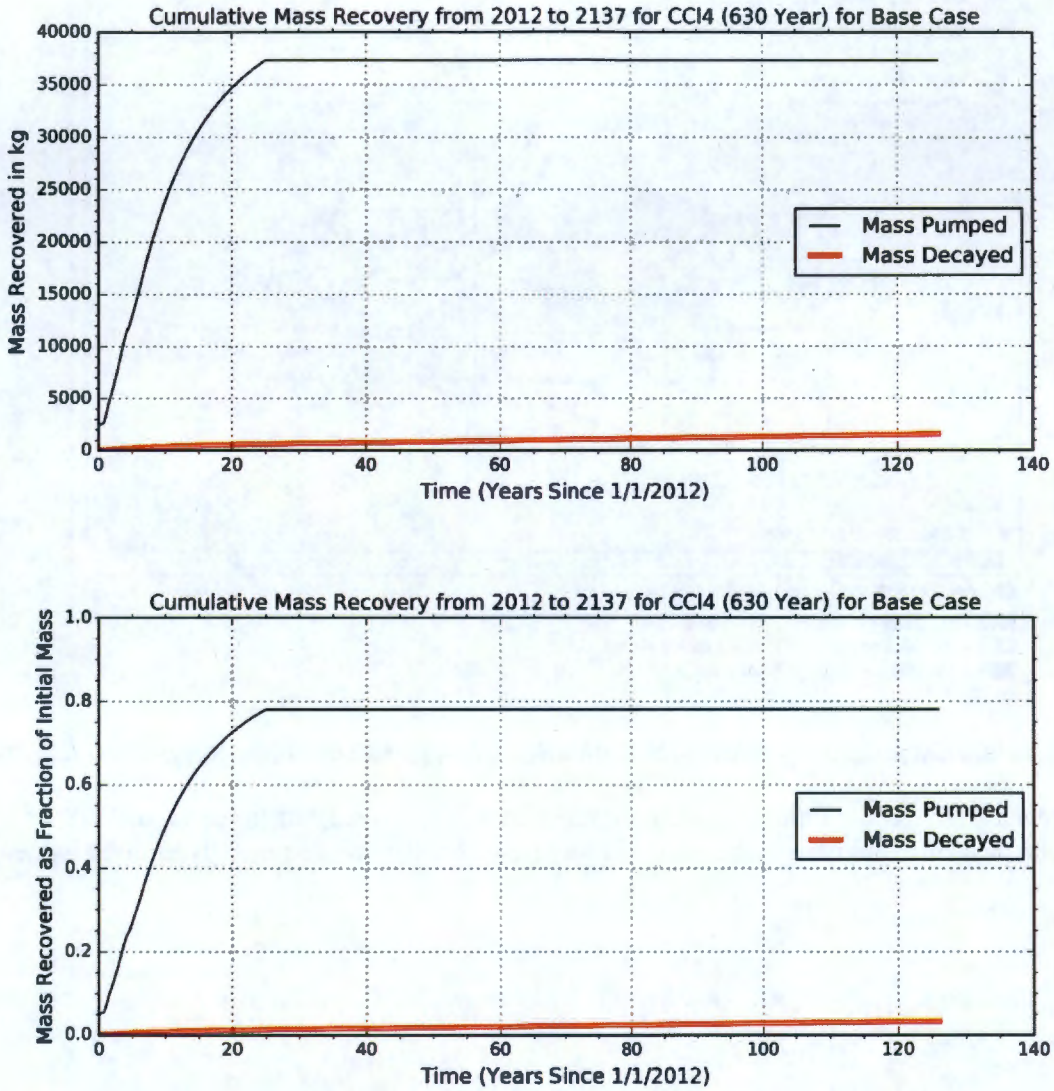


Figure 27. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass (bottom) – Baseline Pumping

Simulated UCL95 concentrations are shown in Figure 28. Four curves are shown for the pumping period representing the lower, medium, and upper Ringold Unit E concentration zones and the Ringold Unit A as described in Section 2.4.1. The overall pattern during pumping is similar to the UCL95 concentrations determined assuming a 41-yr and 100-yr half-lives shown earlier, but the concentrations at the end of remediation are higher; there is almost no remediation benefit from decay because of the long half-life relative to the remediation time.

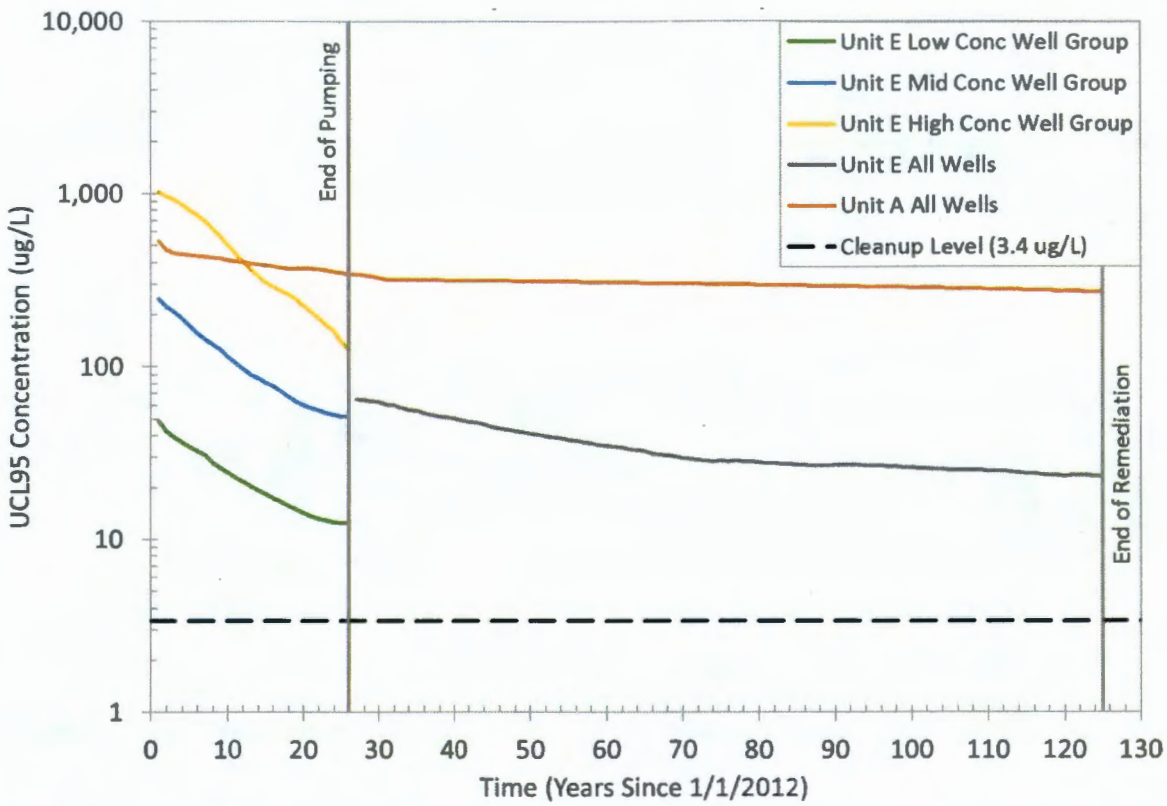


Figure 28. Simulated UCL95 Concentrations for Carbon Tetrachloride – Baseline Pumping - 630-yr half-life

6.1.4 Chromium (VI)

The Ringold Unit A does not have a Cr(VI) plume, and was therefore not included in this analysis. Small areas above the cleanup level are associated with 200-UP-1 (not analyzed as discussed in Section 1), and at the 241-S and 241-SX Tank Farms (analyzed separately in ECF-200W-17-0094, *Fate and Transport Analysis for WMA S-SX Groundwater Plumes in the 200-UP-1 Operable Unit*) and no maps are shown here.

A Cr(VI) source has been estimated for 216-S-10 Pond, WMA S-SX Tank Farms, WMA T-TX Tank farms and nearby cribs. Figure 29 shows the simulated extent in 2037. Note the plumes developing at the source areas at the water table. The plume in the southeastern area is from 200-UP-1, and is not part of this analysis. Figure 30 and Figure 31 show the simulated extents in 2137. The plumes are better developed, with the largest extent associated with the WMA T Tank Farm and nearby cribs. Note that the chromium plume from the 216-S-10 Pond (southeast plume in Figure 29, Figure 30, and Figure 31) remains small throughout the simulations.

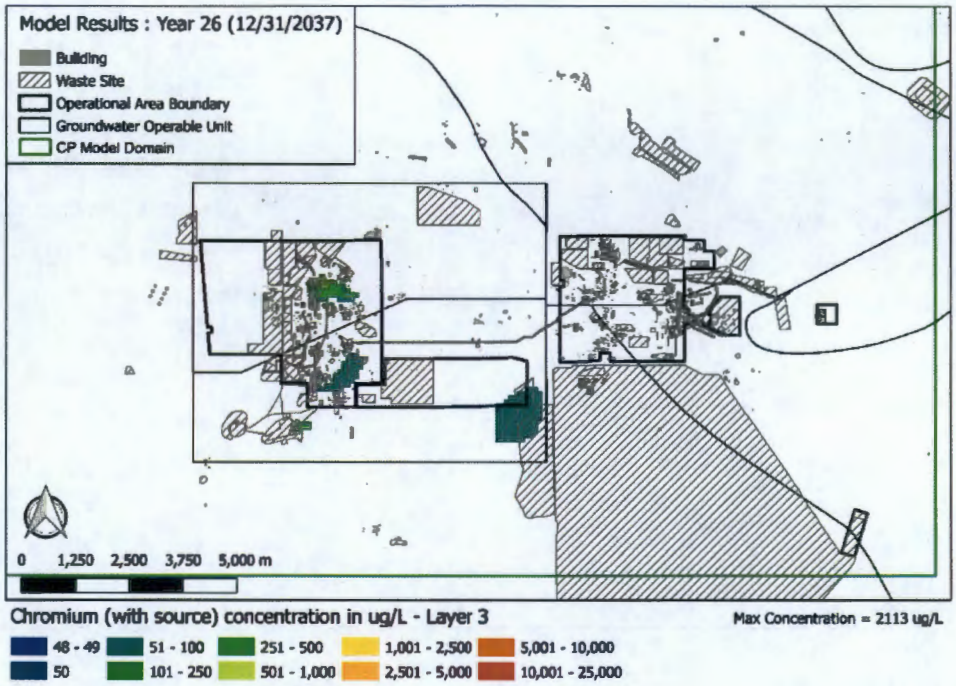


Figure 29. Simulated Chromium(VI) Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping - Source

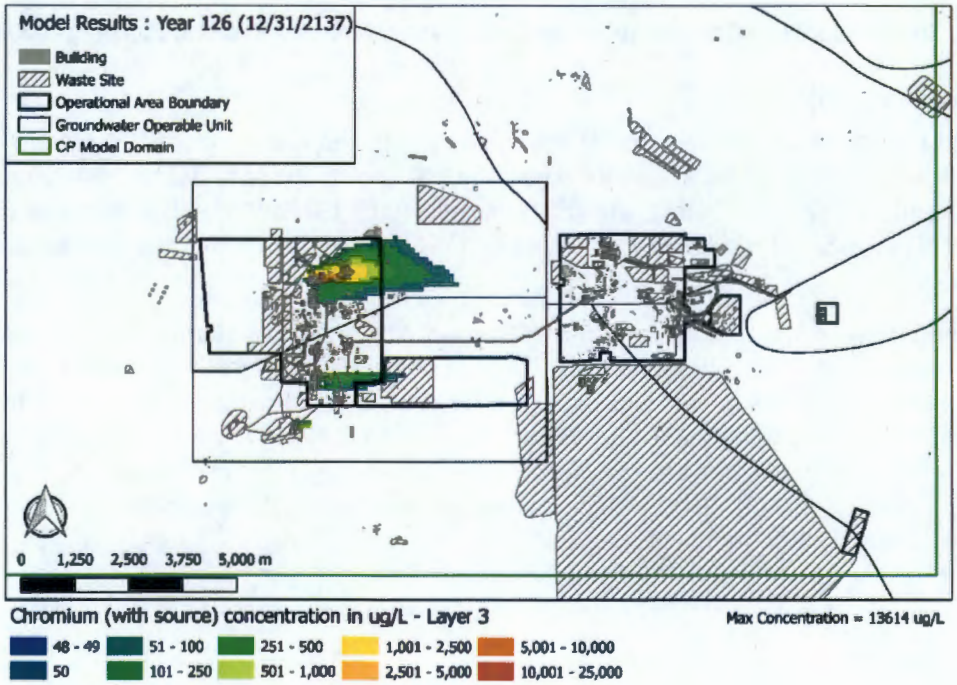


Figure 30. Simulated Chromium(VI) Distribution at the water table in the Ringold Unit E in 2137 - Source

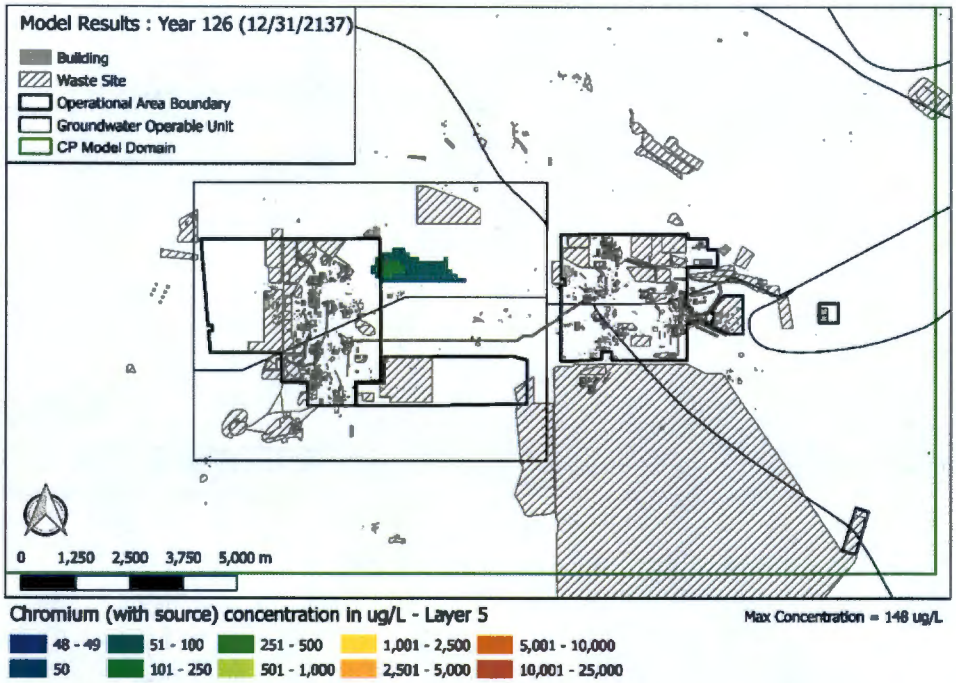


Figure 31. Simulated Chromium(VI) Distribution at the base of the Ringold Unit E in 2137 - Source

Figure 32 shows the computed mass recovery with and without sources.

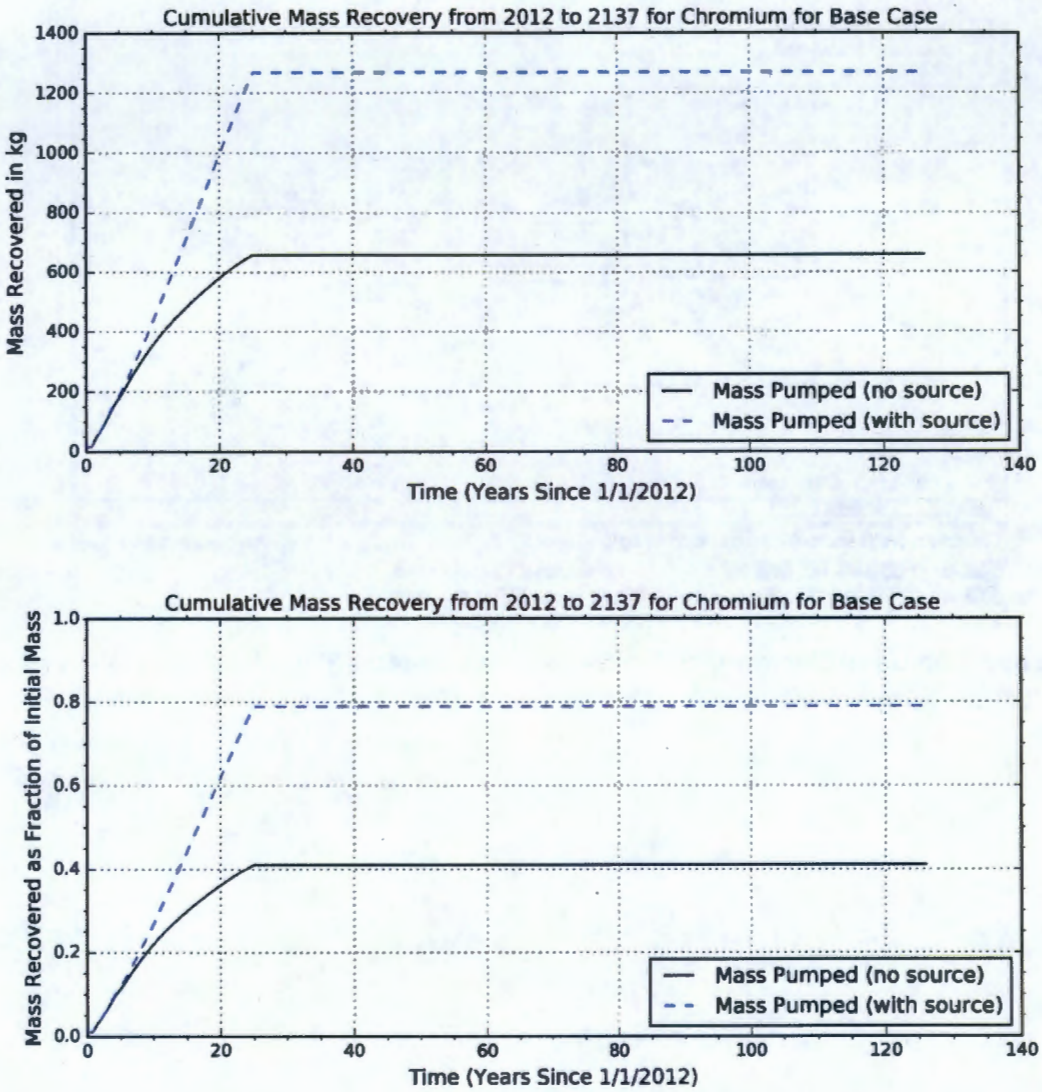


Figure 32. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial Cr(VI) mass (bottom) – Baseline Pumping

The UCL95s computed from model simulated concentrations are shown in Figure 33. With sources, plumes rebound in concentration consistent with plume extents previously presented.

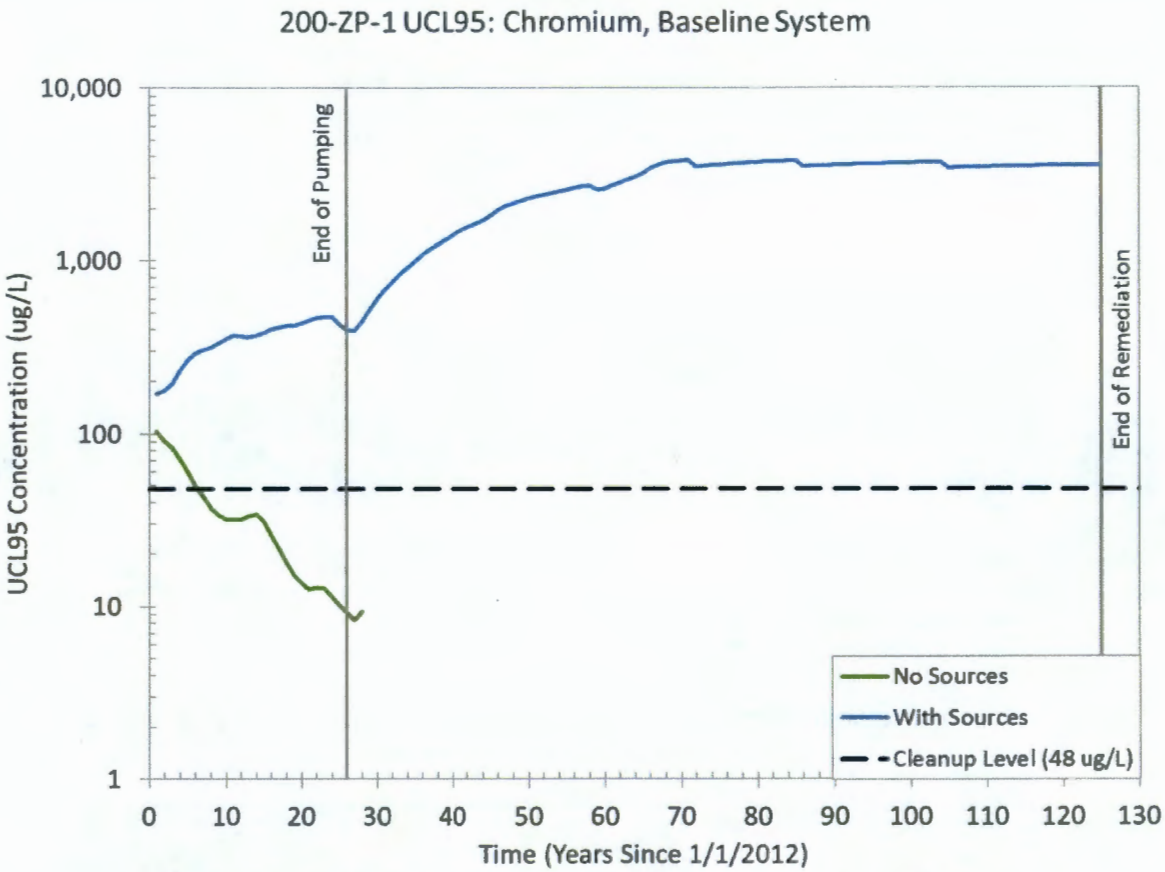


Figure 33. Simulated UCL95 for Cr(VI) with and without sources – Baseline Pumping

6.1.5 Nitrate

Figure 34, Figure 35, and Figure 36 show the simulated nitrate plume extent after 25 years of pumping in 2037. Areas remain above the cleanup level of 45,000 µg/L, particularly in the Ringold Unit A. Figure 37, Figure 38, and Figure 39 show the simulated extents in 2137. Small areas in the Ringold Unit E are above cleanup levels, but Unit A shows a peak concentration of about 175,000 µg/L.

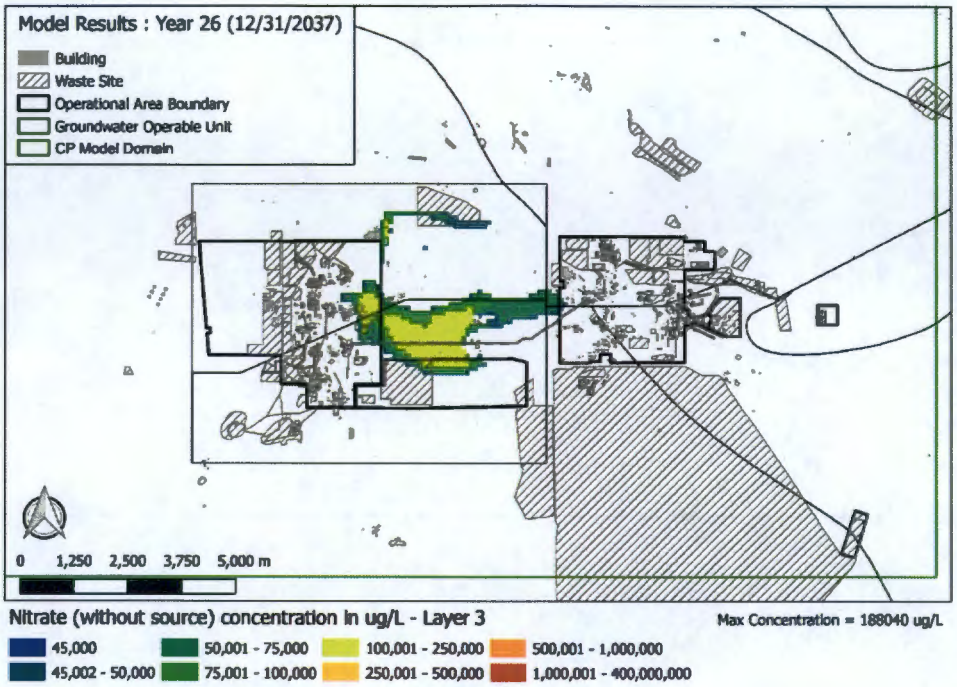


Figure 34. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping – No Source

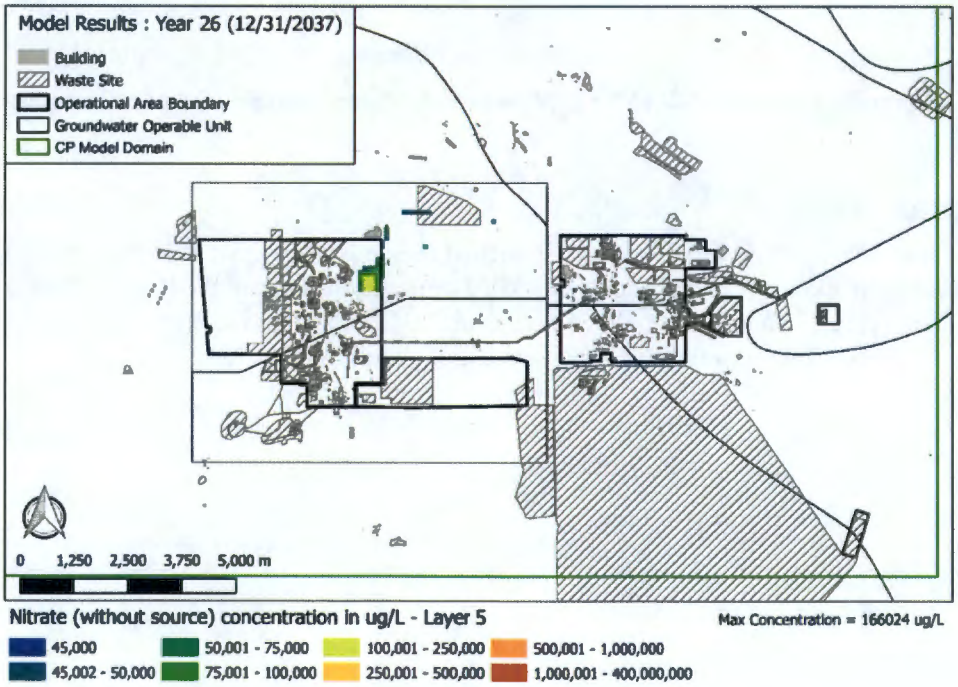


Figure 35. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2037 after 25 years of baseline pumping– No Source

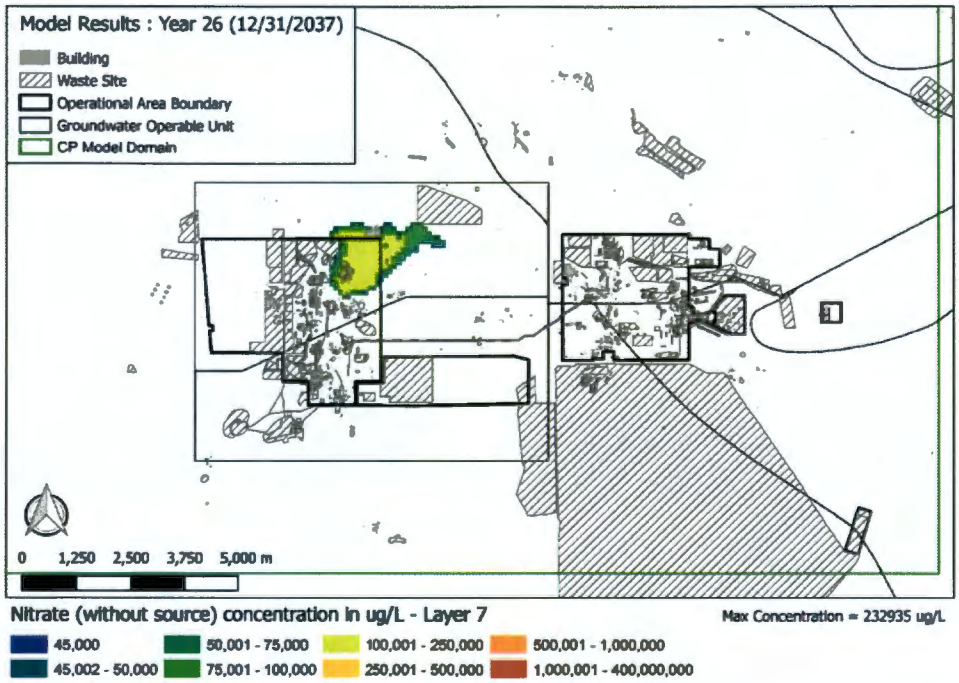


Figure 36. Simulated Nitrate Distribution in the Ringold Unit A in 2037 after 25 years of baseline pumping– No Source

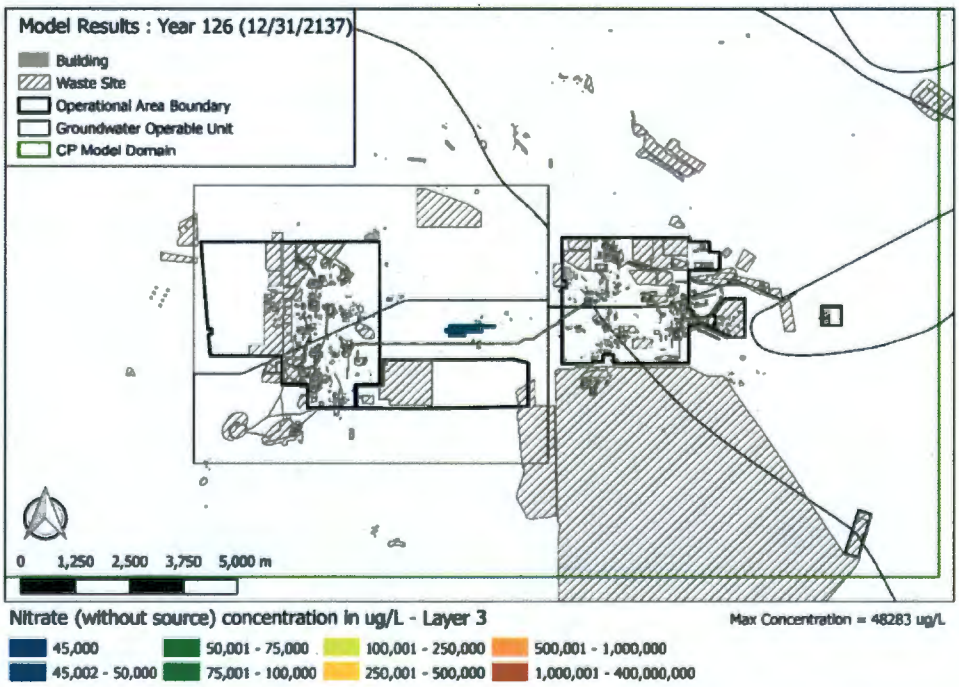


Figure 37. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2137 – No Source

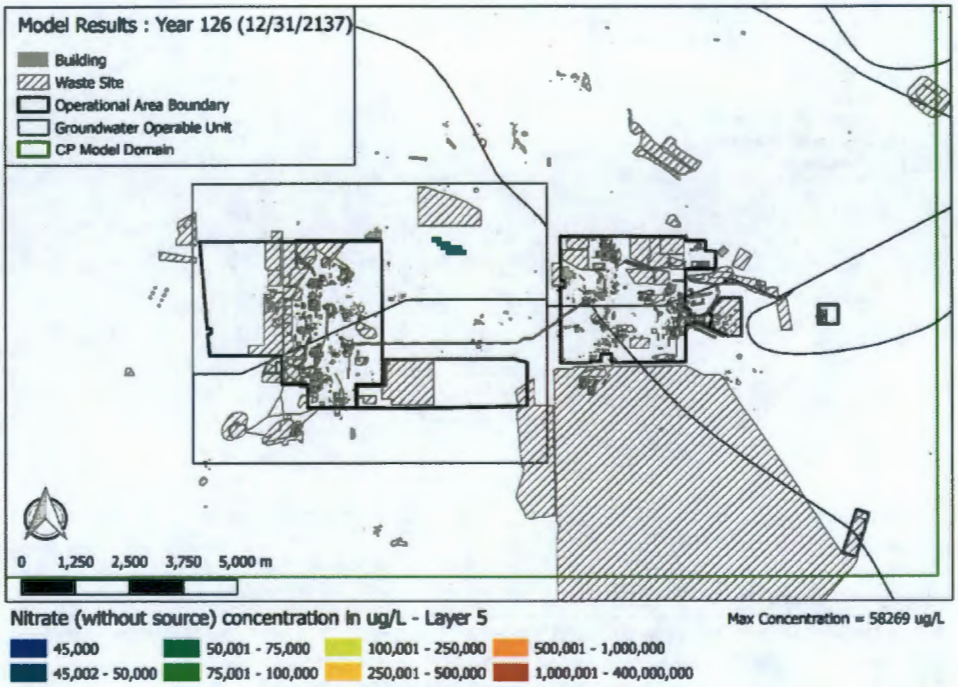


Figure 38. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2137 – No Source

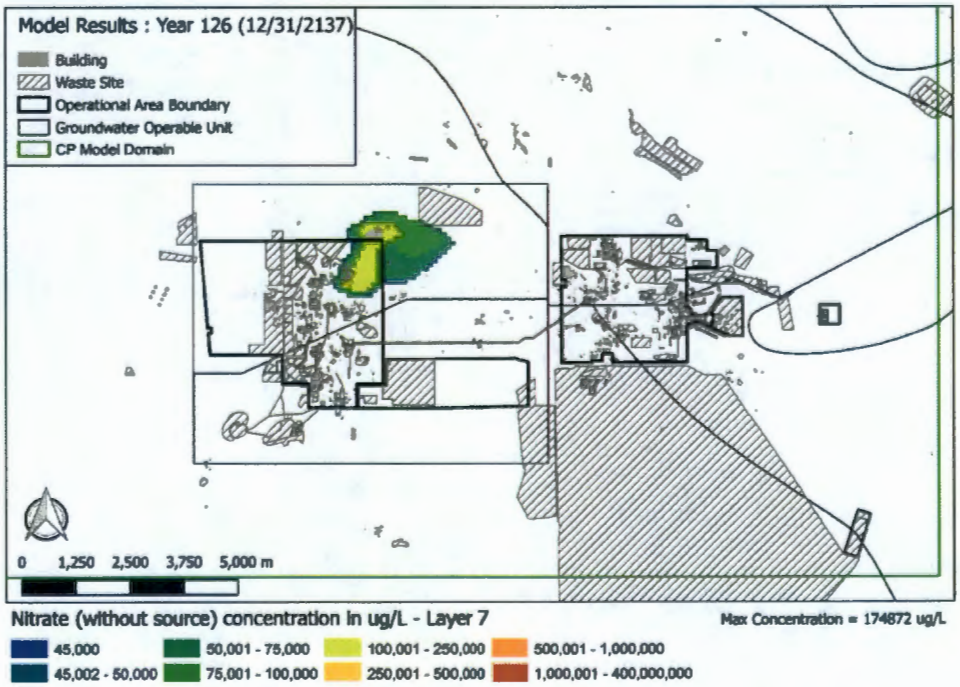


Figure 39. Simulated Nitrate Distribution in the Ringold Unit A in 2137 – No Source

Sources of nitrate have been estimated for the 216-S-25 Crib, 216-U-1 and U-2 Cribs, 216-Z-1A Tile Field, WMA S-SX Tank Farms, WMA T-TX Tank Farms, WMA T Tank Farms and nearby cribs, and WMA U Tank Farm. Figure 40, Figure 41, and Figure 42 show the simulated plume extents in 2037. The plume extents are similar to those in 2037 assuming no sources, with higher concentrations near the source areas. However, the plume extent in 2137 is different than the no source case as shown in Figure 43, Figure 44, and Figure 45 with plume extents like those currently interpreted to exist.

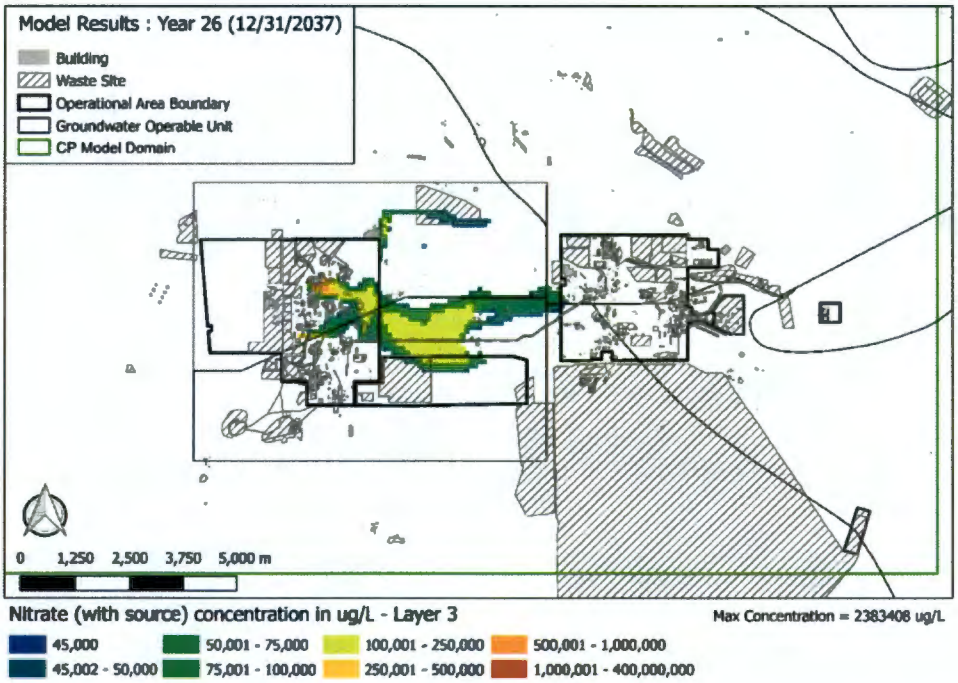


Figure 40. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping –Source

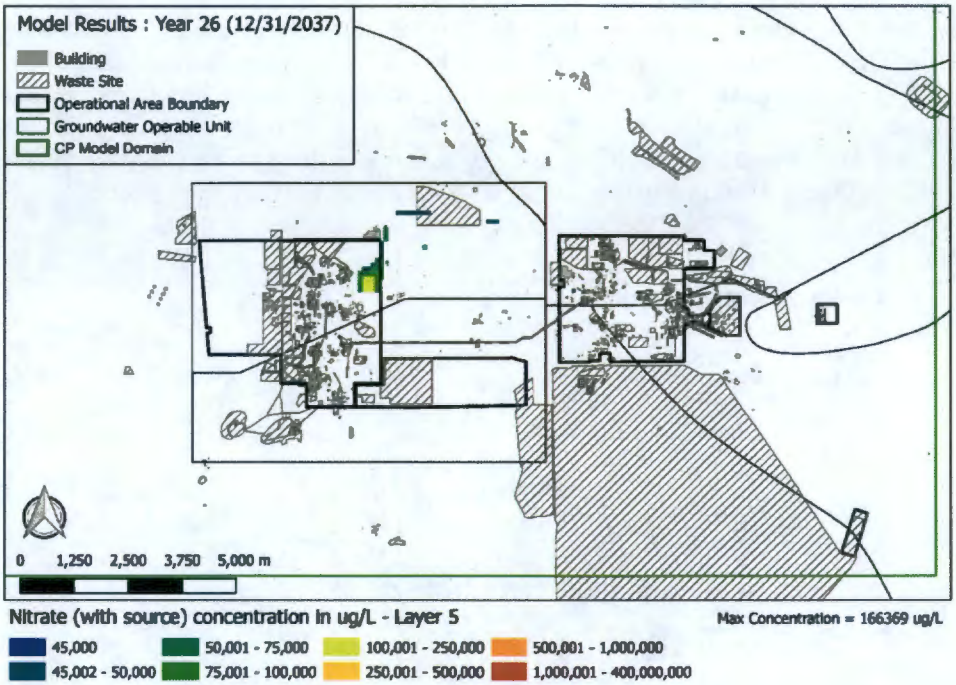


Figure 41. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2037 after 25 years of baseline pumping –Source

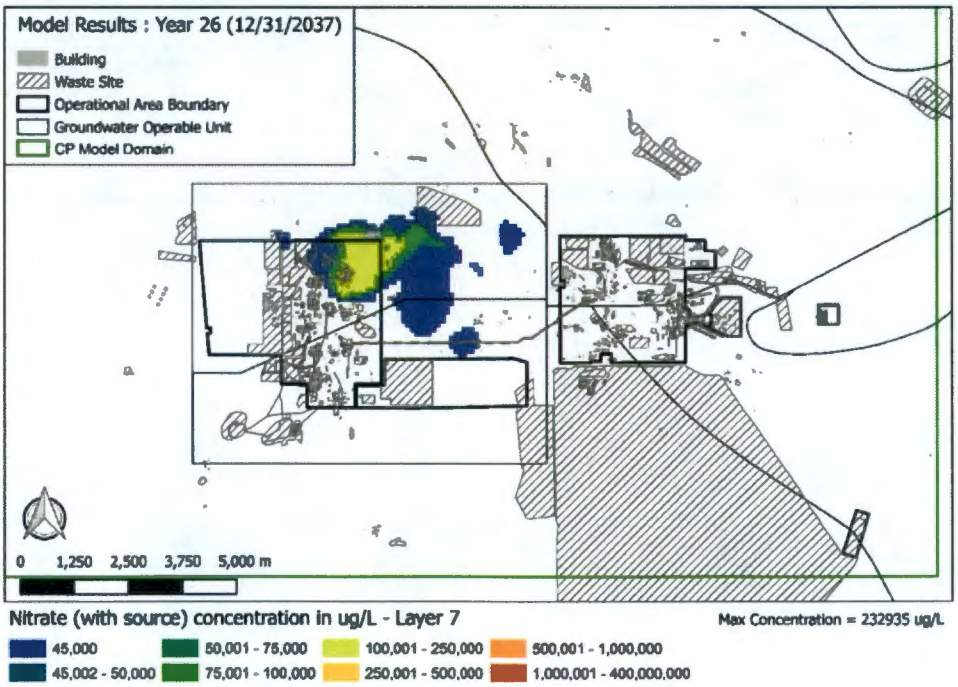


Figure 42. Simulated Nitrate Distribution in the Ringold Unit A in 2037 after 25 years of baseline pumping – Source

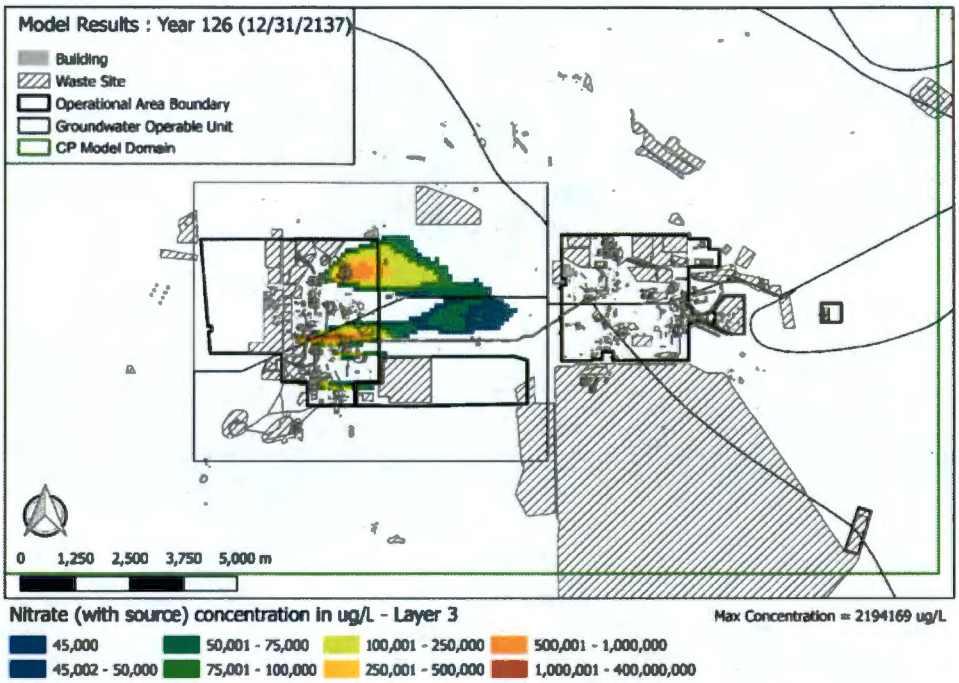


Figure 43. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2137–Source

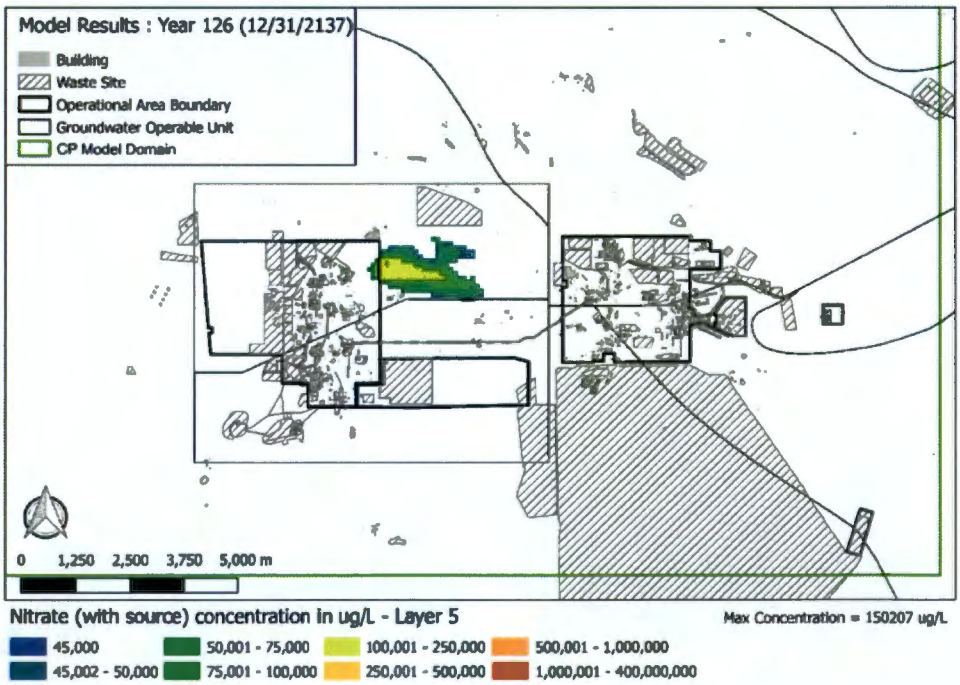


Figure 44. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2137–Source

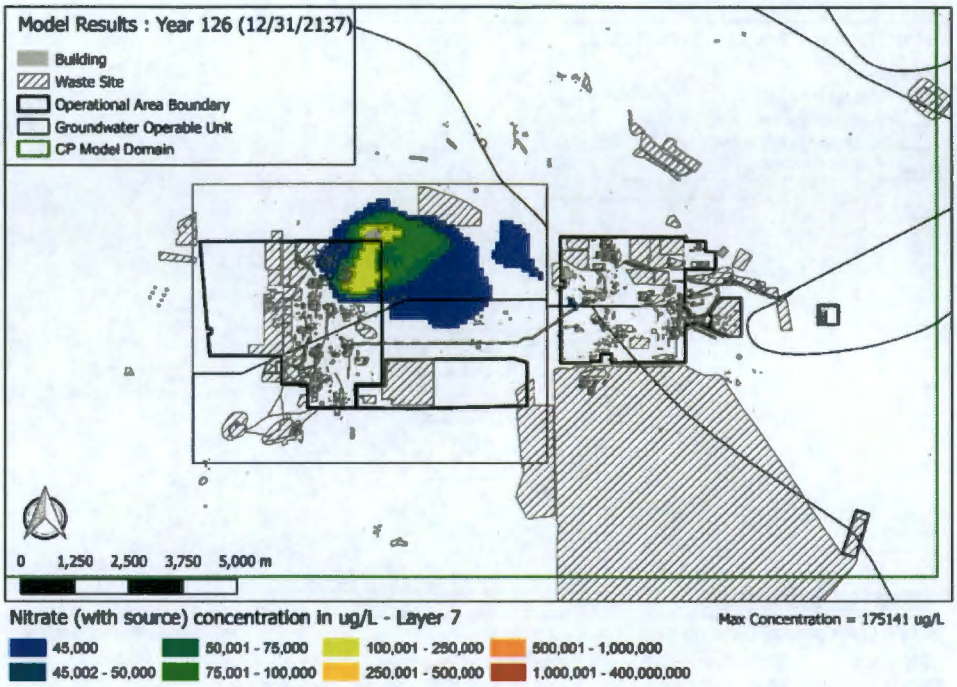


Figure 45. Simulated Nitrate Distribution in the Ringold Unit A in 2137–Source

Simulated nitrate mass extracted with and without sources is shown in Figure 46.

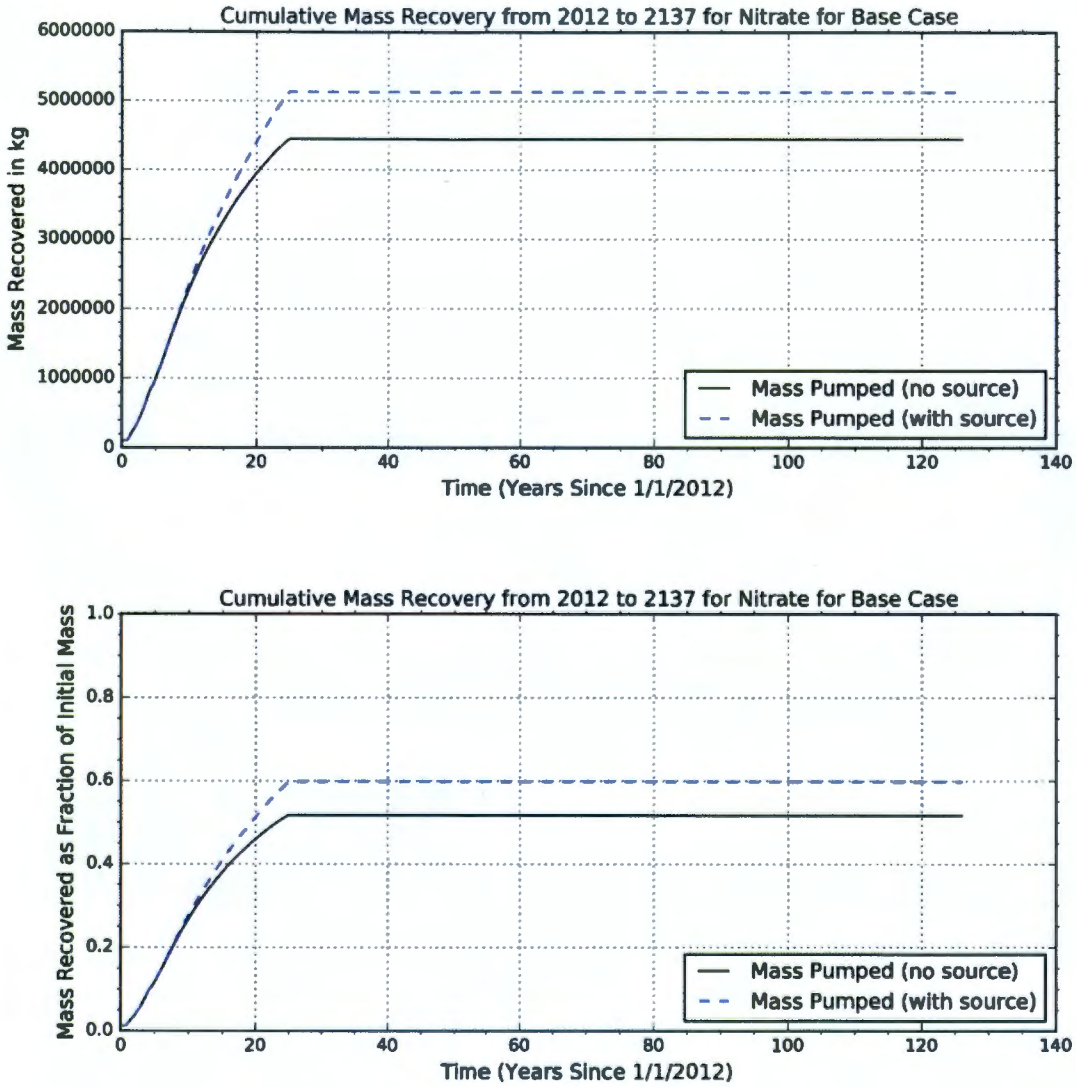


Figure 46. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of nitrate initial mass (bottom) – Baseline Pumping

The UCL95 concentrations computed from the transport simulations are shown for 200-ZP-1 and 200-UP-1 in Figure 47 and Figure 48, respectively. The 200-UP-1 results show cleanup being reached sooner than 200-ZP-1, which shows a rebound at later times even without a source because much of the nitrate plume mass is located in 200-ZP-1. Continuing sources negatively impact cleanup efforts in about 30 years, although this time is uncertain due to the assumptions and data limitations in the source term analysis.

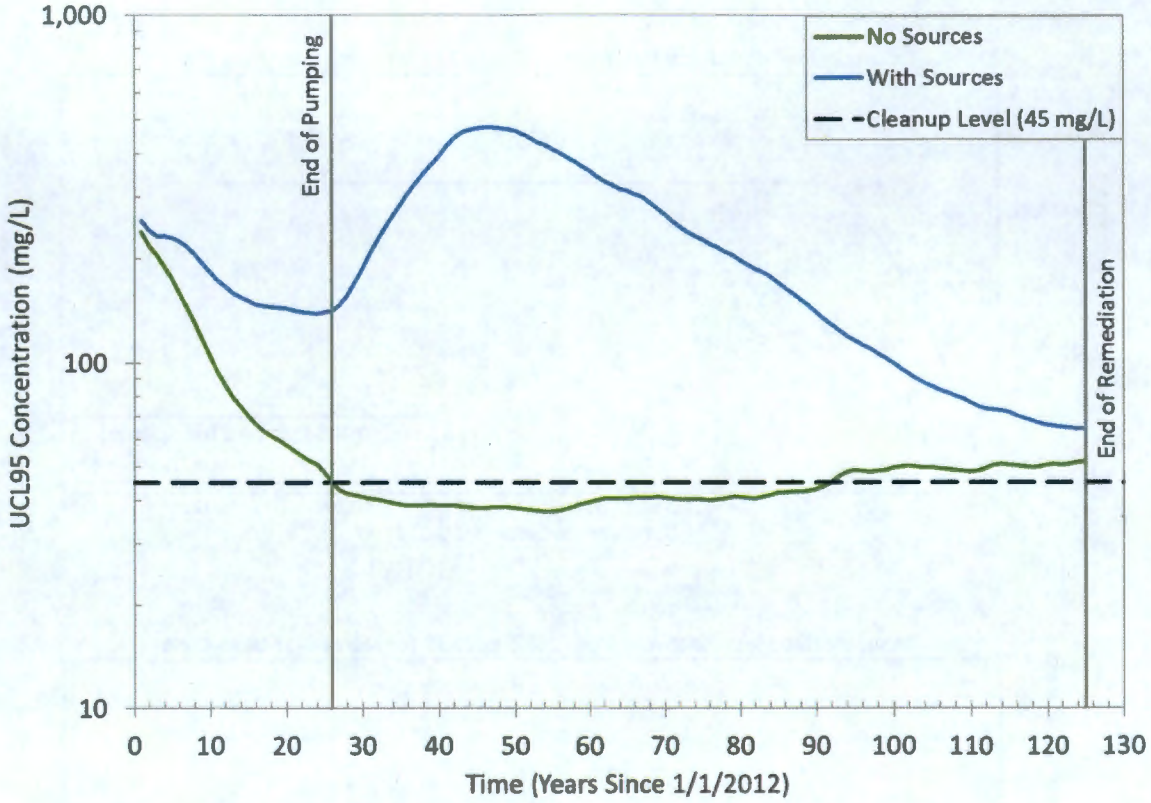


Figure 47. Simulated UCL95 for 200-ZP-1 Nitrate – Baseline Pumping

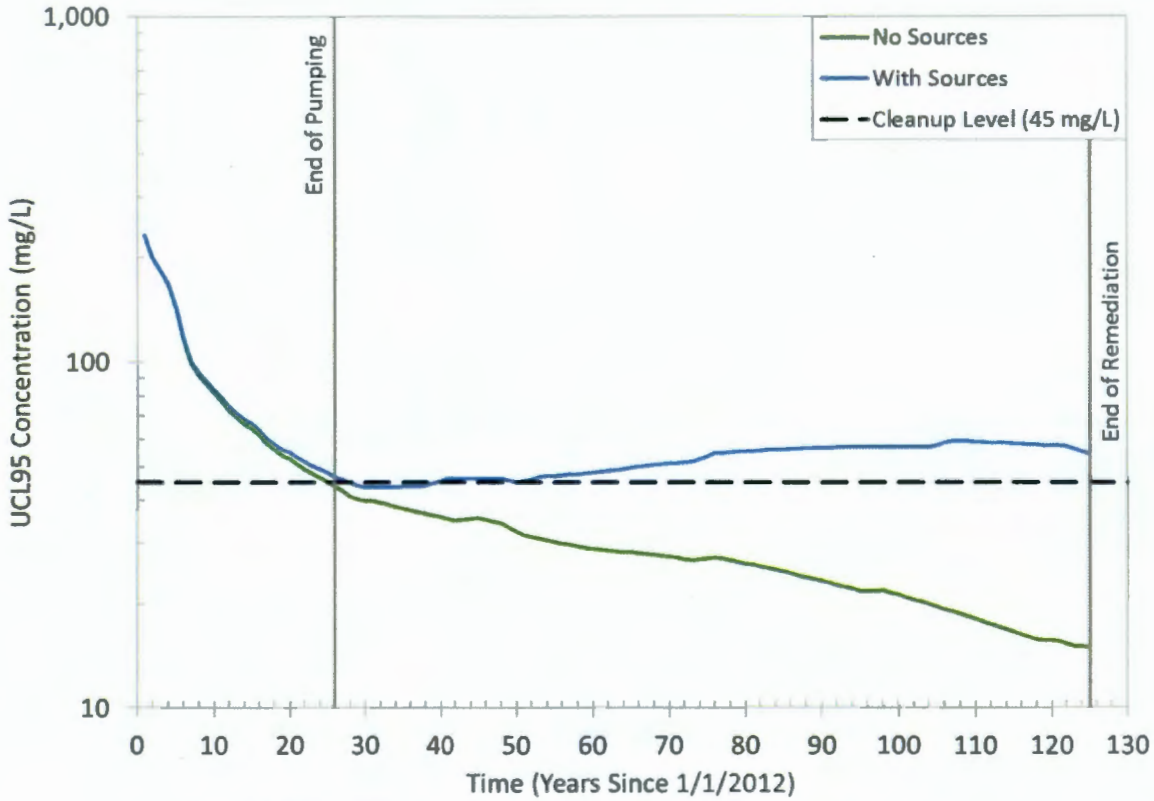


Figure 48. Simulated UCL95 for 200-UP-1 Nitrate – Baseline Pumping

6.1.6 Trichloroethene (TCE)

Figure 49, Figure 50, and Figure 51 show the simulated trichloroethene plume extent after 25 years of pumping in 2037. The highest concentrations are in the Ringold Unit A. After 125 years of cleanup time, including MNA, the simulated plume extents are as shown in Figure 52, Figure 53, and Figure 54 – the concentrations are below the MCL of 5 µg/L, but above the cleanup level of 1 µg/L (see Table 3-1 in DOE/RL-2016-20). The highest concentrations are in the Ringold Unit A. No source is interpreted to exist for TCE. Figure 55 shows the simulated mass extracted. The UCL95 computed from model results is shown in Figure 56; the UCL95 remains above the cleanup level throughout the 125-year cleanup period.

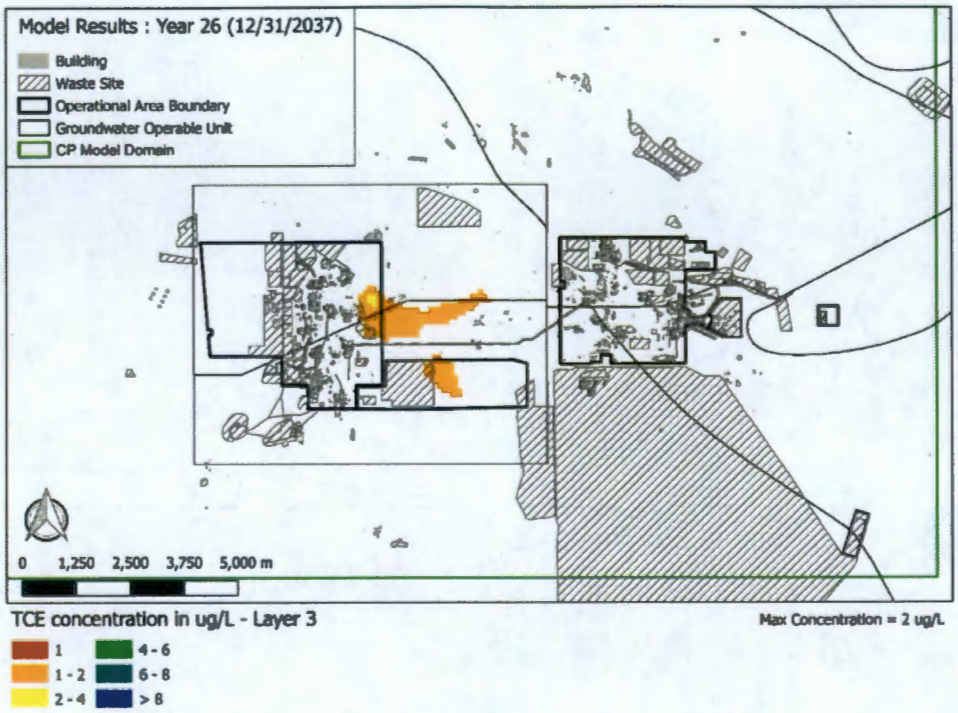


Figure 49. Simulated TCE Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping

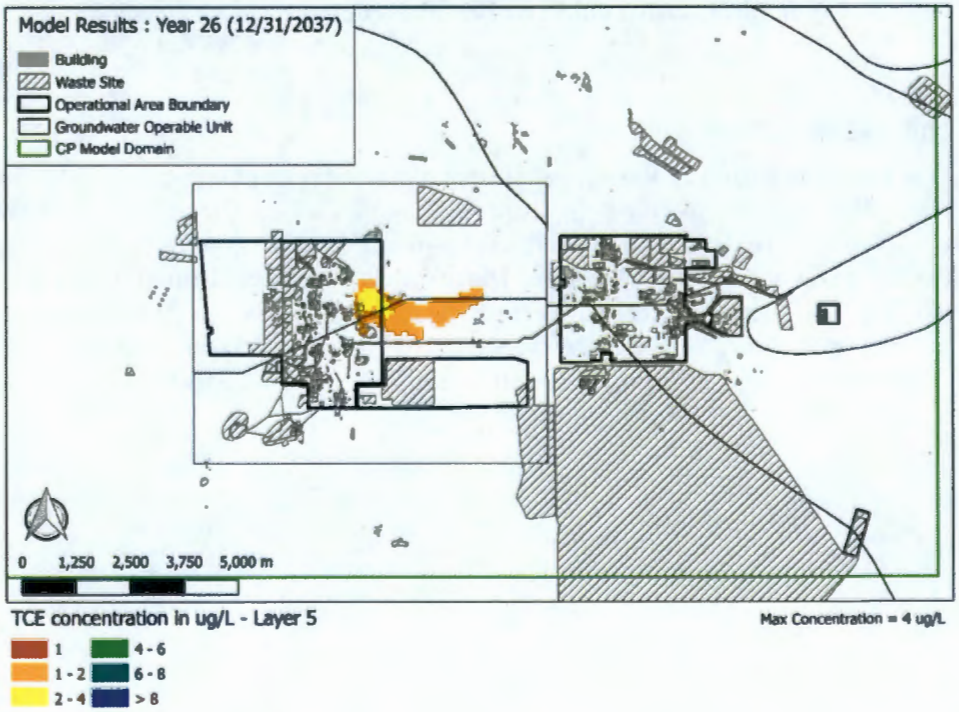


Figure 50. Simulated TCE Distribution at the base of the Ringold Unit E in 2037 after 25 years of baseline pumping

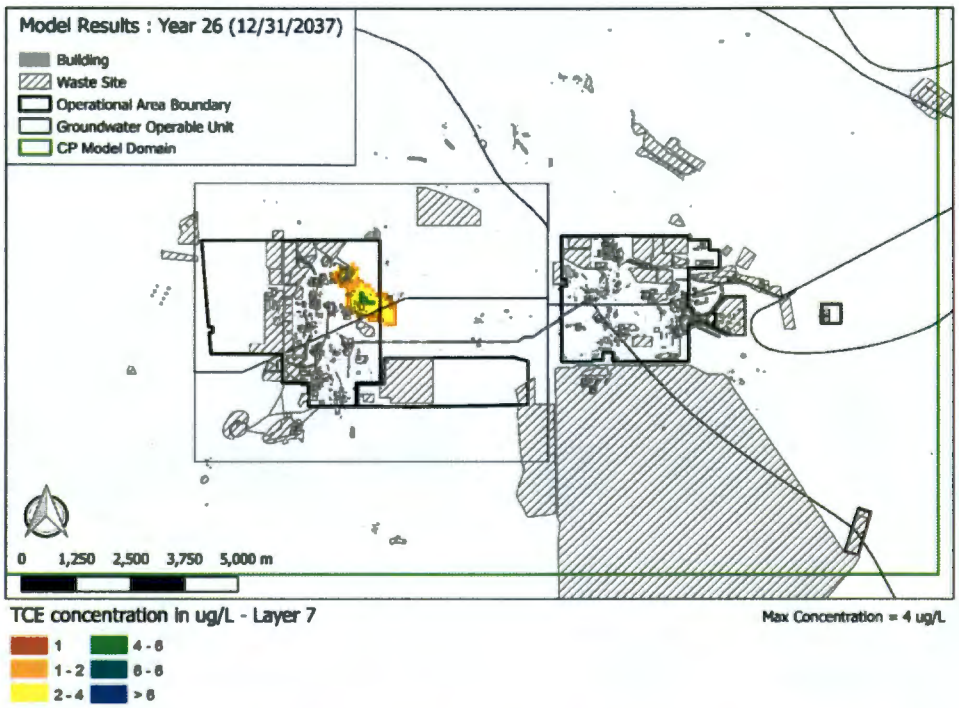


Figure 51. Simulated TCE Distribution in the Ringold Unit A in 2037 after 25 years of baseline pumping

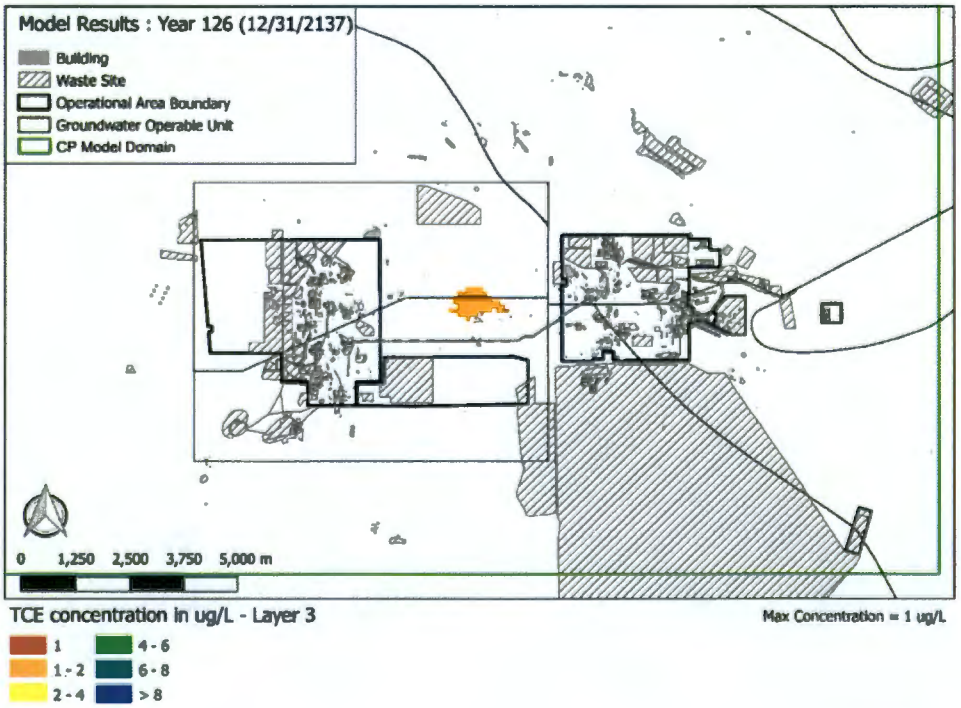


Figure 52. Simulated TCE Distribution at the water table in the Ringold Unit E in 2137

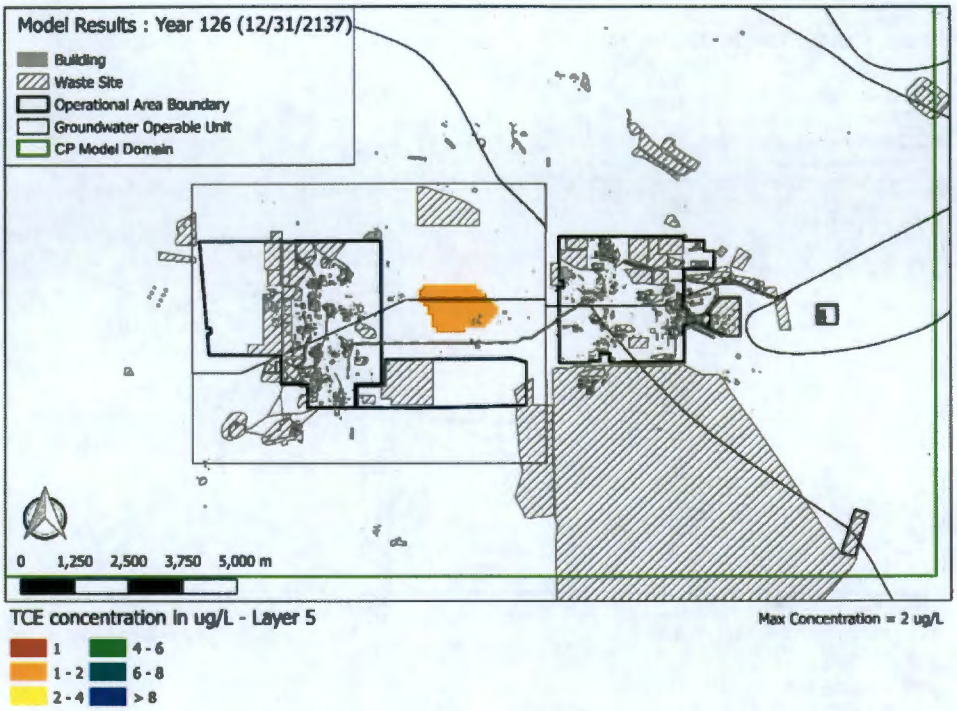


Figure 53. Simulated TCE Distribution at the base of the Ringold Unit E in 2137

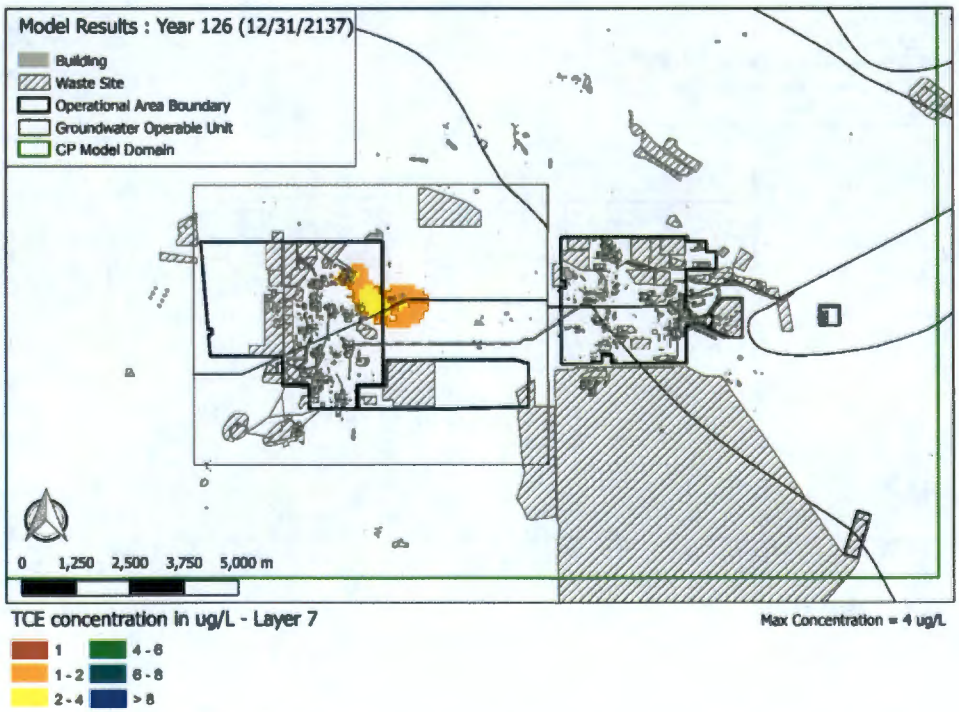


Figure 54. Simulated TCE Distribution in the Ringold Unit A in 2137

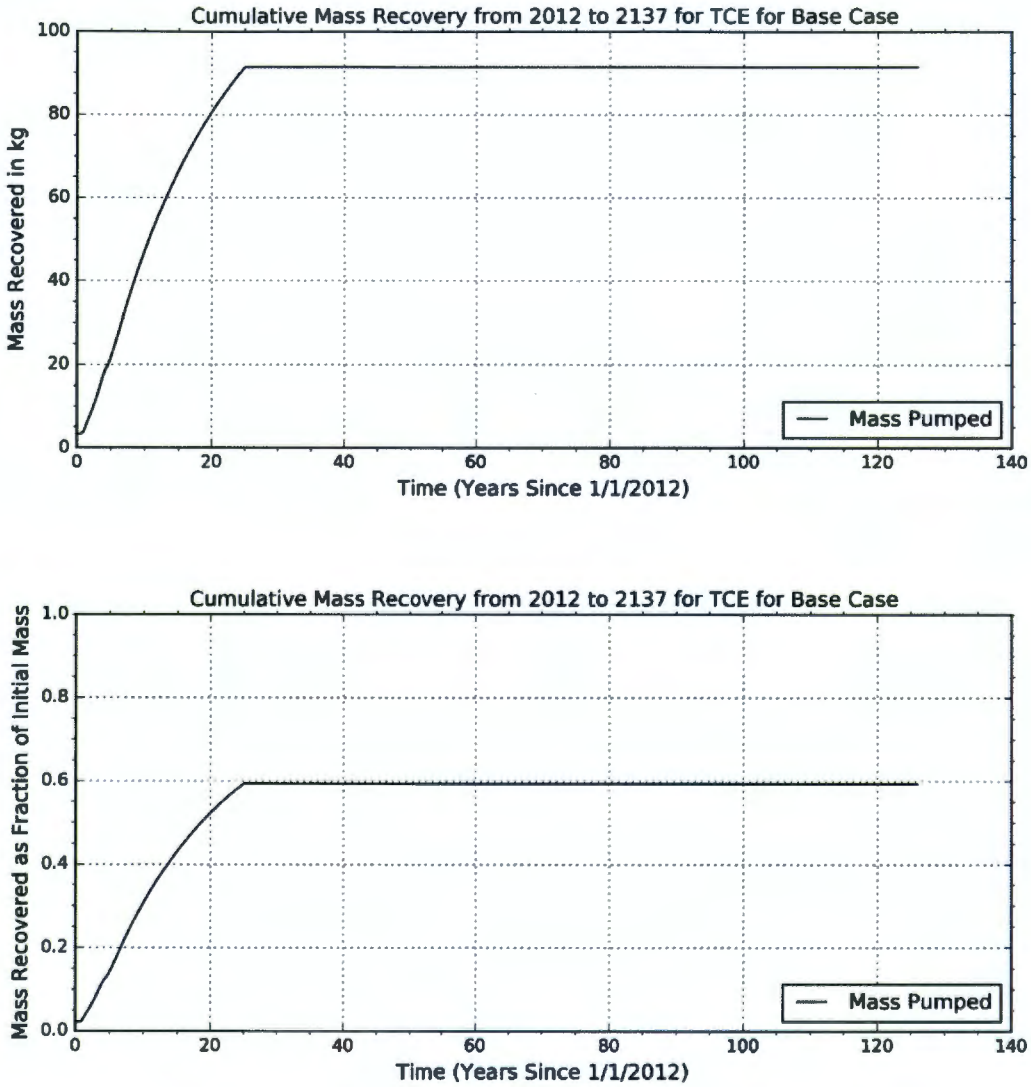


Figure 55. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial TCE mass (bottom) – Baseline Pumping

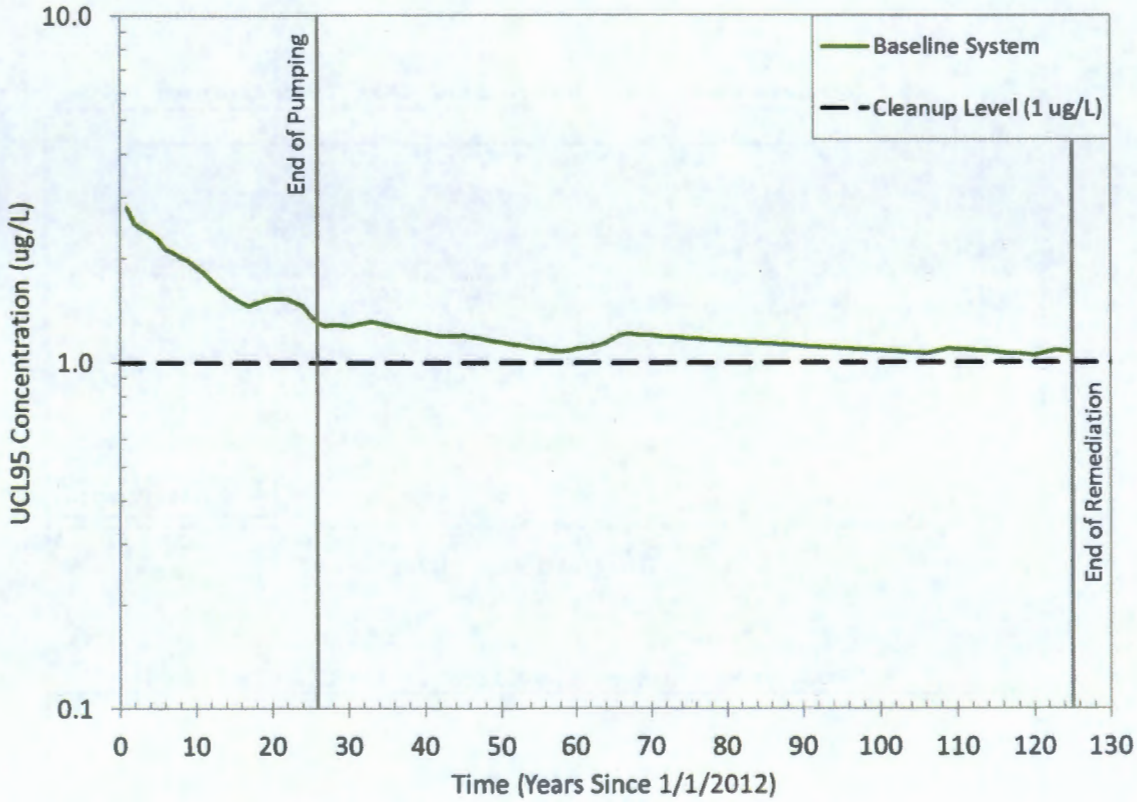


Figure 56. Simulated UCL95 for TCE – Baseline Pumping

6.1.7 Technetium-99 (Tc-99)

Areas with existing Tc-99 above the cleanup level cleanup level in 200-ZP-1 are associated with the WMA T and WMA TX-TY Tank Farms. Concentrations in simulations without sources decline to below the cleanup level before the end of pumping (2037), so no plume maps are shown. Technetium-99 in the 200-UP-1 OU is analyzed separately in ECF-200W-17-0094 and ECF-200UP1-17-0093, *Fate and Transport Analysis for U Plant Groundwater Plumes in the 200-UP-1 Operable Unit.*

Sources of Tc-99 were estimated for the 216-U-1 and U-2 Cribs, WMA S-SX Tank Farms, WMA TX-TY Tank Farms and nearby cribs, WMA T Tank Farms, and WMA U Tank Farms. Figure 57 shows the simulated plume extent at the water table in the Ringold Unit E after 25 years of pumping (2037) with a source. No other layers have concentrations above the cleanup level. WMA T has the highest concentrations. Figure 58, Figure 59, and Figure 60 show simulated Tc-99 concentrations in 2137. Note that the entire Ringold Unit E, and a small part of the Ringold Unit A have concentrations above the cleanup level.

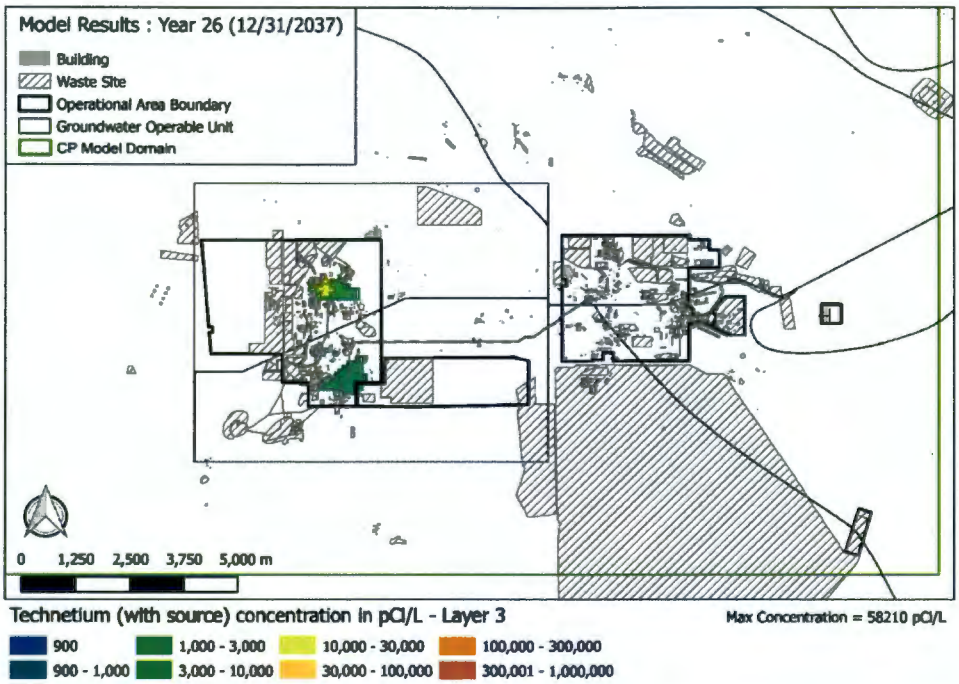


Figure 57. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping –Source

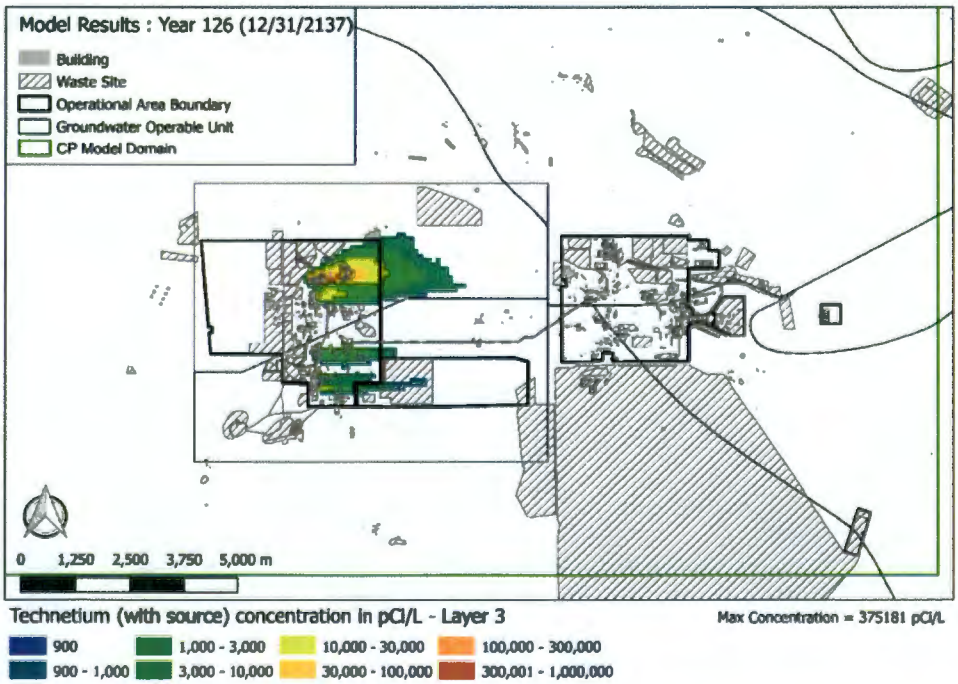


Figure 58. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2137 –Source

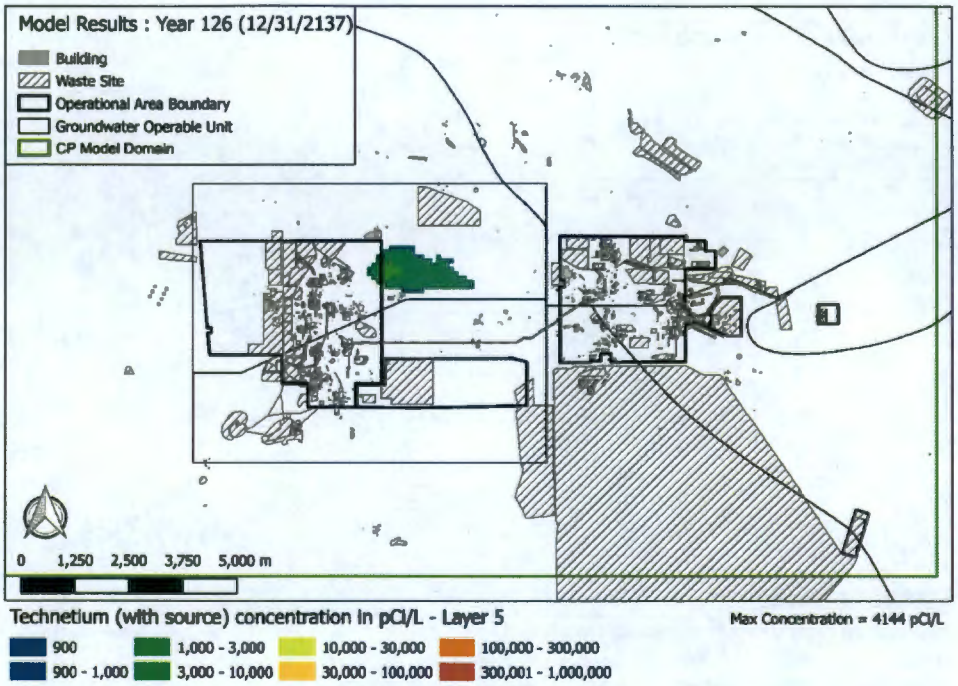


Figure 59. Simulated Tc-99 Distribution at the base of the Ringold Unit E in 2137 –Source

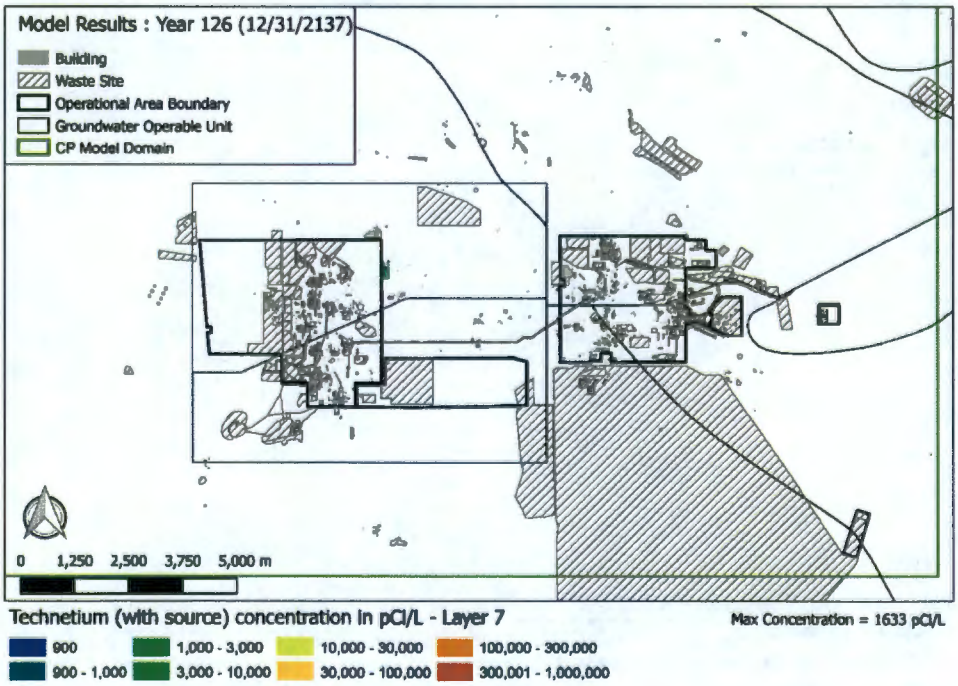


Figure 60. Simulated Tc-99 Distribution in the Ringold Unit A in 2137 –Source

Simulated mass extracted is shown in Figure 61; note the extra mass (about four times that initially present) from the source term. Because Tc-99 is mobile in groundwater the remediation system captures some mass entering the aquifer from the source.

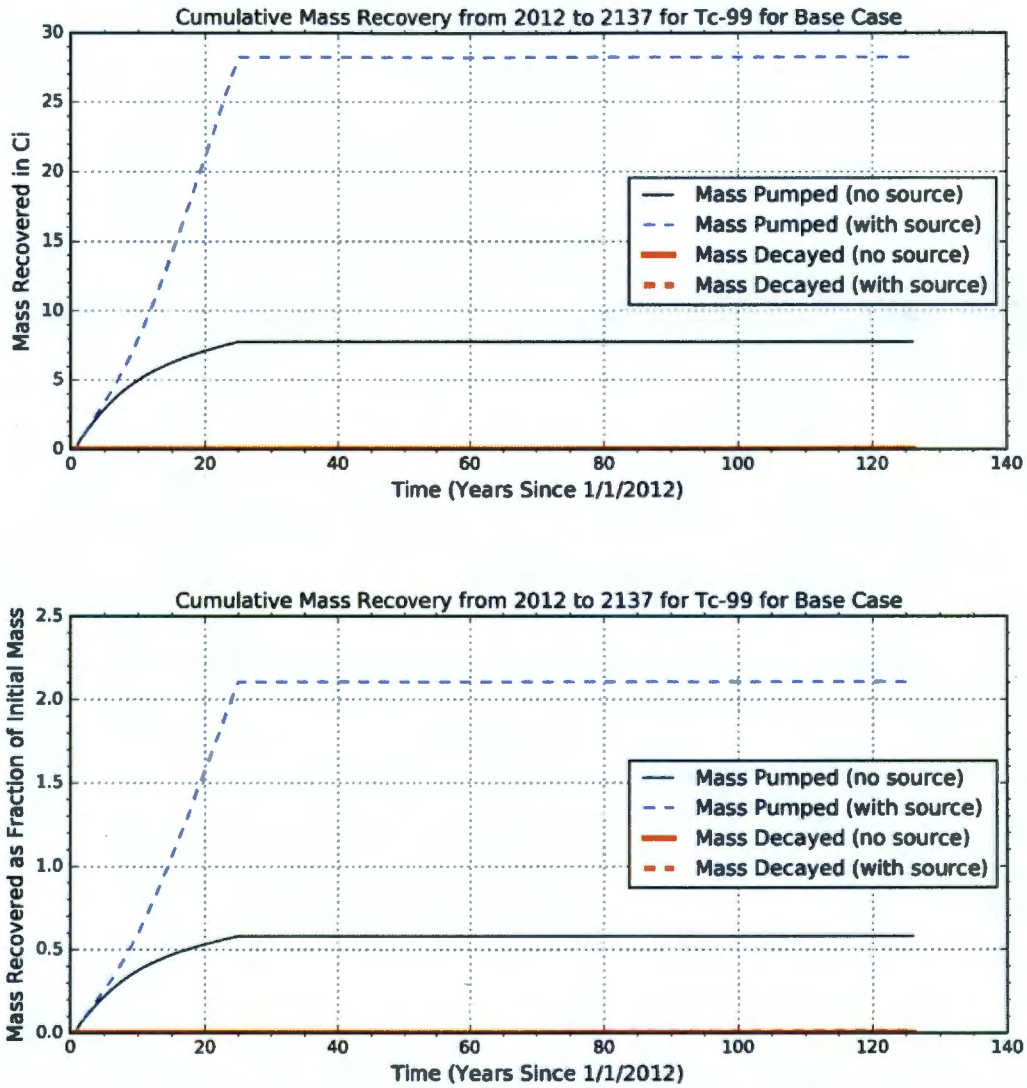


Figure 61. Simulated Cumulative Mass Pumped in Curies (top) and fraction of initial Tc-99 mass (bottom) – Baseline Pumping

The UCL95s for Tc-99 with and without sources are shown in Figure 62. Without sources Tc-99 groundwater remediation in 200-ZP-1 could be complete within 20 years.

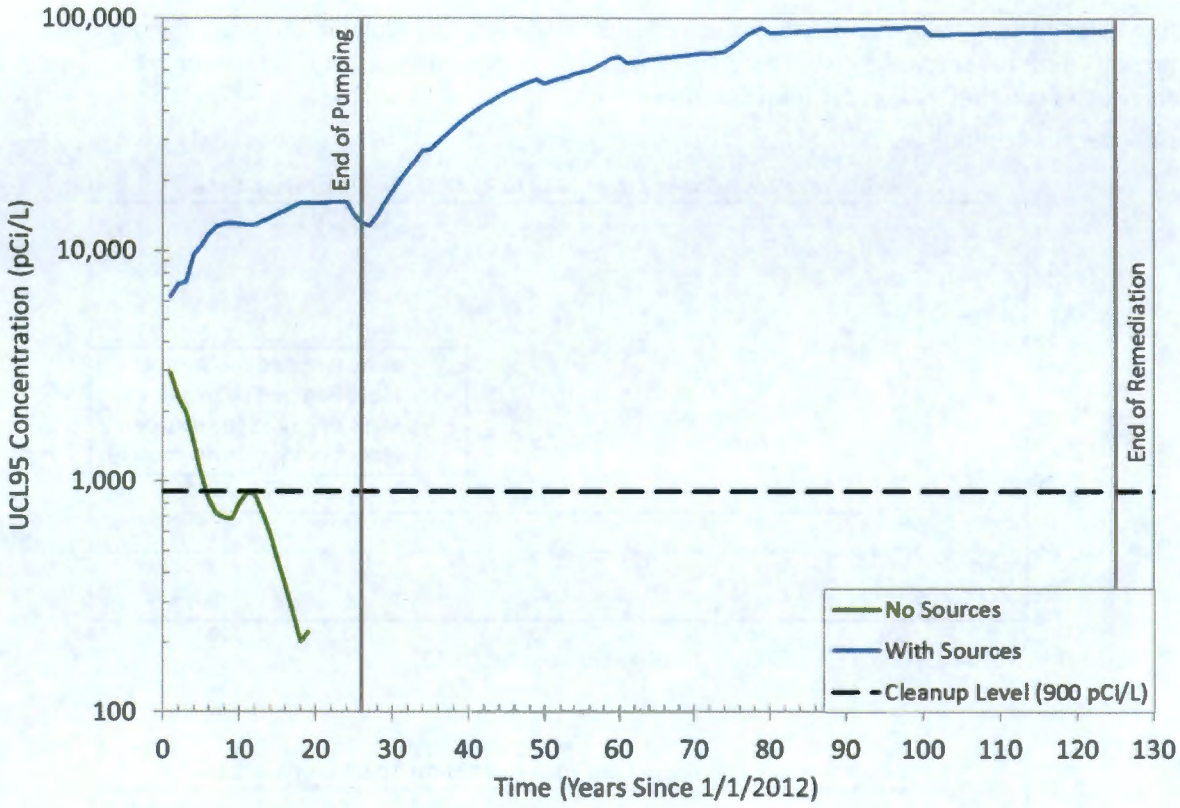


Figure 62. Simulated UCL95 for Tc-99 with and without sources – Baseline Pumping

6.1.8 Tritium

Only the water table Ringold Unit E has tritium above the cleanup level in 2037 (Figure 63) and there are no areas in the model domain with tritium concentrations above 20,000 pCi/L in 2137 (maps are not shown). Sources were estimated, but when included in the simulations they do not result in concentrations above 20,000 pCi/L other than as shown. Figure 64 shows the mass recovered.

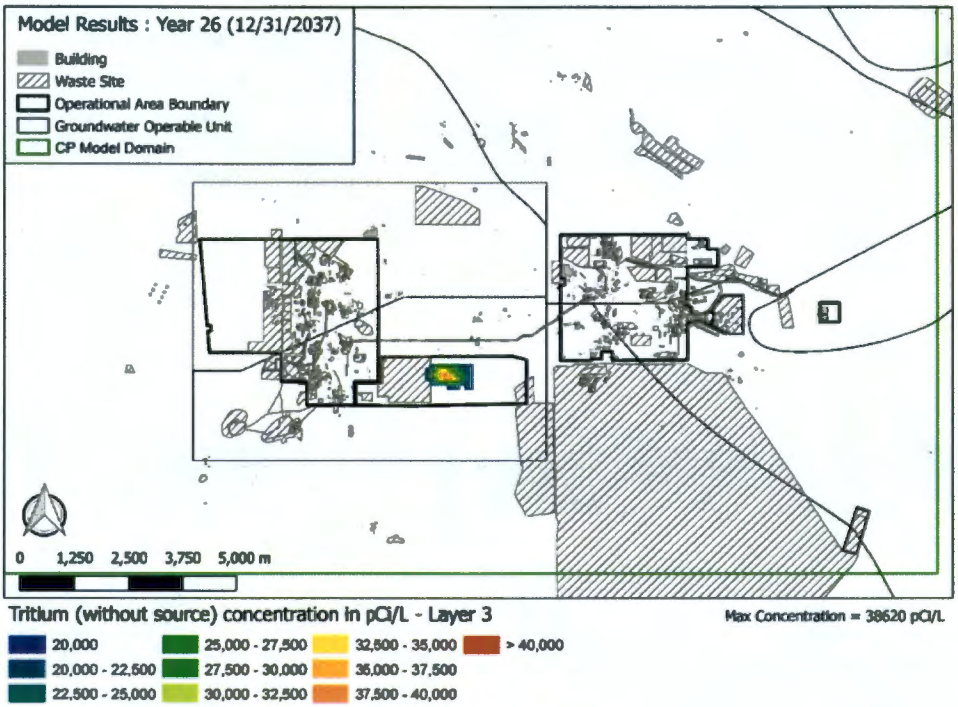


Figure 63. Simulated Tritium Distribution at the water table in the Ringold Unit E in 2037 after 25 years of baseline pumping – No Source

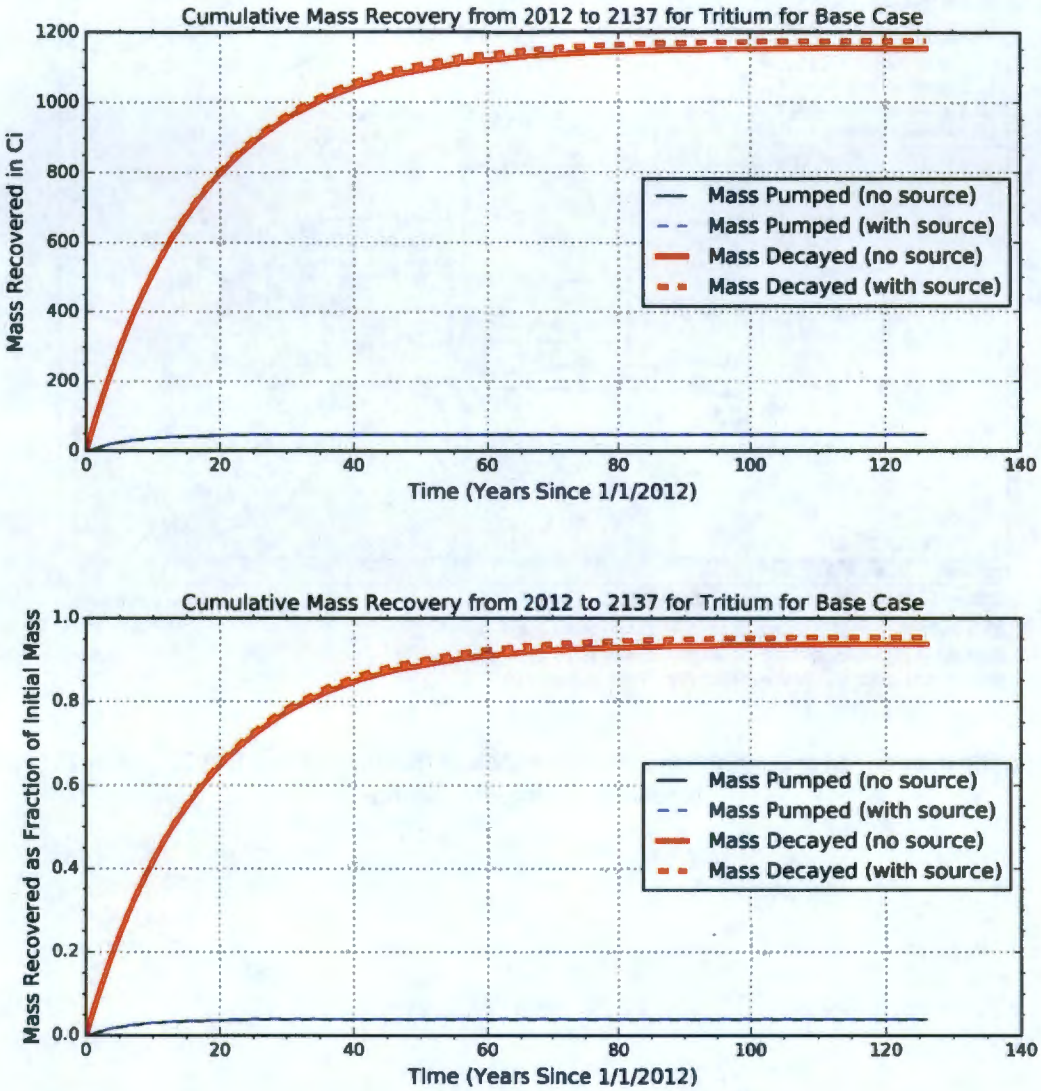


Figure 64. Simulated Cumulative Mass Pumped in Curies (top) and fraction of initial tritium mass (bottom) – Baseline Pumping

Figure 65 shows the UCL95 concentrations for tritium computed from simulated concentrations. Note that the UCL95 rebounds shortly after pumping ends for the no source case. This is because several wells are dropped from the calculation as their concentration declines to less than 1/10th of the cleanup level causing the mean concentration of the remaining wells used in the calculation to be higher. which remain in the source case at concentrations below the cleanup level, thus lowering the mean. Even with sources, radioactive decay reduces concentrations to below the cleanup level in the next 40 years.

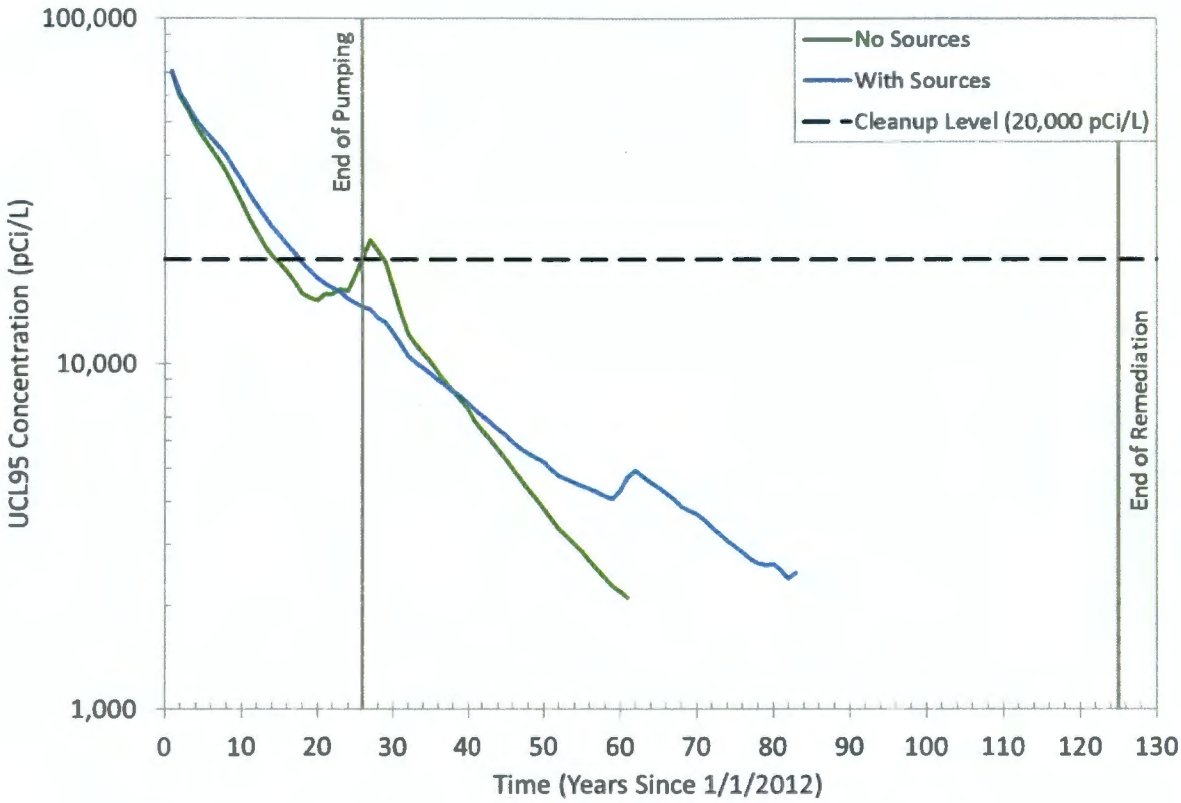


Figure 65. Simulated UCL95 for Tritium with and without sources – Baseline Pumping

6.2 Forecast of Optimized Operations

6.2.1 Pumping Optimization Results

Figure 66 and Figure 67 summarize the extraction and injection rates from the baseline and optimized pumping cases over time, respectively. In these two figures, total values are reported at the end of each of the model stress periods between 1/1/2017 and 12/31/2037. Pumping period intervals used by the optimizer are also noted in these figures by indicating the end of each period along the time axis. Total baseline extraction pumping is around 2,150 gallons per minute (gpm), while the total injection rate is slightly higher at 2,210 gpm. Extraction in the Ringold Unit E is slightly higher than injection (2,050 vs 1,820 gpm at the end 2037). In contrast, extraction rates at Ringold Unit A are lower than injection (75 gpm vs 370 gpm). Optimized pumping summaries reflect both the increase in the total pumping limit and the effect of head limit constraints in the CPGWM. In this case, extraction and injection are both the same at the end of the optimization period at around 3,600 gpm, but changes over time given head-limit constraints caused by variations in pumping and hydraulic head. Extraction and injection rates for Ringold Unit E are higher (13% and 38%, respectively) when compared against the final rates in the baseline simulation. In contrast, the optimized extraction rate for the Ringold Unit A is 16 times higher (1,220 gpm) than baseline, while total injection rates are three times higher (1,060 gpm).

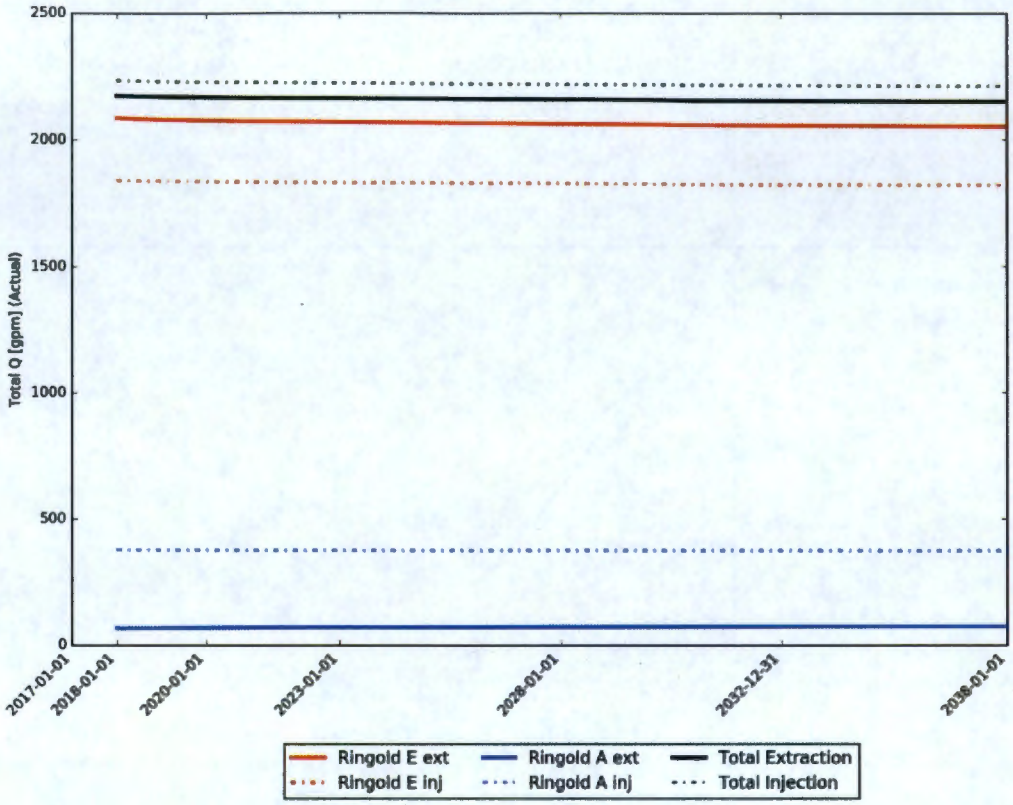


Figure 66. Summary of total extraction and in injection in the baseline pumping scenario

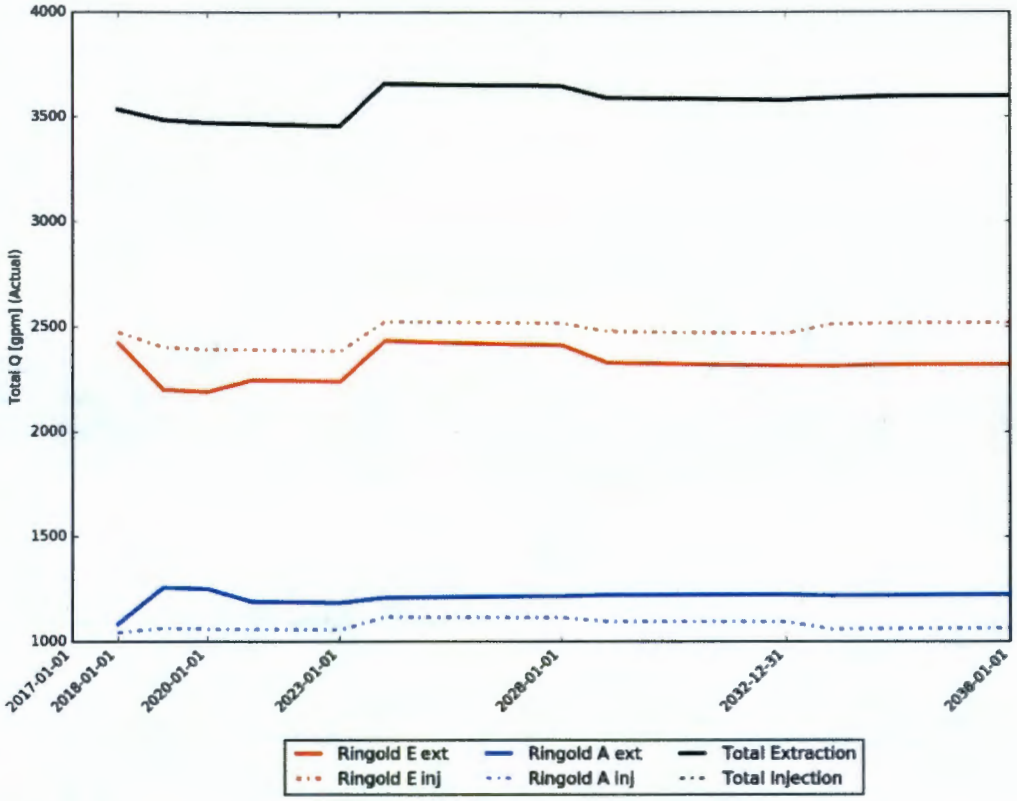


Figure 67. Summary of total extraction and in injection in the optimized pumping scenario

The spatial distribution of pumping for both baseline and optimized cases as well as the carbon tetrachloride concentrations at the end of the optimization period for the Ringold Unit E, are shown in Figure 68. Baseline pumping distribution for extraction and injection wells and corresponding carbon tetrachloride plume are shown at the top of the figure, while the optimized pumping rates and corresponding plume are shown at the bottom. Carbon tetrachloride concentration values are shown from the center of the Ringold E (layer 4 of the CPGWM) for illustration (the plume is 3D), and total rates are for pumping from the Ringold Unit E (layers 1 through 5 of the CPGWM). For the baseline case, extraction is concentrated at the center of the plume, with some wells pumping in areas below clean up level of 3.4 μg/L. In contrast, the optimized pumping is focused more to the east along two lines of wells parallel to the 200 West Area boundary. The optimized injection pattern is relatively similar with more wells operating in the upgradient area to the west.

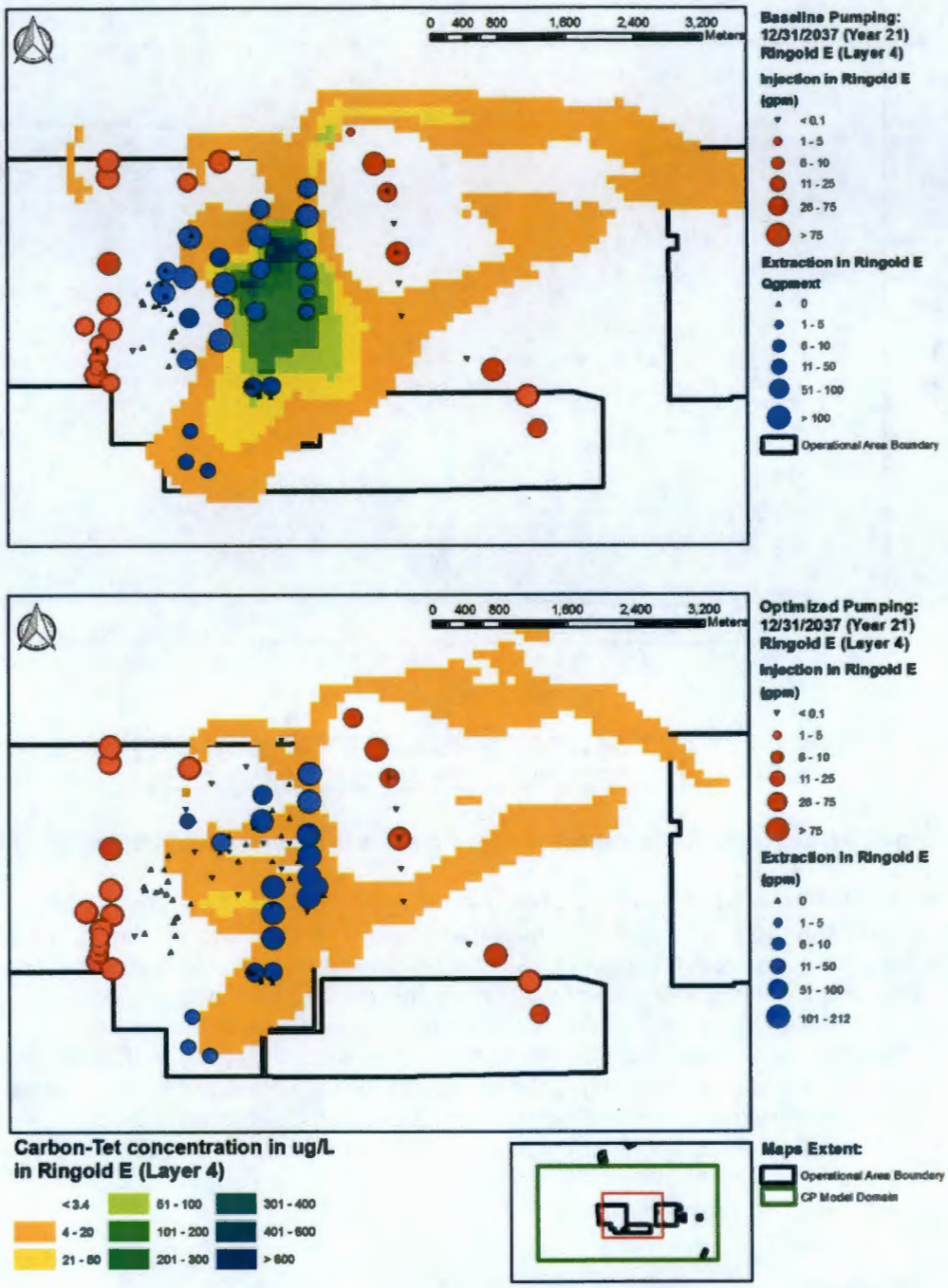


Figure 68. Pumping rates and simulated carbon tetrachloride concentrations for baseline and optimized pumping scenarios in the Ringold Unit E

Figure 69 shows the pattern of injection and extraction for the Ringold Unit A. In the optimized case, injection was moved from the east towards a line of new injection wells surrounding the high concentration portion of the plume on the west, and four additional wells at the center of the plume. As

explained before, pumping for this unit increased by a factor of 16, with 13 new extraction wells and 13 new injection wells.

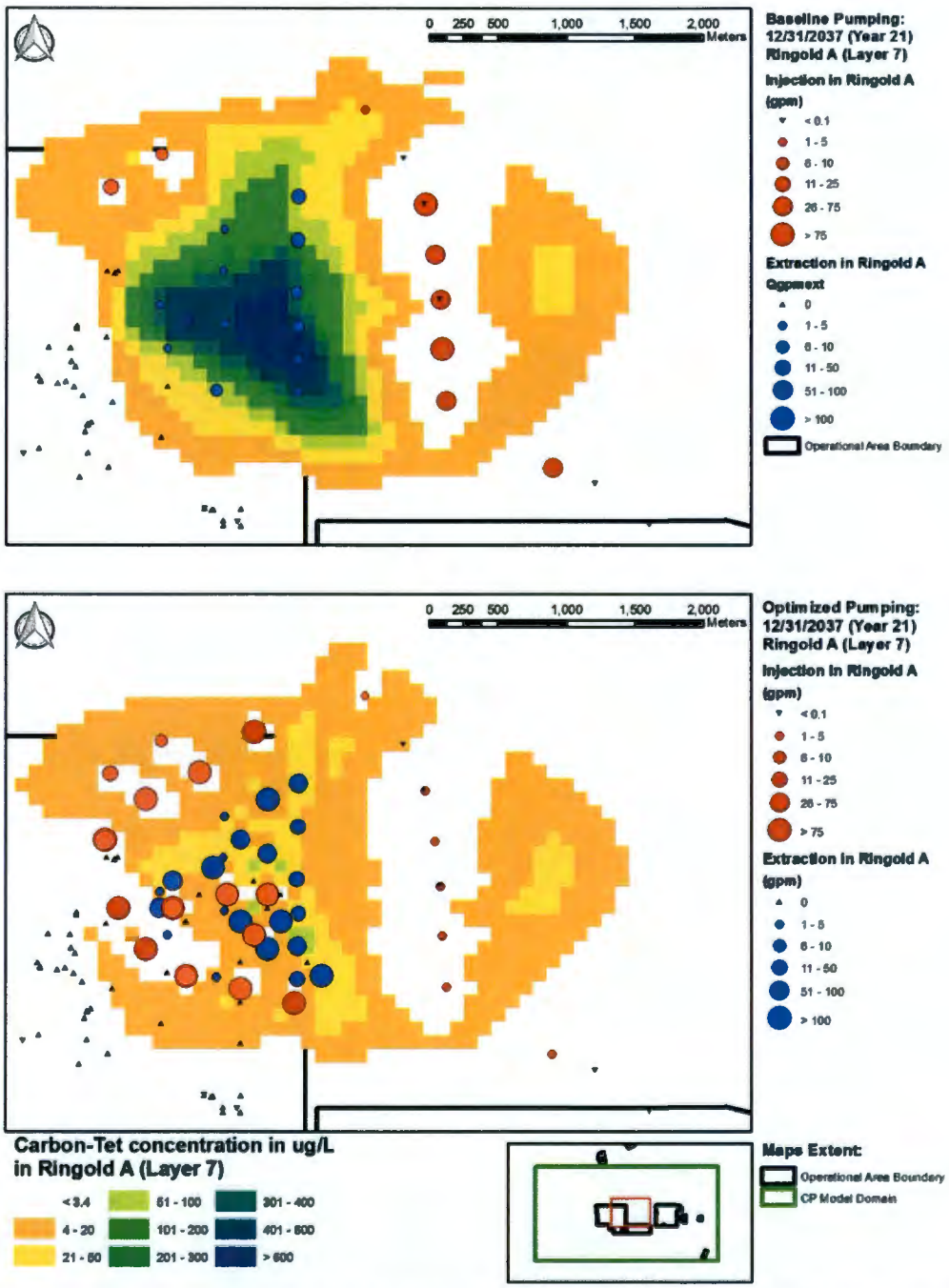


Figure 69. Pumping rates and simulated carbon tetrachloride concentrations for baseline and optimized pumping scenarios in the Ringold Unit A

6.2.2 Carbon Tetrachloride – 41-year half-life

Figure 70, Figure 71, and Figure 72 show the simulated plume extent after 25 years of optimized pumping in 2037. Note that the simulated peak concentrations are near or below 100 µg/L. After another 100 years

of elapsed time there are no carbon tetrachloride concentrations above cleanup level in the Ringold Unit E, and the Ringold Unit A concentrations are shown in Figure 73; peak concentration is about four times the cleanup level, but this is greatly reduced from the base case described in Section 6.1.1.

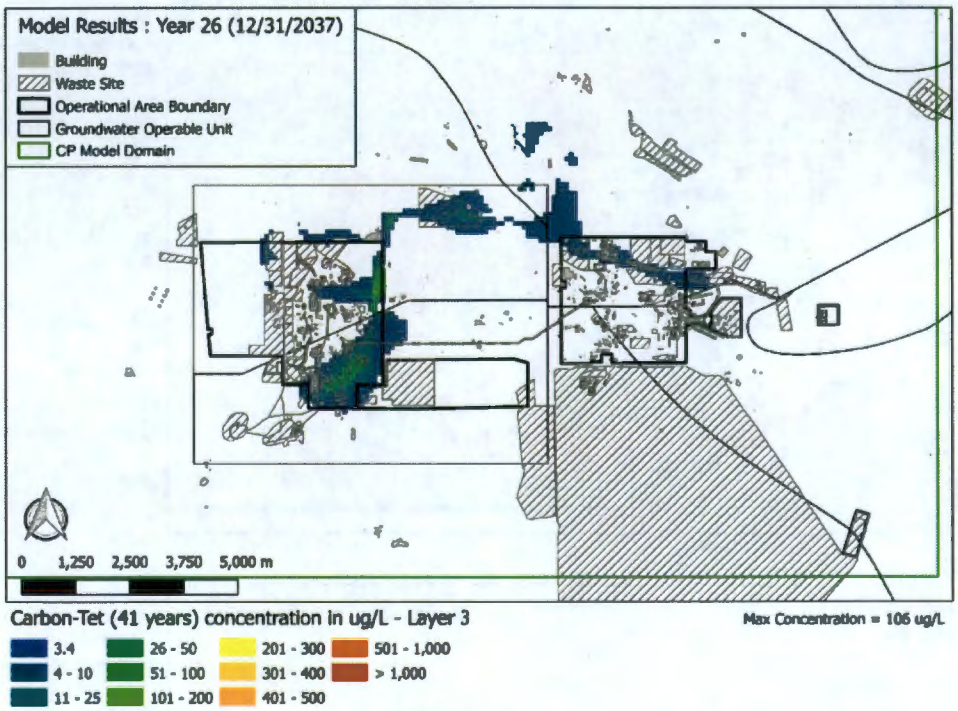


Figure 70. Simulated Carbon Tetrachloride Distribution (41-year half-life) at the Ringold Unit E Water Table in 2037 after 25 years of optimized pumping

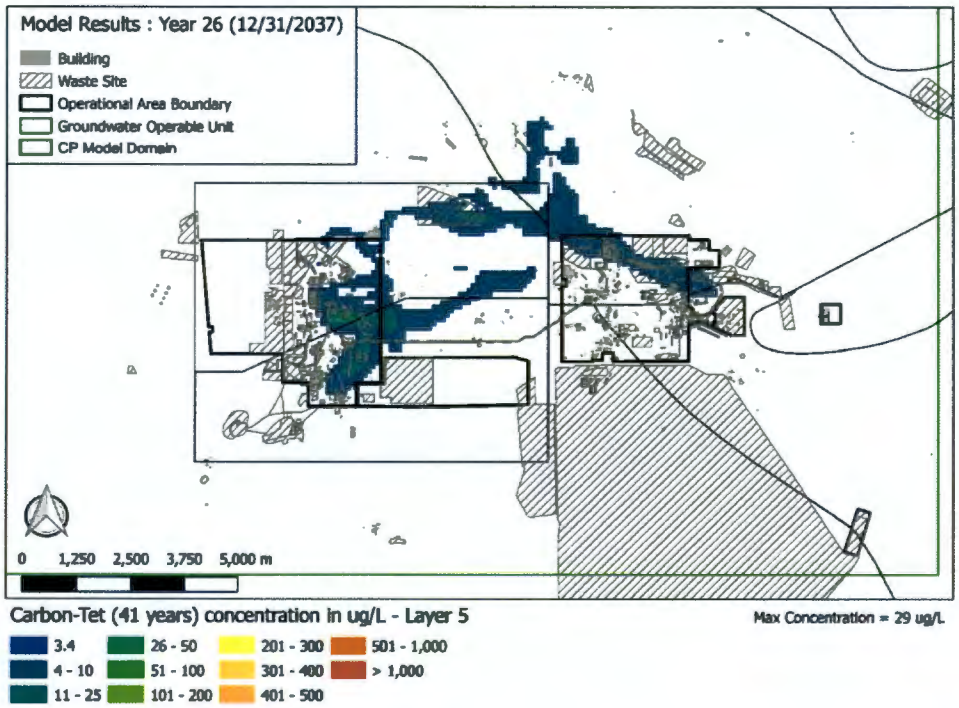


Figure 71. Simulated Carbon Tetrachloride Distribution (41-year half-life) at the base of Ringold Unit E in 2037 after 25 years of optimized pumping

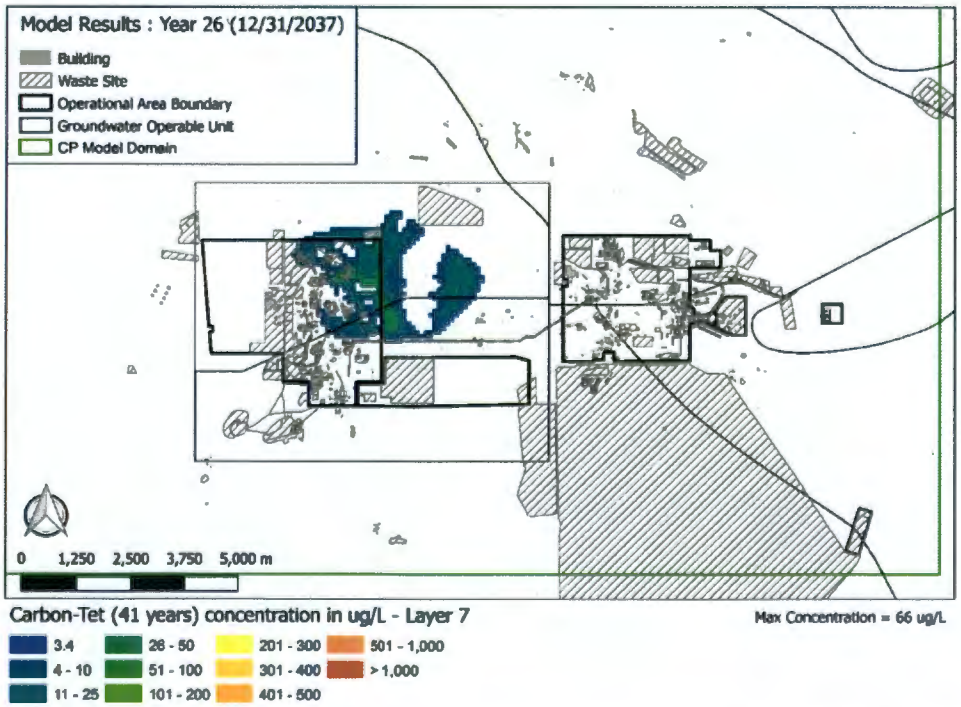


Figure 72. Simulated Carbon Tetrachloride Distribution (41-year half-life) in the Ringold Unit A in 2037 after 25 years of optimized pumping

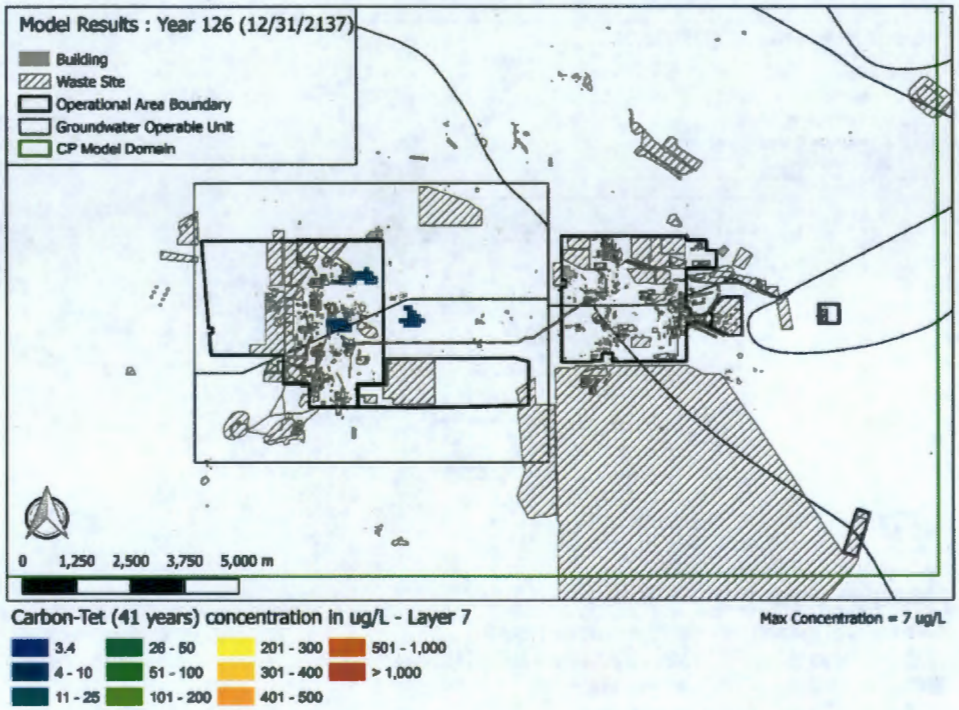


Figure 73. Simulated Carbon Tetrachloride (41-year half-life) Distribution in the Ringold Unit A in 2137

Simulated pumped carbon tetrachloride mass removed is shown as mass and fraction of initial mass (Figure 74).

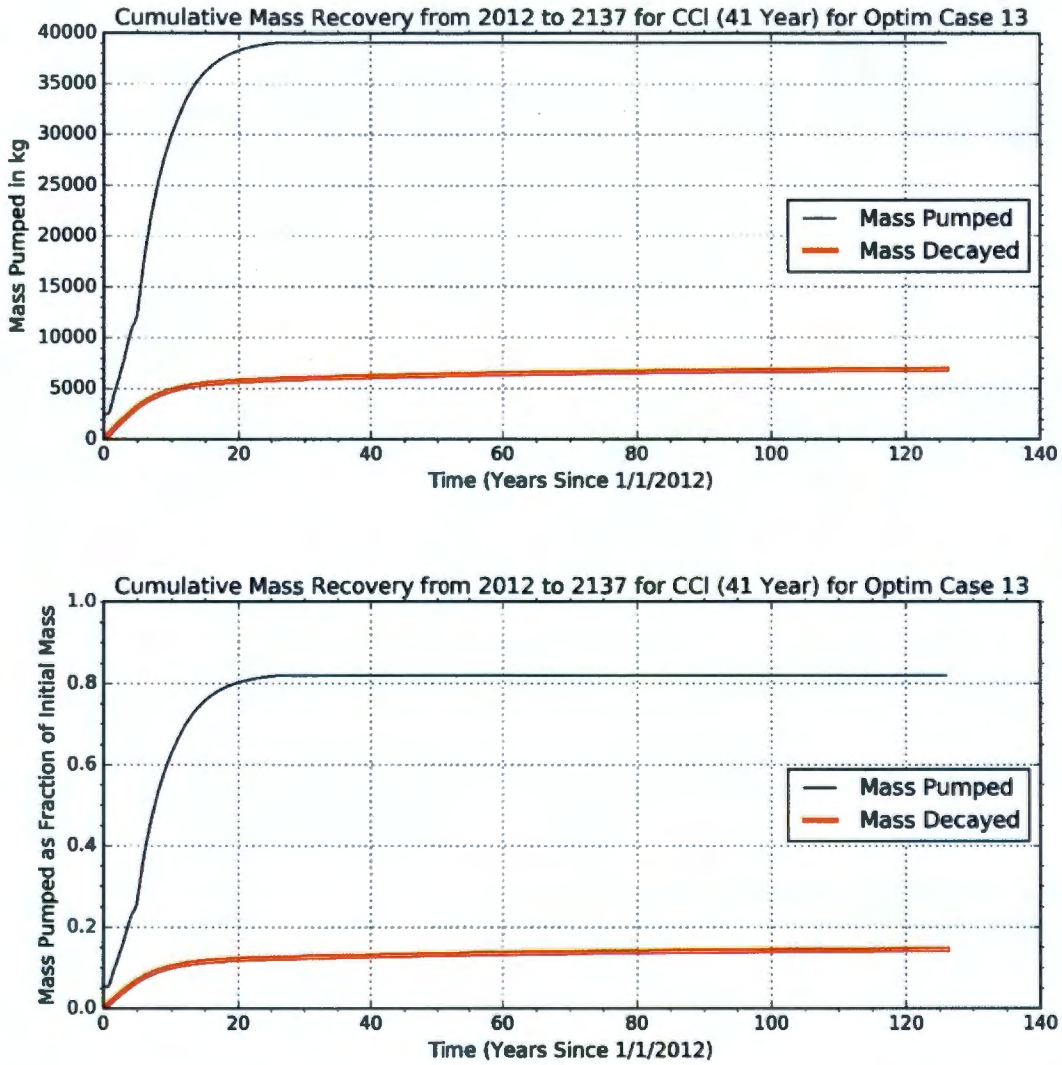


Figure 74. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass (bottom) – Optimized Pumping

The UCL95 concentrations of carbon tetrachloride computed from the simulated concentrations are shown in Figure 75. Note the consistent concentration decline throughout the optimized pumping period as compared to that in the baseline forecast (Figure 12). The Ringold Unit E reaches the cleanup goal after about 65 years after remediation starts; the Ringold A takes the full 100-yr MNA period because it is somewhat isolated from the Ringold Unit E by the Ringold Lower Mud (RLM), and has a lower transmissivity resulting in lower velocities.

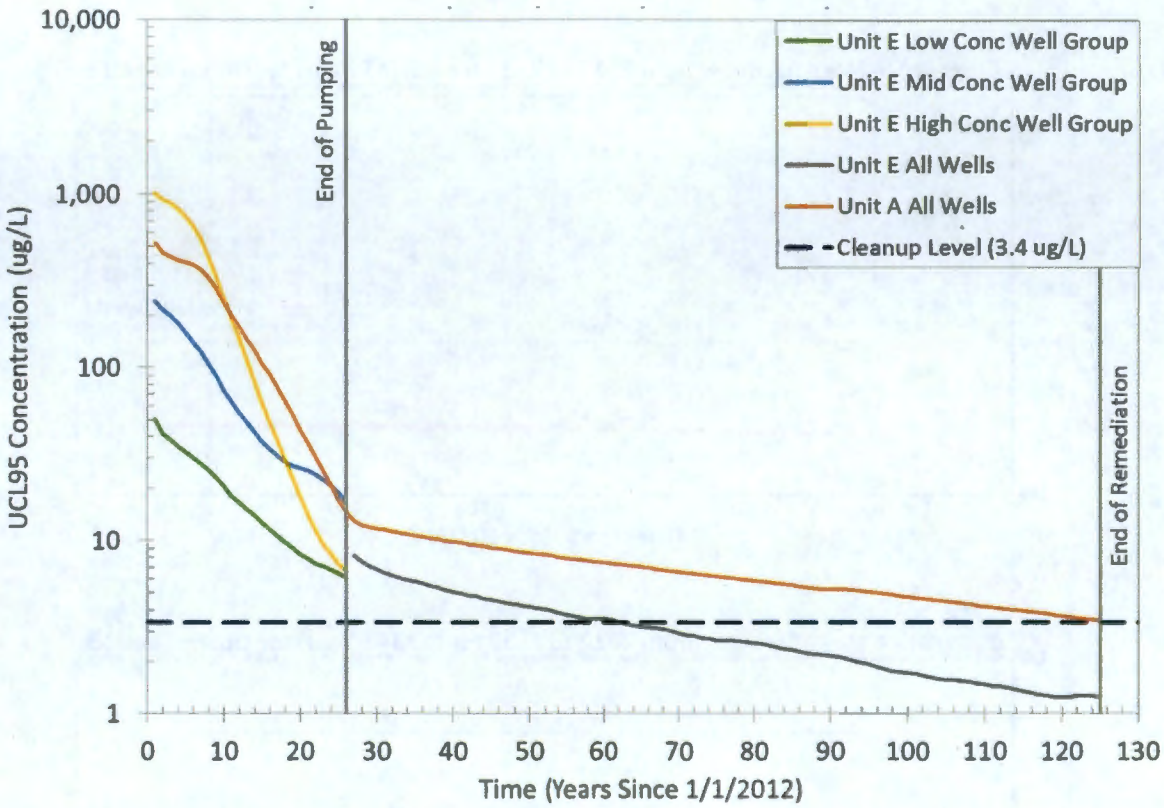


Figure 75. Simulated UCL95 Concentrations for Carbon Tetrachloride – Optimized Pumping - 41-yr half-life

6.2.3 Carbon Tetrachloride – 100-year half-life

Figure 76, Figure 77, and Figure 78 show the simulated extent of the carbon tetrachloride plume with a 100-year half-life at the end of 25 years of optimized pumping in 2037. Peak concentrations are higher than those simulated with a 41-year half-life. Simulated Ringold Unit E concentrations are the highest. Similarly, simulated concentrations in 2137 are greater than those with a 41-year half-life, and above the cleanup level.

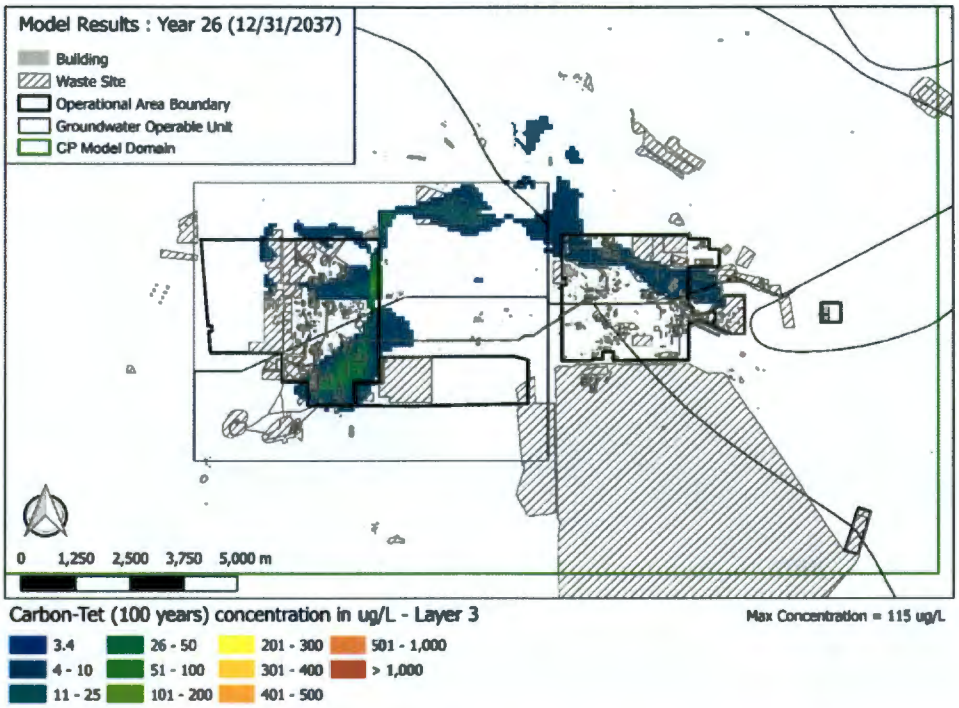


Figure 76. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the water table in Ringold Unit E in 2037 after 25 years of optimized pumping

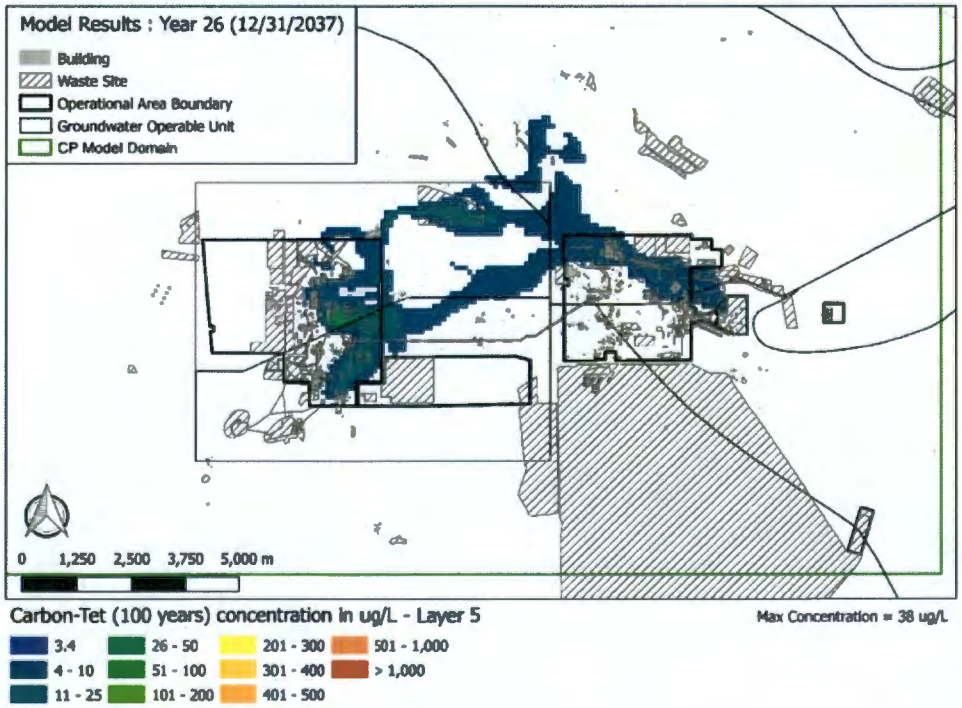


Figure 77. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the base of Ringold Unit E in 2037 after 25 years of optimized pumping

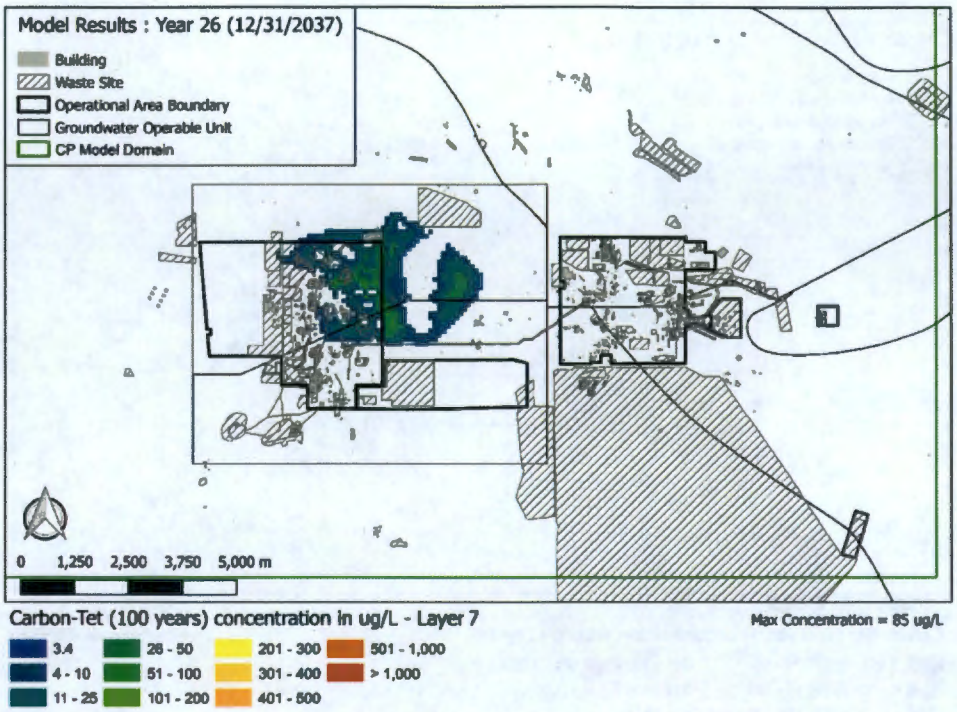


Figure 78. Simulated Carbon Tetrachloride Distribution (100-year half-life) in the Ringold Unit A in 2037 after 25 years of optimized pumping

Figure 79, Figure 80, and Figure 81 show the simulated extent of carbon tetrachloride in 2137. The Ringold Units E and A are above cleanup in some areas by factors of 2 to 6; decay is required to reduce the concentrations to the cleanup level.

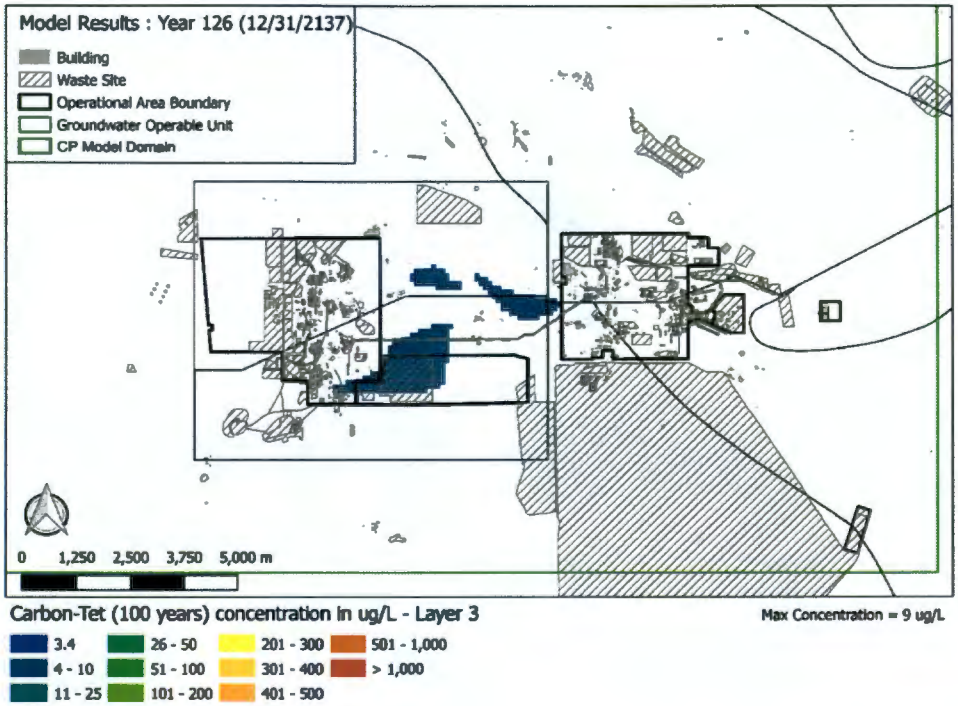


Figure 79. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the water table in Ringold Unit E in 2137

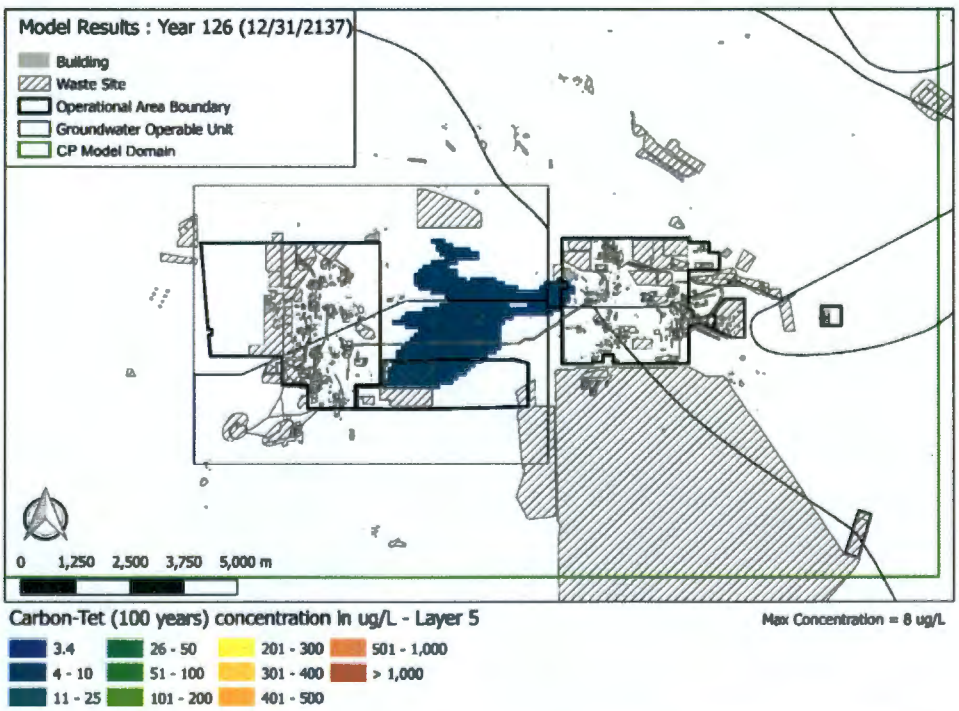


Figure 80. Simulated Carbon Tetrachloride Distribution (100-year half-life) at the base of Ringold Unit E in 2137

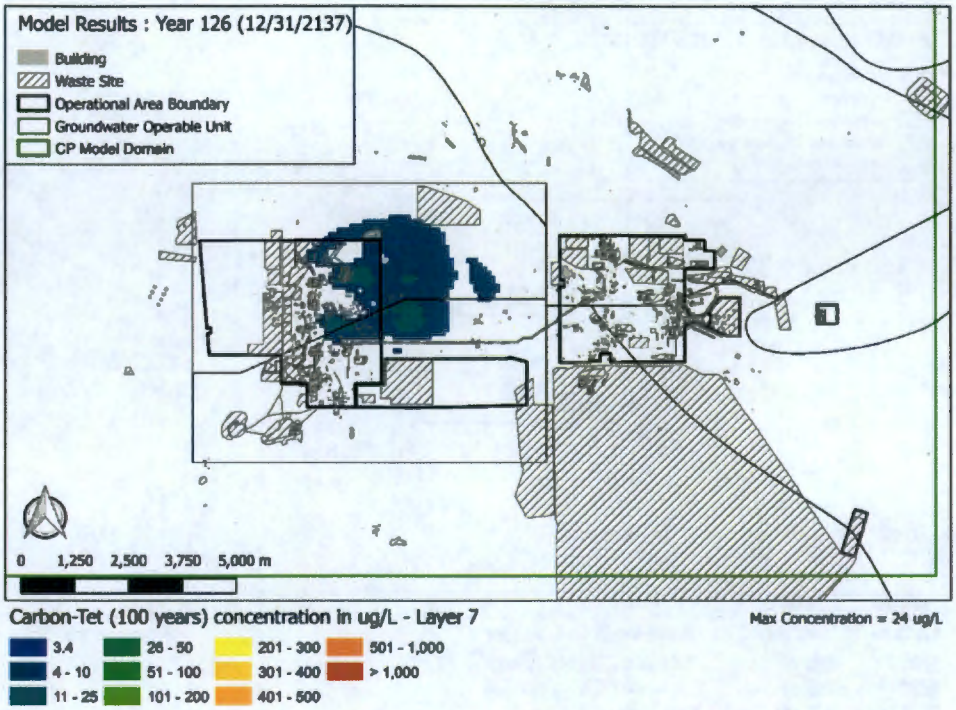


Figure 81. Simulated Carbon Tetrachloride Distribution (100-year half-life) in the Ringold Unit A in 2137

Simulated pumped mass removed is shown as mass and fraction of initial mass (Figure 82); more mass is recovered by pumping with a 100-yr than a 41-yr half-life because less decays during pumping operations.

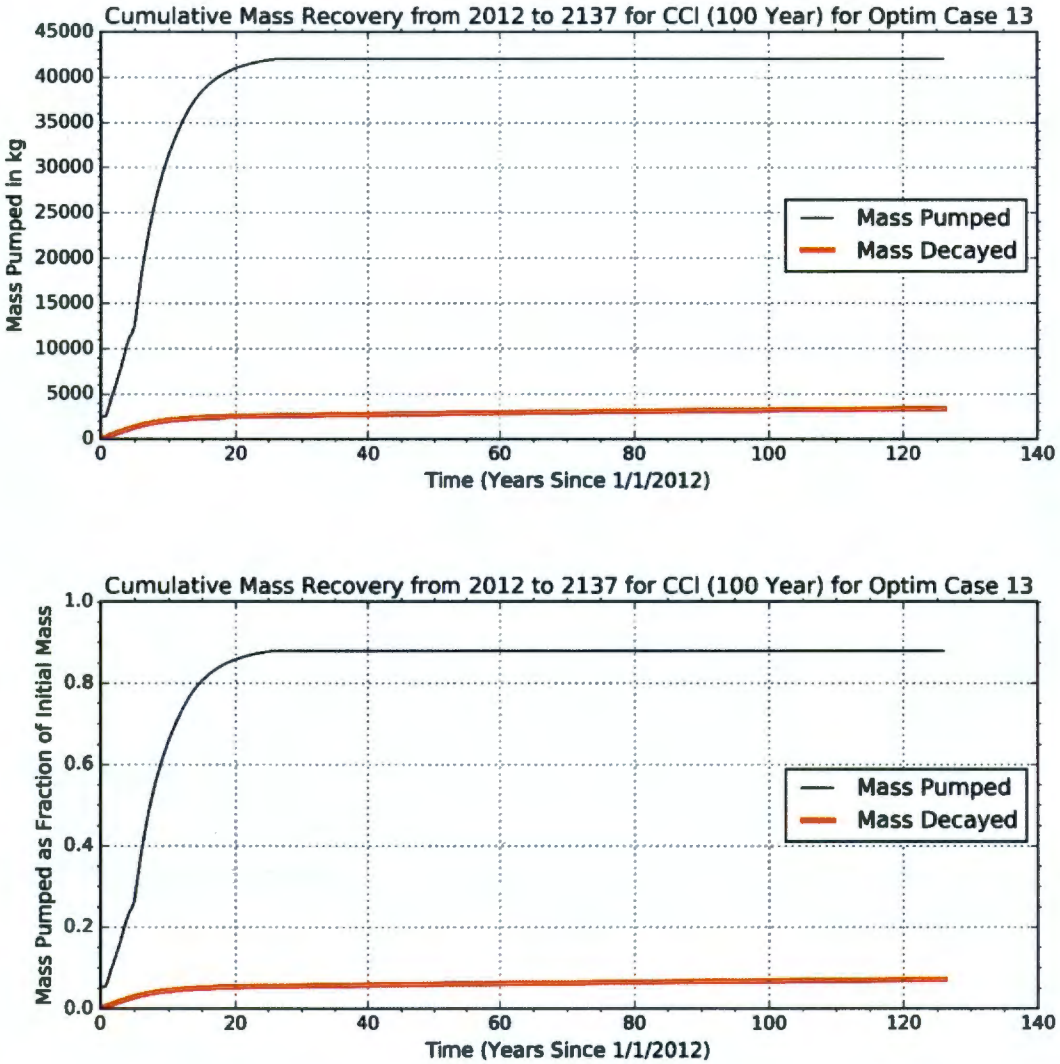


Figure 82. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial carbon tetrachloride mass (bottom) – Optimized Pumping

The UCL95 concentrations computed from the simulated concentrations are shown in Figure 83. Note the consistent concentration decline throughout the optimized pumping period as compared to that in the baseline forecast (Figure 12). The Ringold Unit E reaches the cleanup goal (as an average) after about 110 years after remediation starts; concentrations in the Ringold Unit A do not reach the cleanup level after 125 years without the benefit of decay. This illustrates the key role of abiotic decay in achieving cleanup goals.

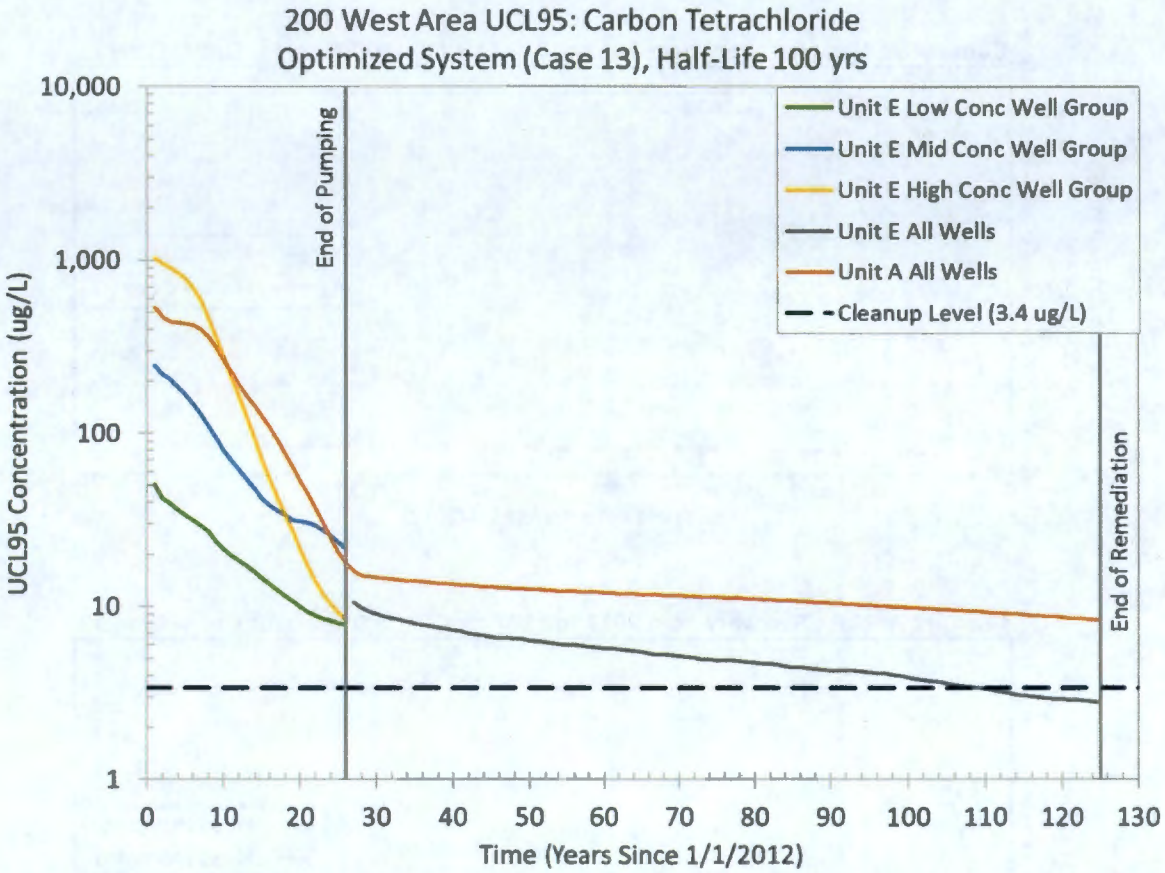


Figure 83. Simulated UCL95 Concentrations for Carbon Tetrachloride – Optimized Pumping - 100-yr half-life

6.2.4 Chromium (VI)

Areas with existing Cr(VI) contamination above the cleanup level in 200-ZP-1 are the WMA T and WMA TX-TY Tank Farms. Chromium (VI) at the 216-S-10 Pond in the 200-UP-1 OU was also assessed (the southeast Cr[VI] plume associated with 200-UP-1 was not analyzed as discussed in Section 1, and Cr(VI) at the WMA S-SX Tank Farms was analyzed separately in ECF-200W-17-0094). No Cr(VI) above the cleanup level is present in 2037 in the no source case, and no maps are shown.

A Cr(VI) source has been estimated for 216-S-10 Pond, WMA S-SX Tank Farms, WMA T, and WMA TX-TY Tank Farms and nearby cribs, and Figure 84 and Figure 85 show the simulated extent in 2037. Note the plumes developing at the source areas at the water table, but not at the base of the Ringold Unit E. Figure 86 and Figure 87 show the simulated plume extents in 2137. The plumes are better developed, with the largest extent associated with the WMA T and WMA TX-TY Tank Farms and nearby cribs.

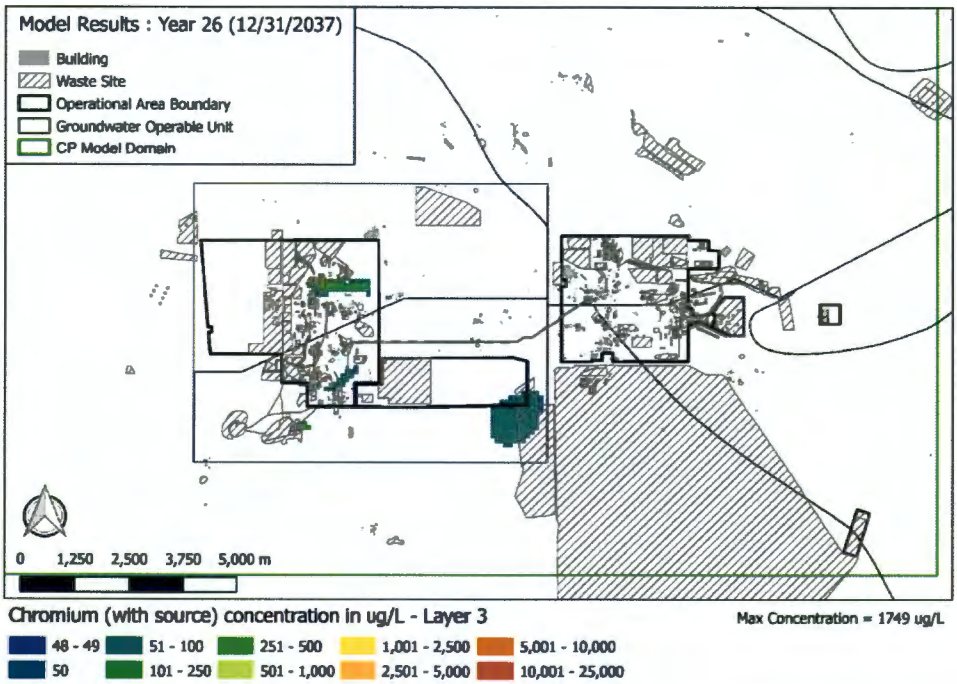


Figure 84. Simulated Chromium(VI) Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping - Source

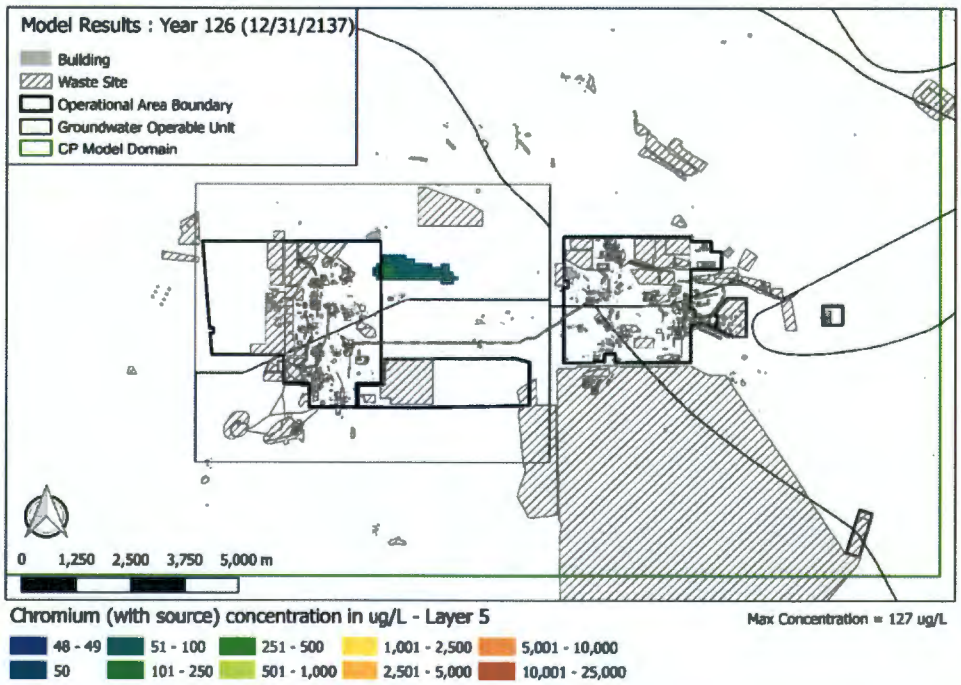


Figure 85. Simulated Chromium(VI) Distribution at the base of the Ringold Unit E in 2037 after 25 years of optimized pumping- Source

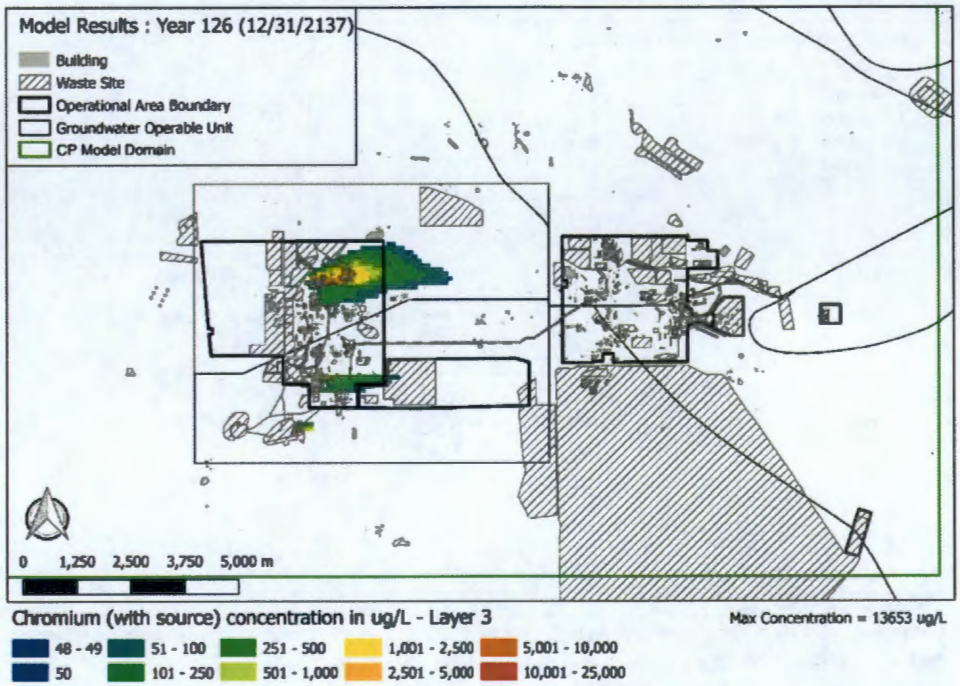


Figure 86. Simulated Chromium(VI) Distribution at the water table in the Ringold Unit E in 2137 - Source

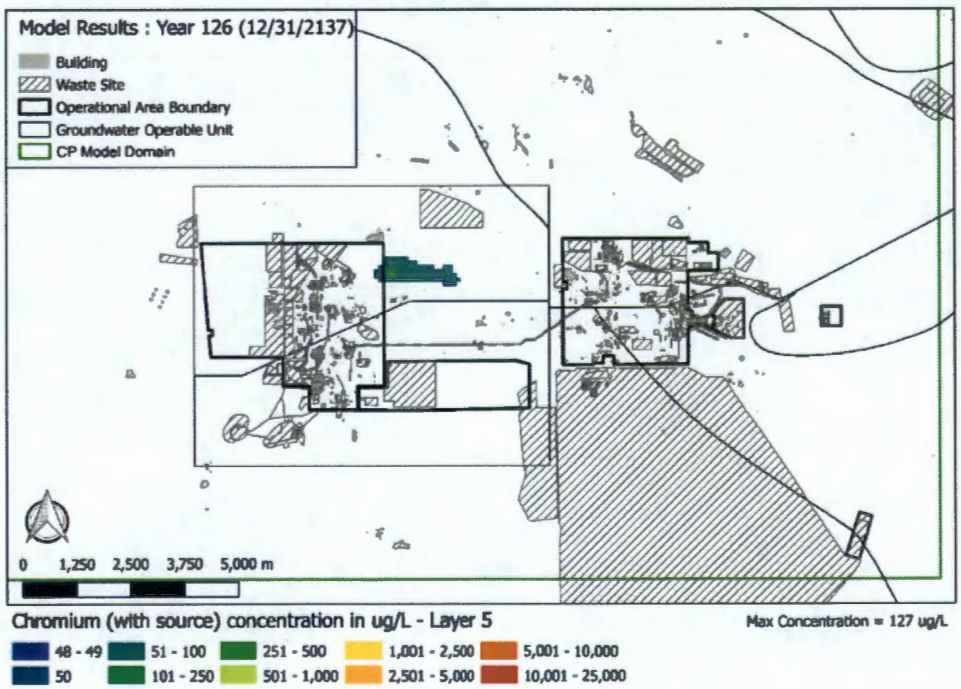


Figure 87. Simulated Chromium(VI) Distribution at the base of the Ringold Unit E in 2137 - Source

Figure 88 shows the computed mass recovery with and without sources. Because chromium is mobile in groundwater some of the chromium entering the aquifer from the sources is captured by the remediation wells during their operation, thus some of the effect of the sources is ameliorated.

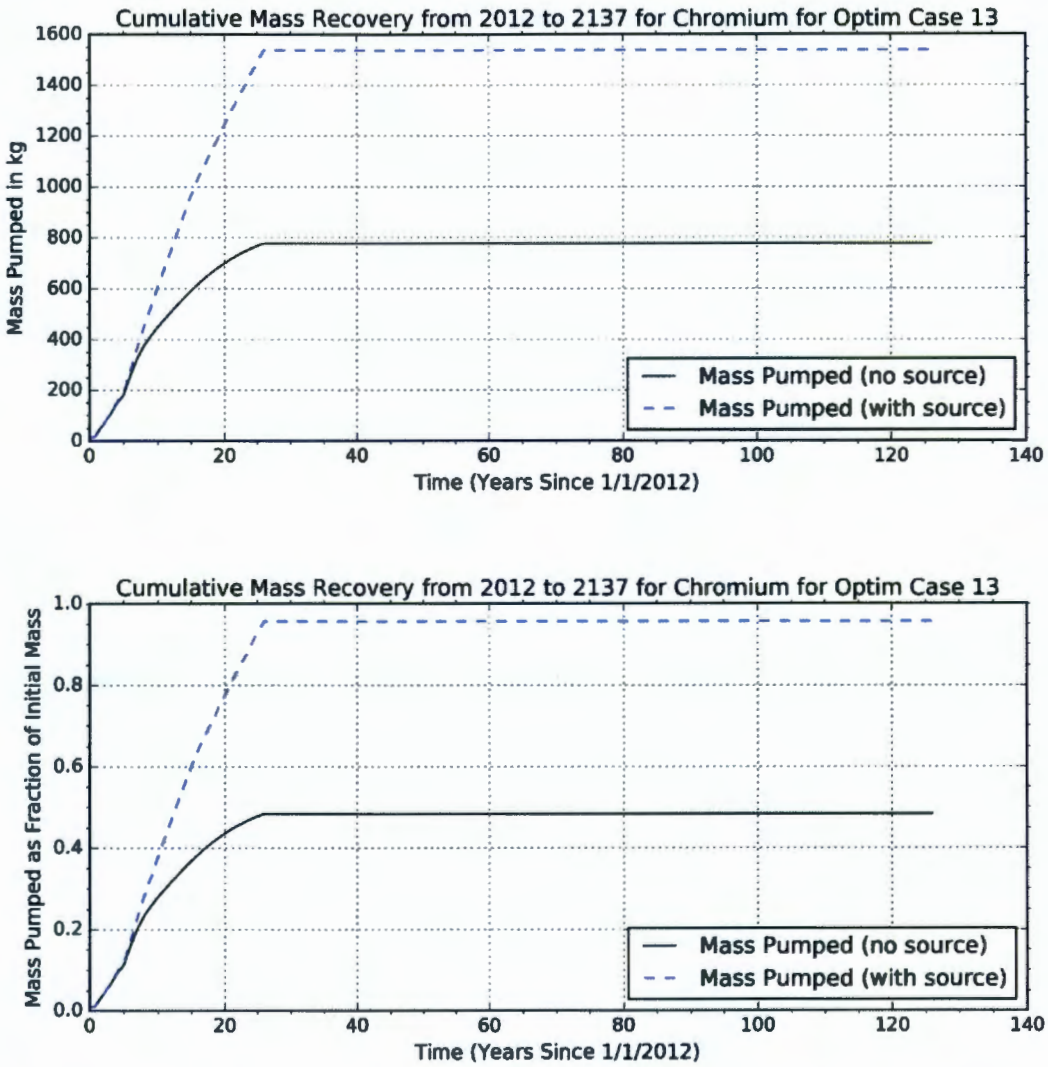


Figure 88. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial Cr(VI) mass (bottom) – Optimized Pumping

The UCL95s computed from the simulated concentrations are shown in Figure 89. Concentrations in the Ringold Unit E decline to below the cleanup level after about 10 years after remediation starts with no sources; sources prevent cleanup from occurring.

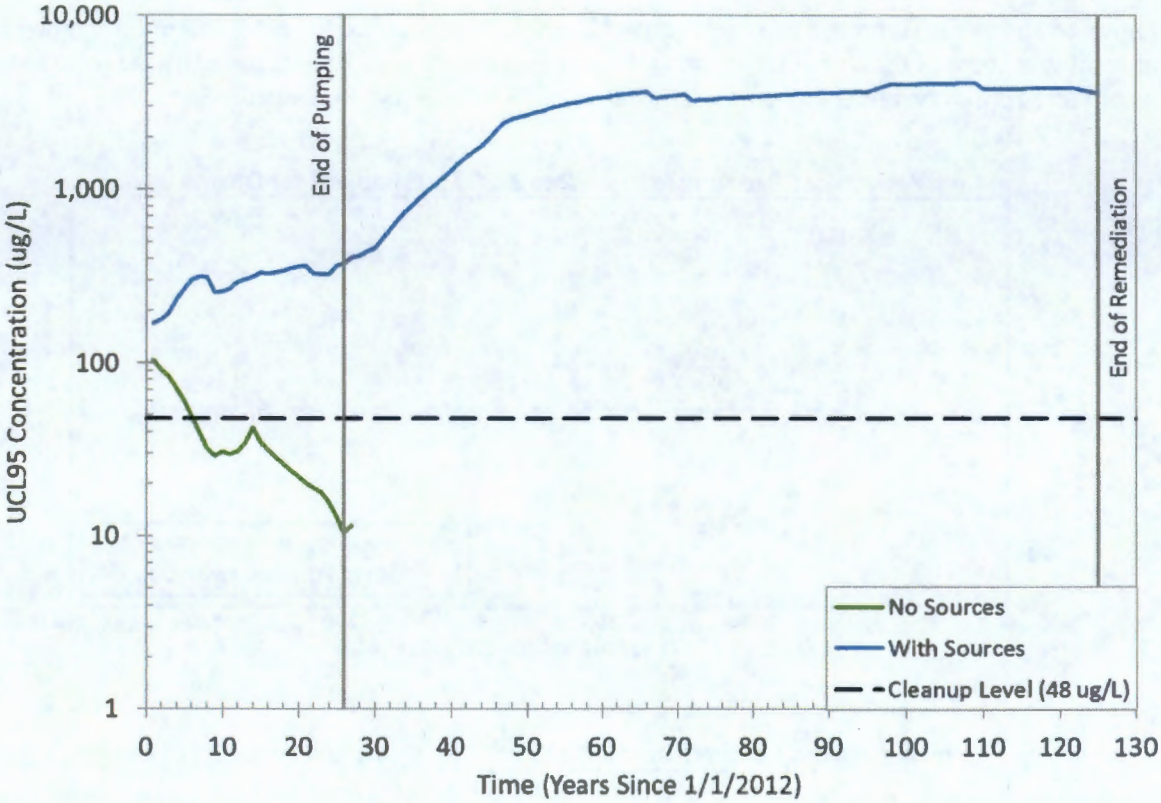


Figure 89. Simulated UCL95 for Cr(VI) with and without sources – Optimized Pumping

6.2.5 Nitrate

Figure 90, Figure 91, and Figure 92 show the simulated nitrate extent after 25 years of optimized pumping in 2037. Areas remain above the cleanup level of 45,000 µg/L. In 2137 all concentrations are below the cleanup level, and no maps are shown.

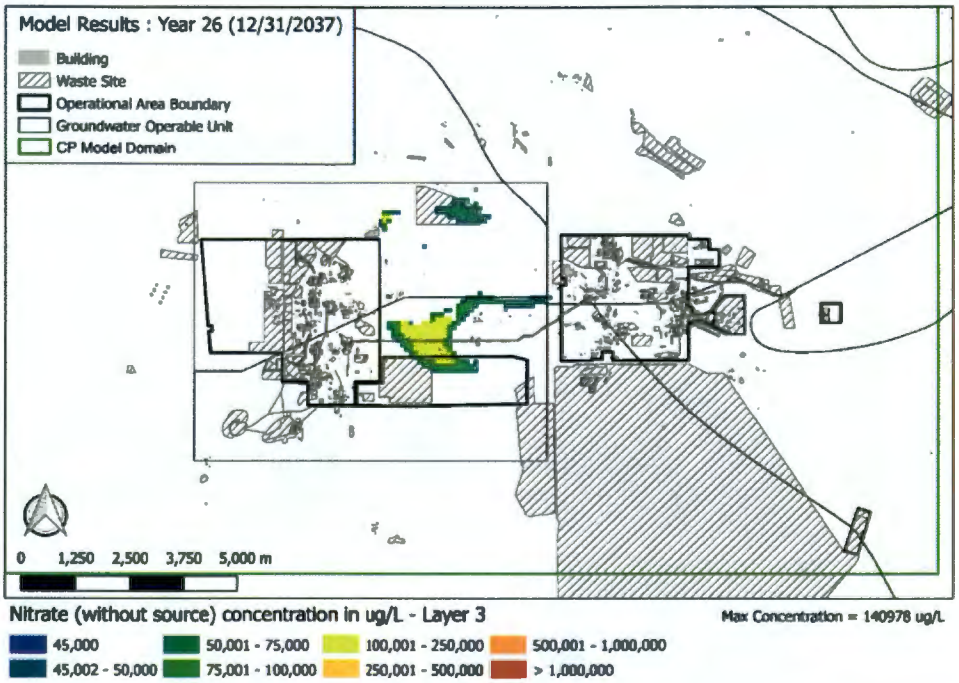


Figure 90. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping – No Source

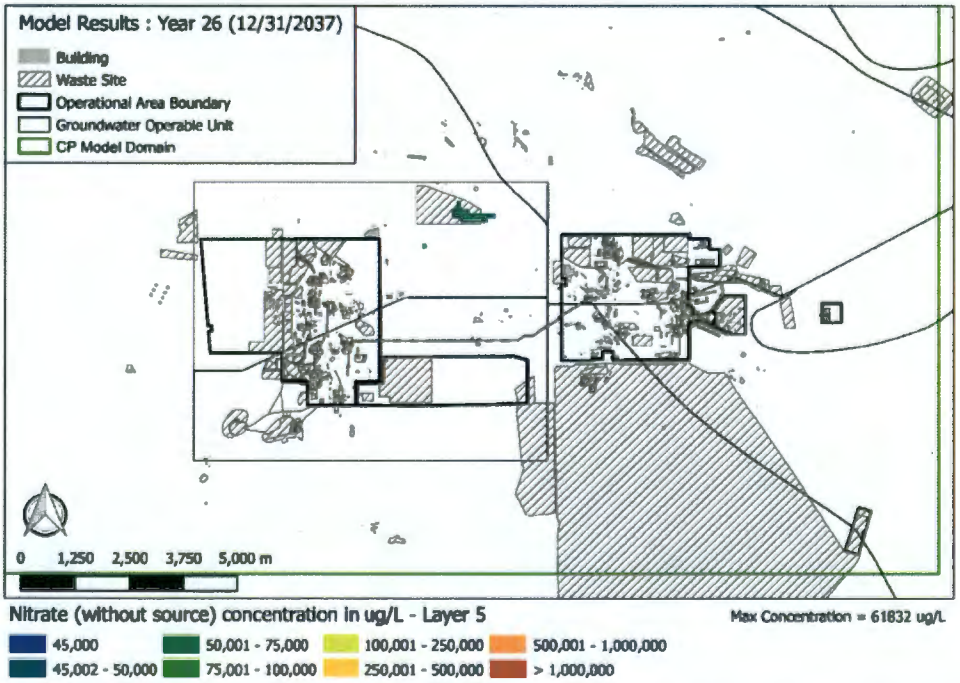


Figure 91. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2037 after 25 years of optimized pumping– No Source

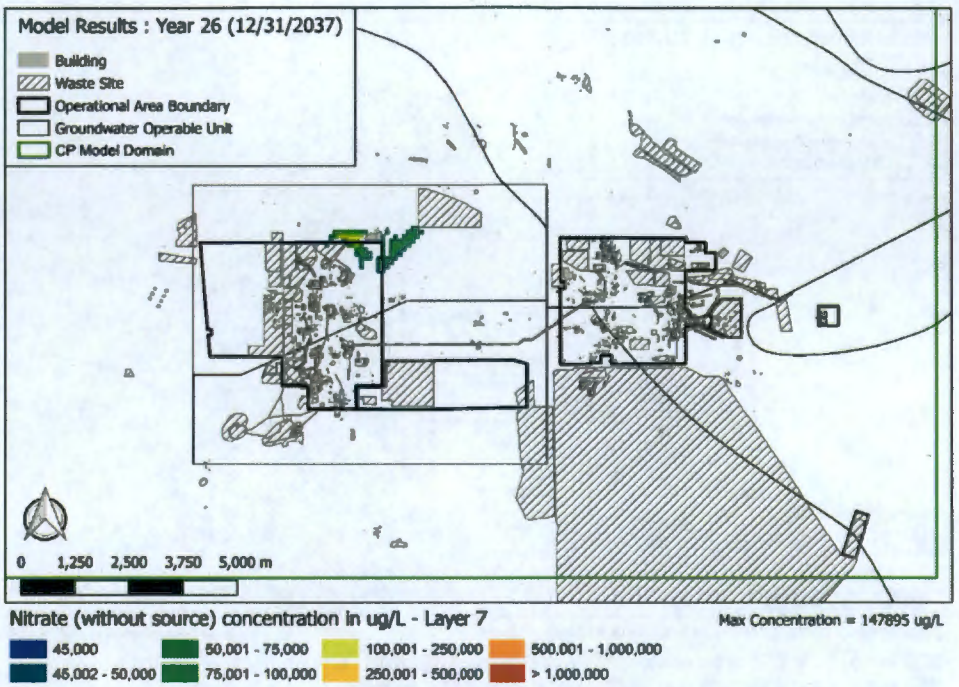


Figure 92. Simulated Nitrate Distribution in the Ringold Unit A in 2037 after 25 years of optimized pumping–No Source

Sources of nitrate have been estimated for the 216-S-25 Crib, 216-U-1 and U-2 Cribs, 216-Z-1A Tile Field, WMA S-SX Tank Farms, WMA T and WMT TX-TY Tank Farms and nearby cribs, and WMA U Tank Farm. Figure 93, Figure 94, and Figure 95 show the simulated extents in 2037 with sources. The plume extents are similar to those computed assuming no sources in 2037, with higher concentrations near the source areas. However, the outcome in 2137 is different than the no source case as shown in Figure 96, Figure 97, and Figure 98 with plume extents like those currently interpreted to exist.

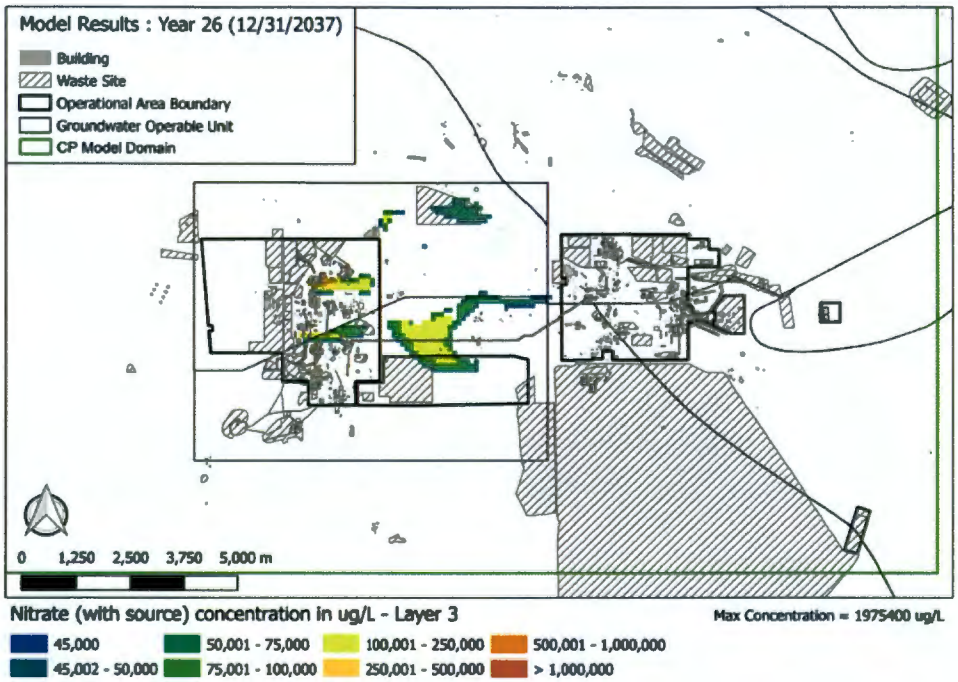


Figure 93. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping –Source

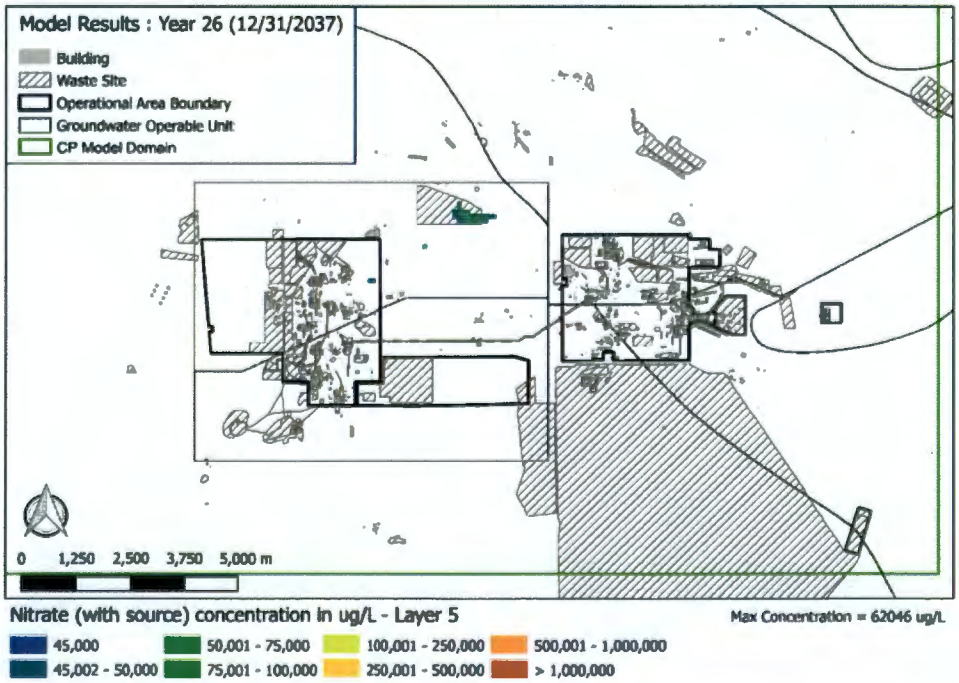


Figure 94. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2037 after 25 years of optimized pumping –Source

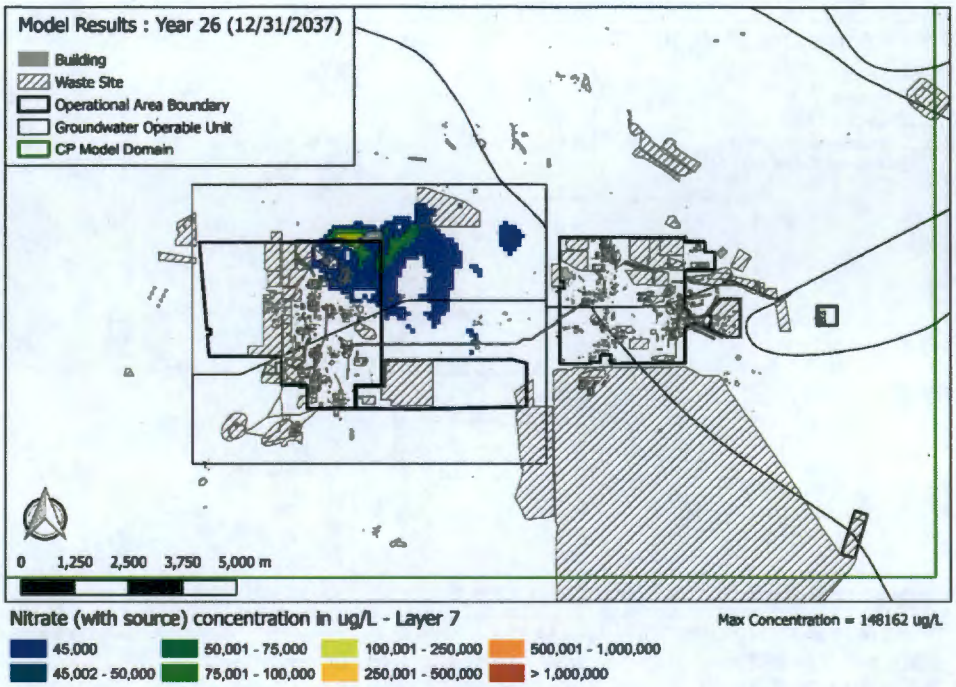


Figure 95. Simulated Nitrate Distribution in the Ringold Unit A in 2037 after 25 years of optimized pumping – Source

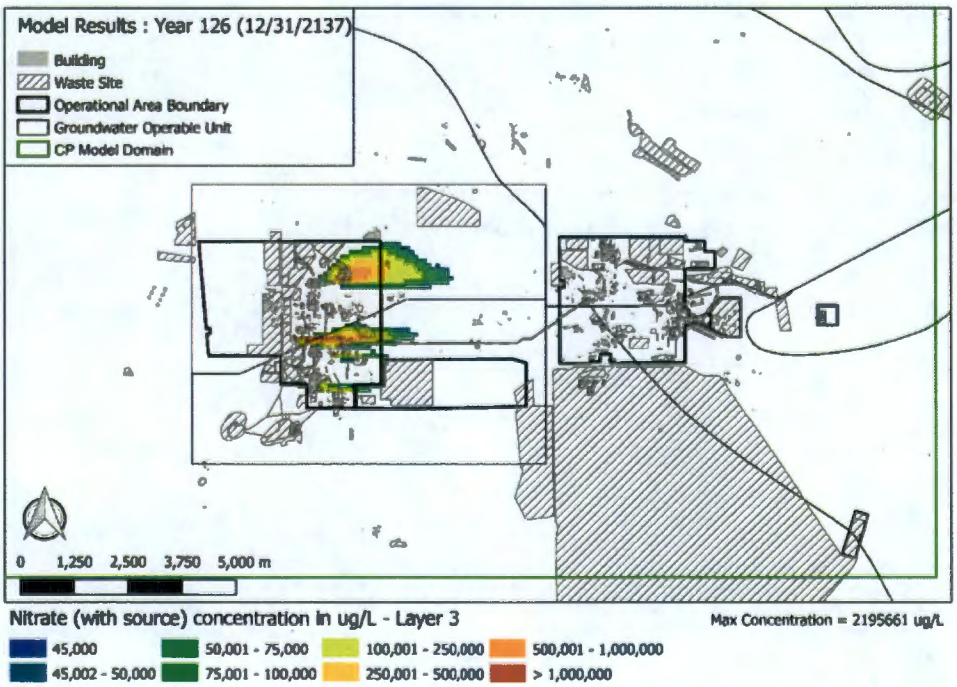


Figure 96. Simulated Nitrate Distribution at the water table in the Ringold Unit E in 2137–Source

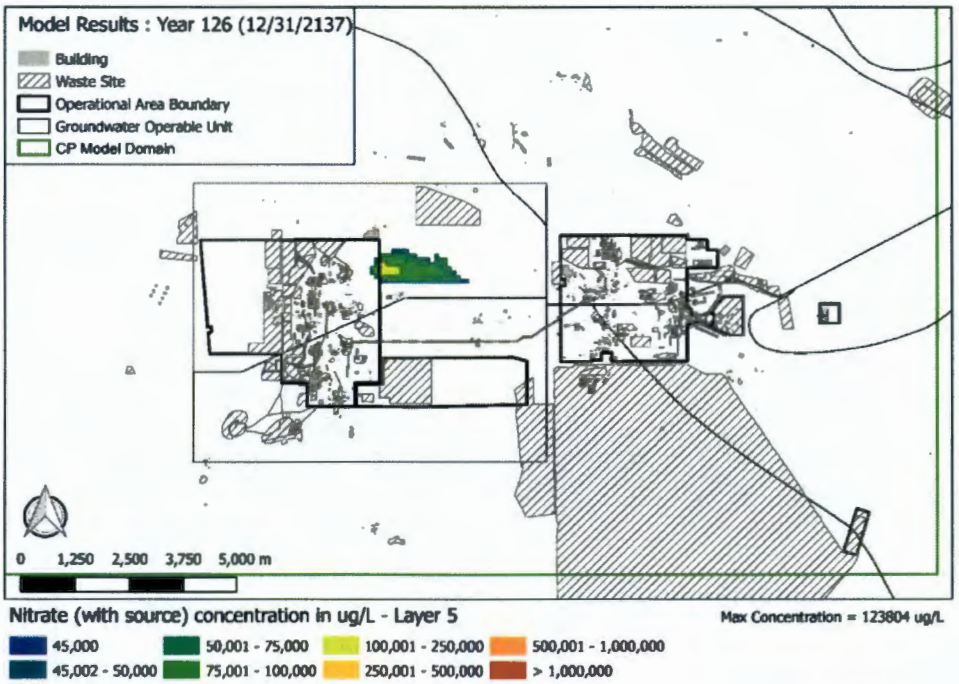


Figure 97. Simulated Nitrate Distribution at the base of the Ringold Unit E in 2137–Source

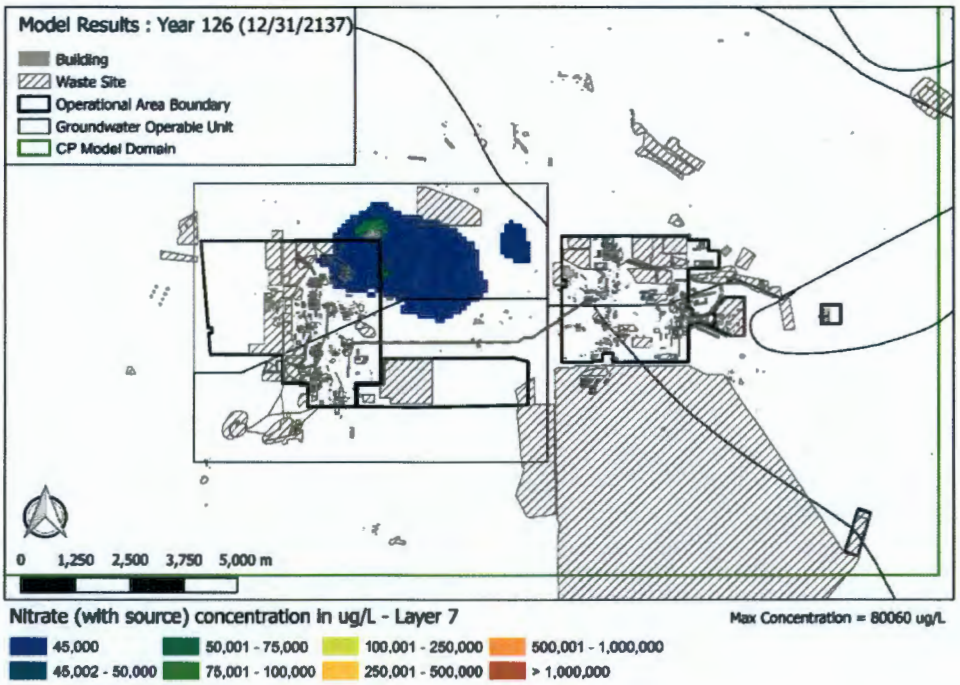


Figure 98. Simulated Nitrate Distribution in the Ringold Unit A in 2137 –Source

Simulated mass extracted with and without sources is shown in Figure 99.

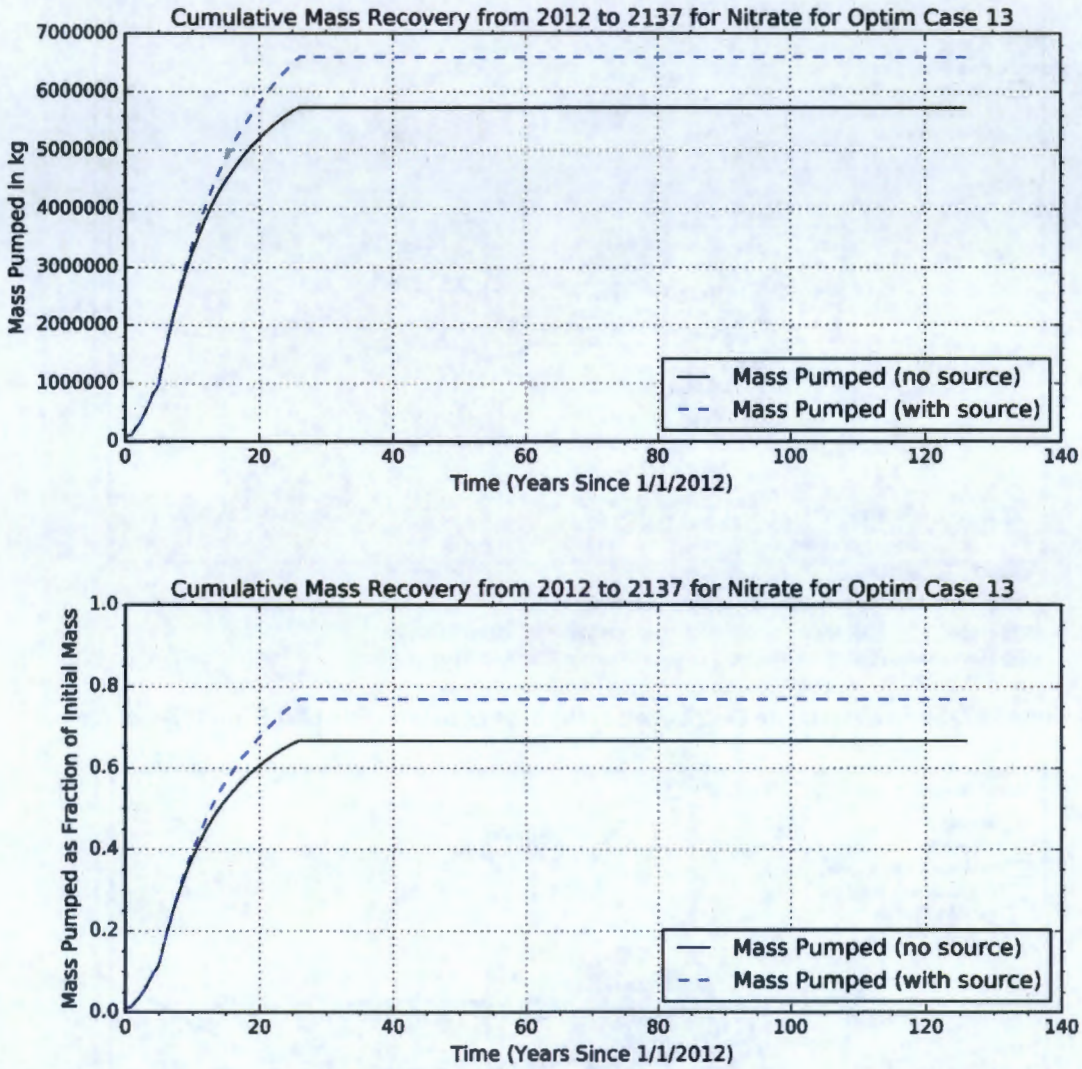


Figure 99. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of nitrate initial mass (bottom) – Optimized Pumping

The UCL95s for 200-ZP-1 computed from the simulated concentrations are shown in Figure 100. Note that the source significantly delays cleanup from being achieved during pumping, but ultimately cleanup is achieved. In contrast, sources have less influence on cleanup progress during pumping in 200-UP-1 (Figure 101).

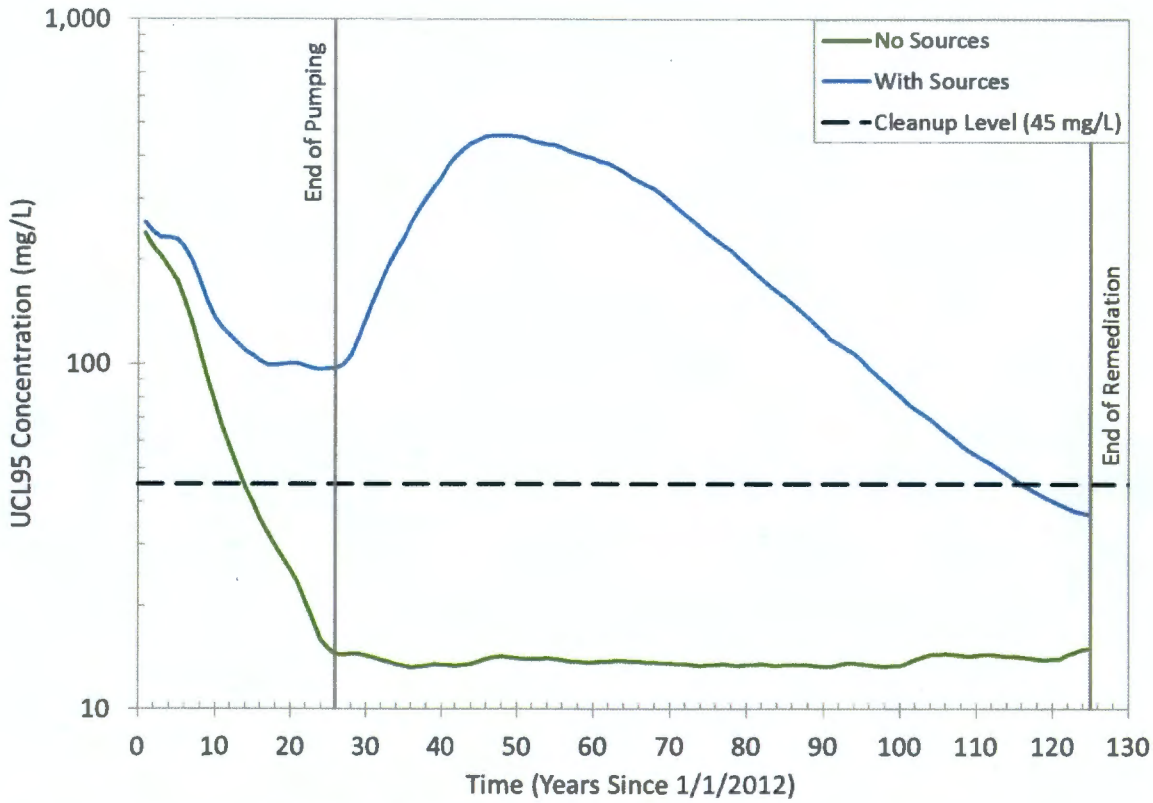


Figure 100. Simulated UCL95 for 200-ZP-1 Nitrate with and without sources – Optimized Pumping

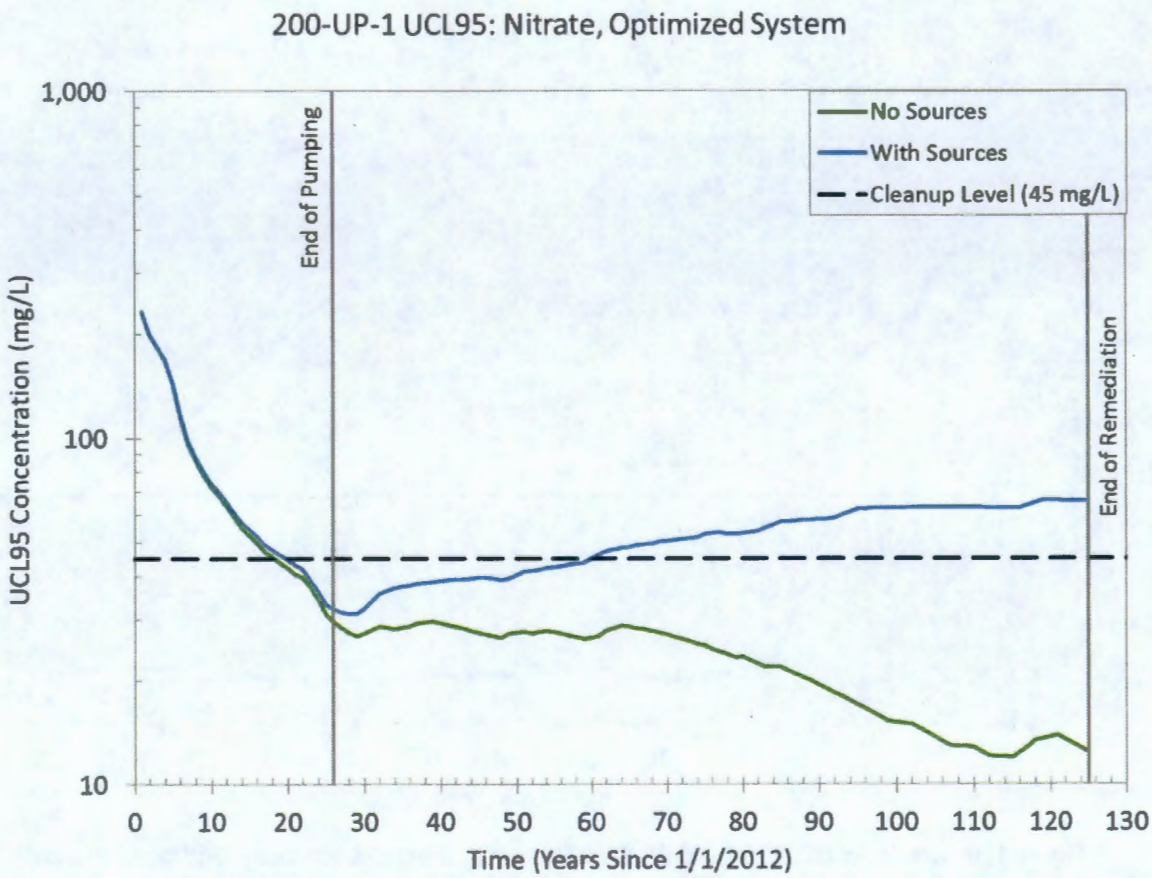


Figure 101. Simulated UCL95 for 200-UP-1 Nitrate with and without sources – Optimized Pumping

6.2.6 Technetium-99

Areas with existing Tc-99 above the cleanup level in 200-ZP-1 are the WMA T and WMA TX-TY Tank Farms; Tc-99 plumes associated with 200-UP-1 were analyzed in ECF-200W-17-0094 and ECF-200UP1-17-0093.

Figure 102 shows the simulated extent of Tc-99 in 2037 without sources. All the Tc-99 contamination in 200-ZP-1 has been removed from the aquifer by the pump-and-treat system. The only contamination remaining in 200 West is associated with 200-UP-1. No contamination occurred in the simulated results above cleanup level at the base of Ringold Unit E or Ringold Unit A in 2037 and 2137.

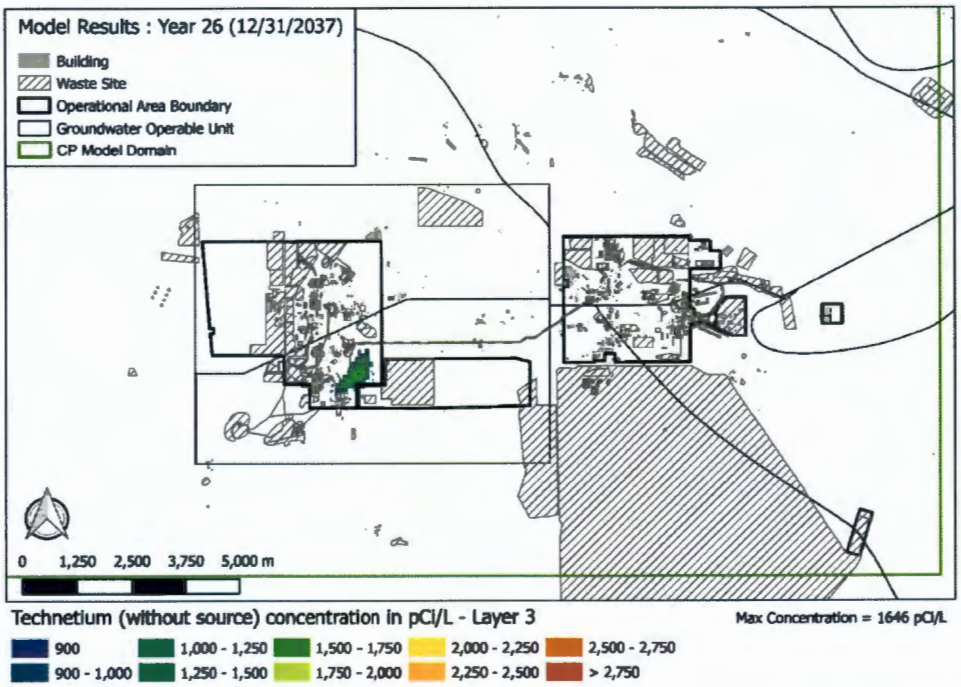


Figure 102. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping – No Source

Sources of Tc-99 were estimated for the 216-U-1 and U-2 Cribs, WMA S-SX Tank Farms, WMA T and WMA TX-TY Tank Farms and nearby cribs, and WMA U Tank Farms. Figure 103 shows the simulated plume extent at the water table in the Ringold Unit E after 25 years of pumping (2037) with a source. No other layers have concentrations above the cleanup level. WMA T and WMA TX-TY has the highest simulated concentrations. Figure 104, Figure 105, and Figure 106 show simulated concentrations in 2137. Note that Ringold Unit E, and part of the Ringold Unit A have concentrations above the cleanup level.

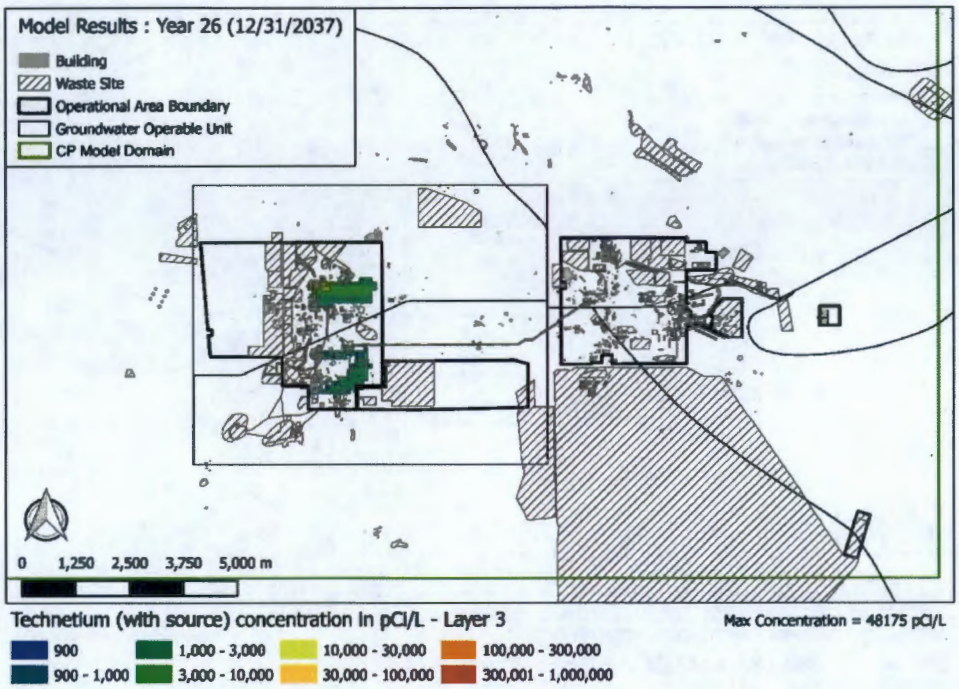


Figure 103. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping –Source

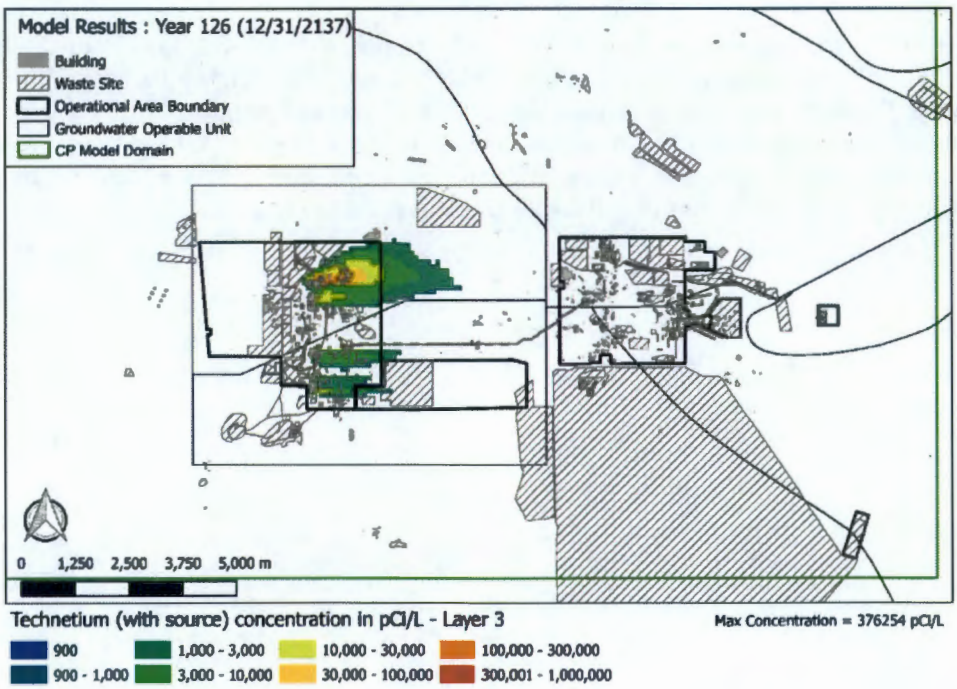


Figure 104. Simulated Tc-99 Distribution at the water table in the Ringold Unit E in 2137 –Source

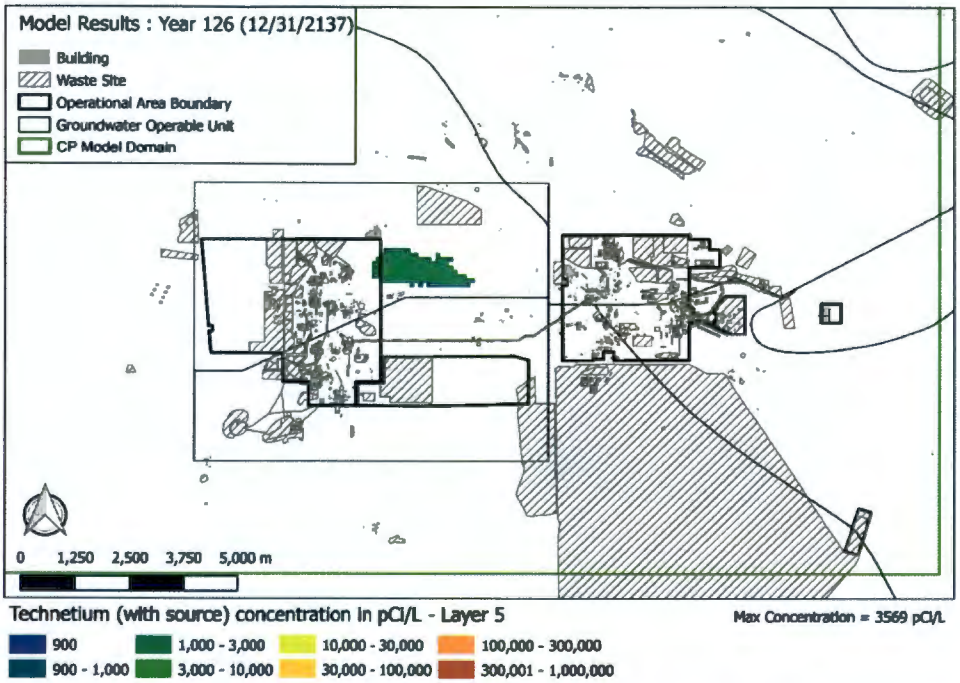


Figure 105. Simulated Tc-99 Distribution at the base of the Ringold Unit E in 2137 –Source

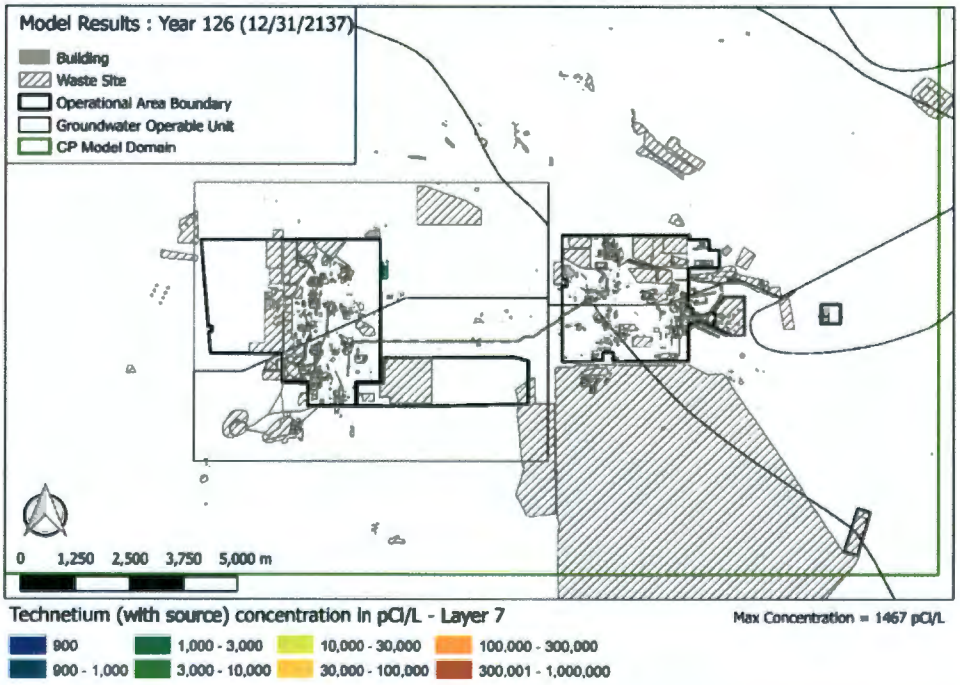


Figure 106. Simulated Tc-99 Distribution at the water table in the Ringold Unit A in 2137 –Source

Simulated mass extracted is shown in Figure 107, note the extra mass removed from the aquifer as a result of including the source terms in the simulation.

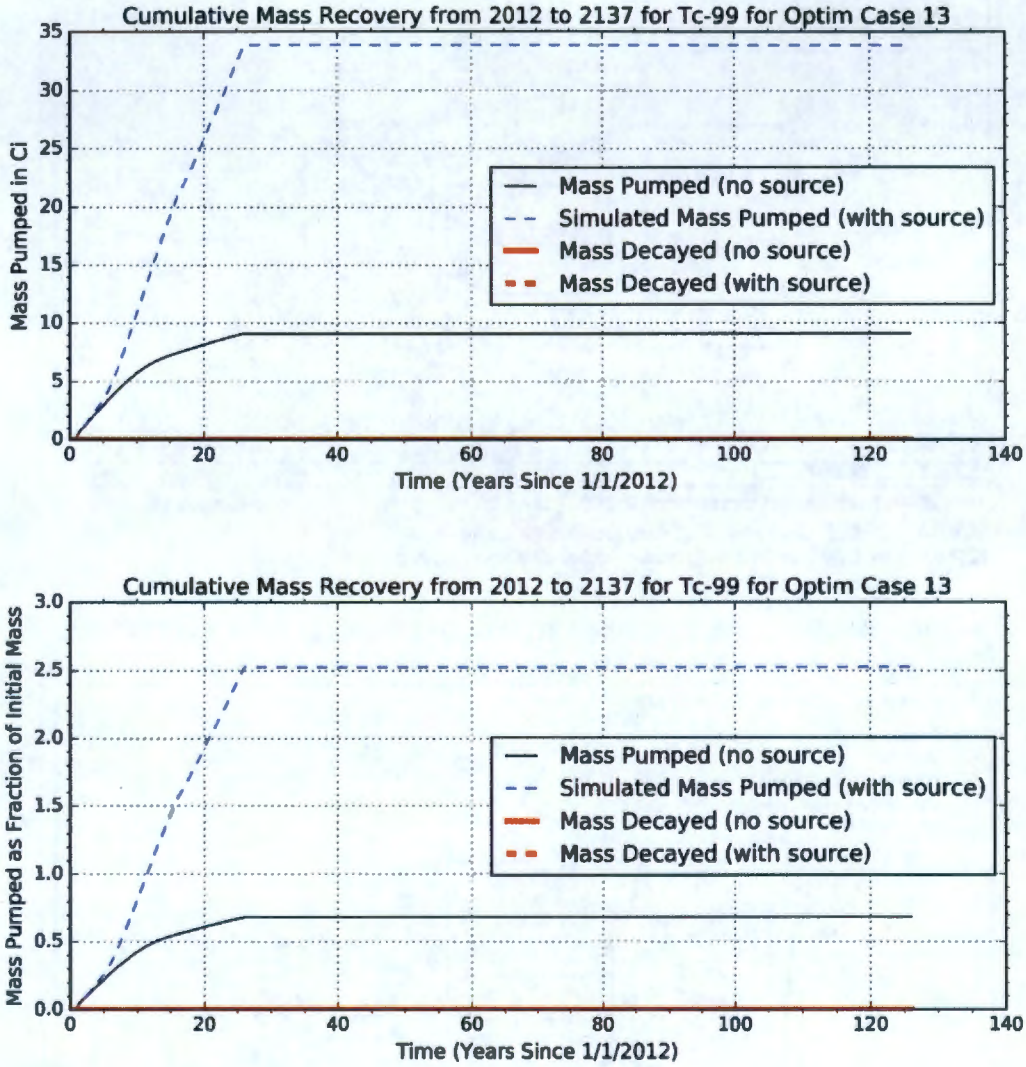


Figure 107. Simulated Cumulative Mass Pumped in Curies (top) and fraction of initial Tc-99 mass (bottom) – Optimized Pumping

The UCL95s computed from the simulation results are shown in Figure 108.

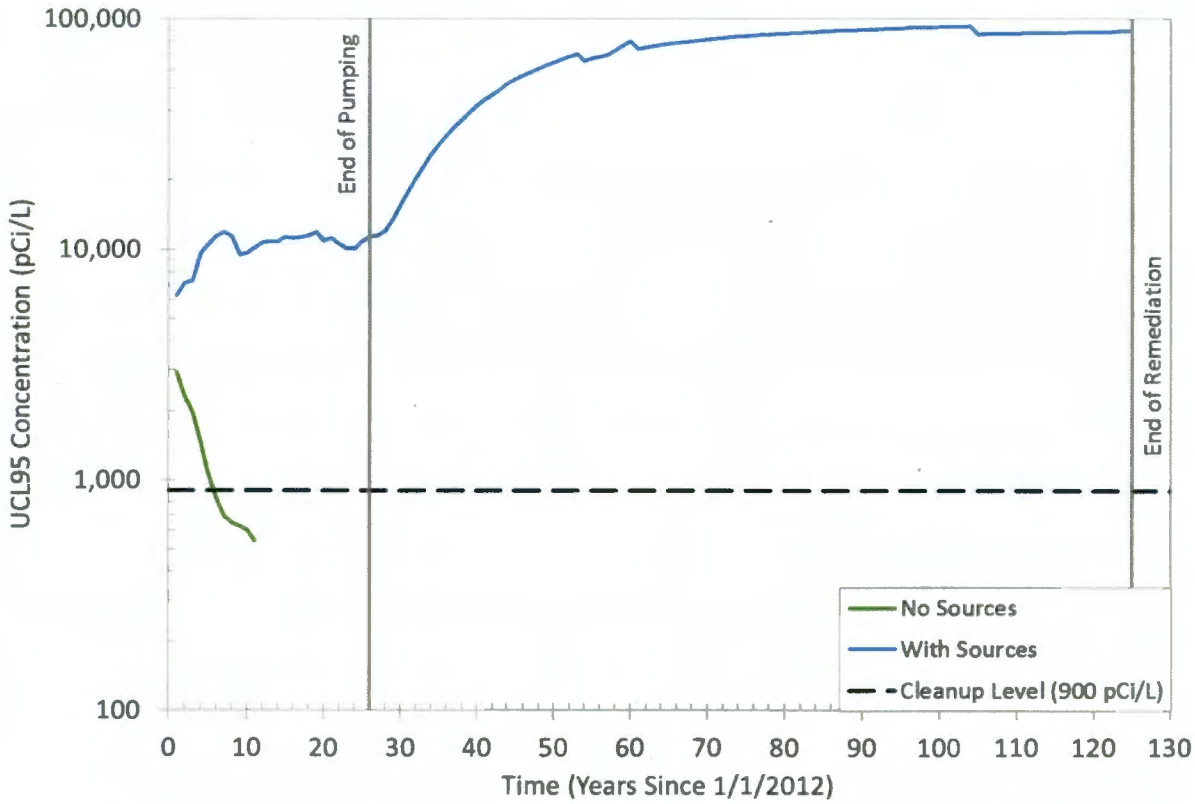


Figure 108. Simulated UCL95 for Tc-99 with and without sources – Optimized Pumping

6.2.7 Trichloroethene

Figure 109 and Figure 110 shows the simulated TCE plume extents after 25 years of pumping in 2037. No TCE plume above the cleanup level is interpreted in the Ringold Unit A, thus no results are shown. Additionally, by 2137 no concentrations exceed the cleanup level and no maps are shown. No source is interpreted for TCE. Figure 111 shows the simulated mass extracted.

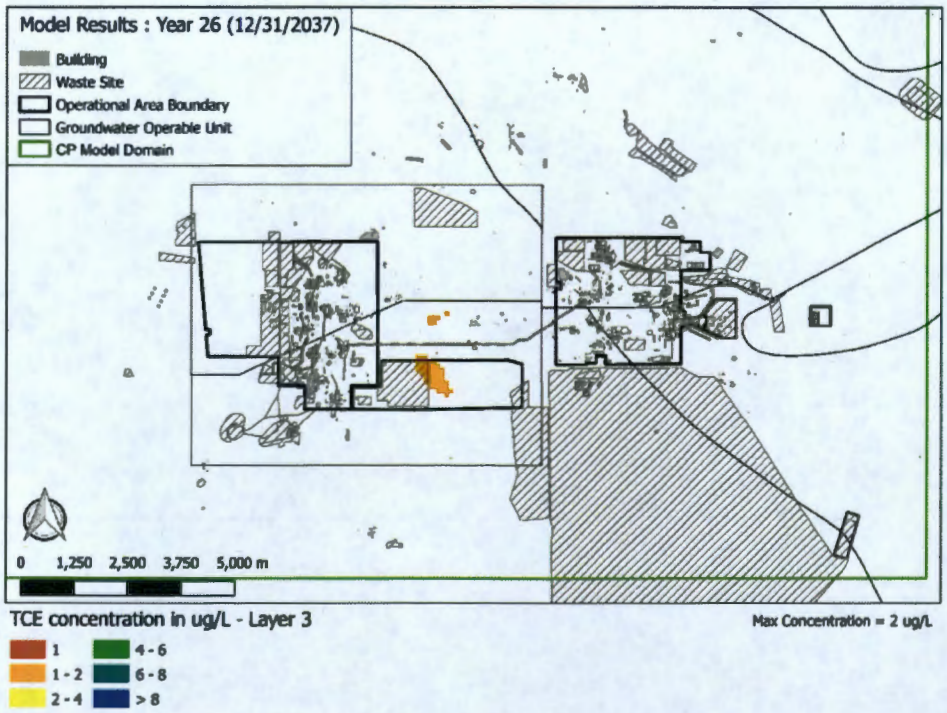


Figure 109. Simulated TCE Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping

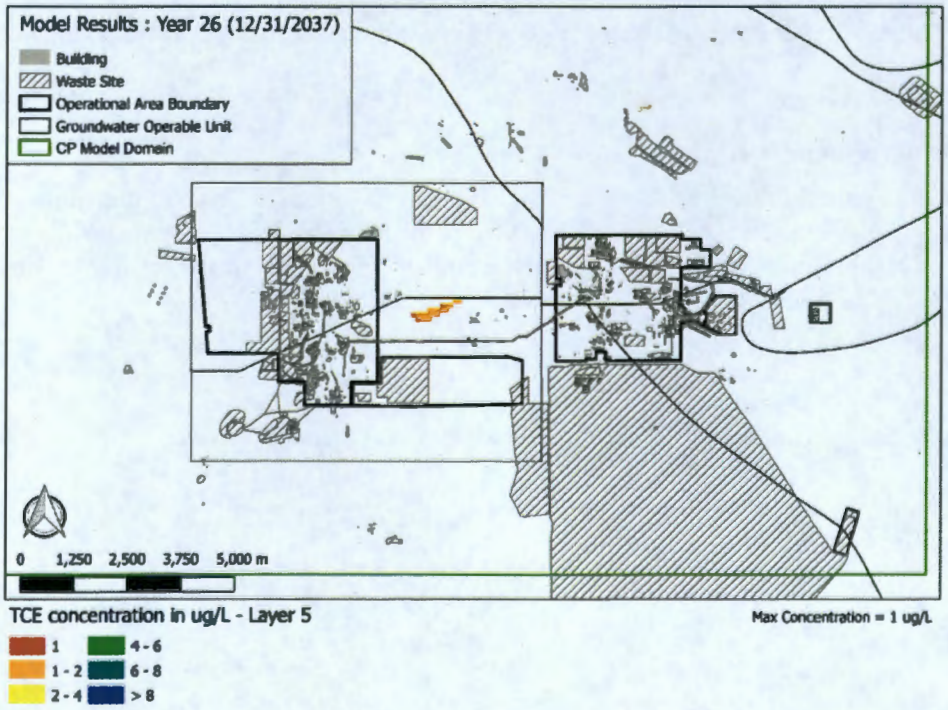
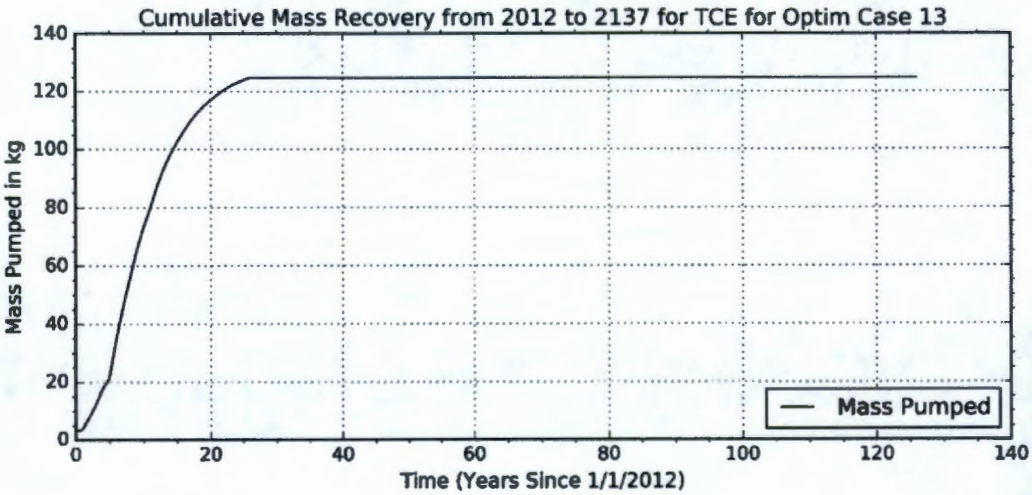


Figure 110. Simulated TCE Distribution at the base of the Ringold Unit E in 2037 after 25 years of optimized pumping



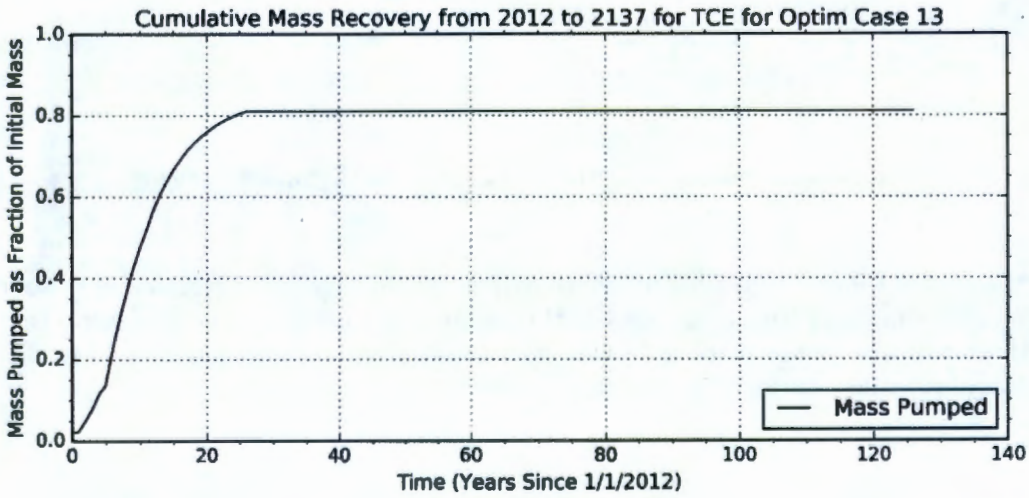


Figure 111. Simulated Cumulative Mass Pumped in kilograms (top) and fraction of initial TCE mass (bottom) – Optimized Pumping

The UCL95s for the baseline and optimized pumping scenarios are shown in Figure 112. Note that, even though the system was not optimized for TCE, the footprint of the TCE plume is sufficiently coincident with the carbon tetrachloride plume to benefit from its optimization.

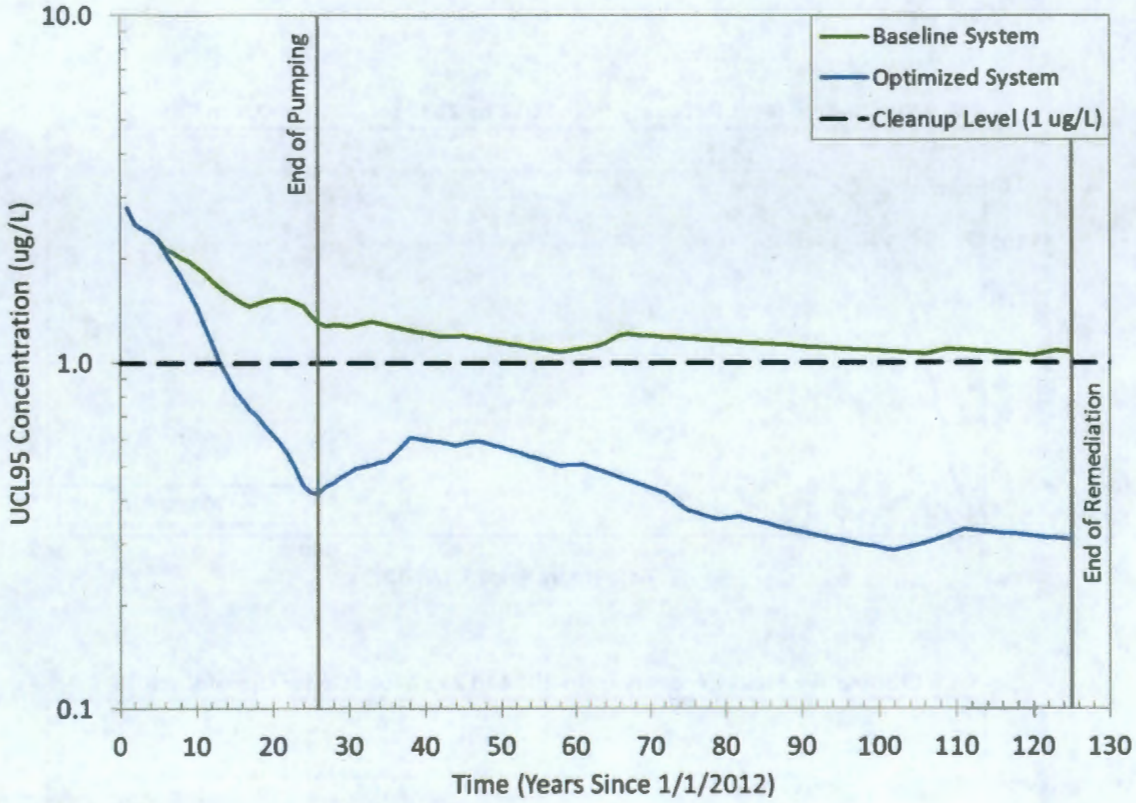


Figure 112. Simulated UCL95 for TCE Baseline and Optimized Pumping

6.2.8 Tritium

Only the water table Ringold Unit E has tritium above the cleanup level in 2037 (Figure 113); no part of the model has tritium above the cleanup level in 2137 and maps are not shown. Sources were estimated, but not do result in concentrations above the cleanup level other than as shown in Figure 113 – the sources decay before they can affect groundwater concentrations.

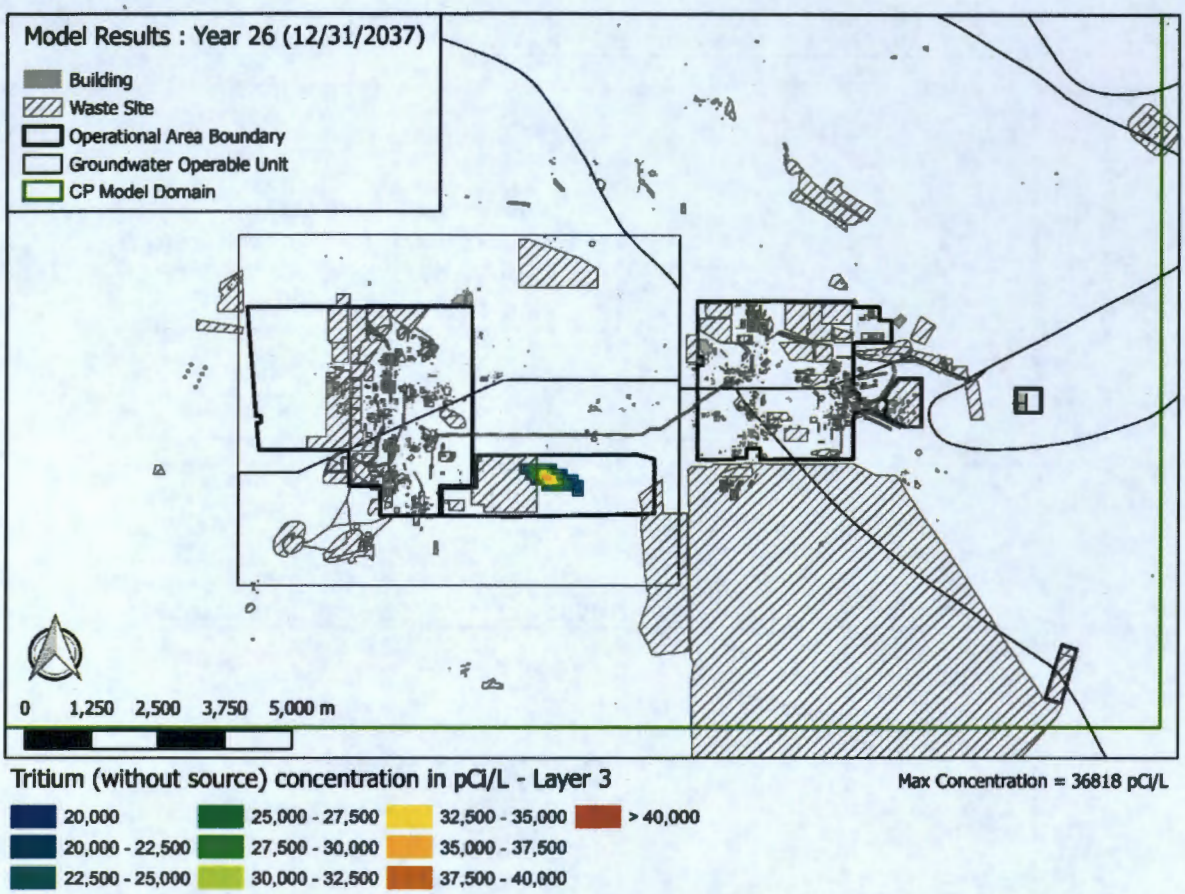


Figure 113. Simulated Tritium Distribution at the water table in the Ringold Unit E in 2037 after 25 years of optimized pumping – No Source

Figure 114 shows the simulated extracted mass; note the subtle inflection in 2018, when the optimized pumping begins. The major inflection reflects the depletion of the plume. The fraction of mass pumped is small because most of the tritium occurs in 200-UP-1 whereas the majority of pumping is in 200-ZP-1.

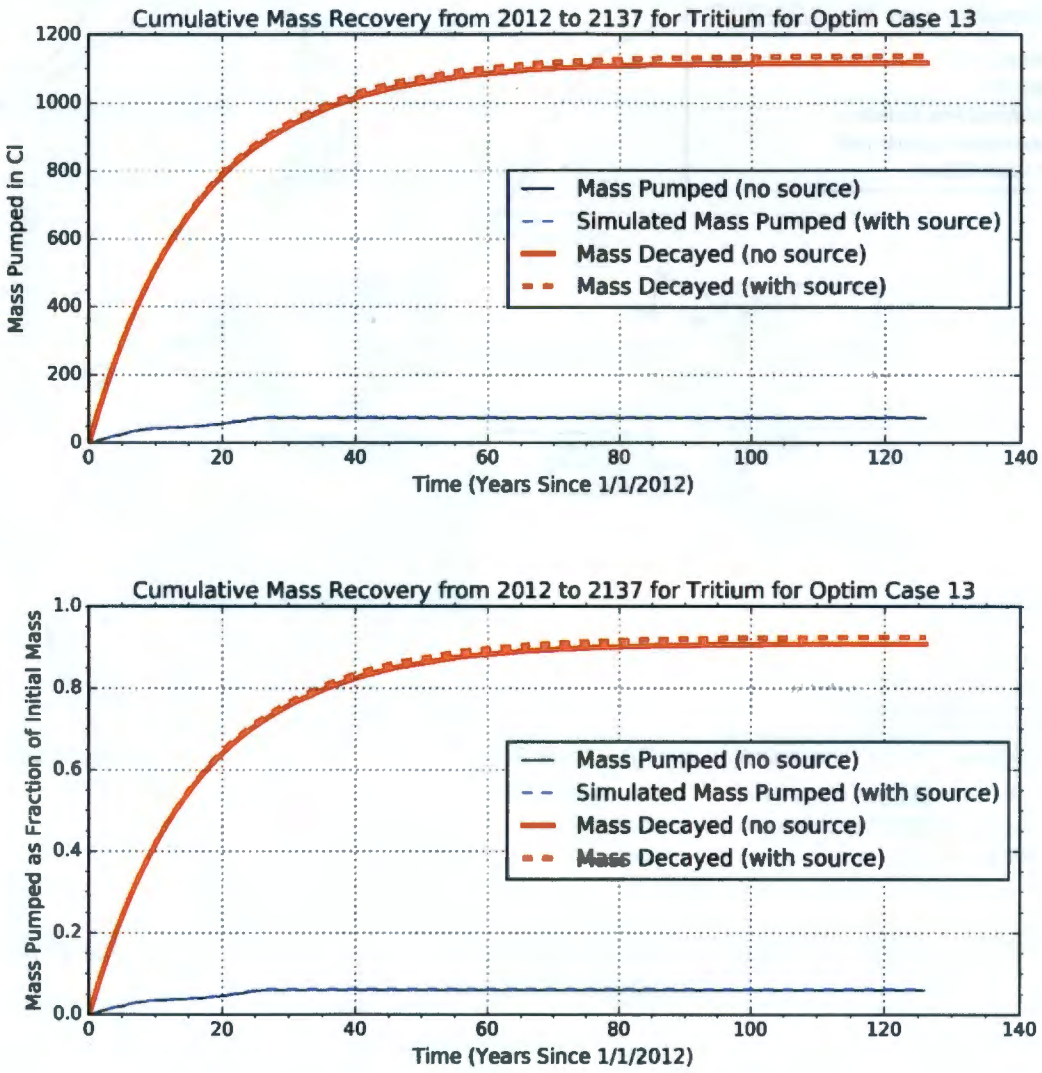


Figure 114. Simulated Cumulative Mass Pumped in Curies (top) and fraction of initial tritium mass (bottom) – Optimized Pumping

The UCL95s computed from the transport simulations are shown in Figure 115. Radioactive decay reduces concentrations to below the cleanup level with or without sources, although it takes about two additional half-lives (about 24 years) with sources.

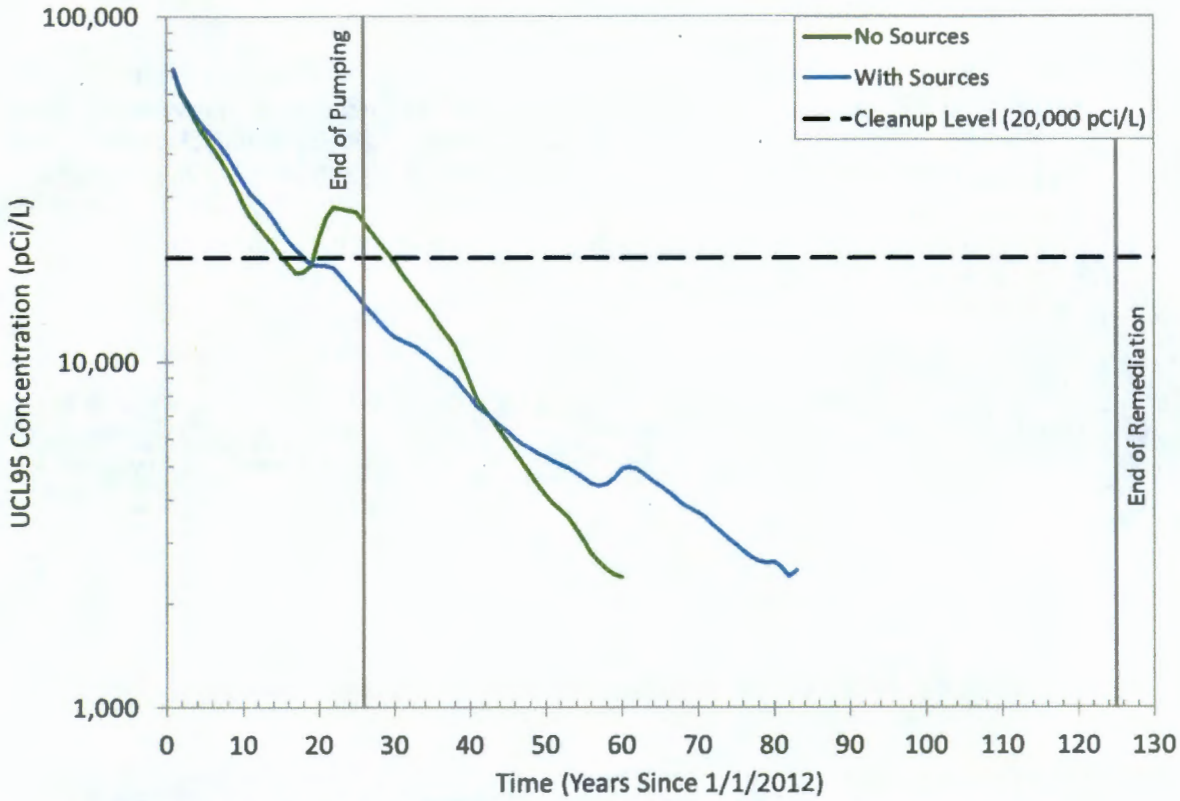


Figure 115. Simulated UCL95 for Tritium with and without sources – Optimized Pumping

6.3 Conclusions

Conclusions from this analysis are as follows:

1. Projected baseline pumping suggests that operating the 200 West P&T system for 25 years, followed by 100-years of MNA will not achieve the carbon tetrachloride cleanup level within the remediation period.
2. Optimization of the P&T system for carbon tetrachloride recovery shows that increasing the flow rate to about 3,600 gpm and modifying the extraction and injection well locations may achieve the cleanup levels in the 125-year cleanup time.
3. Optimization increased (by a factor of 16) extraction from the Ringold Unit A.
4. The current system is not sufficiently addressing the high carbon tetrachloride concentration (>500 μg/L in the Ringold Unit E and Ringold Unit A) areas of the plume. This is evident by comparing the first 25 years of the UCL95 curves as shown in Figure 116. Note that the optimized solution causes the UCL95 of the high concentration (>500 μg/L) Ringold Unit E and Ringold Unit A areas to sharply decline compared to the low and medium concentration Ringold Unit E zones.

5. The optimized solution enhances cleanup of coincident plumes such as nitrate as shown in Figure 117.

6. The carbon tetrachloride abiotic decay rate significantly affects the attainment of remediation goals by 2137. If the decay half-life is longer than 41-yrs (the value used in the optimization calculations), cleanup may not be achieved without some combination of higher flow rates and longer pumping times not considered in this ECF. Figure 118 illustrates the UCL95 evolution from the end of pumping to 2137 for 41-yr and 100-yr half-lives. PNNL-22062 gives a Hanford-specific carbon tetrachloride half-life of 630 yrs. The viability of the optimized solution depends on the carbon tetrachloride half-life.

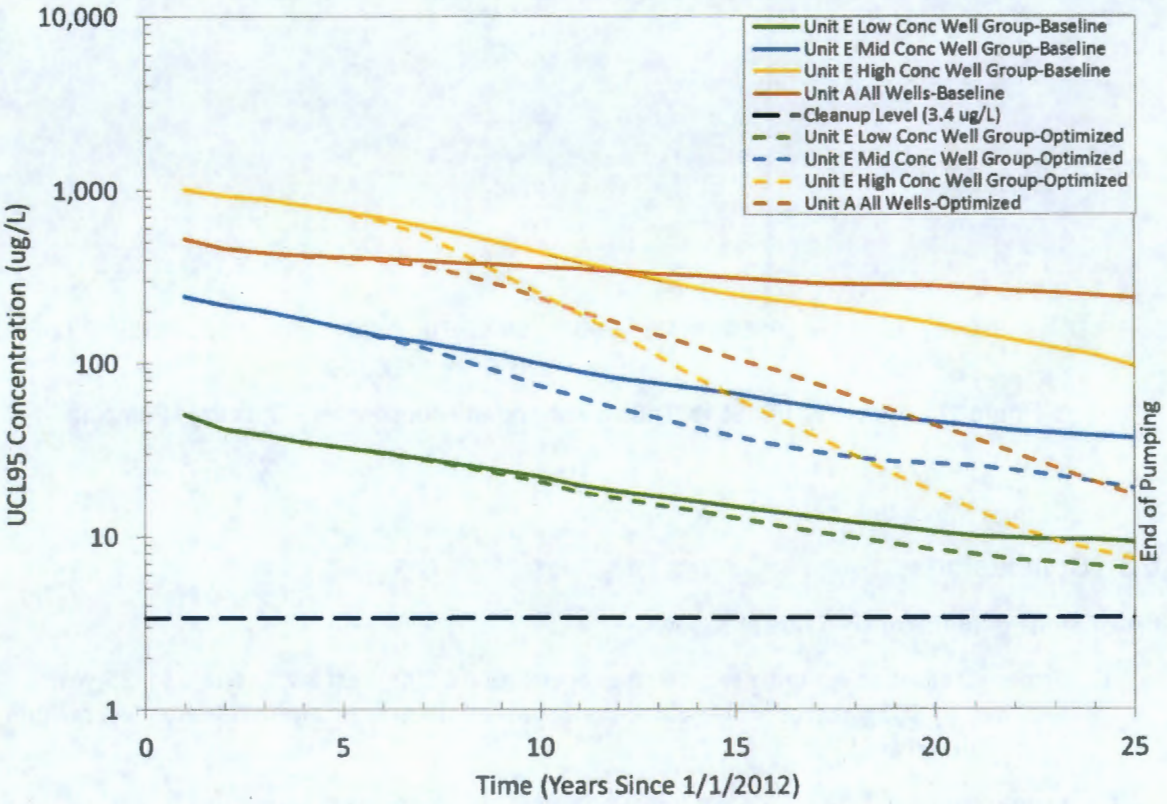


Figure 116 Simulated Carbon Tetrachloride UCL95 for the pumping period - baseline and optimized pumping

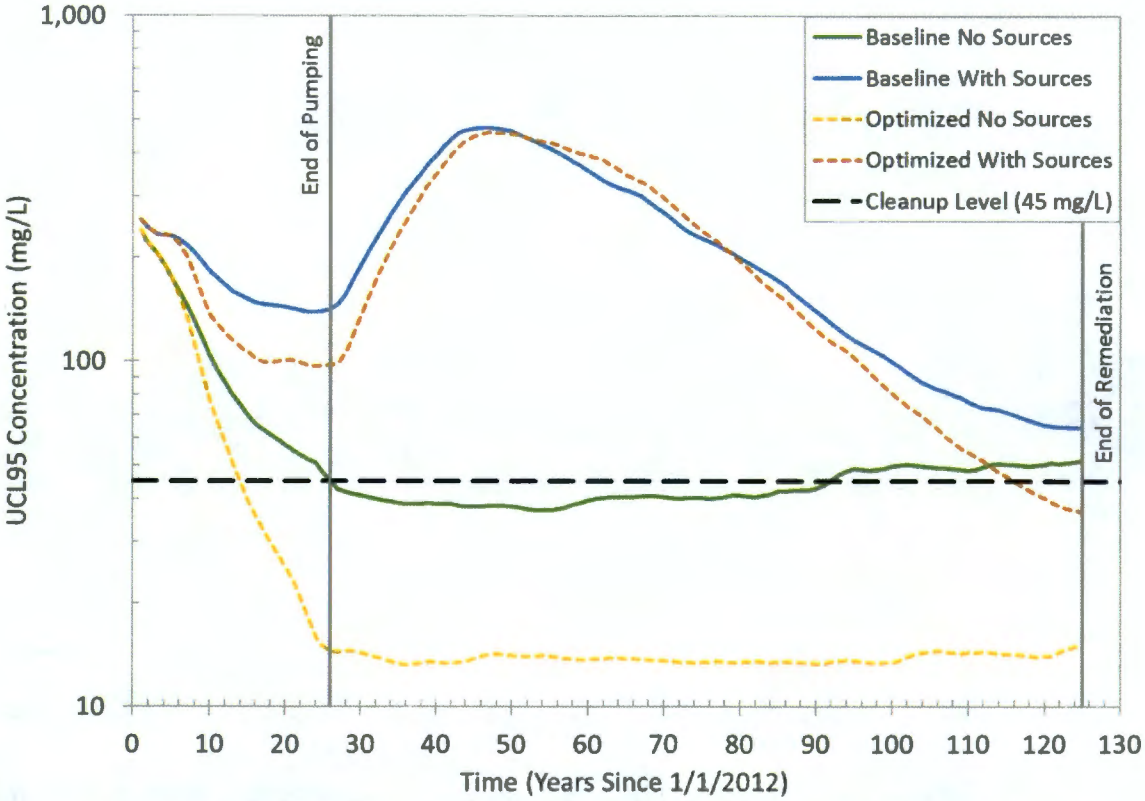


Figure 117 Simulated Nitrate UCL95 for Baseline and Optimized Pumping, with and without sources

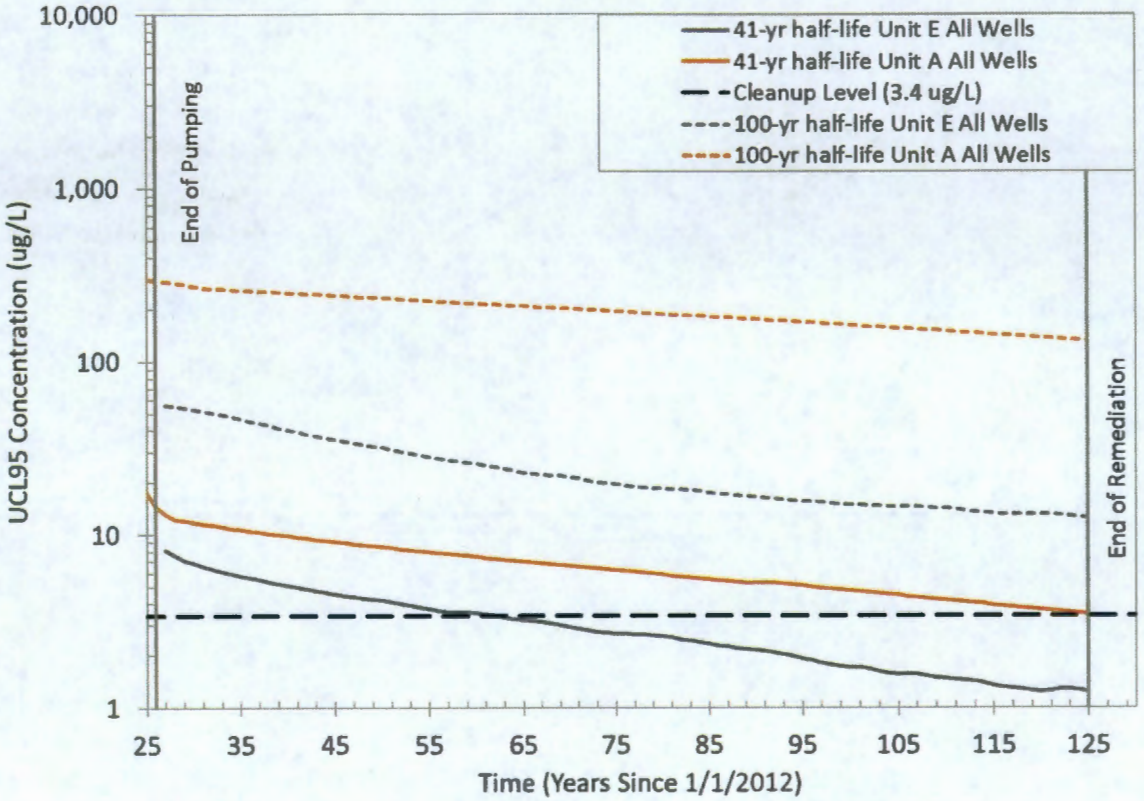


Figure 118 Simulated Carbon Tetrachloride UCL95 for the MNA period - optimized pumping and 41-yr and 100-yr half-life

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Appendix A

Software Installation and Checkout

CHPRC SOFTWARE INSTALLATION AND CHECKOUT FORM

Software Owner Instructions:
Complete Fields 1-13, then run test cases in Field 14. Compare test case results listed in Field 15 to corresponding Test Report outputs. If results are the same, sign and date Field 19. If not, resolve differences and repeat above steps.

Software Subject Matter Expert Instructions:
Assign test personnel. Approve the installation of the code by signing and dating Field 21, then maintain form as part of the software support documentation.

GENERAL INFORMATION:

1. Software Name: MODFLOW and MT3DMS Software Version No.: Bld 8

EXECUTABLE INFORMATION:

2. Executable Name (include path):

Following executable files in directory:
[redacted]\bin-windows

MD5 Signature (unique ID)	Executable File Name	Code
919F74196F5FB5BF0364FC373011B507	mf2k-chprc08dpl.exe	MODFLOW-2000 double precision
EAF037703ADD2C62CDD9CBC47468D2F6	mf2k-chprc08spl.exe	MODFLOW-2000 single precision
4E7F29DD5496D2CBA7144ADACB13DAAD	mf2k-mst-chprc08dpv.exe	MODFLOW-2000-MST double precis.
CEB80288C616E0552E4CE5A2D4719387	mf2k-mst-chprc08spv.exe	MODFLOW-2000-MST single precis.
ECA9828530B68D2D7C34078C019D5D0C	mt3d-chprc08dpl.exe	MT3DMS double precision
0920CC235862665D9400A3FC80F682DD	mt3d-chprc08spl.exe	MT3DMS single precision
5C61432D2C898E83DDFE242C52A755AB	mt3d-mst-chprc08dpv.exe	MT3DMS-MST double precision
68F89DAF2E6913D2578DE53CBD34FBA0	mt3d-mst-chprc08spv.exe	MT3DMS-MST single precision

3. Executable Size (bytes): MD5 signatures above uniquely identify each executable file

COMPILATION INFORMATION:

4. Hardware System (i.e., property number or ID):

Vendor Provided (SSP&A)

5. Operating System (include version number):

Vendor Provided (SSP&A)

INSTALLATION AND CHECKOUT INFORMATION:

6. Hardware System (i.e., property number or ID):

Windows 10 Pro, version 1511, OS Build 10586.1045

7. Operating System (include version number):

Windows 10 Pro, version 1511, OS Build 10586.1045

8. Open Problem Report? ◉ No ○ Yes PR/CR No.

TEST CASE INFORMATION:

9. Directory/Path:

[redacted]\MODFLOW Build8 IandC windows

10. Procedure(s):

CHPRC-00259 Rev. 3, MODFLOW and Related Codes Software Test Plan

11. Libraries:

N/A (static linking)

12. Input Files:

Per CHPRC-00259 Rev. 3

CHPRC SOFTWARE INSTALLATION AND CHECKOUT FORM (continued)

1. Software Name: MODFLOW and MT3DMS Software Version No.: Bld 8

13. Output Files:

Found in test subdirectories

14. Test Cases:

MF-ITC-1 (both standard and MST versions of MODFLOW); run both single & double precision
MT-ITC-1 run for single and double precision, multiple solvers

15. Test Case Results:

The test log, file "test.log" indicates that "all installation tests were successful" and no differences were encountered.

16. Test Performed By: Joan Blainey

17. Test Results: ◉ Satisfactory, Accepted for Use ○ Unsatisfactory

18. Disposition (include HISI update):

Installation added to HISI Entries #2517, 2518

Prepared By: WILLIAM NICHOLS (Affiliate)

19.	Software Owner (Signature)	Print: WE Nichols	Date

20. Test Personnel:

Sign: Joan Blainey	Print: Joan Blainey	Date: 09/06/2017
Sign:	Print:	Date:
Sign:	Print:	Date:

Approved By:

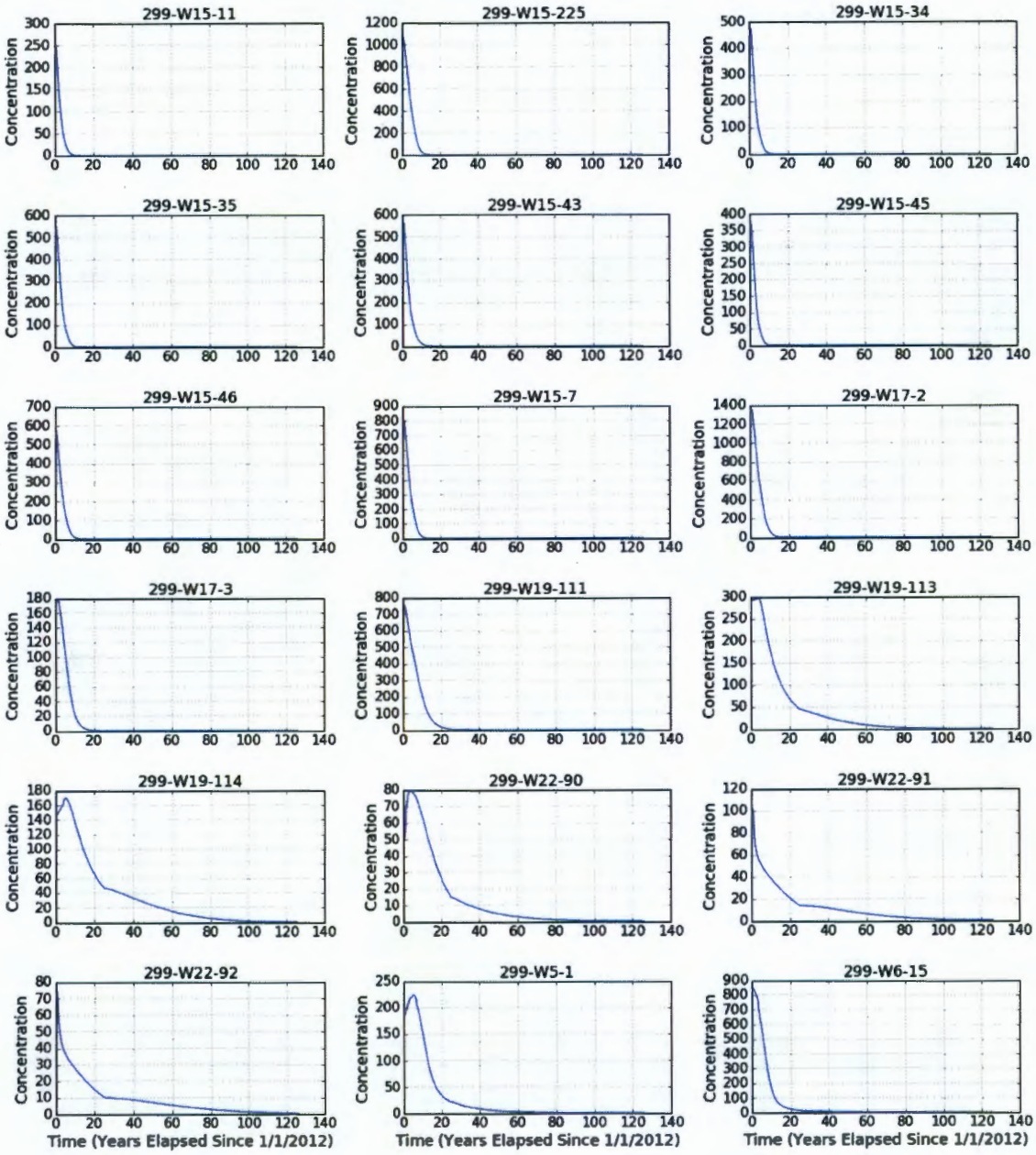
21.	Software SME (Signature)	Print: N/R (CHPRC-00258 Rev. 3)	Date

Appendix B

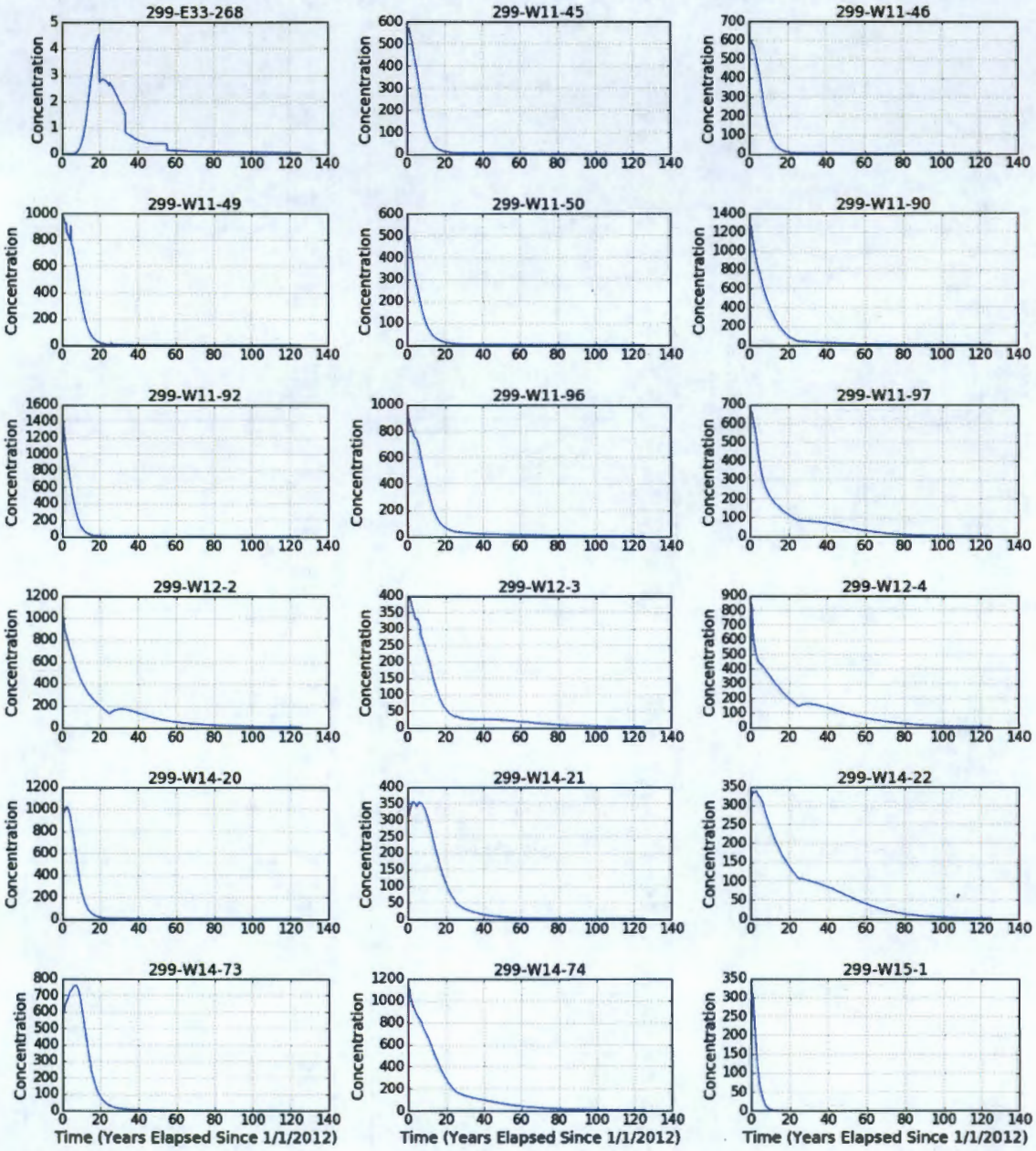
Simulated Pumping Well Concentration Histories

In this appendix, the extraction well concentrations are listed by COC with the baseline or "base case" conditions presented first (Section 6.1) followed by the optimized results (Section 6.2).

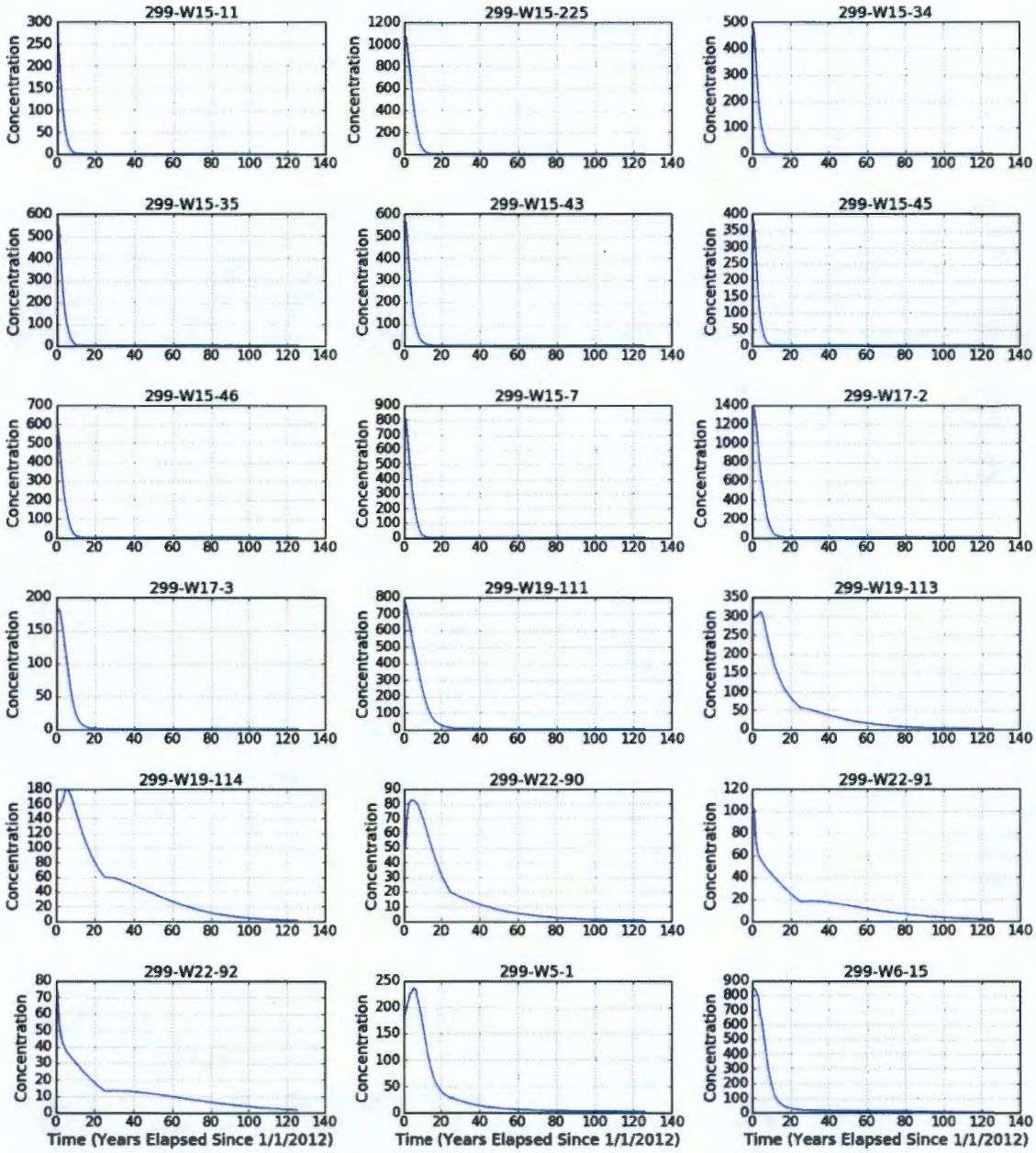
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 41.3 Year Half-Life for Base Case



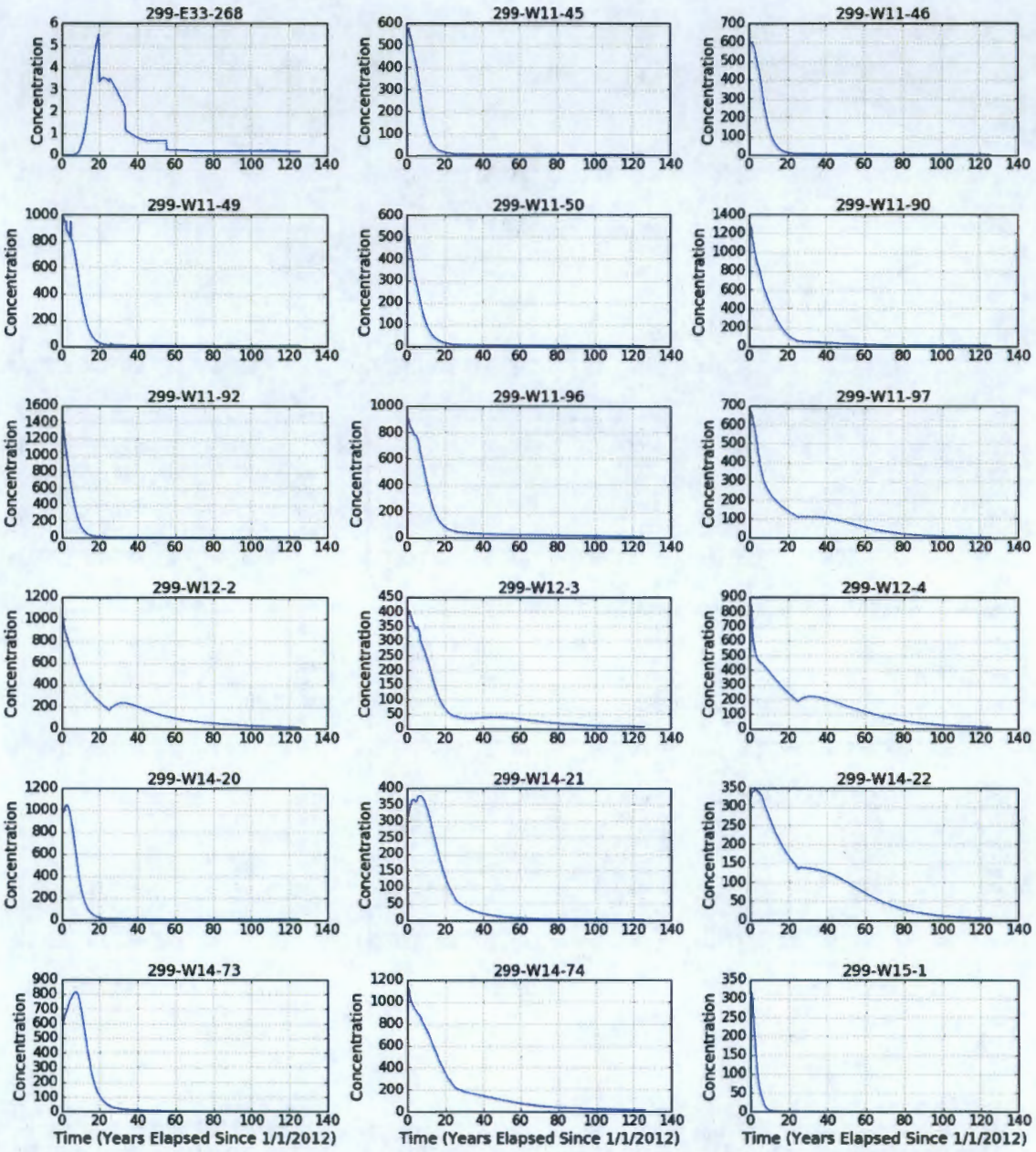
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 41.3 Year Half-Life for Base Case



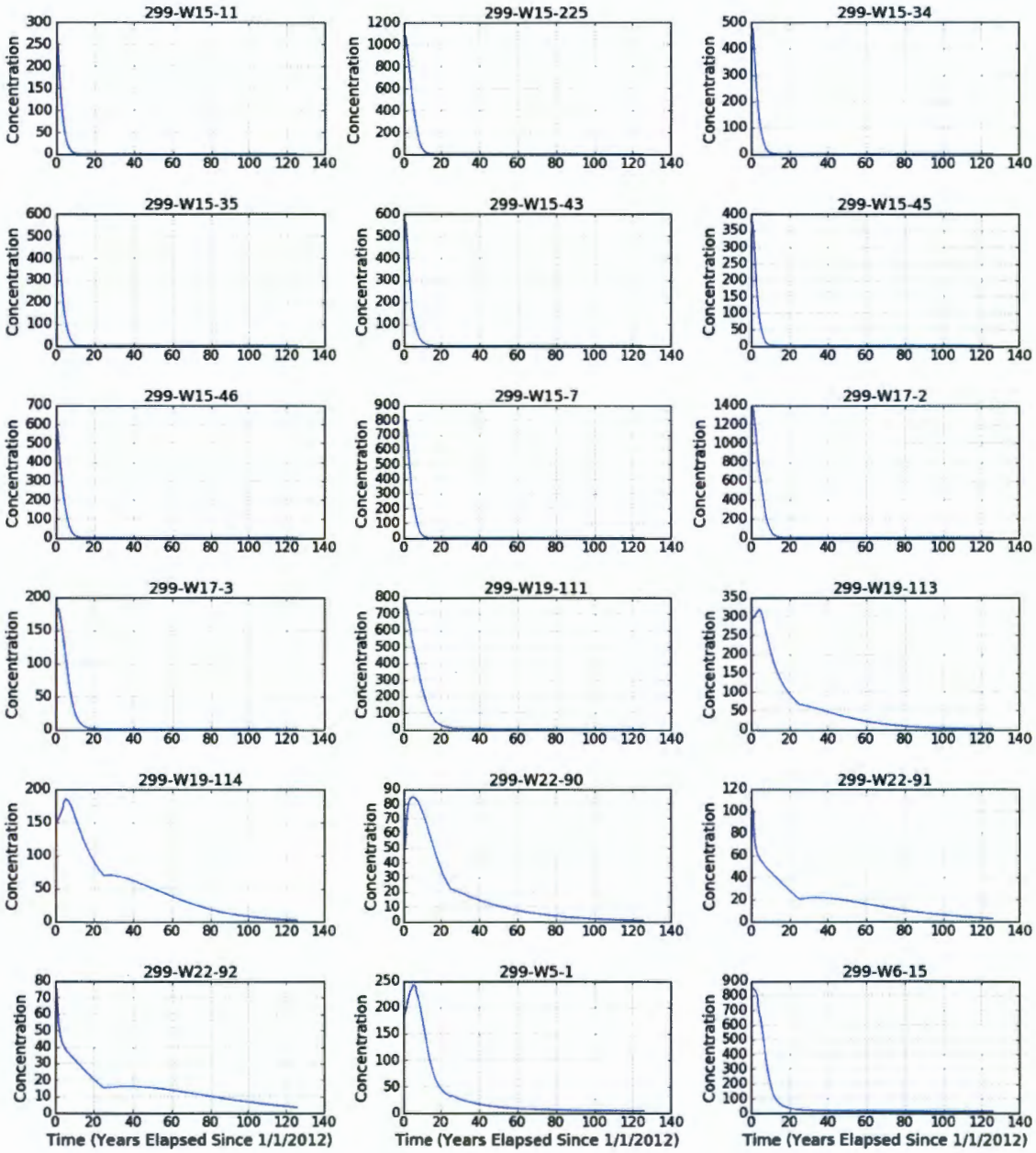
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Base Case



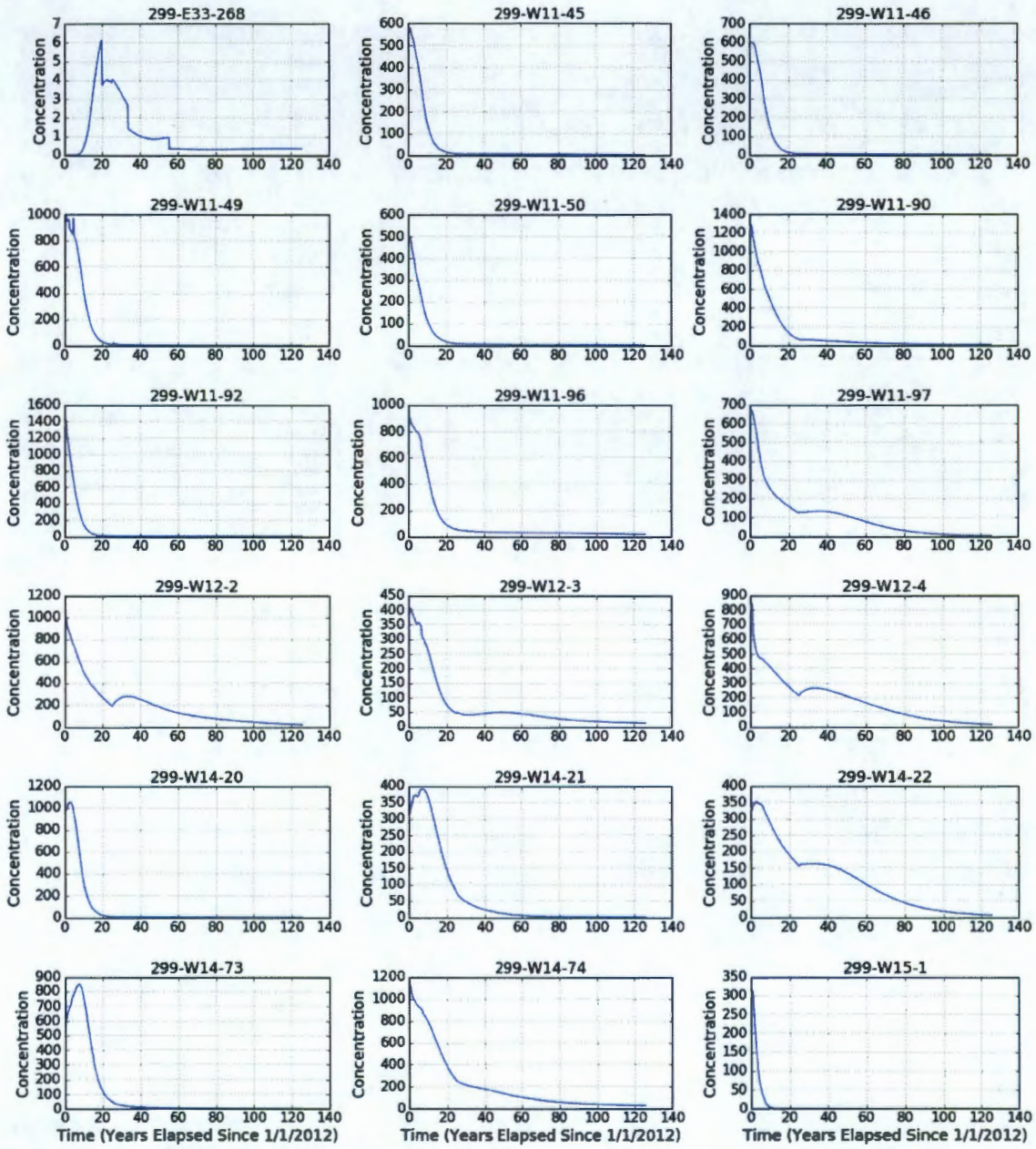
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Base Case



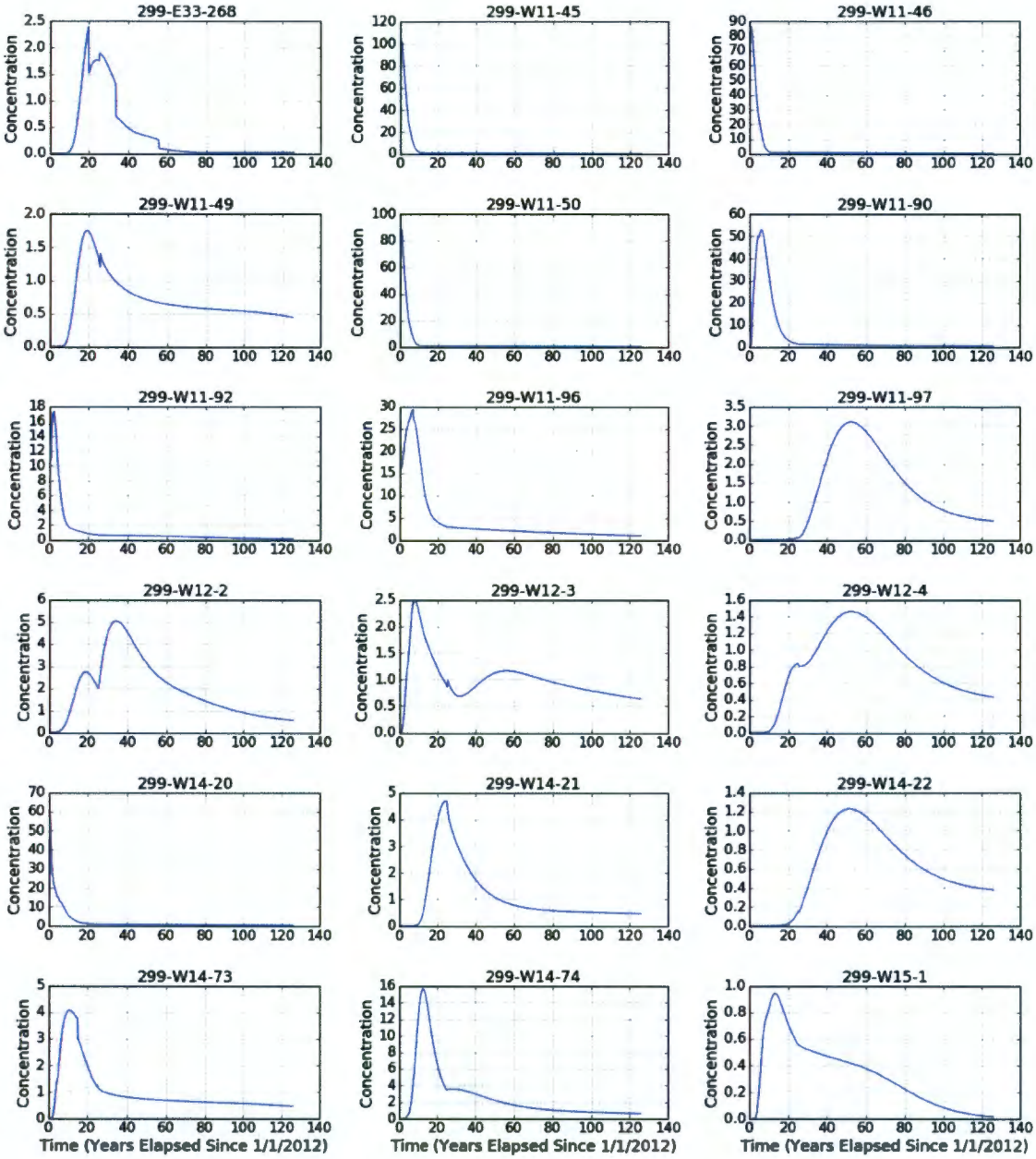
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 630 Year Half-Life for Base Case



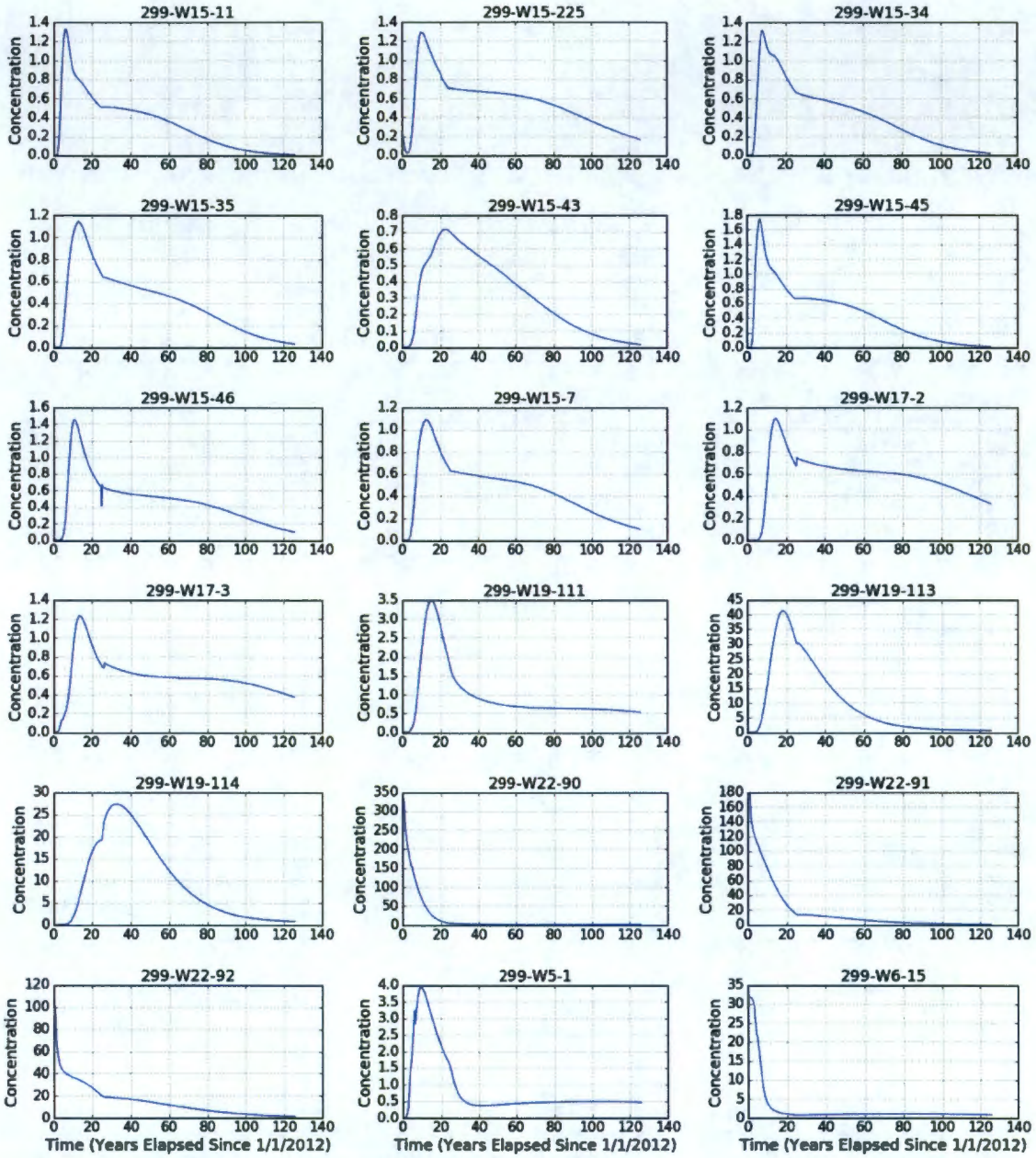
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 630 Year Half-Life for Base Case



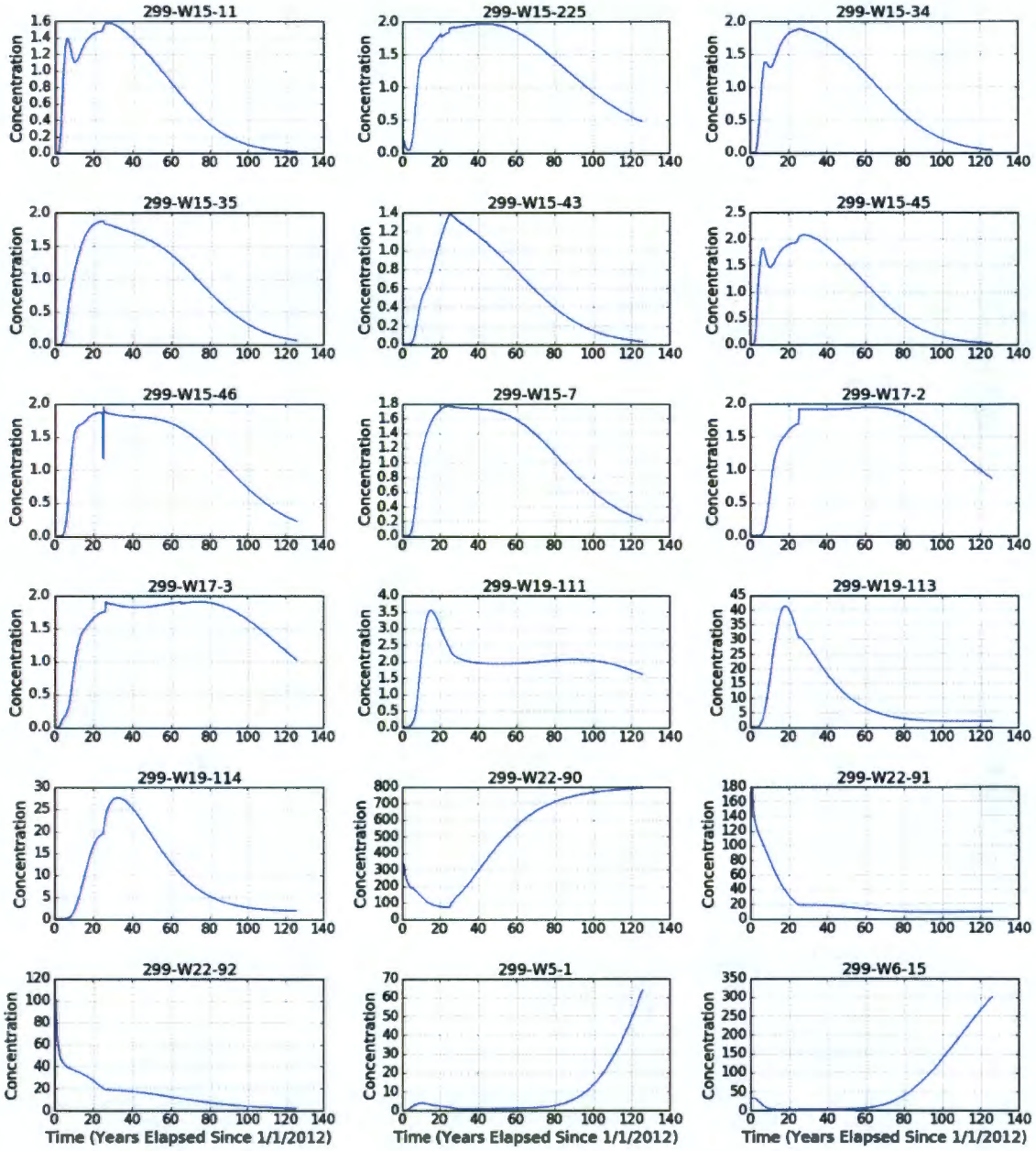
Simulated Extraction Concentrations in ug/L for Chromium for Base Case



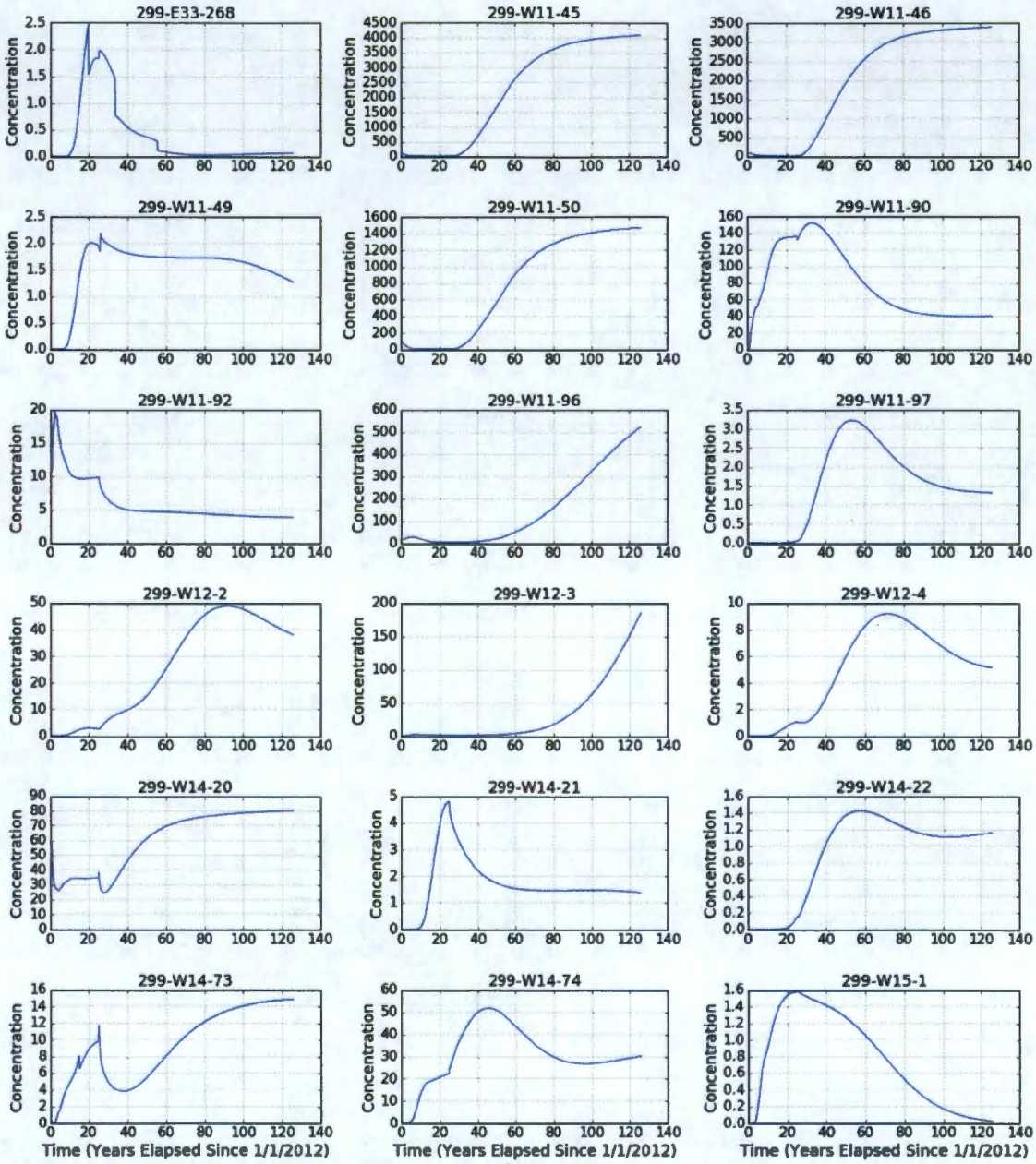
Simulated Extraction Concentrations in ug/L for Chromium for Base Case



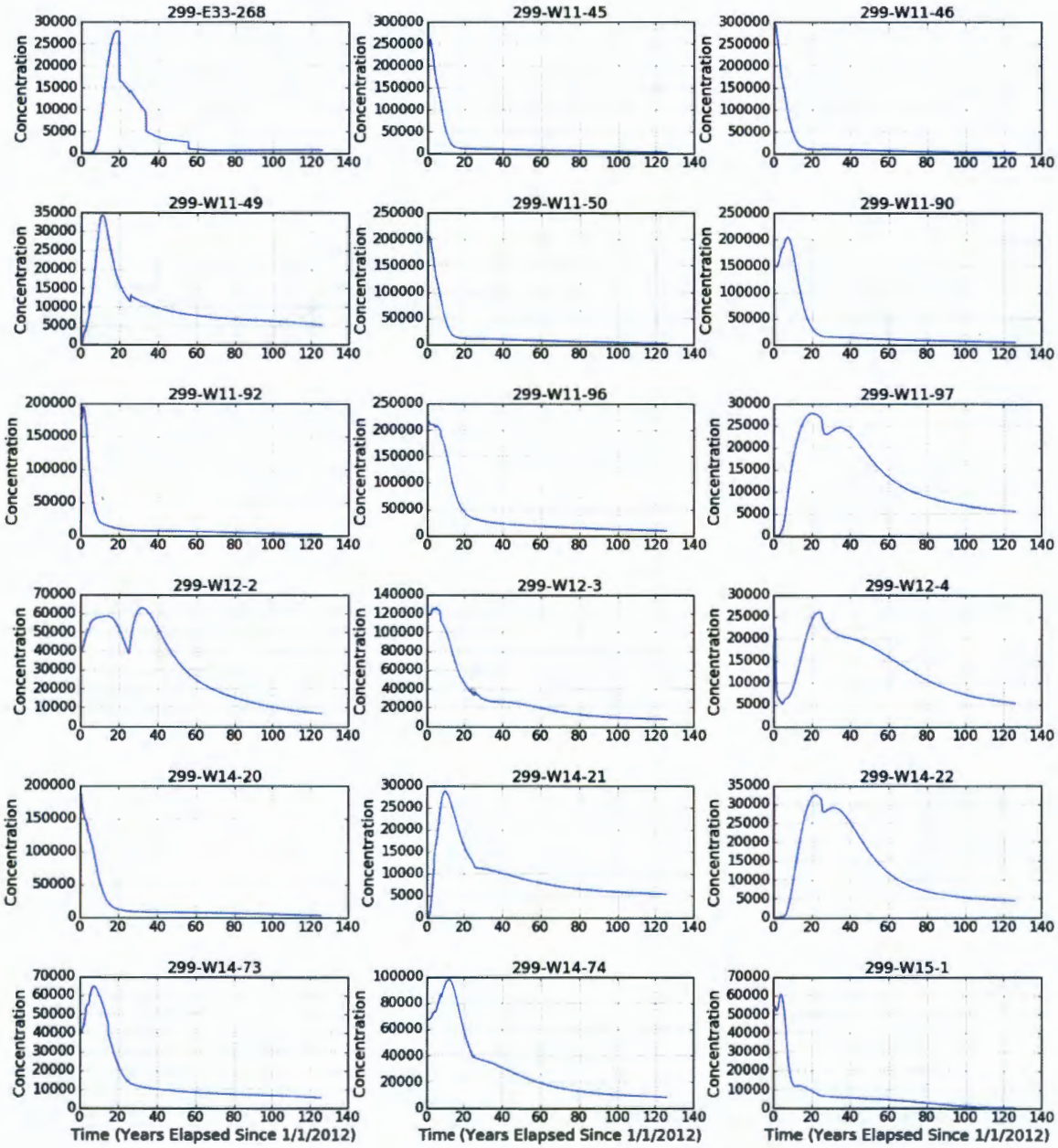
Simulated Extraction Concentrations in ug/L for Chromium With Source for Base Case



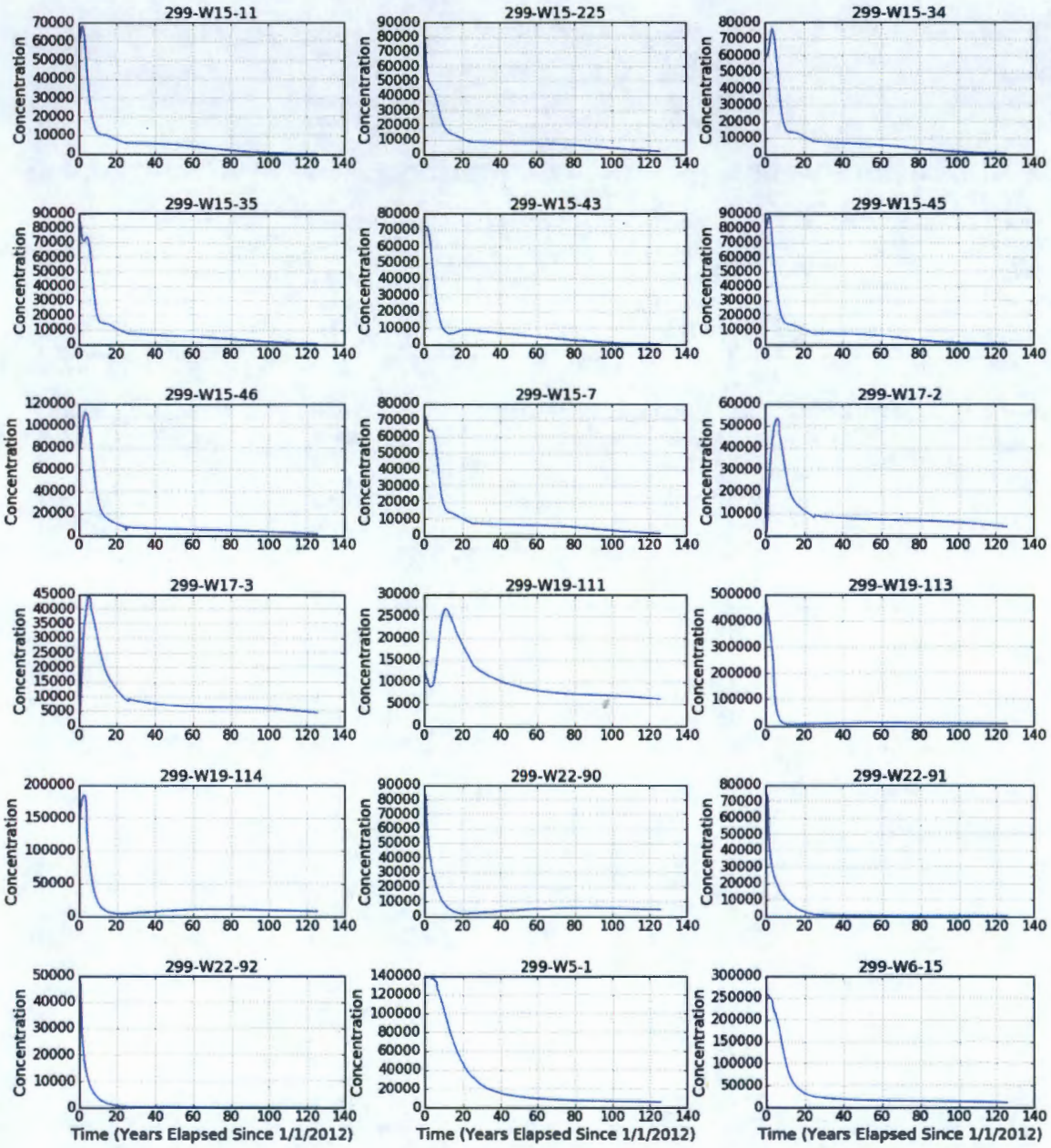
Simulated Extraction Concentrations in ug/L for Chromium With Source for Base Case



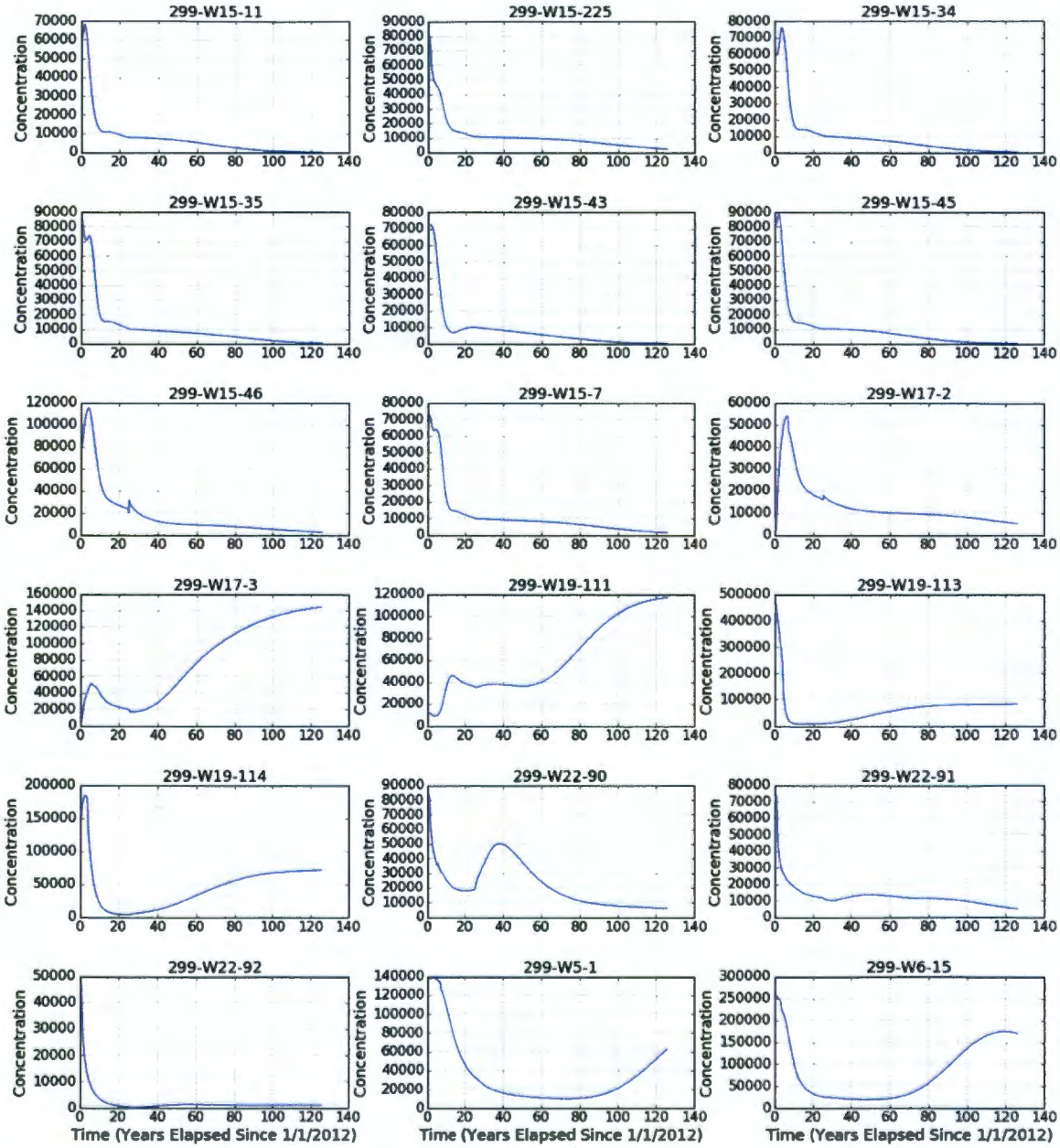
Simulated Extraction Concentrations in ug/L for Nitrate for Base Case



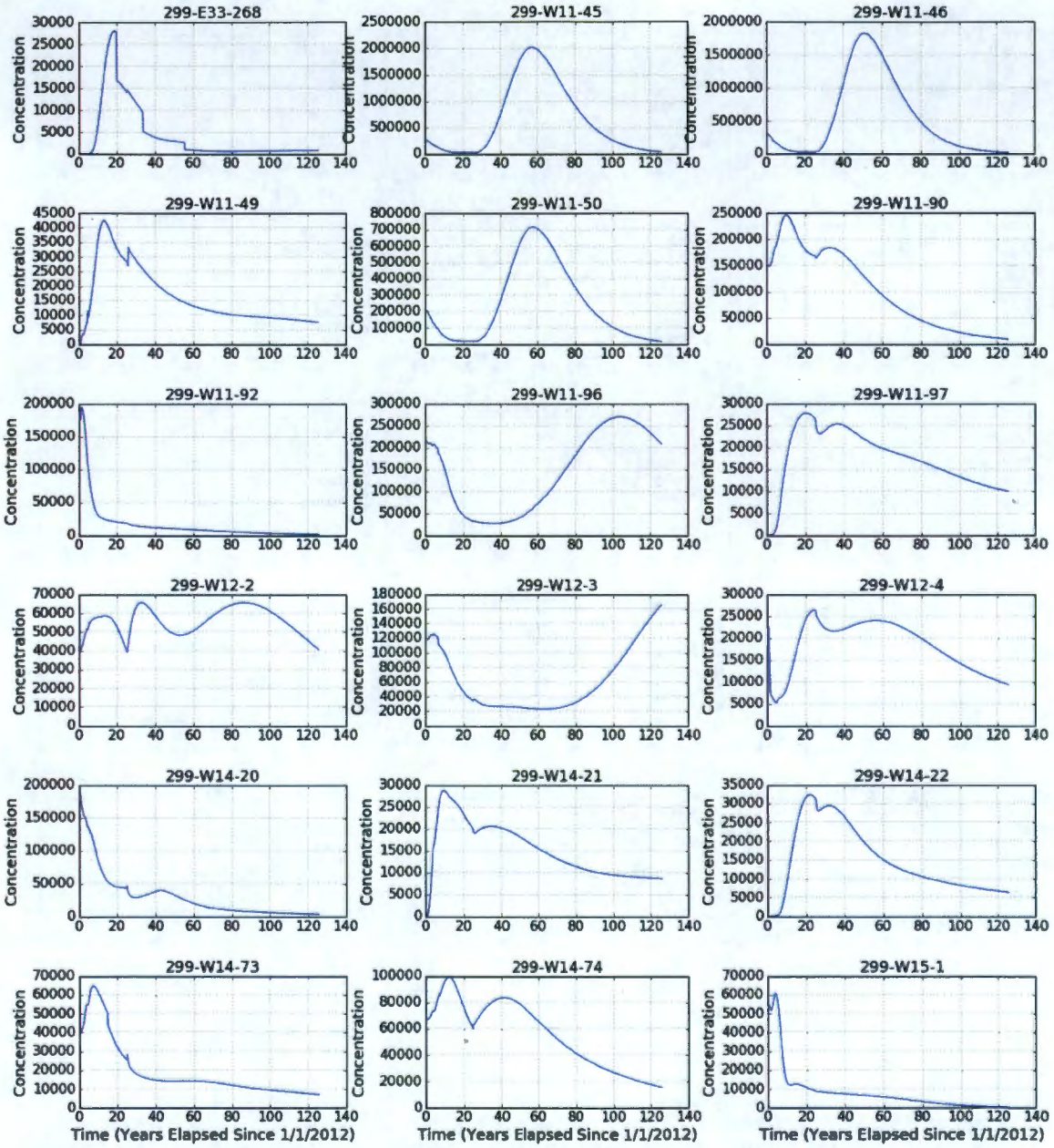
Simulated Extraction Concentrations in ug/L for Nitrate for Base Case



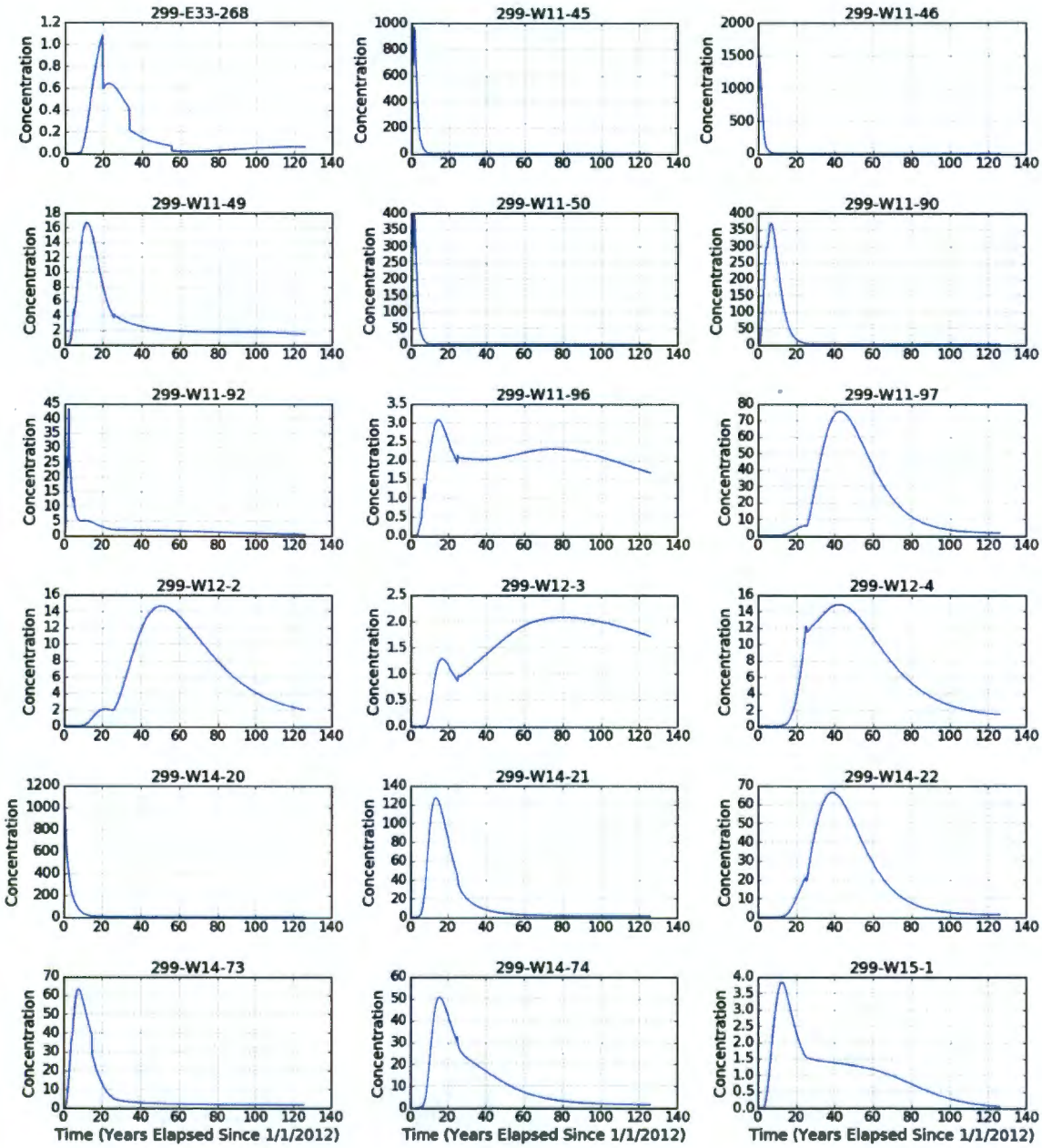
Simulated Extraction Concentrations in ug/L for Nitrate With Source for Base Case



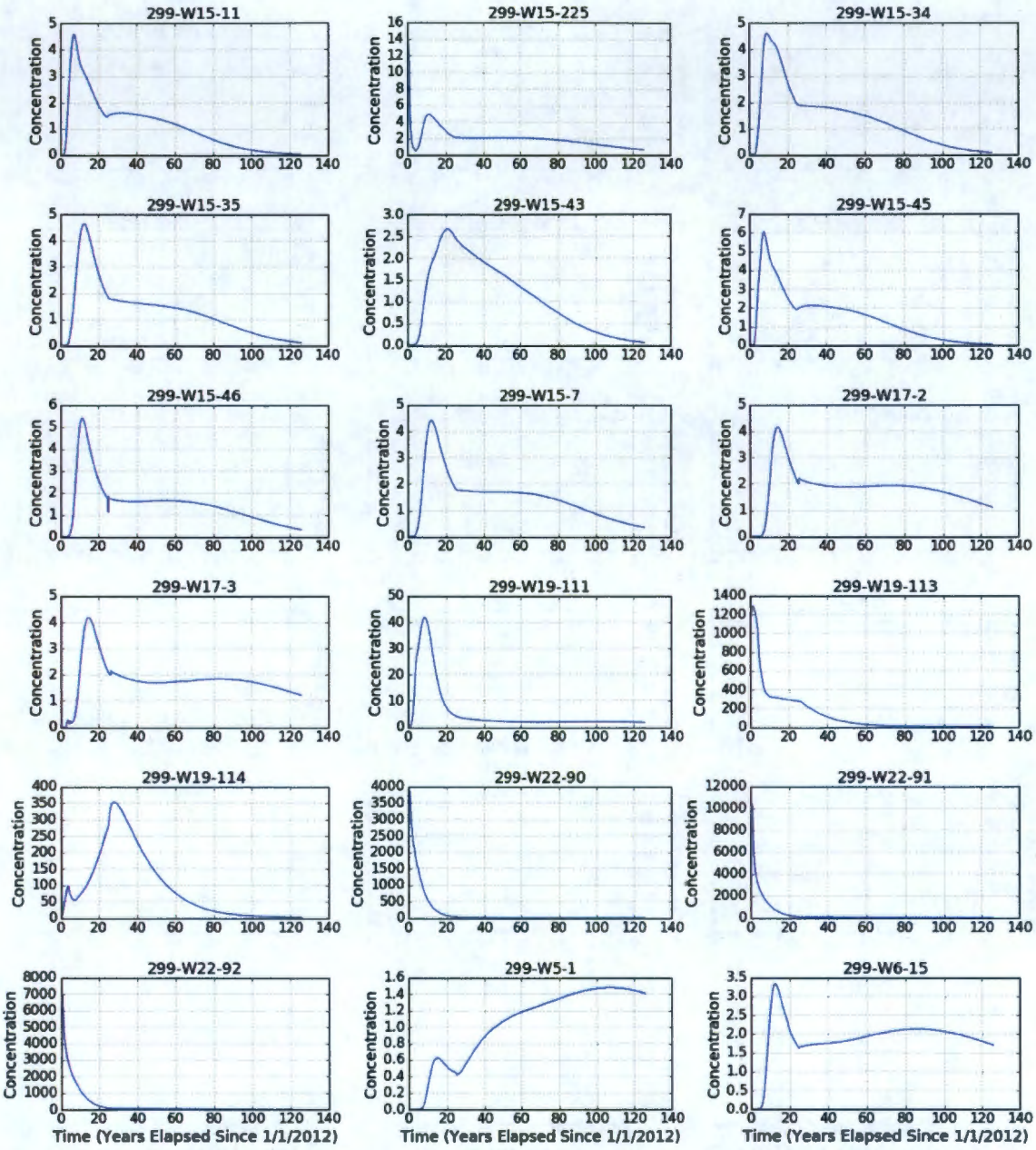
Simulated Extraction Concentrations in ug/L for Nitrate With Source for Base Case



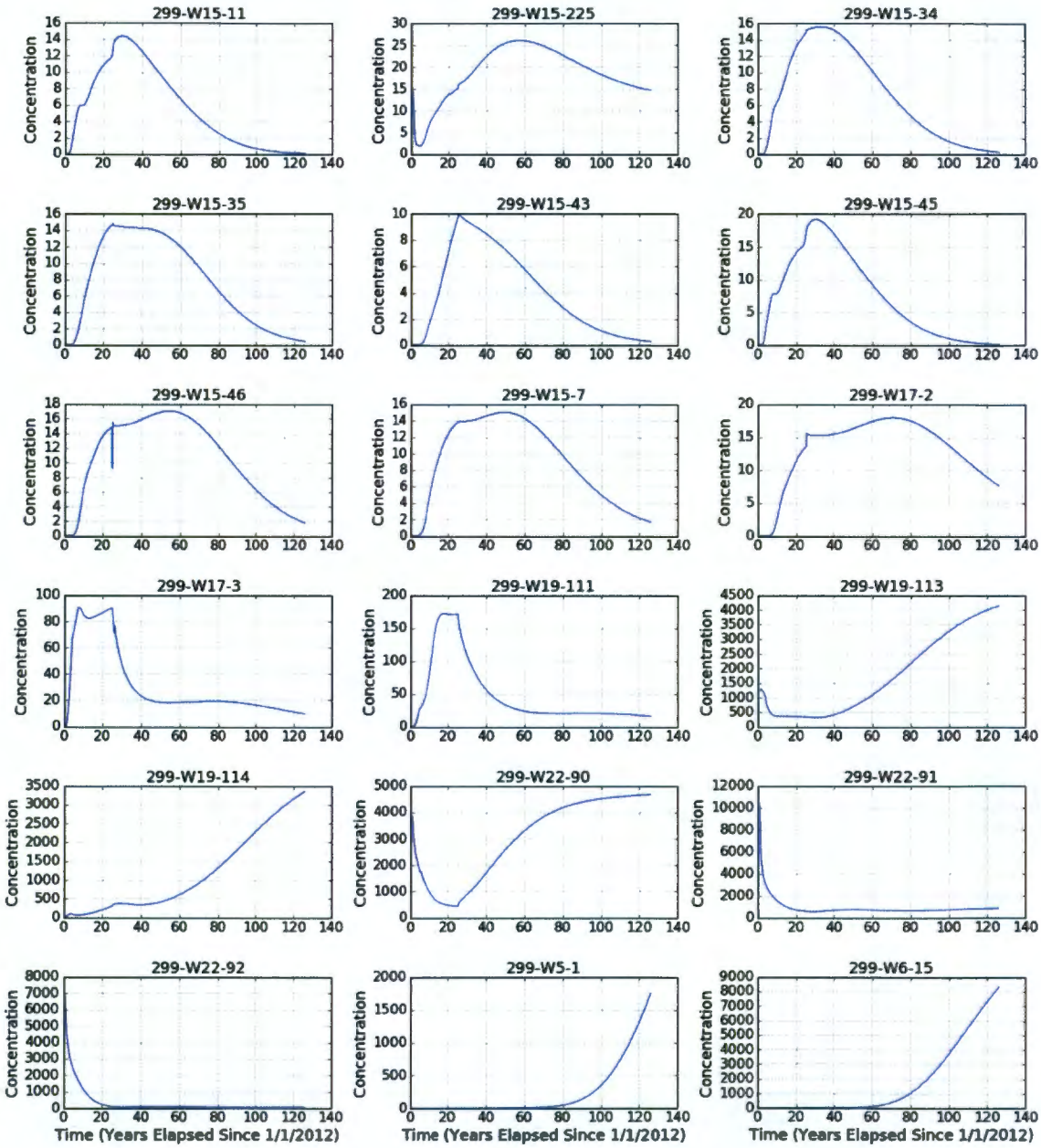
Simulated Extraction Concentrations in pCi/L for Tc-99 for Base Case



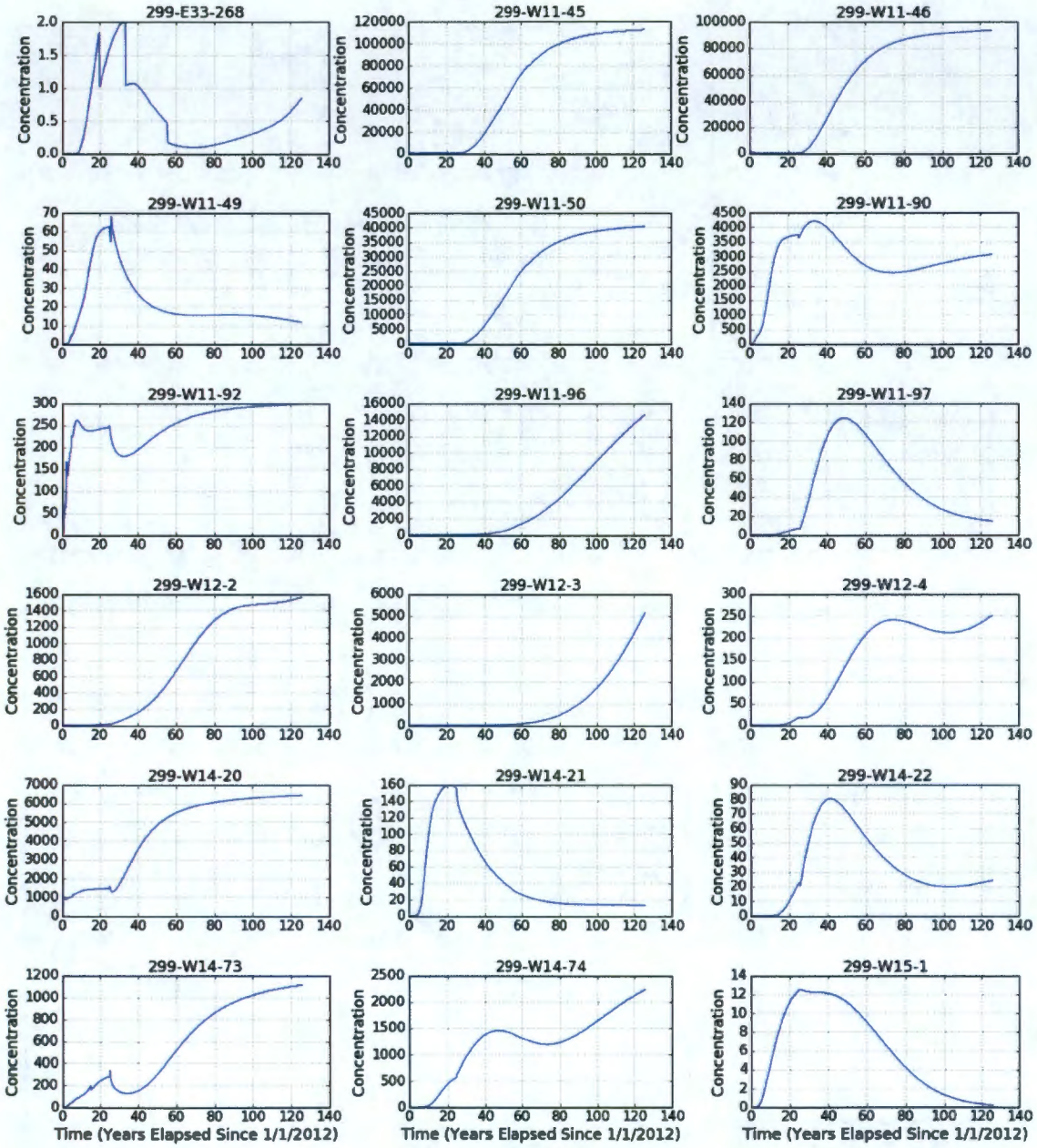
Simulated Extraction Concentrations in pCi/L for Tc-99 for Base Case



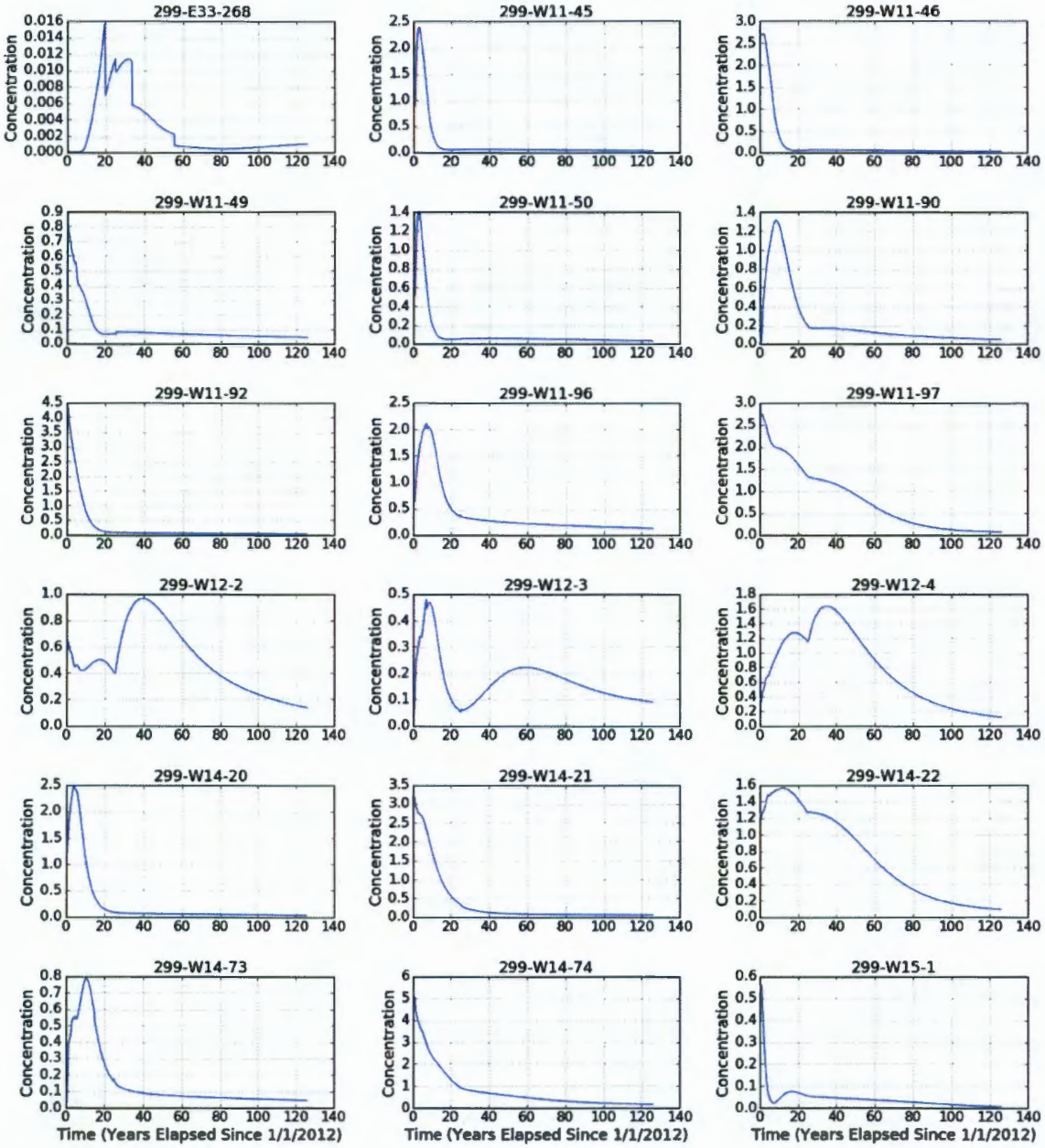
Simulated Extraction Concentrations in pCi/L for Tc-99 With Source for Base Case



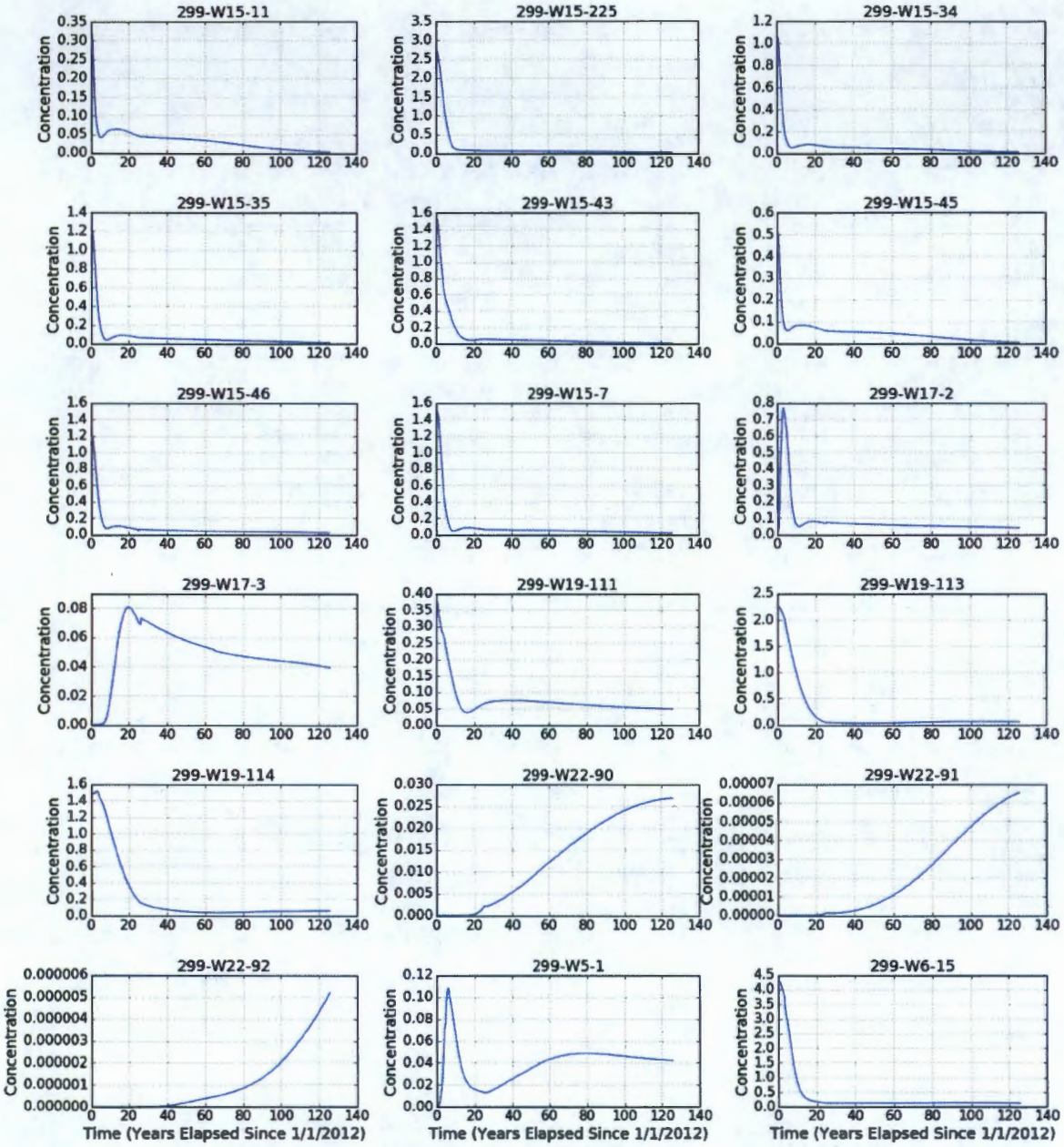
Simulated Extraction Concentrations in pCi/L for Tc-99 With Source for Base Case



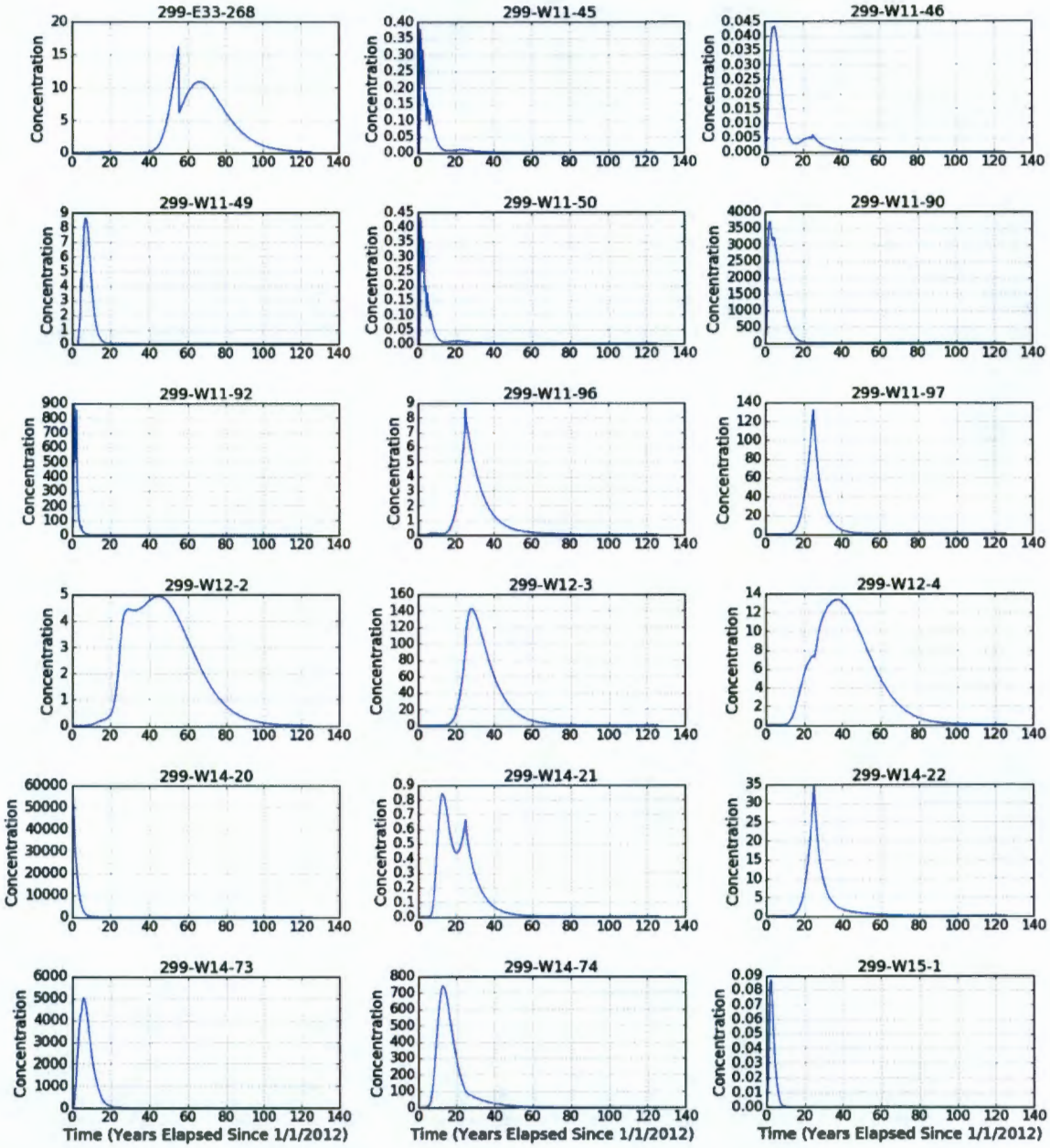
Simulated Extraction Concentrations in ug/L for TCE for Base Case



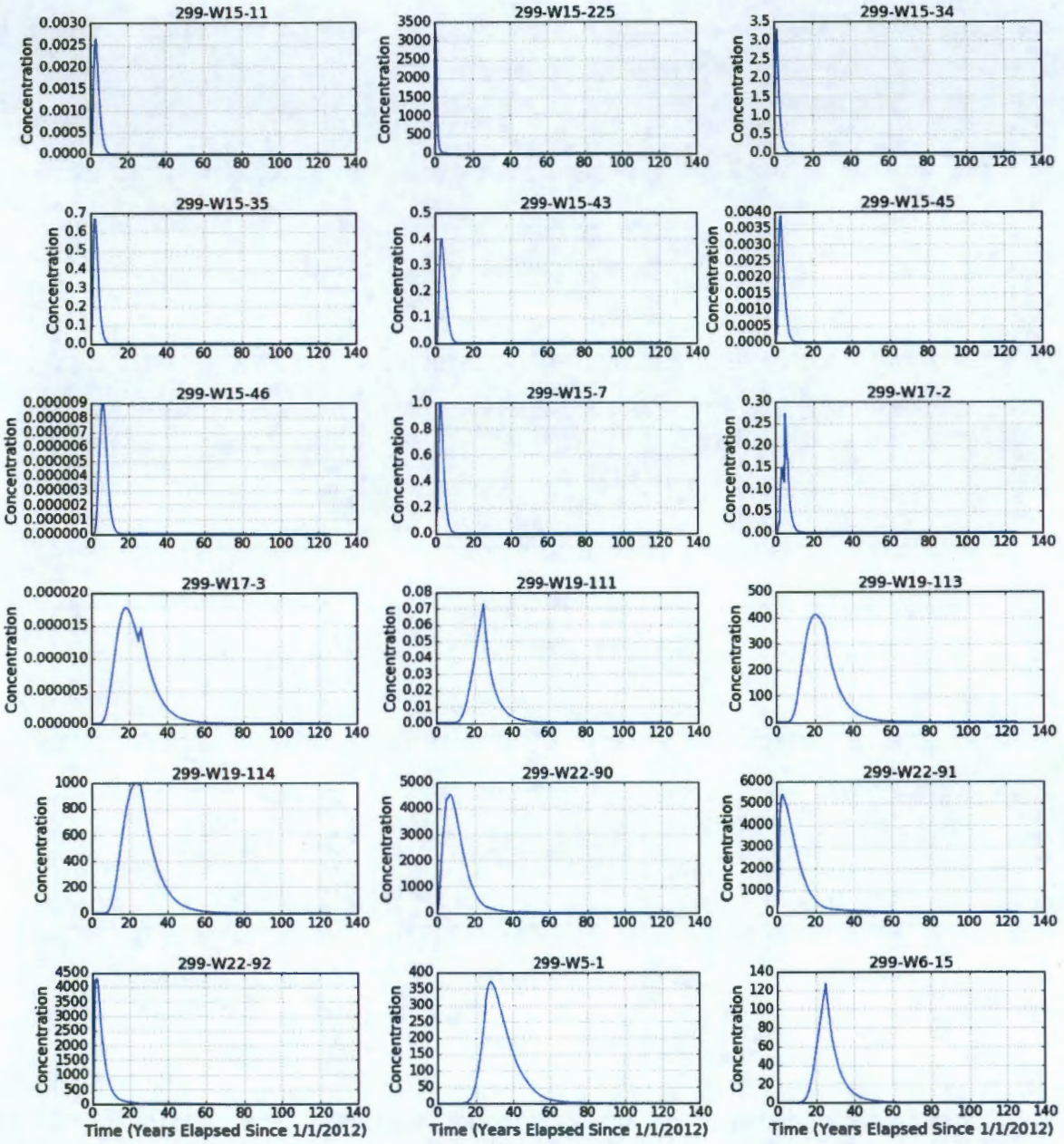
Simulated Extraction Concentrations in ug/L for TCE for Base Case



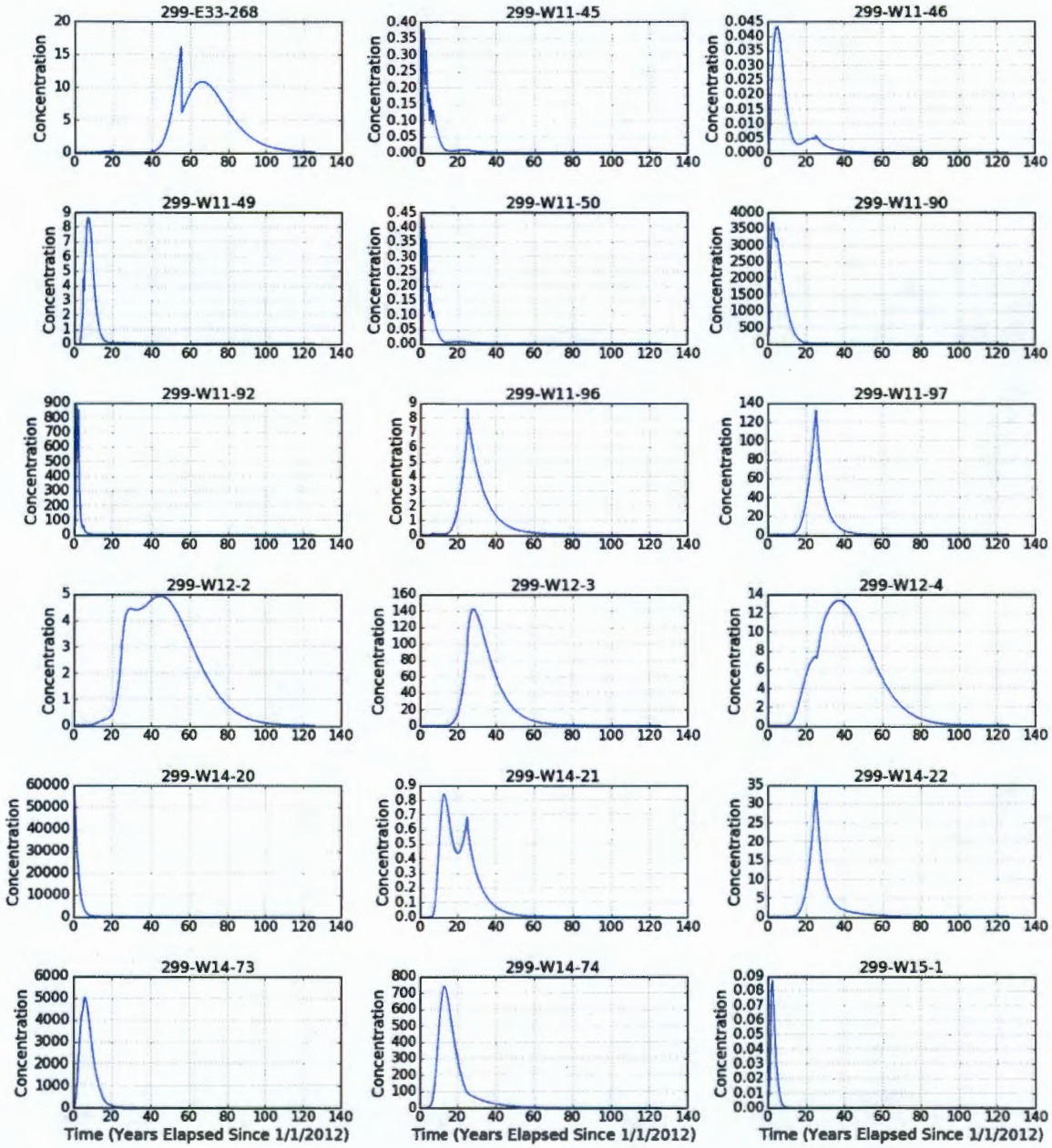
Simulated Extraction Concentrations in pCi/L for Tritium for Base Case



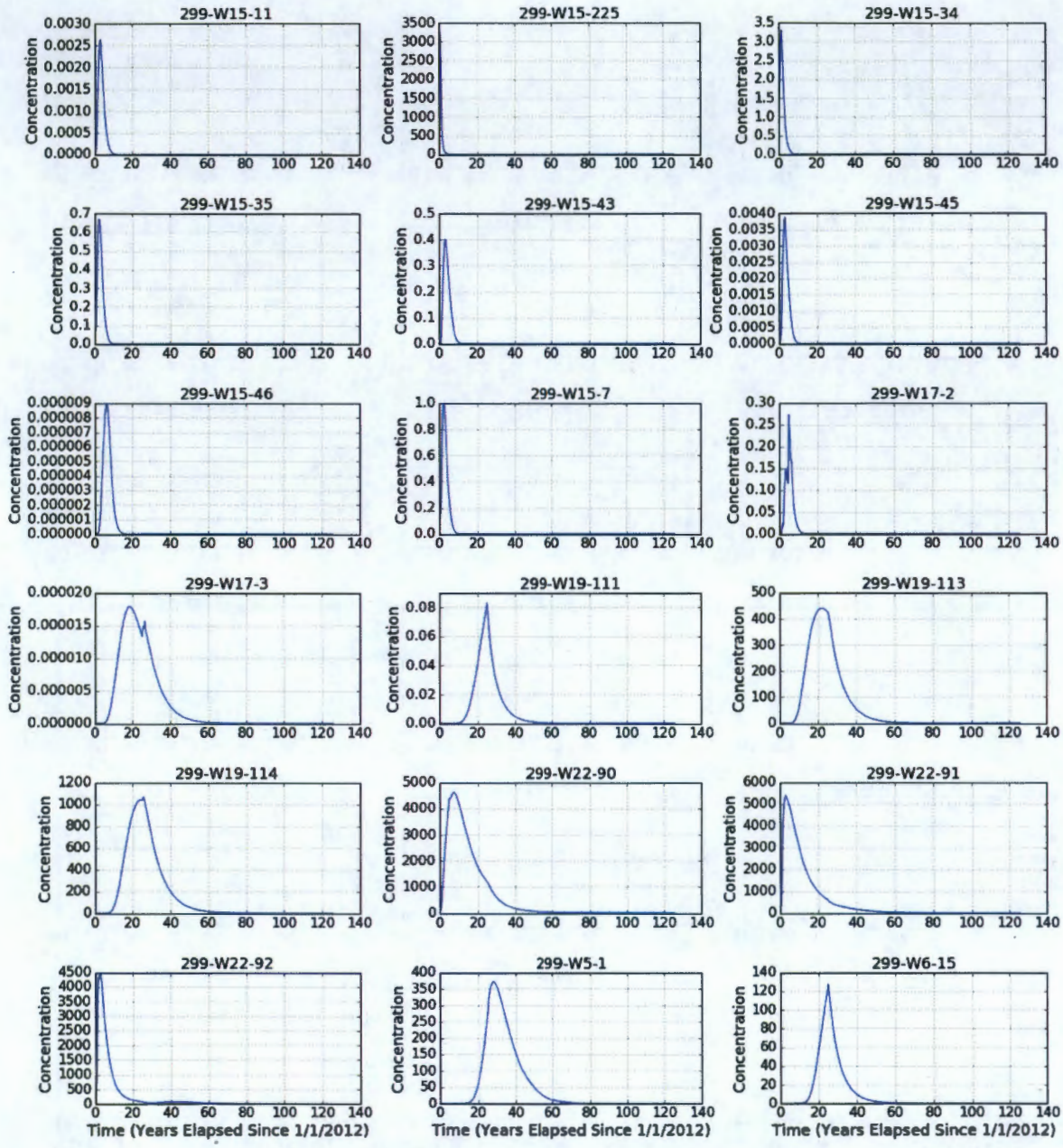
Simulated Extraction Concentrations in pCi/L for Tritium for Base Case



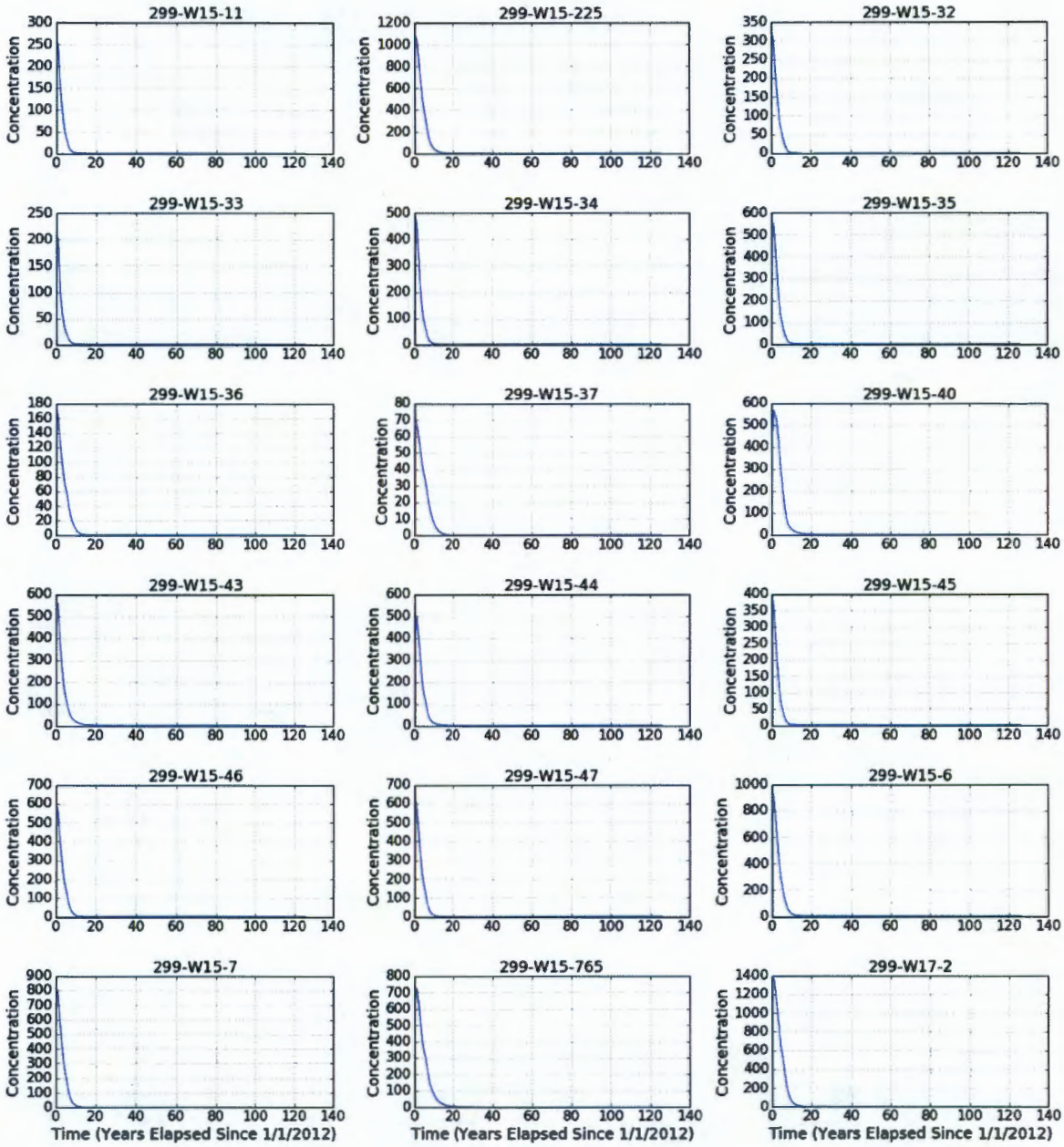
Simulated Extraction Concentrations in pCi/L for Tritium With Source for Base Case



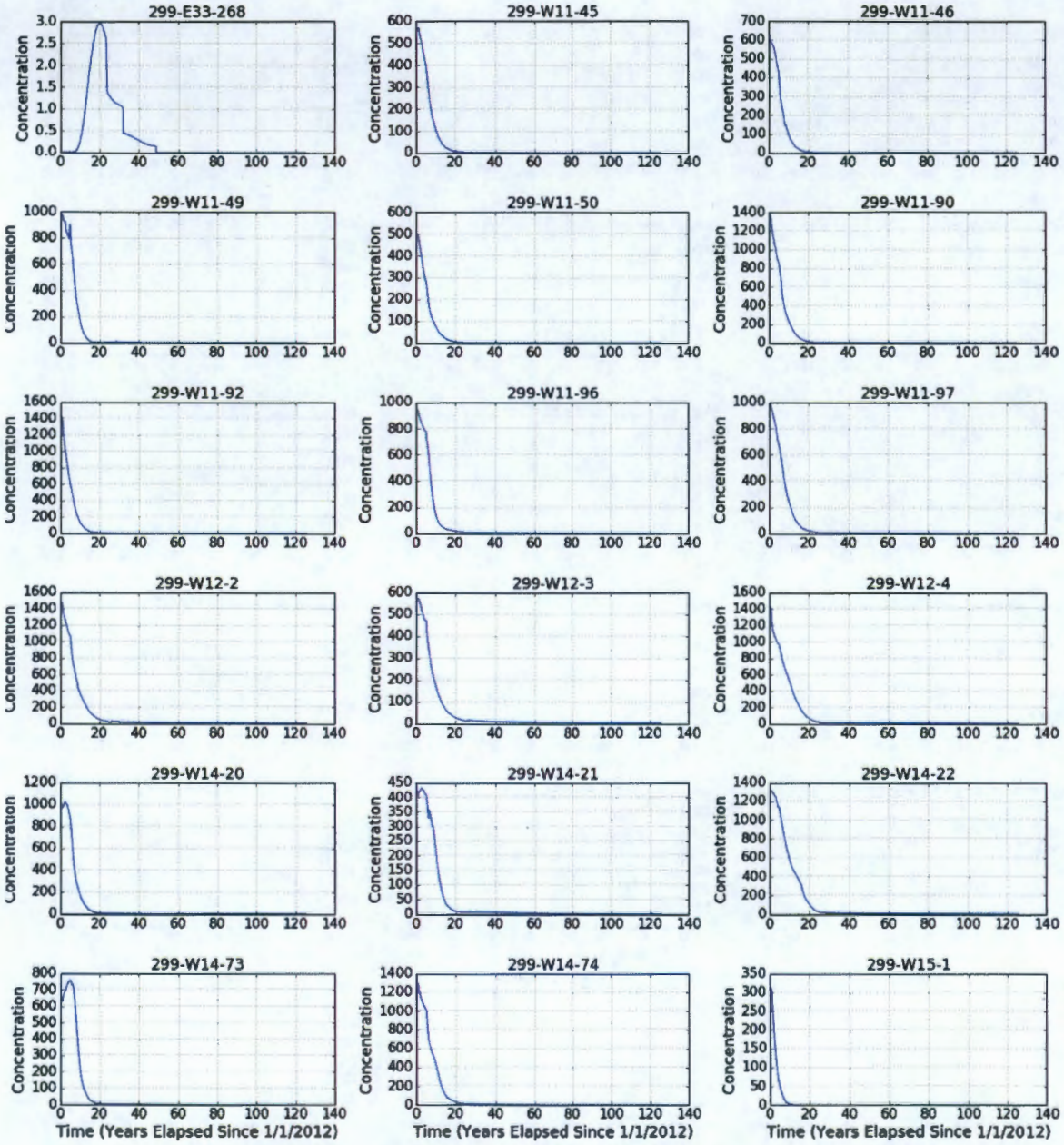
Simulated Extraction Concentrations in pCi/L for Tritium With Source for Base Case



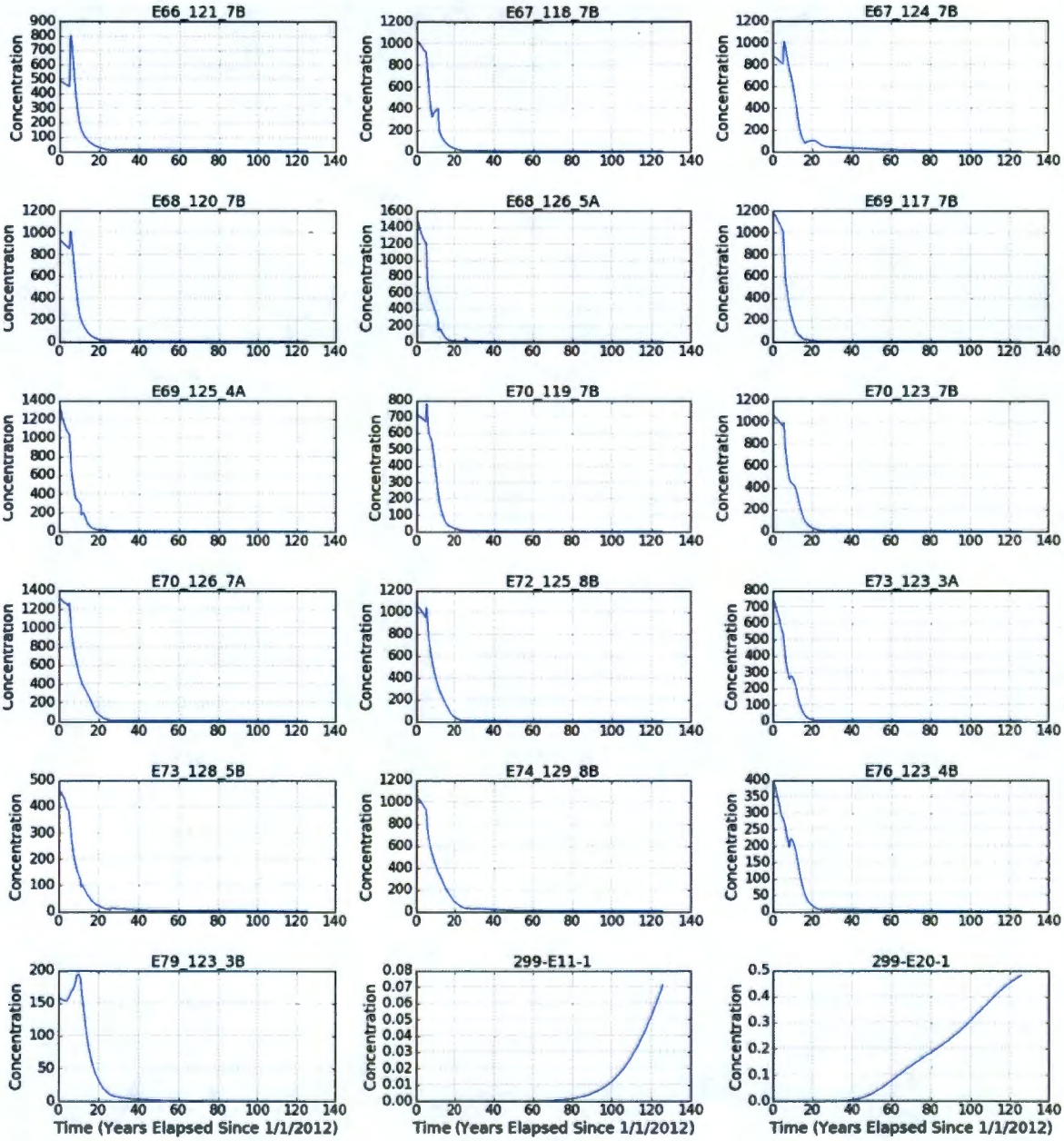
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 41.3 Year Half-Life for Optimization Case 13



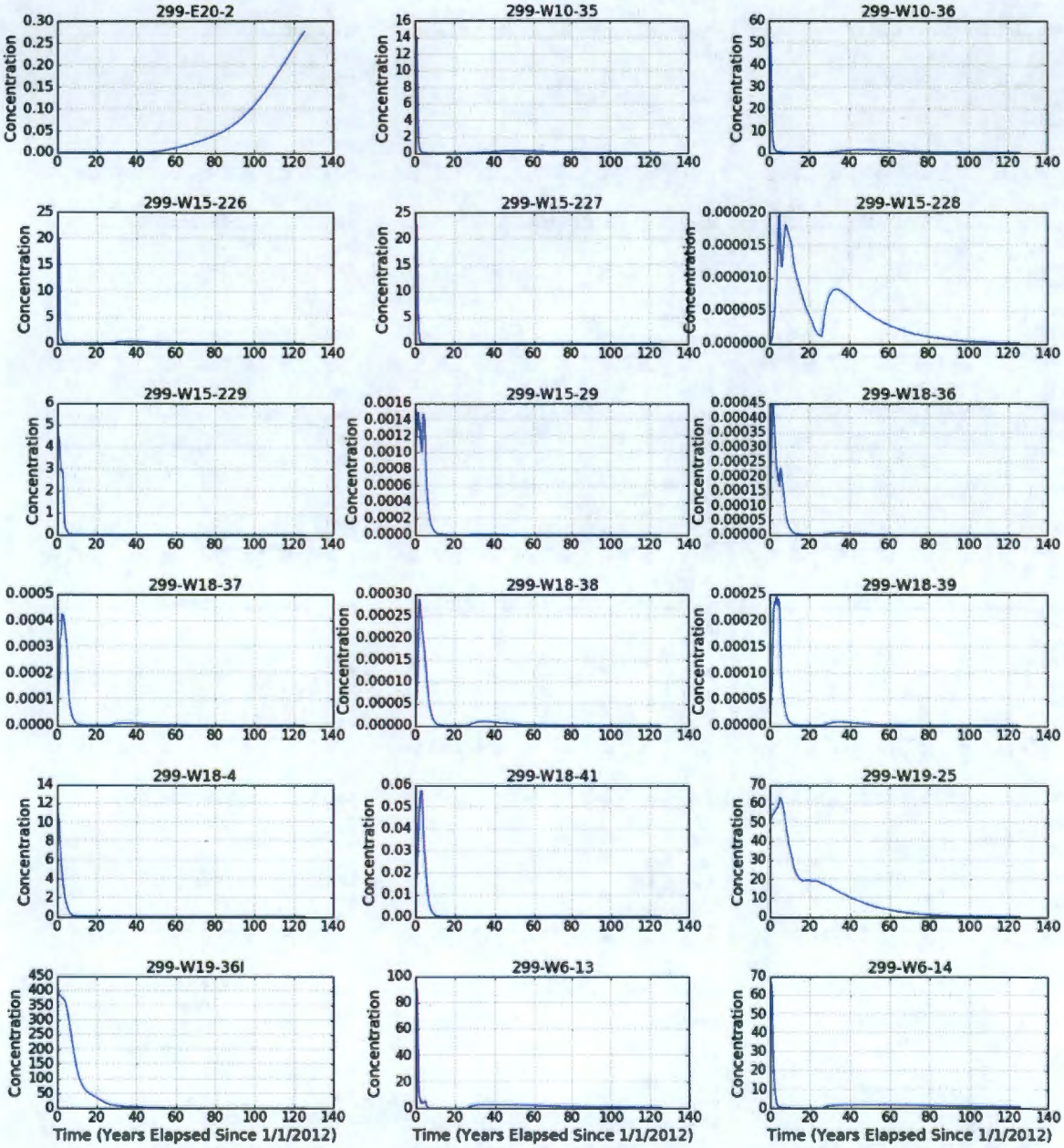
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 41.3 Year Half-Life for Optimization Case 13



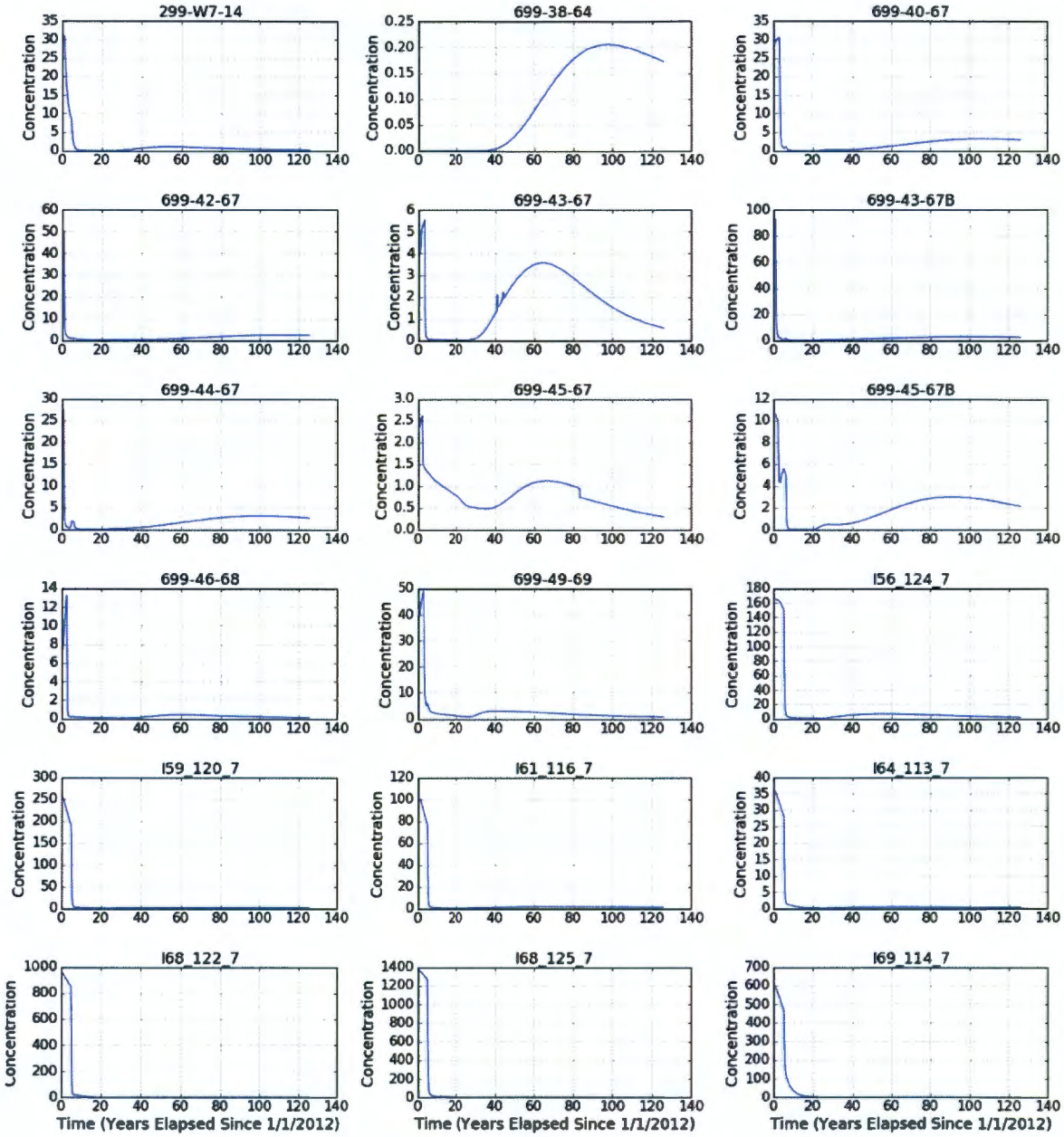
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 41.3 Year Half-Life for Optimization Case 13



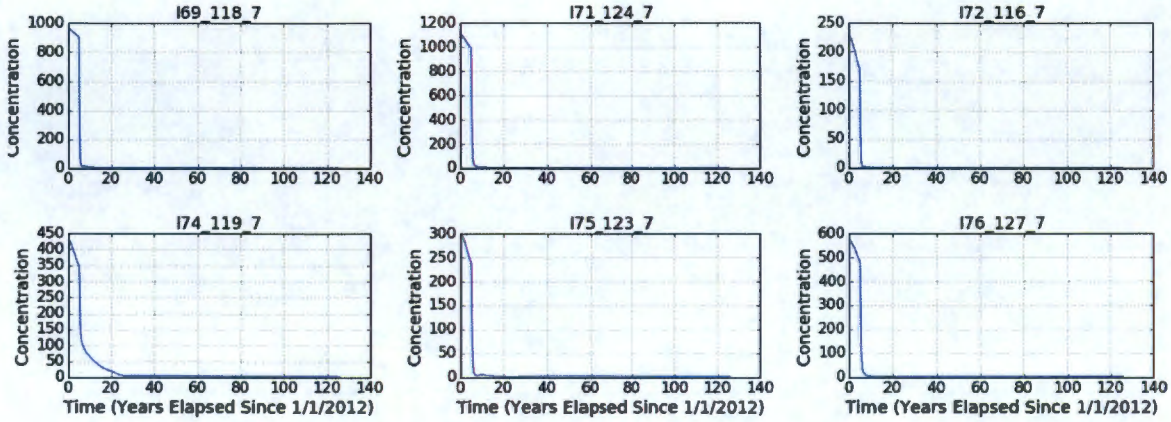
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 41.3 Year Half-Life for Optimization Case 13



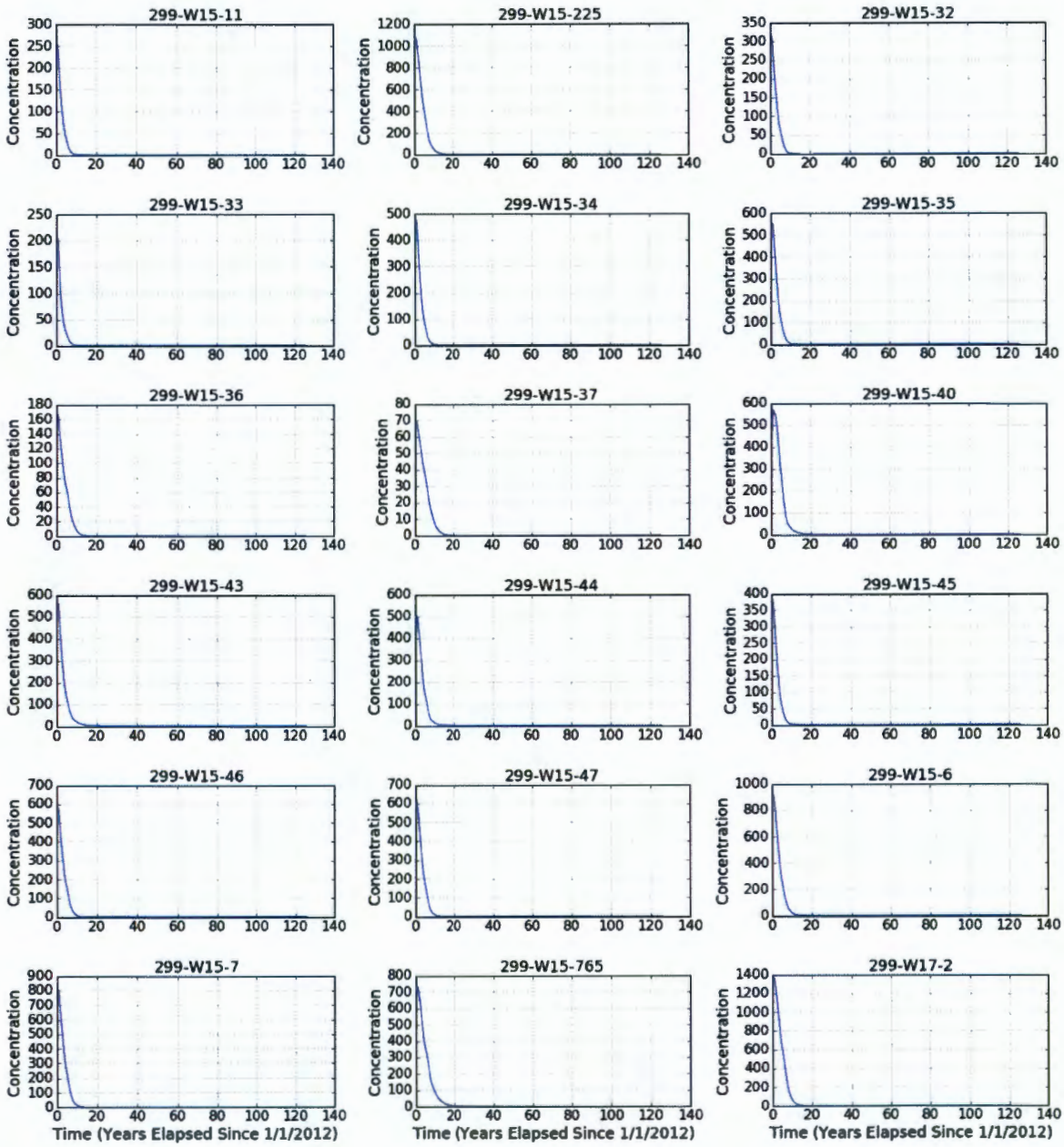
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 41.3 Year Half-Life for Optimization Case 13



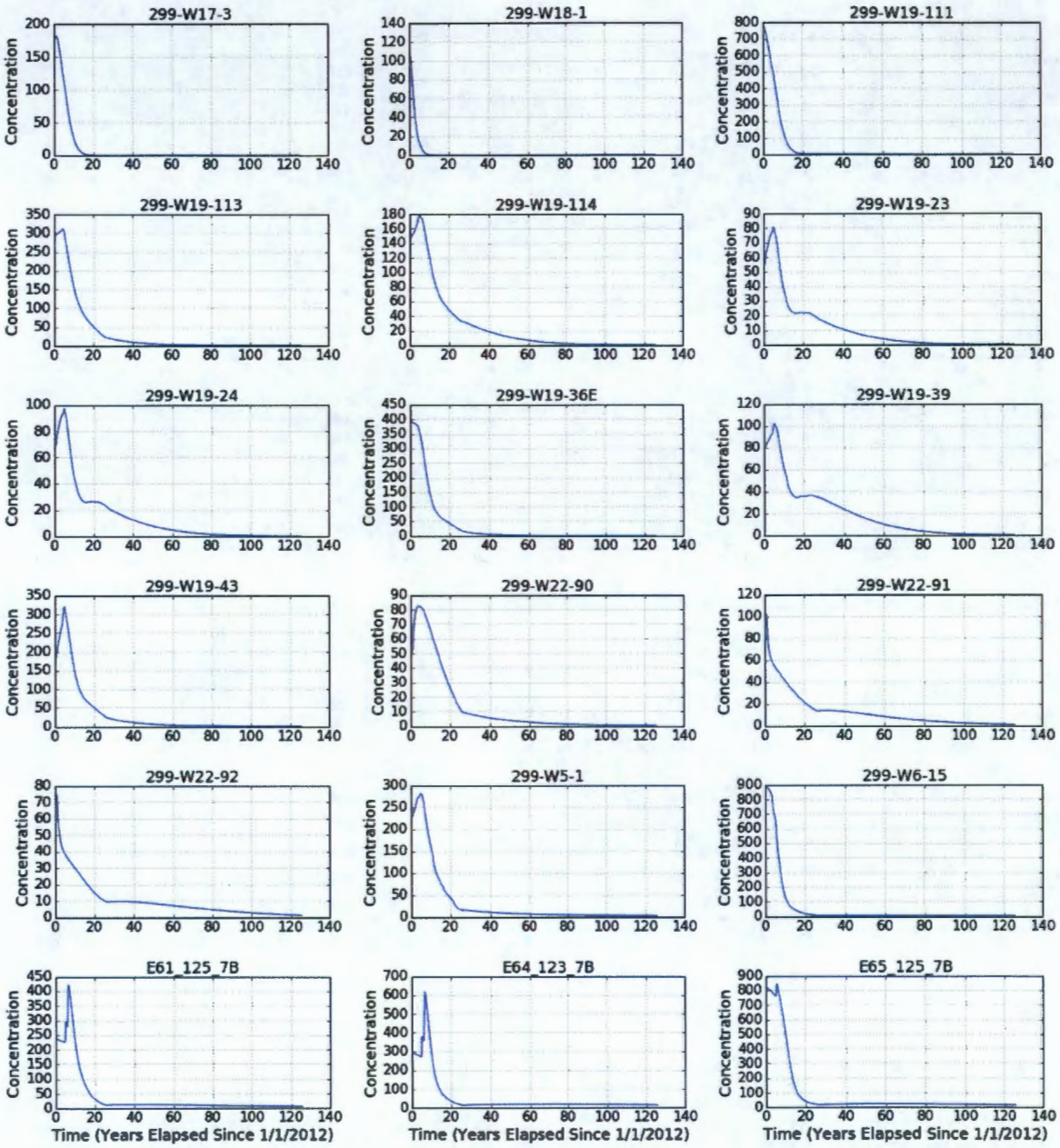
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 41.3 Year Half-Life for Optimization Case 13



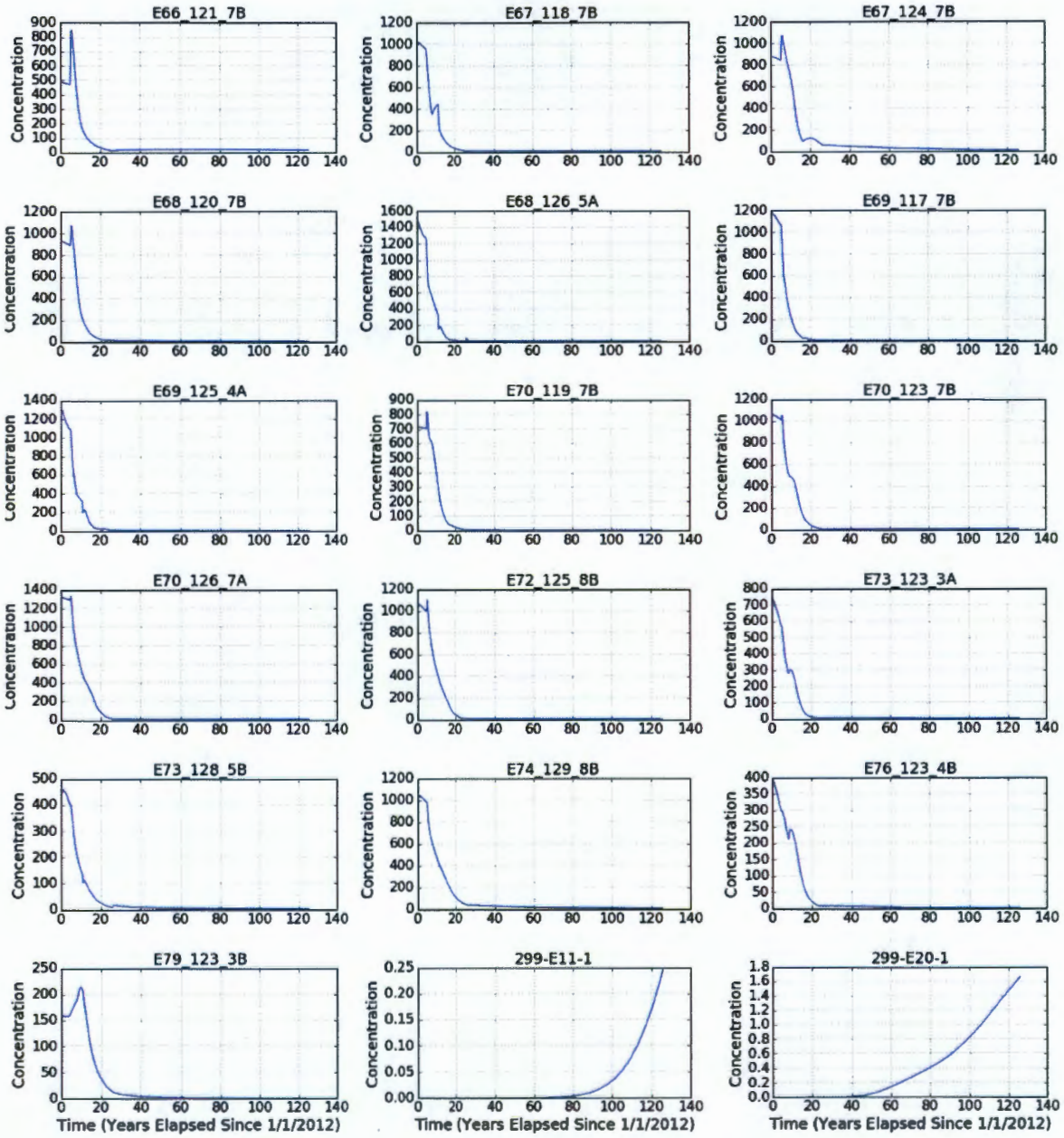
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Optimization Case 13



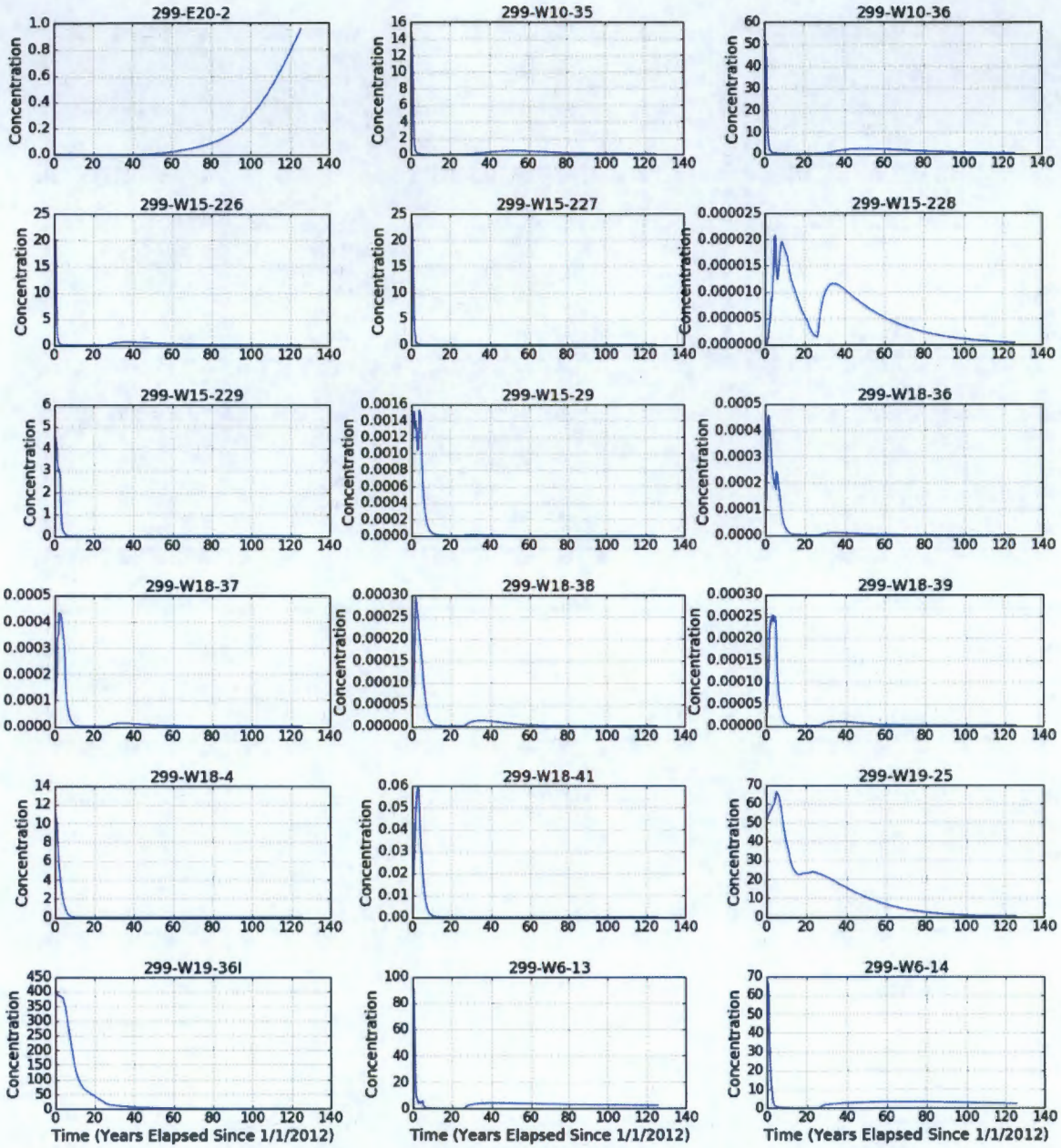
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Optimization Case 13



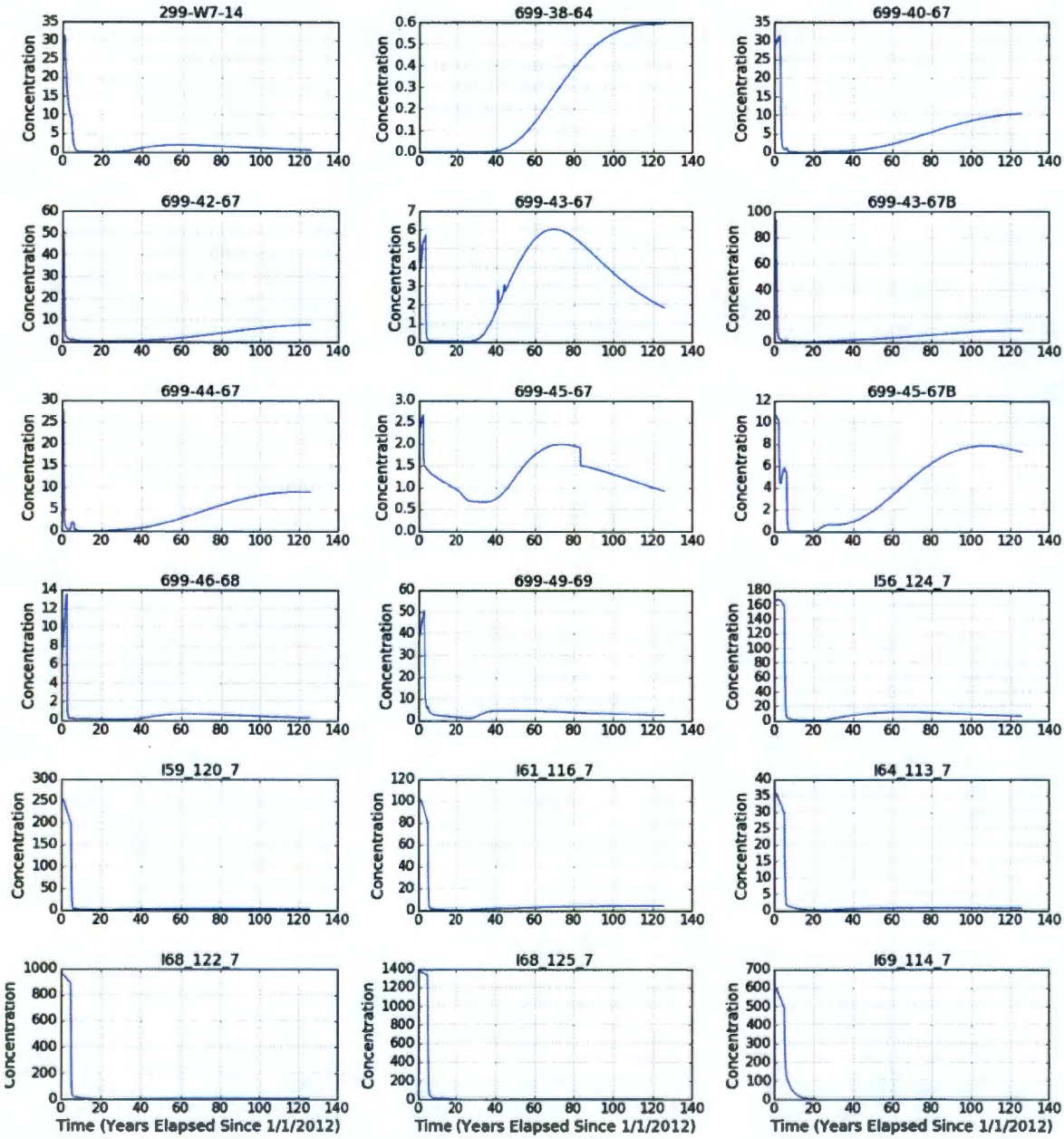
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Optimization Case 13



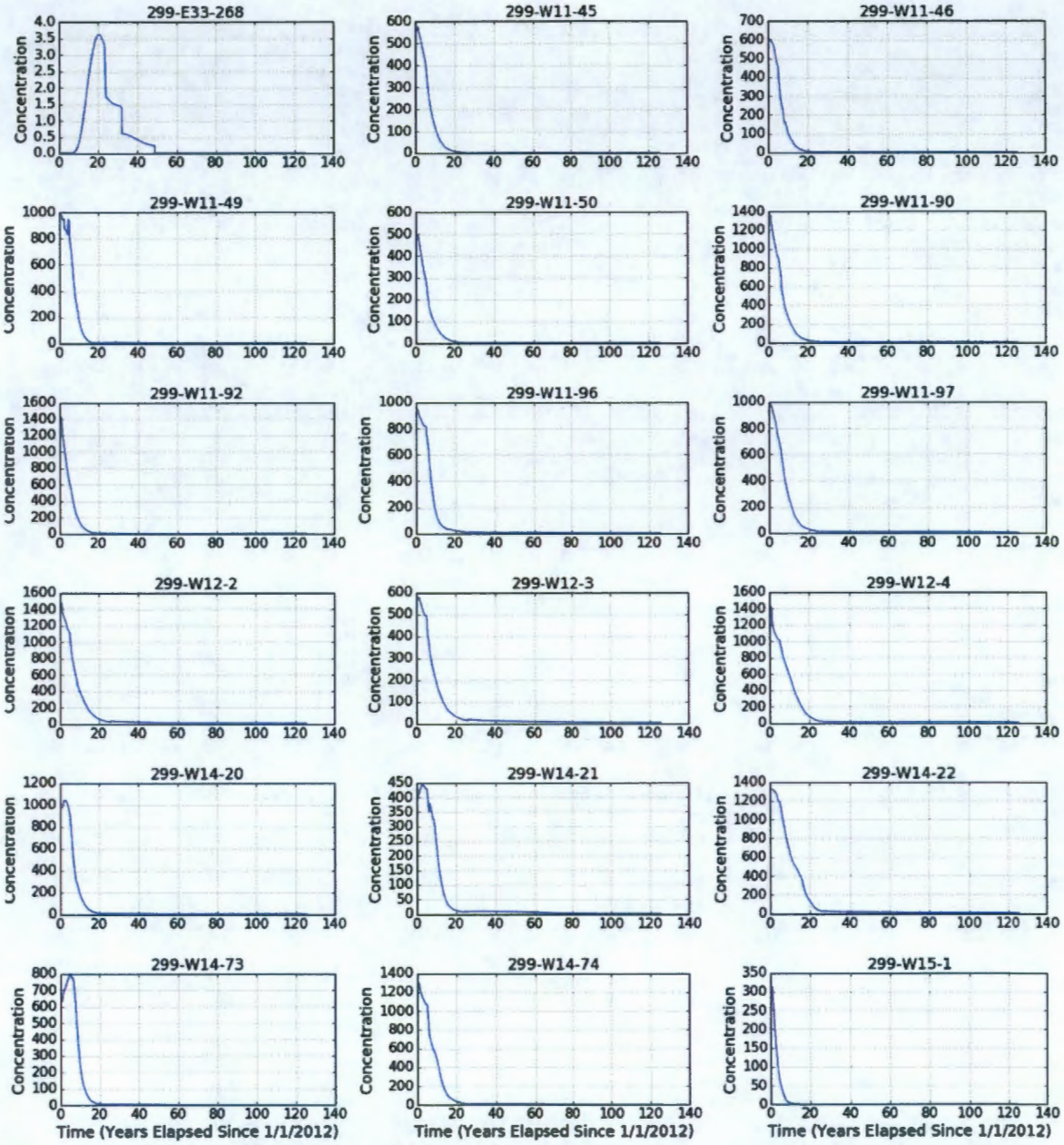
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Optimization Case 13



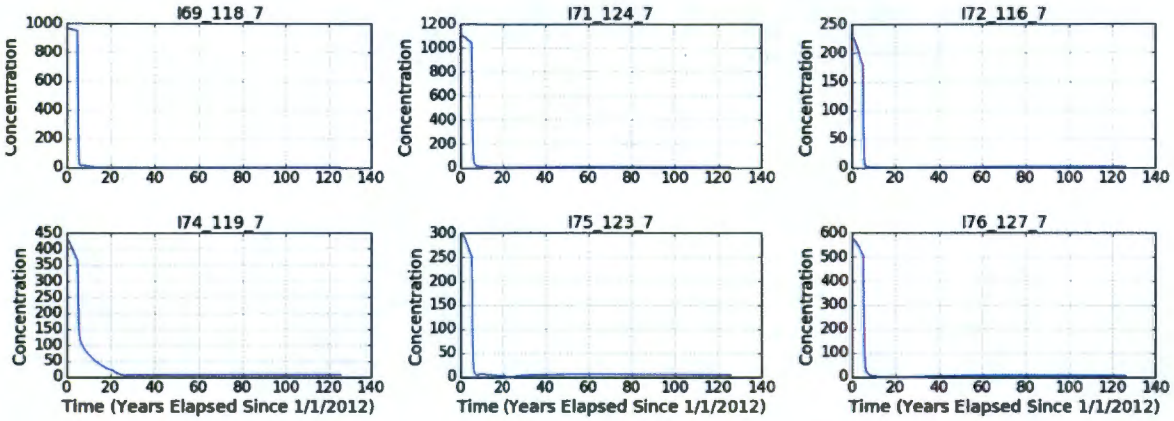
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Optimization Case 13



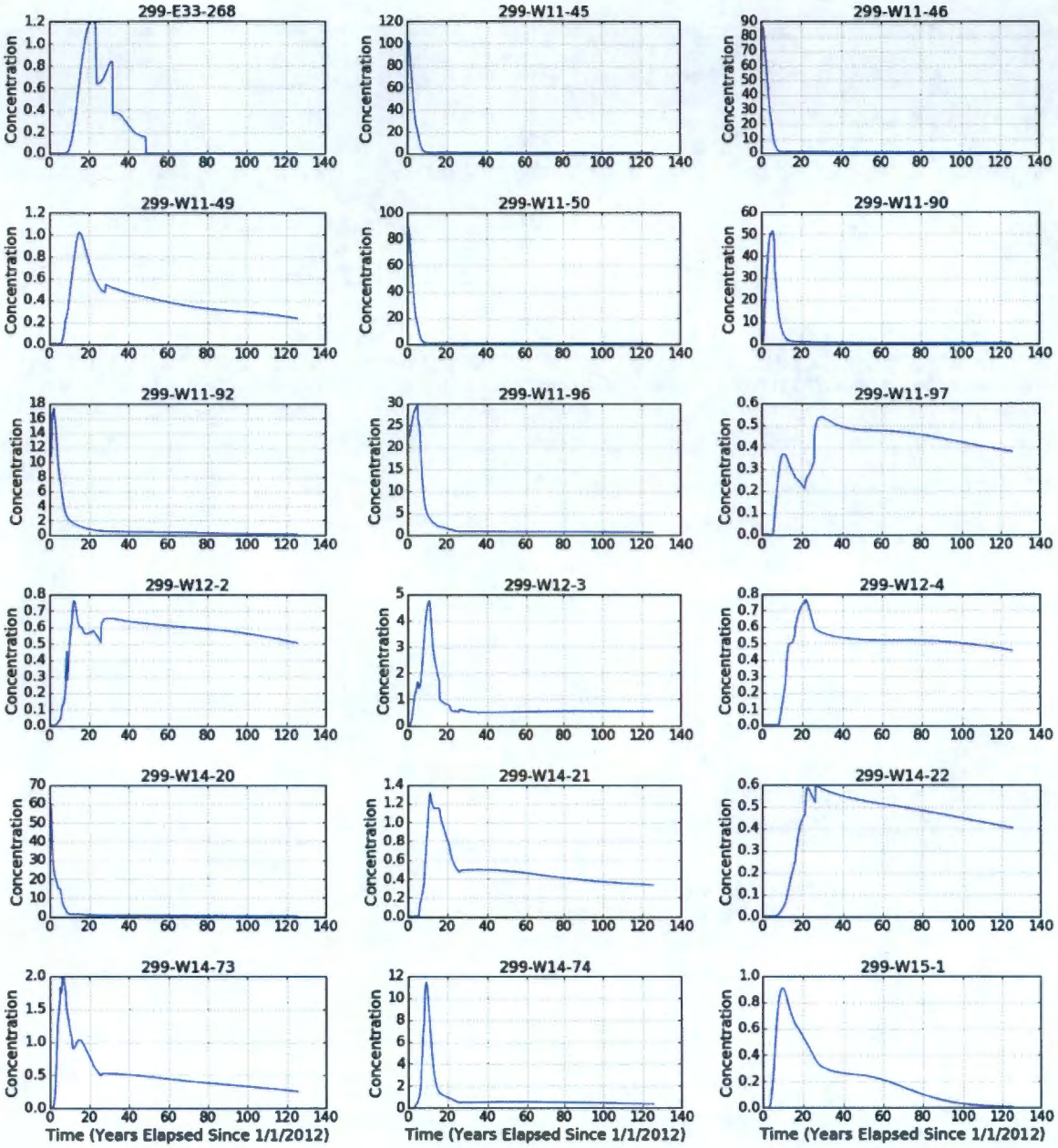
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Optimization Case 13



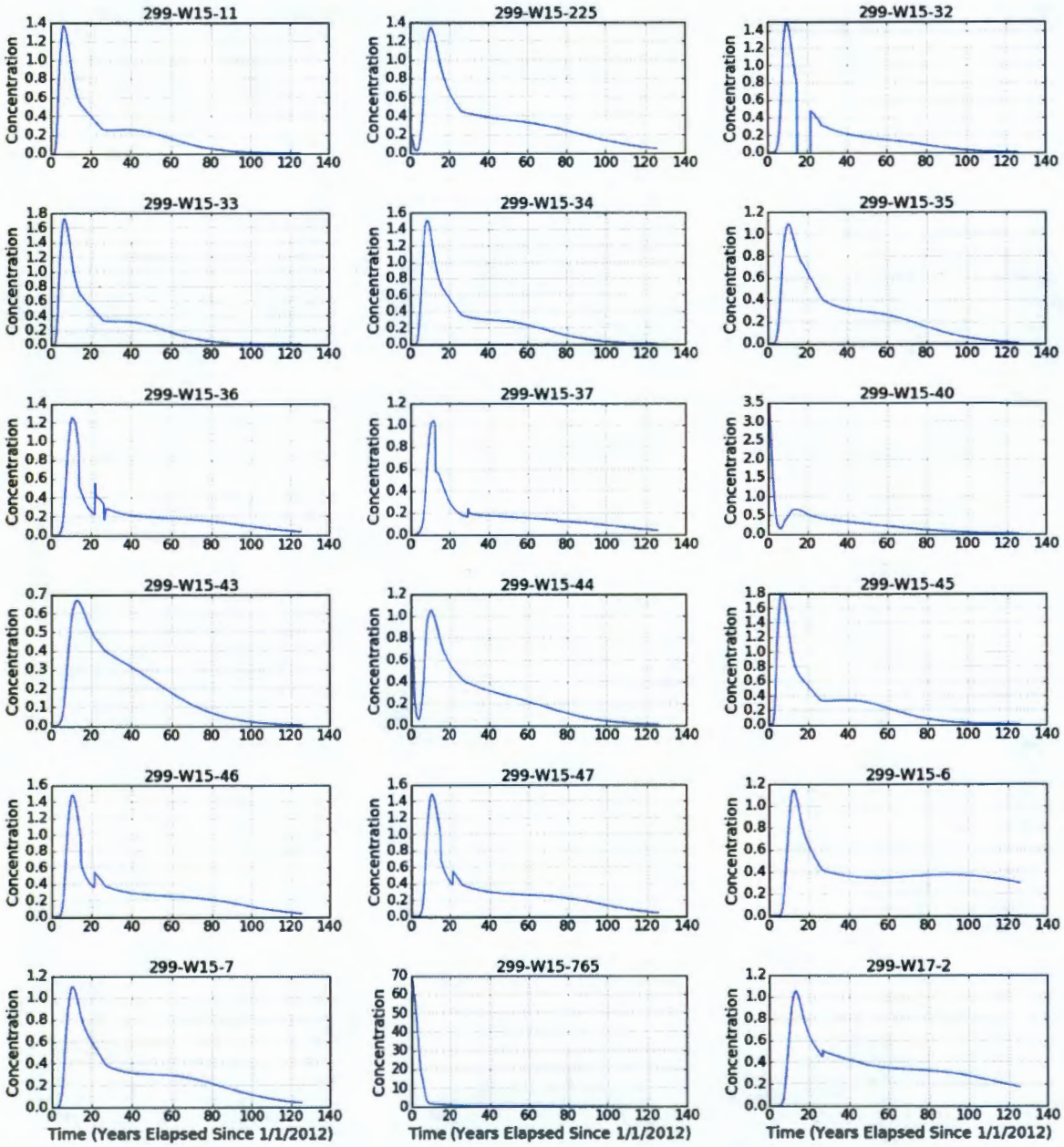
Simulated Extraction Concentrations in ug/L for Carbon Tetrachloride 100 Year Half-Life for Optimization Case 13



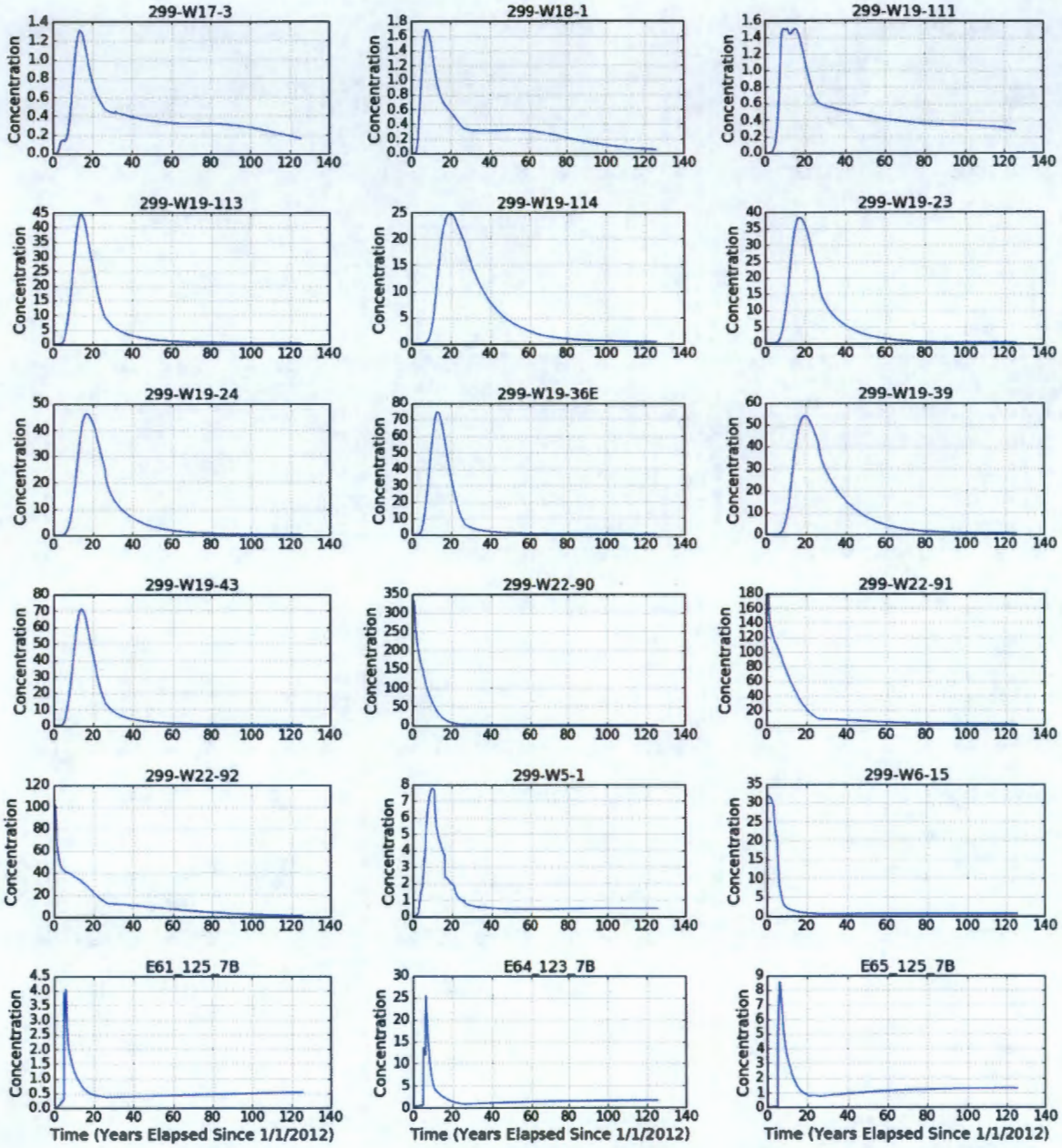
Simulated Extraction Concentrations in ug/L for Chromium for Optimization Case 13



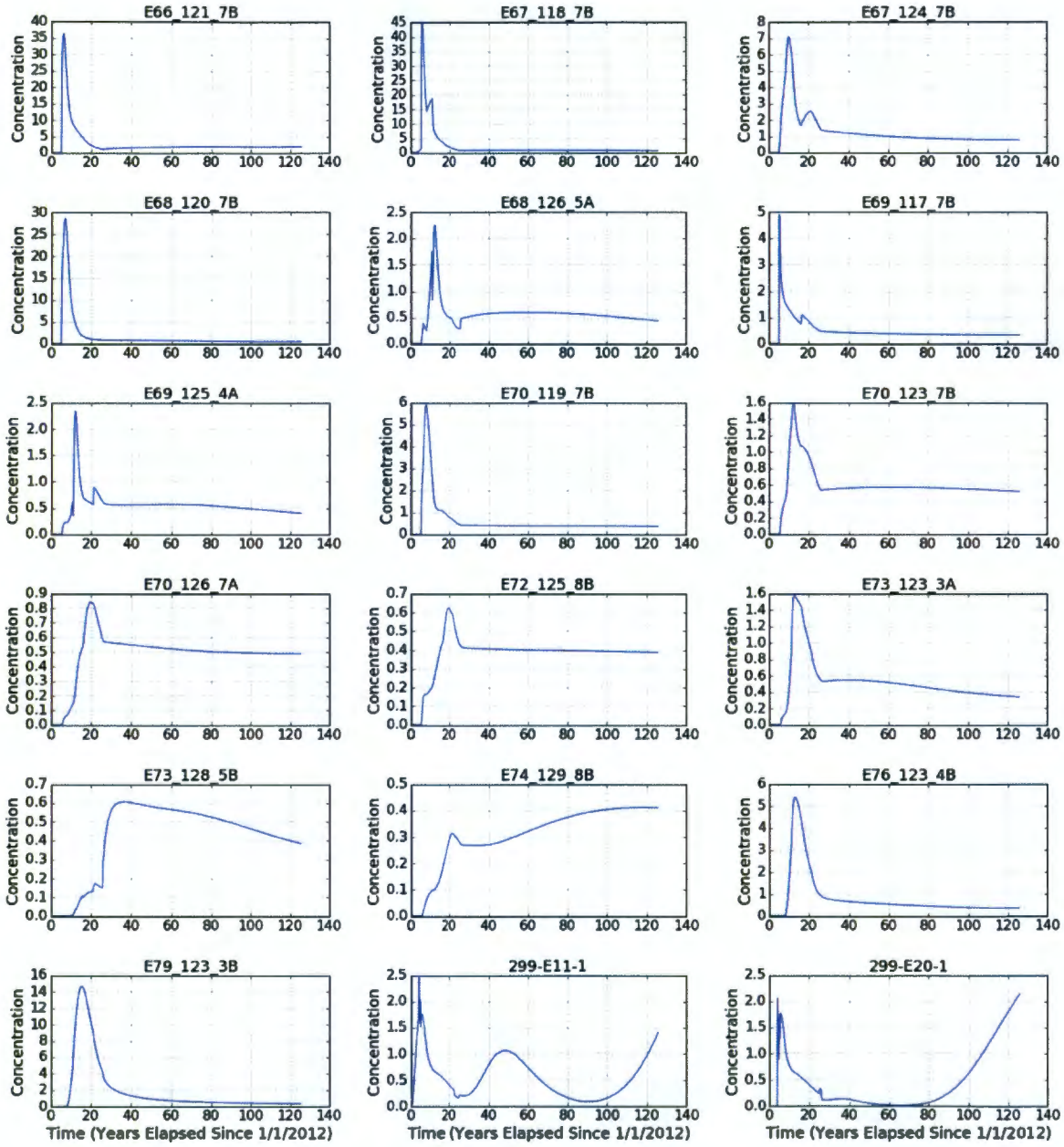
Simulated Extraction Concentrations in ug/L for Chromium for Optimization Case 13



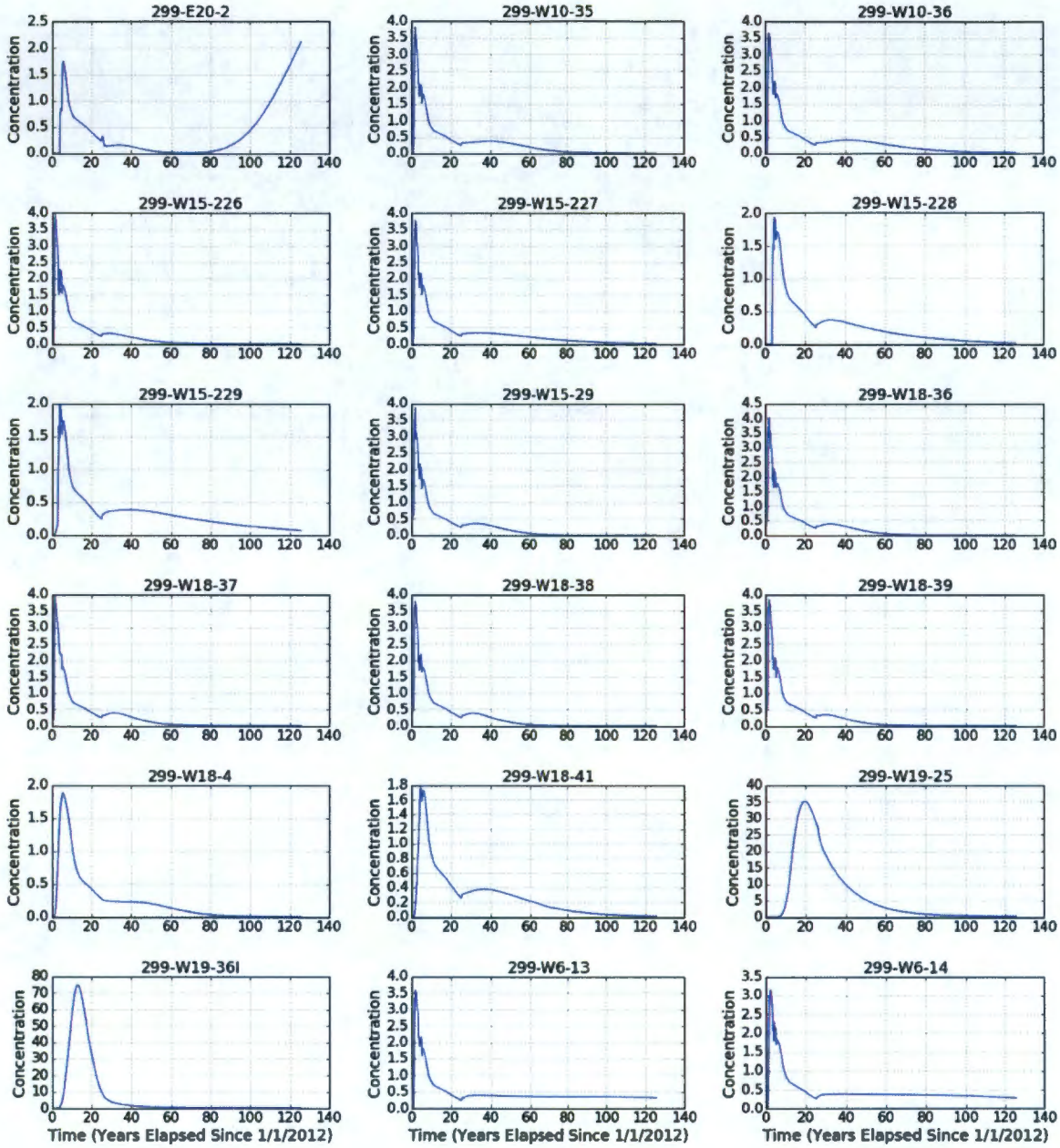
Simulated Extraction Concentrations in ug/L for Chromium for Optimization Case 13



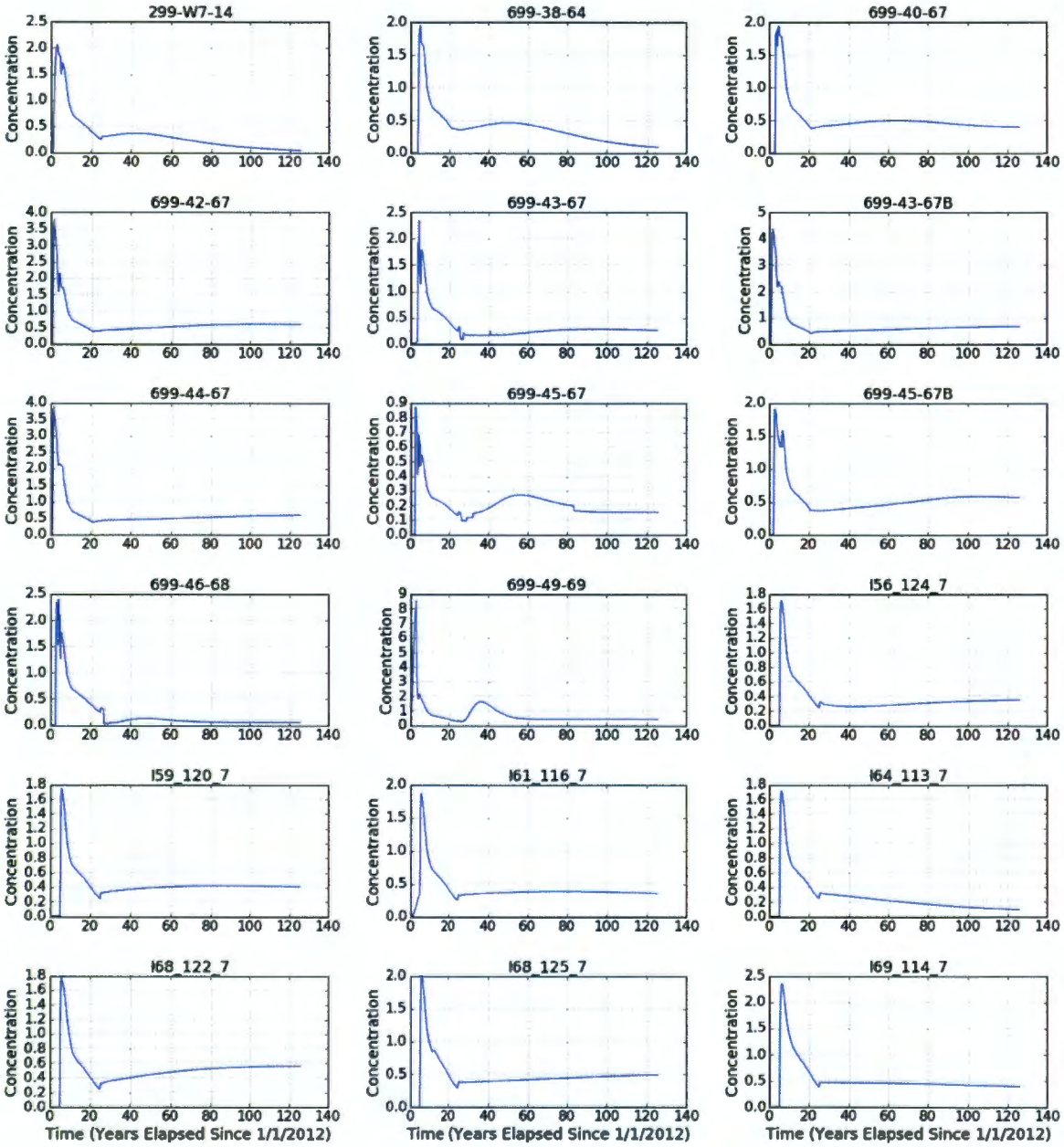
Simulated Extraction Concentrations in ug/L for Chromium for Optimization Case 13



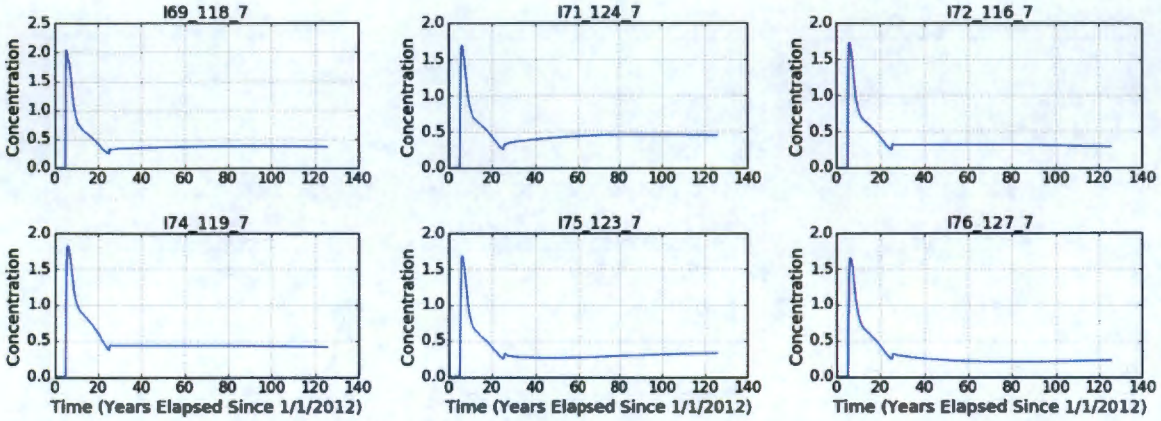
Simulated Extraction Concentrations in ug/L for Chromium for Optimization Case 13



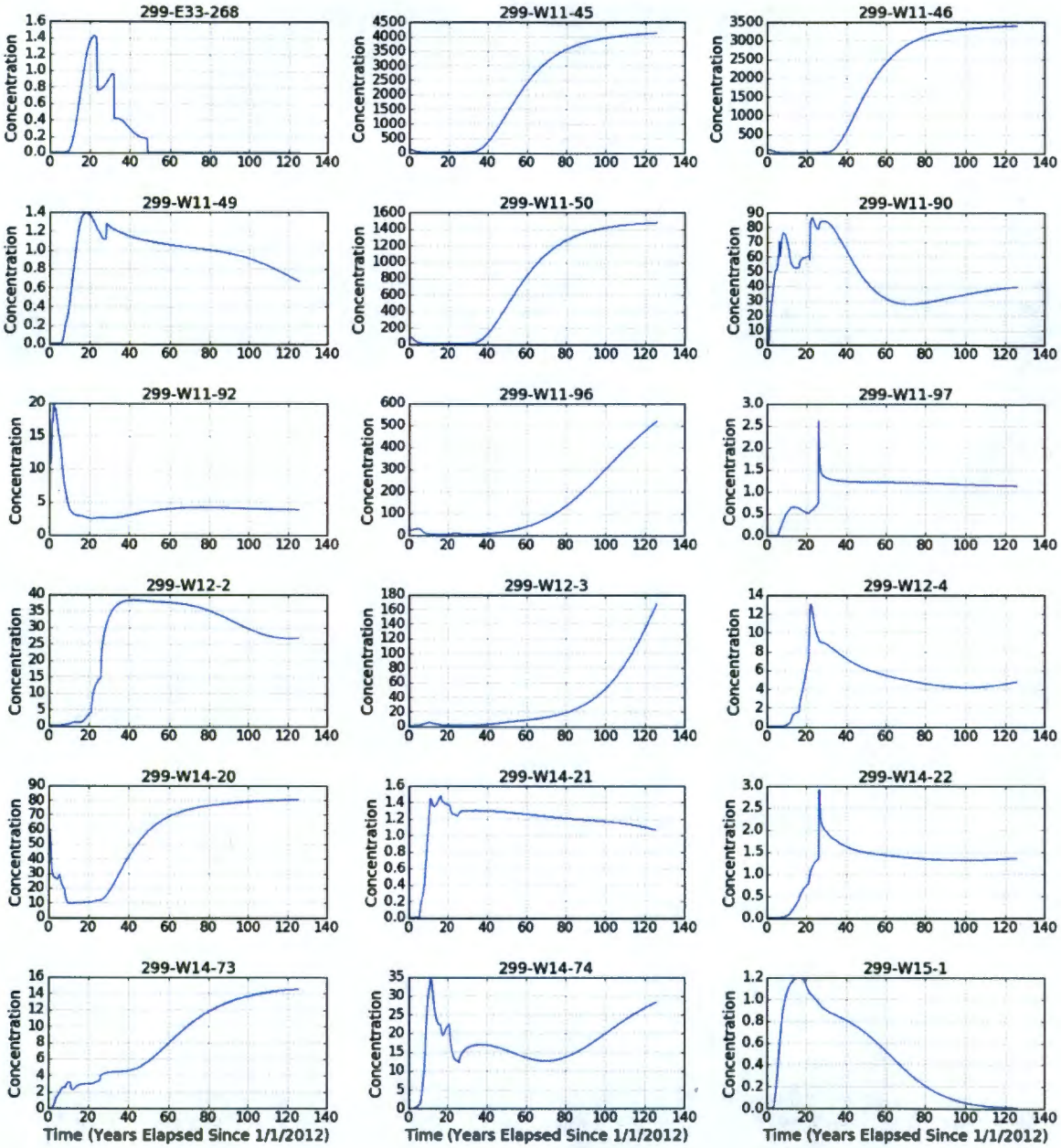
Simulated Extraction Concentrations in ug/L for Chromium for Optimization Case 13



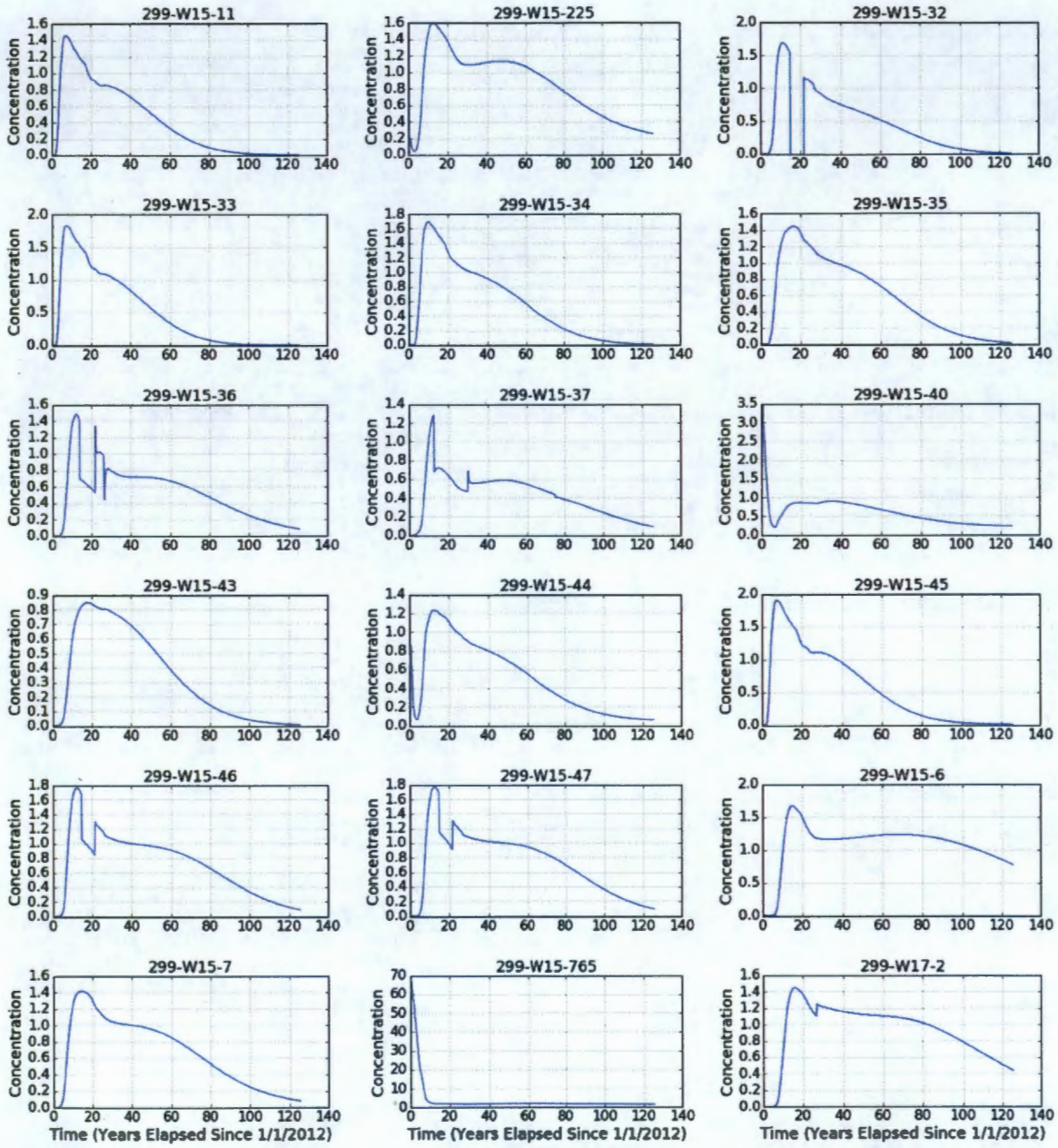
Simulated Extraction Concentrations in ug/L for Chromium for Optimization Case 13



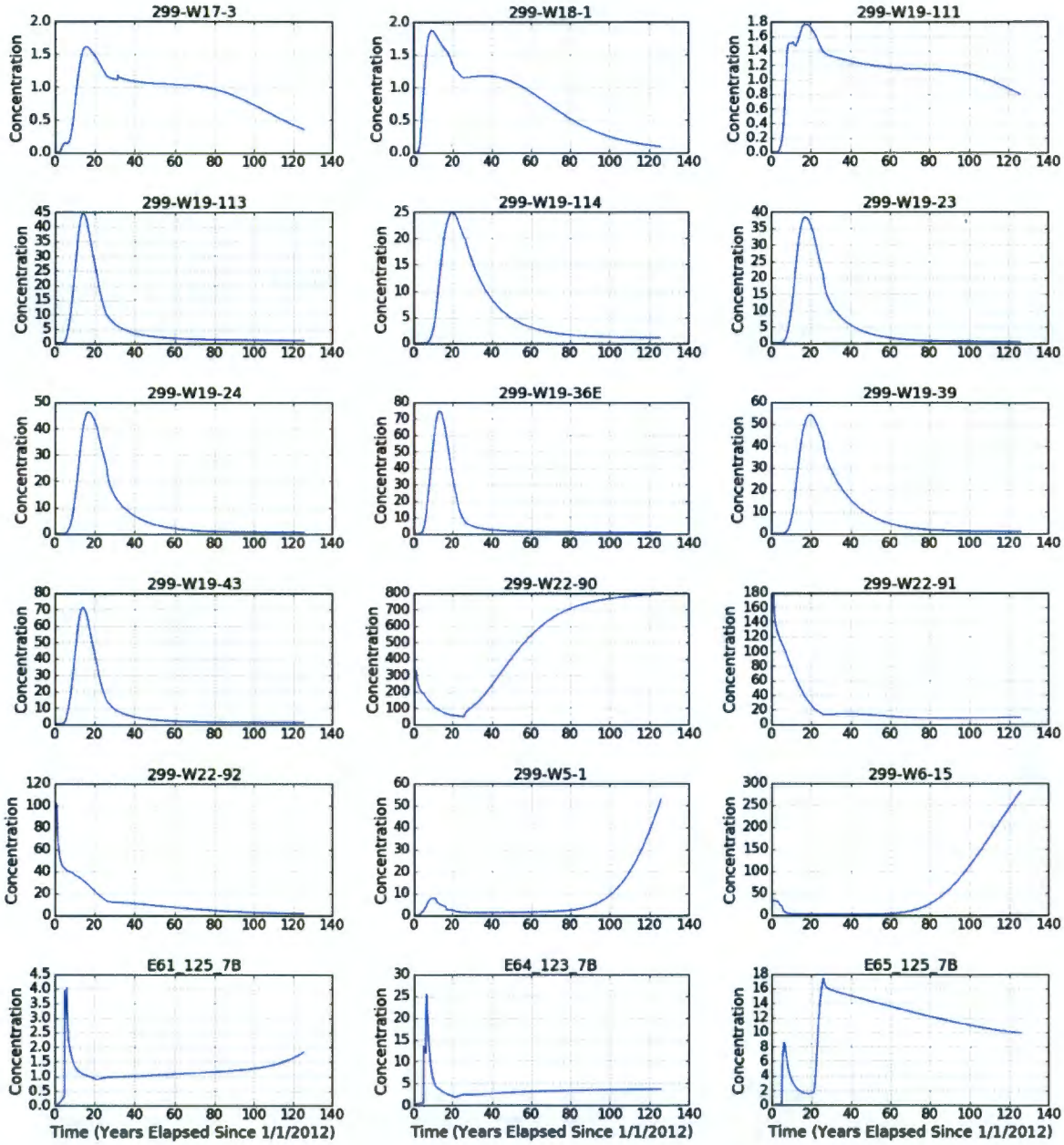
Simulated Extraction Concentrations in ug/L for Chromium With Source for Optimization Case 13



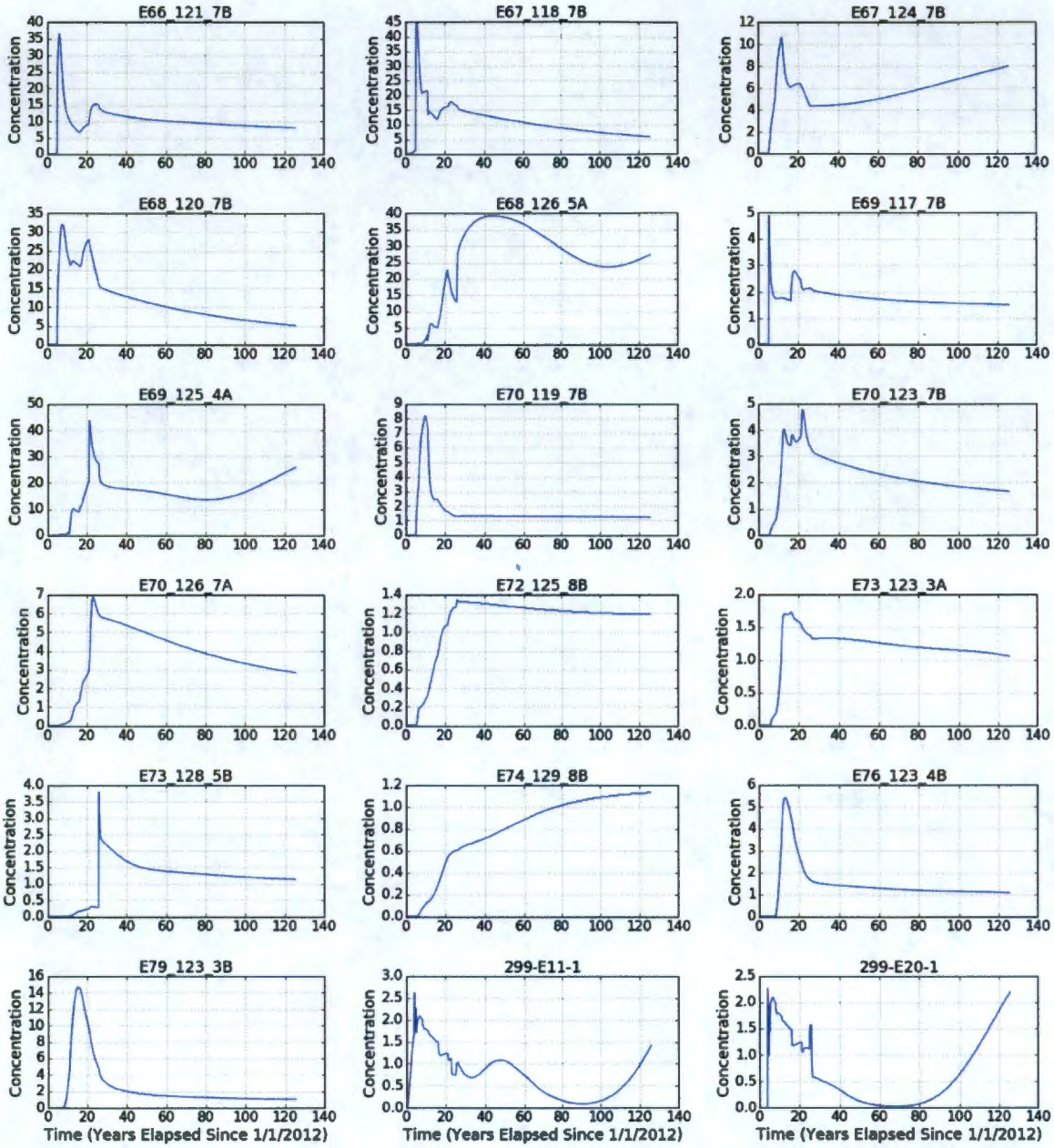
Simulated Extraction Concentrations in ug/L for Chromium With Source for Optimization Case 13



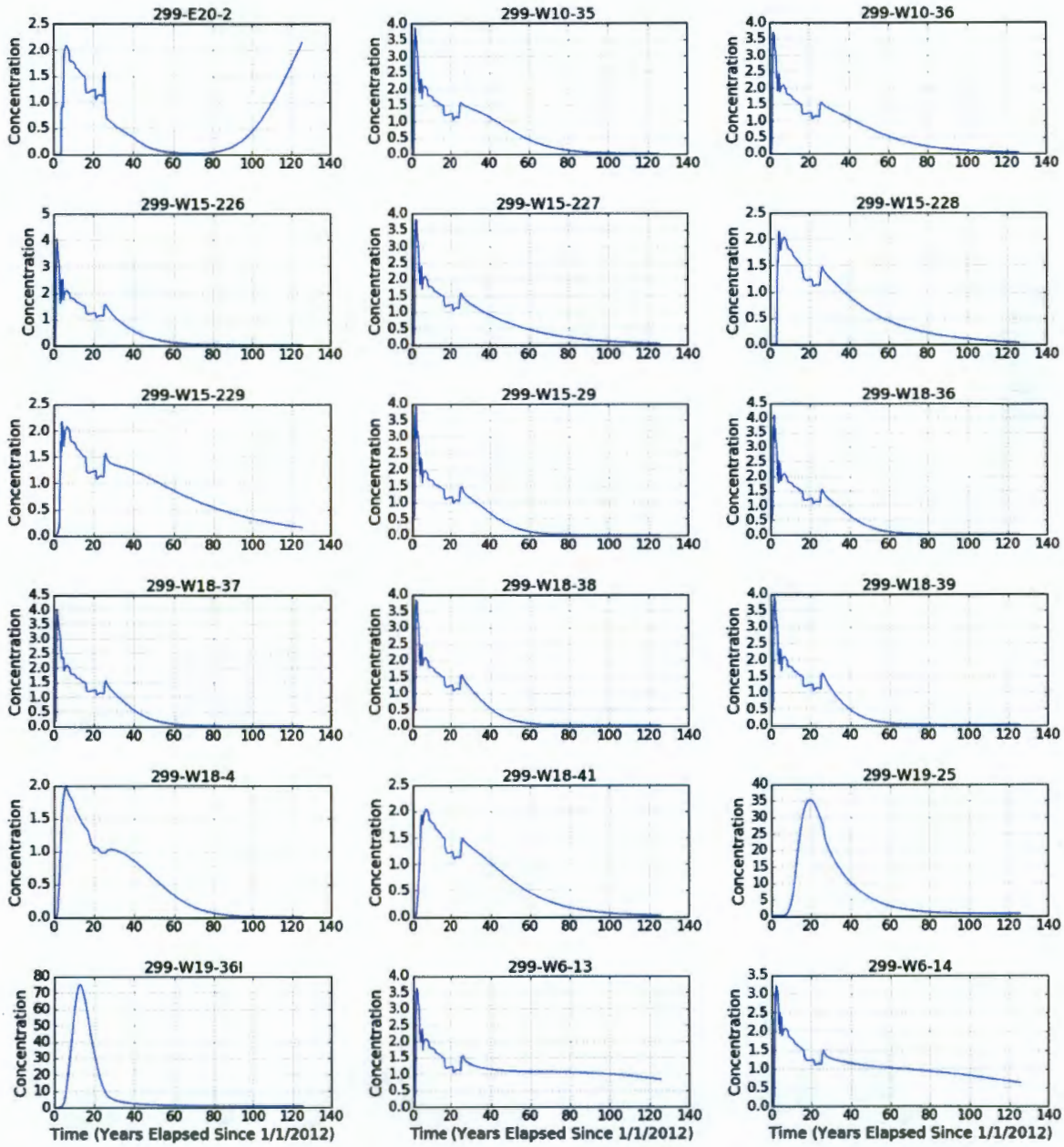
Simulated Extraction Concentrations in ug/L for Chromium With Source for Optimization Case 13



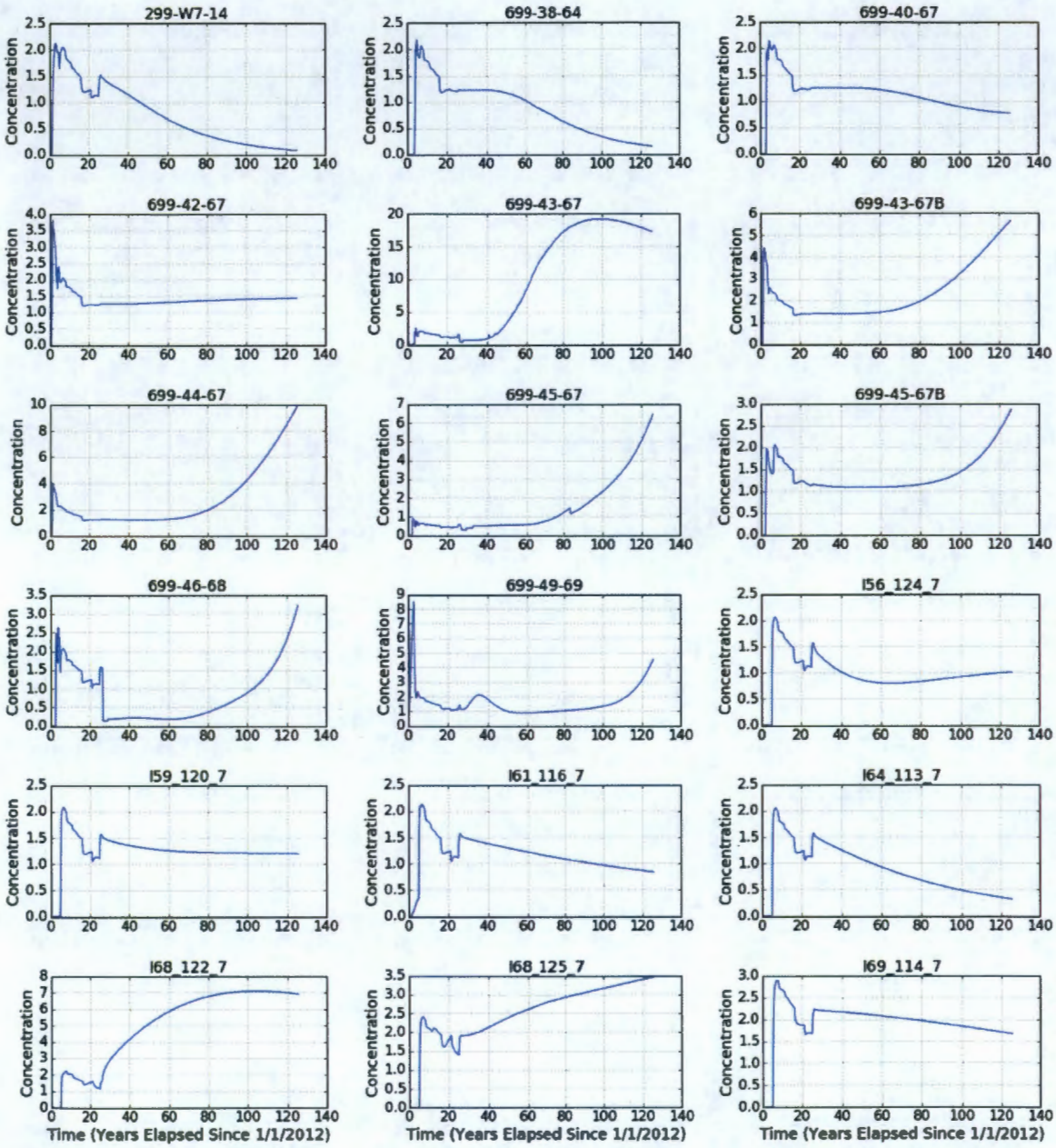
Simulated Extraction Concentrations in ug/L for Chromium With Source for Optimization Case 13



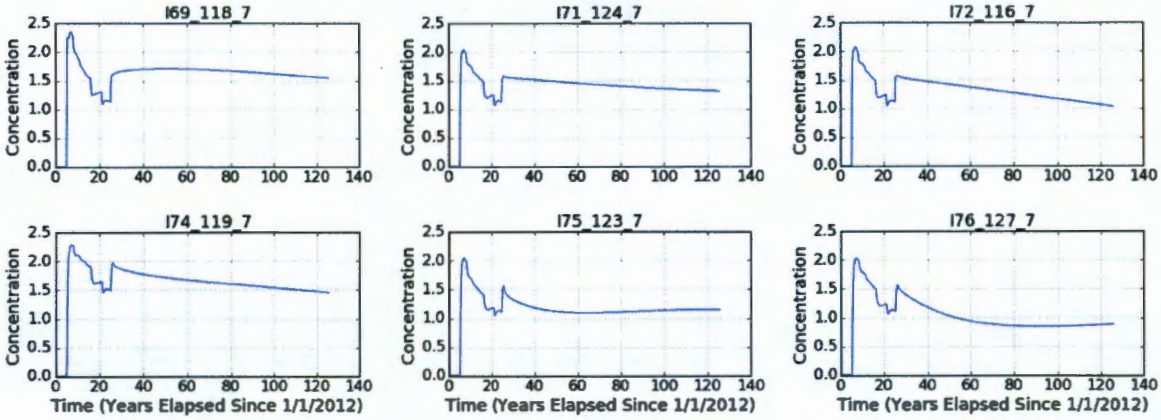
Simulated Extraction Concentrations in ug/L for Chromium With Source for Optimization Case 13



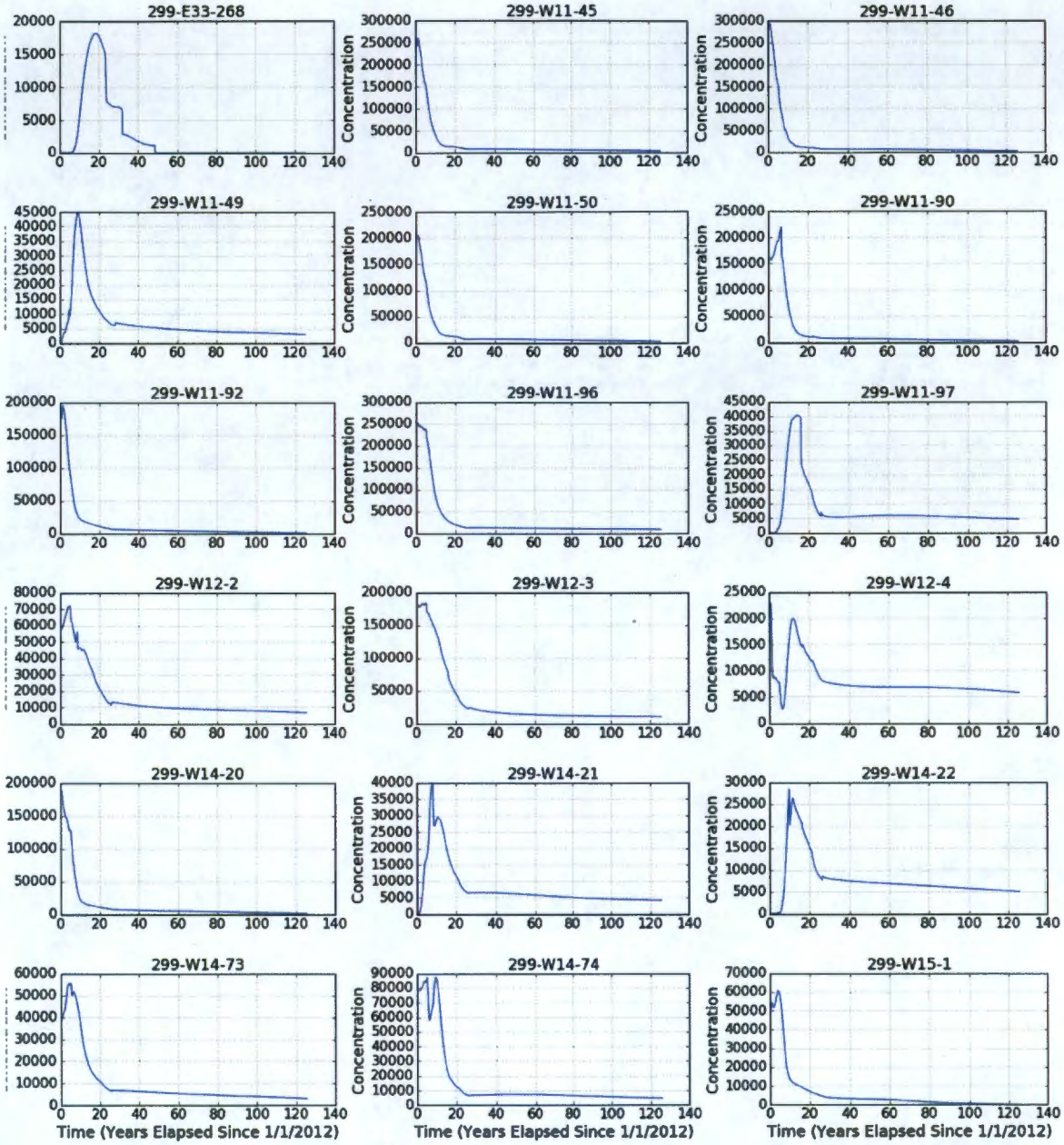
Simulated Extraction Concentrations in ug/L for Chromium With Source for Optimization Case 13



Simulated Extraction Concentrations in ug/L for Chromium With Source for Optimization Case 13



Simulated Extraction Concentrations in ug/L for Nitrate for Optimization Case 13



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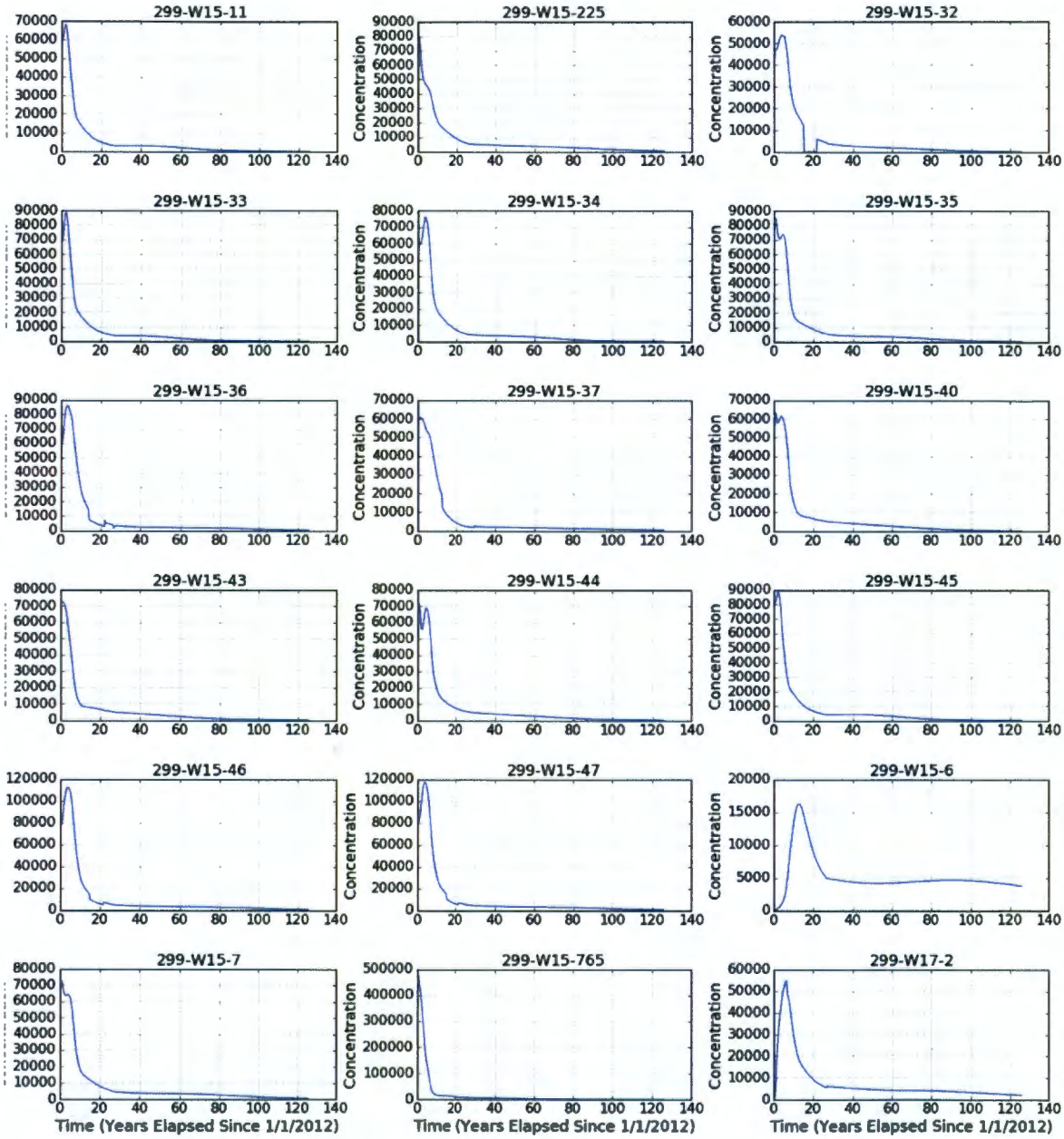

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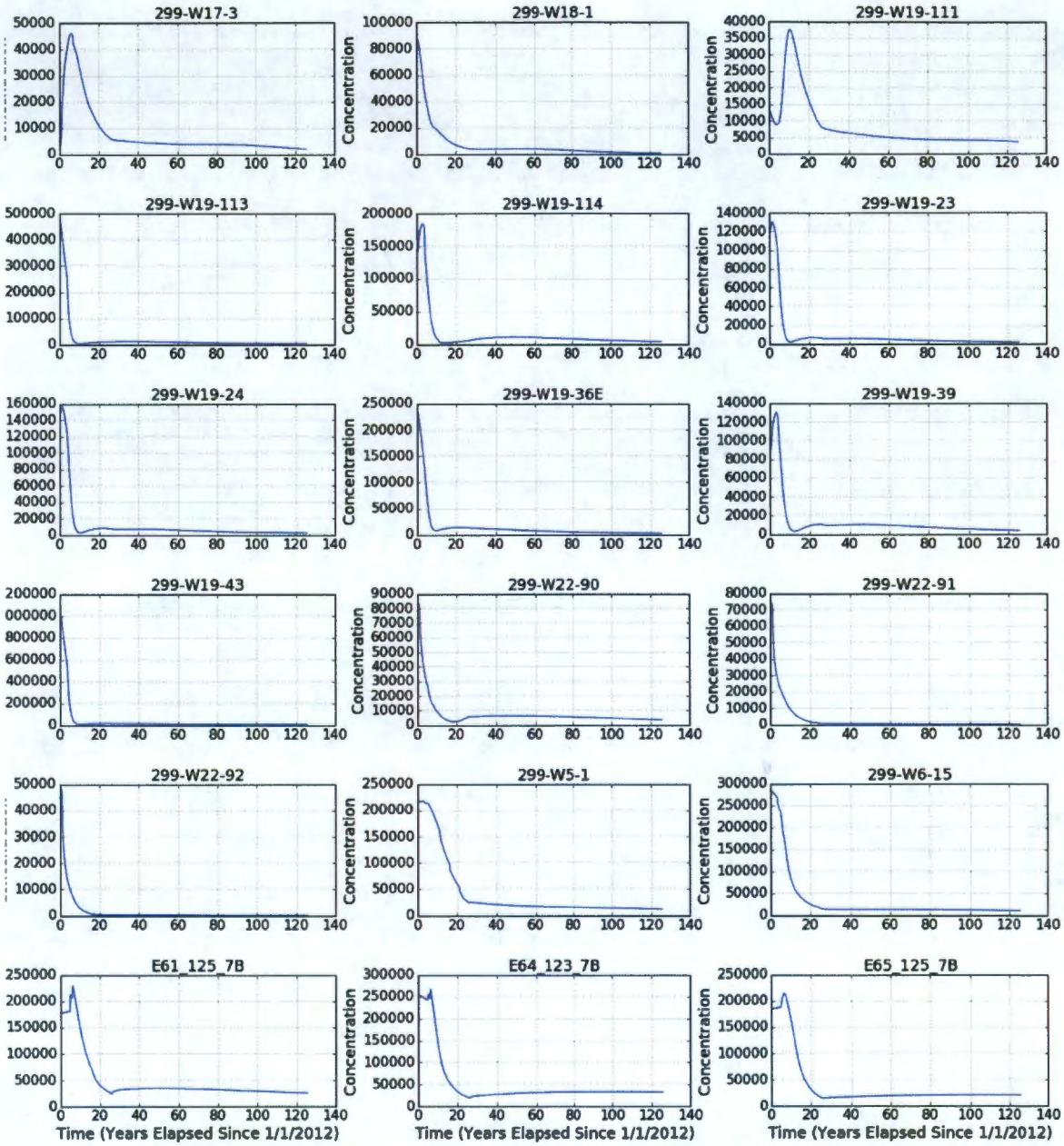

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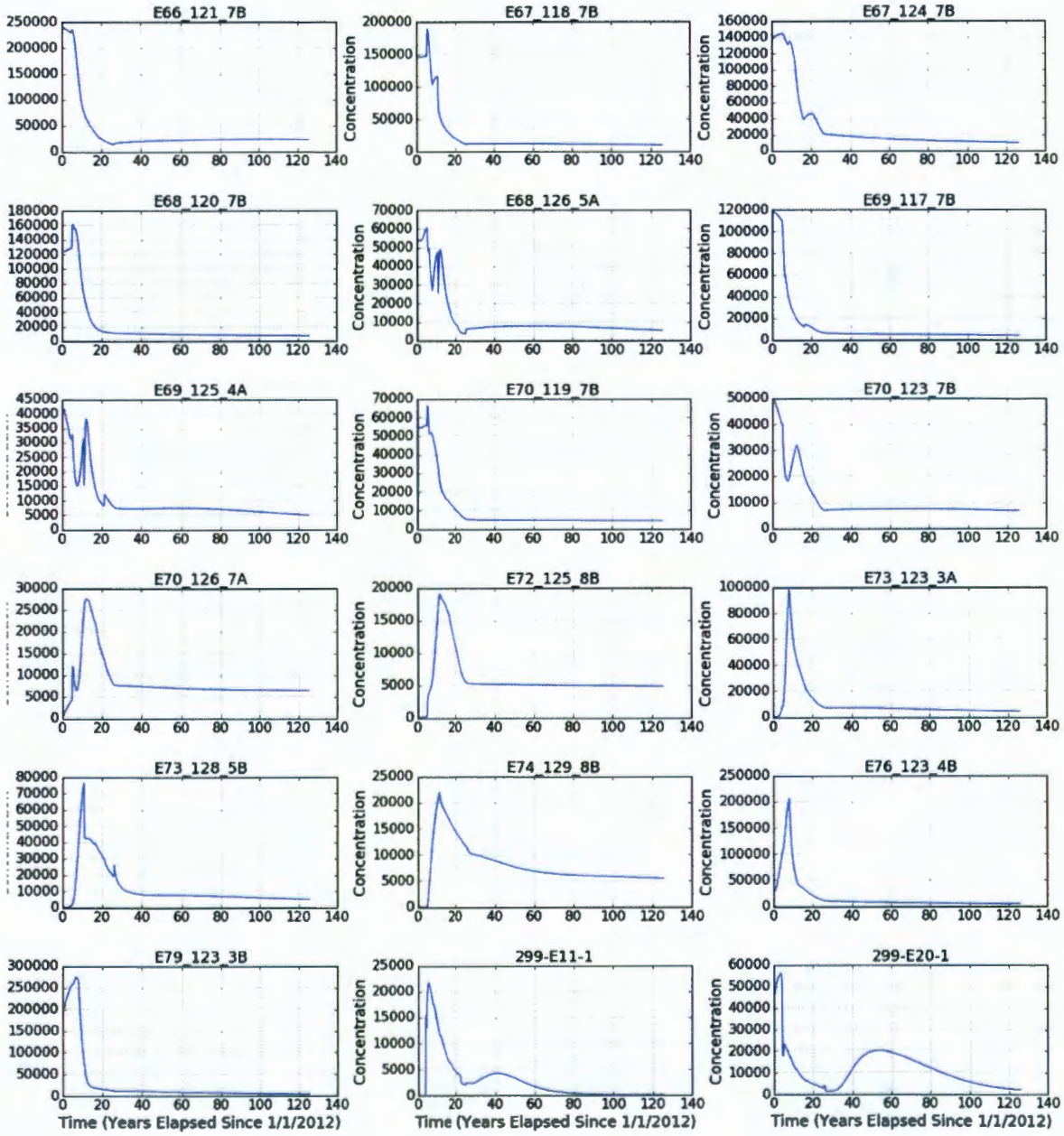

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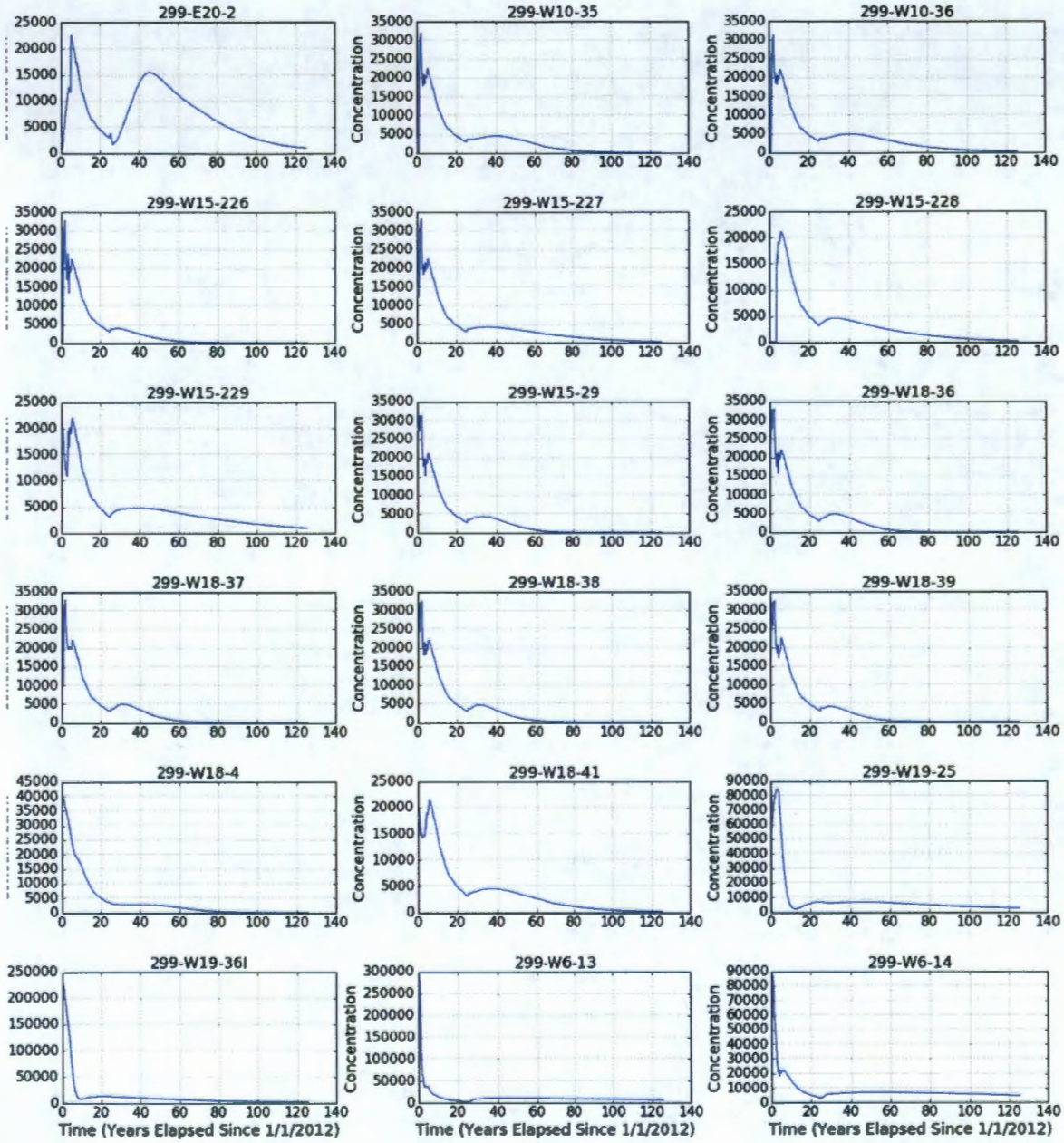
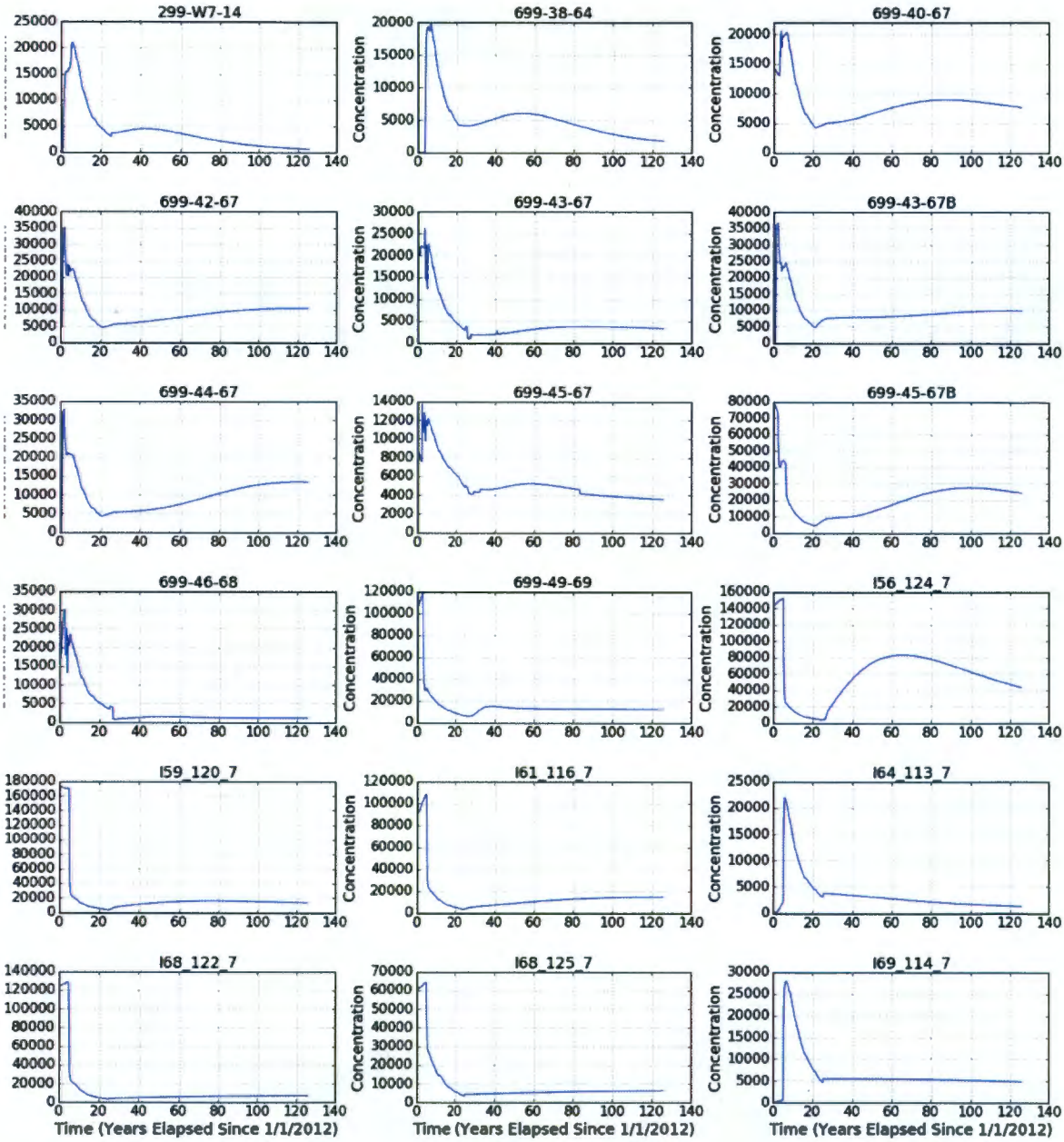
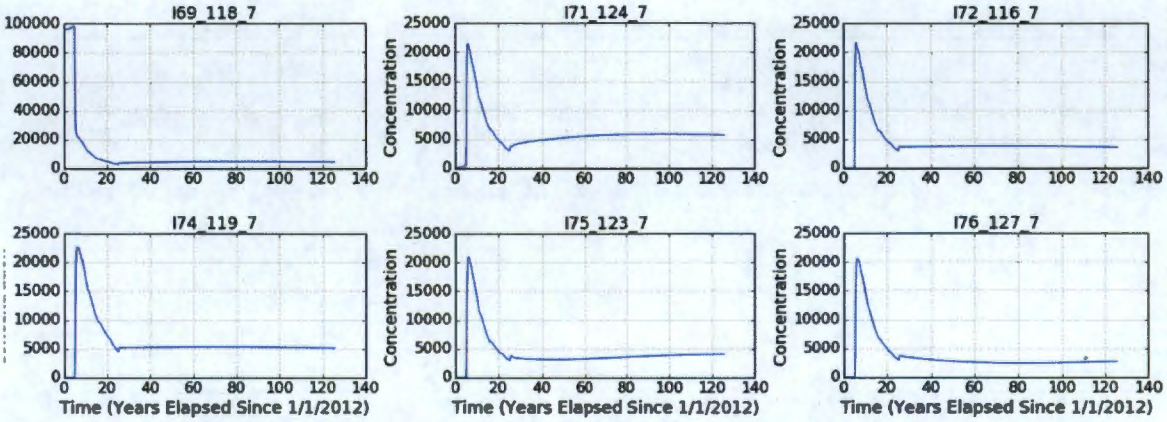


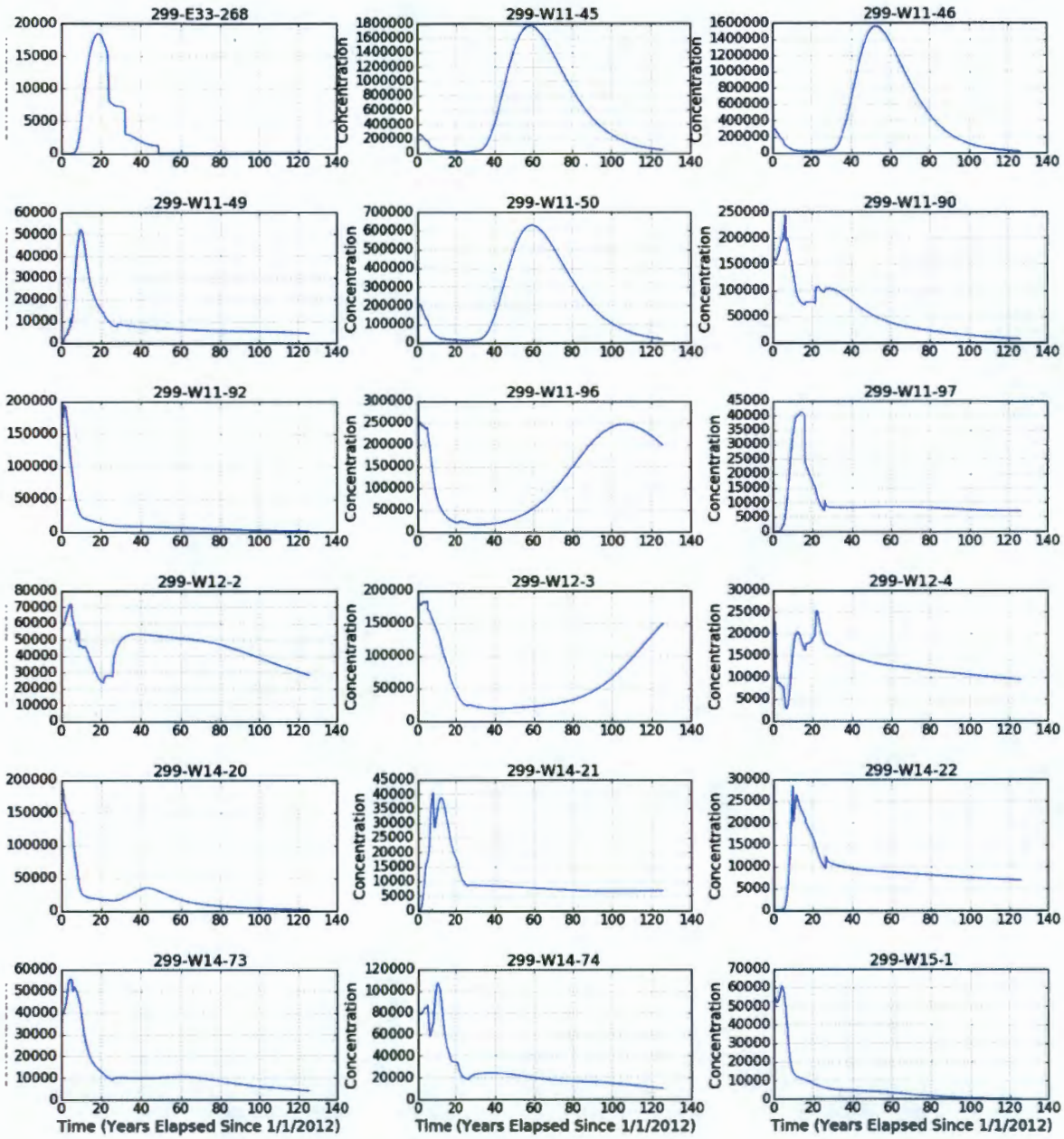
Simulated Extraction Concentrations in ug/L for Nitrate for Optimization Case 13



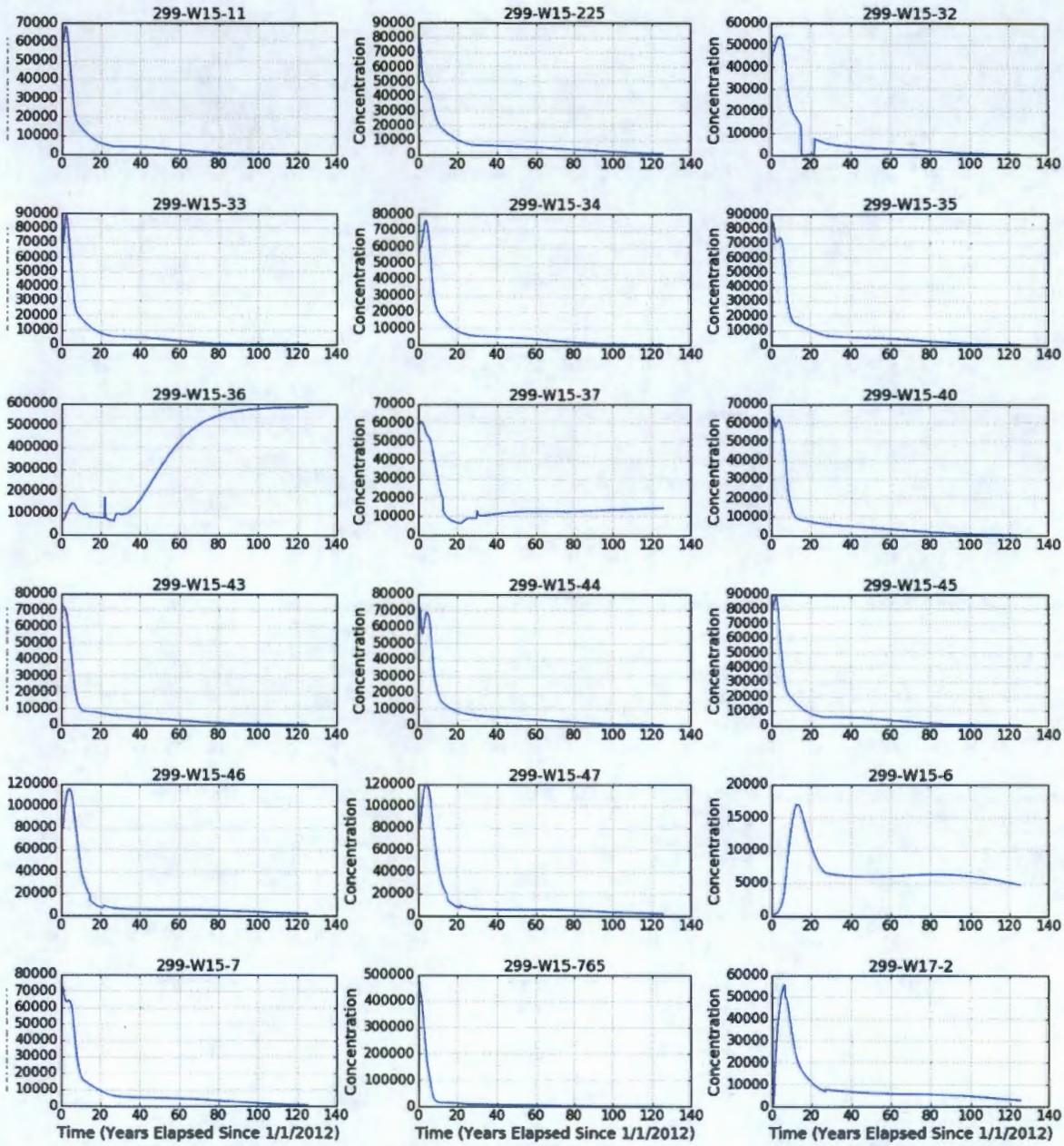
Simulated Extraction Concentrations in ug/L for Nitrate for Optimization Case 13



Simulated Extraction Concentrations in ug/L for Nitrate With Source for Optimization Case 13



Simulated Extraction Concentrations in ug/L for Nitrate With Source for Optimization Case 13



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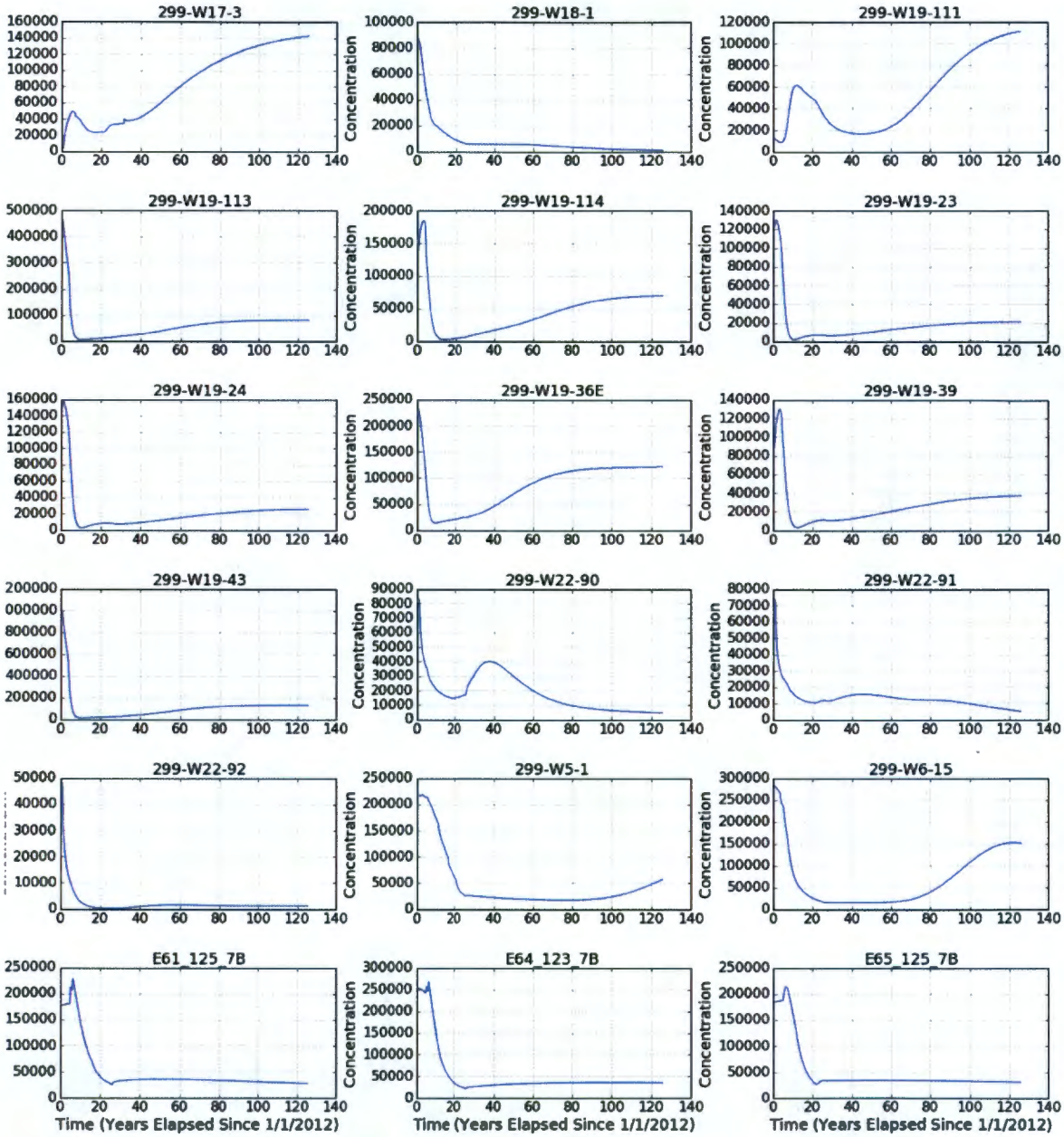

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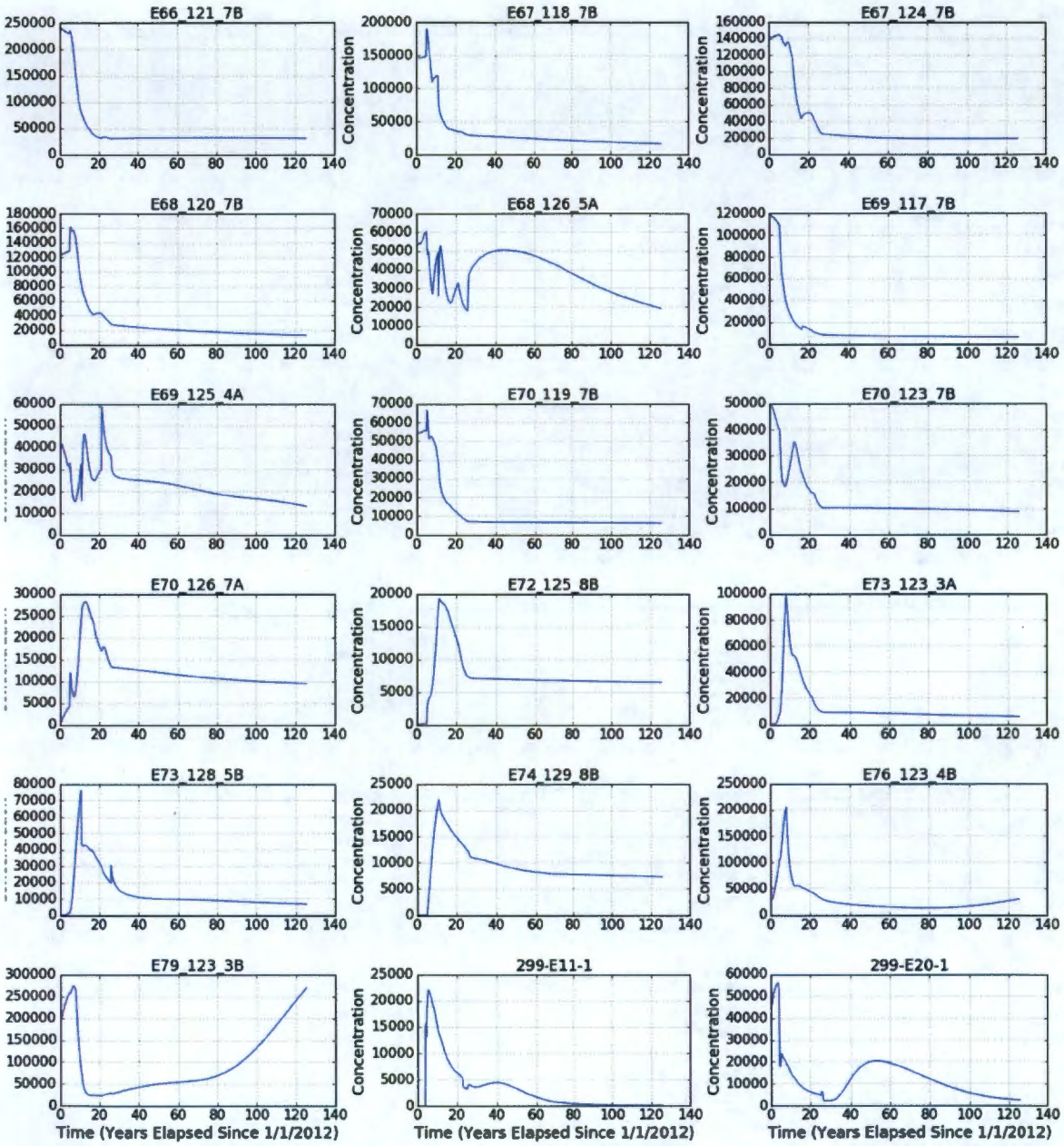

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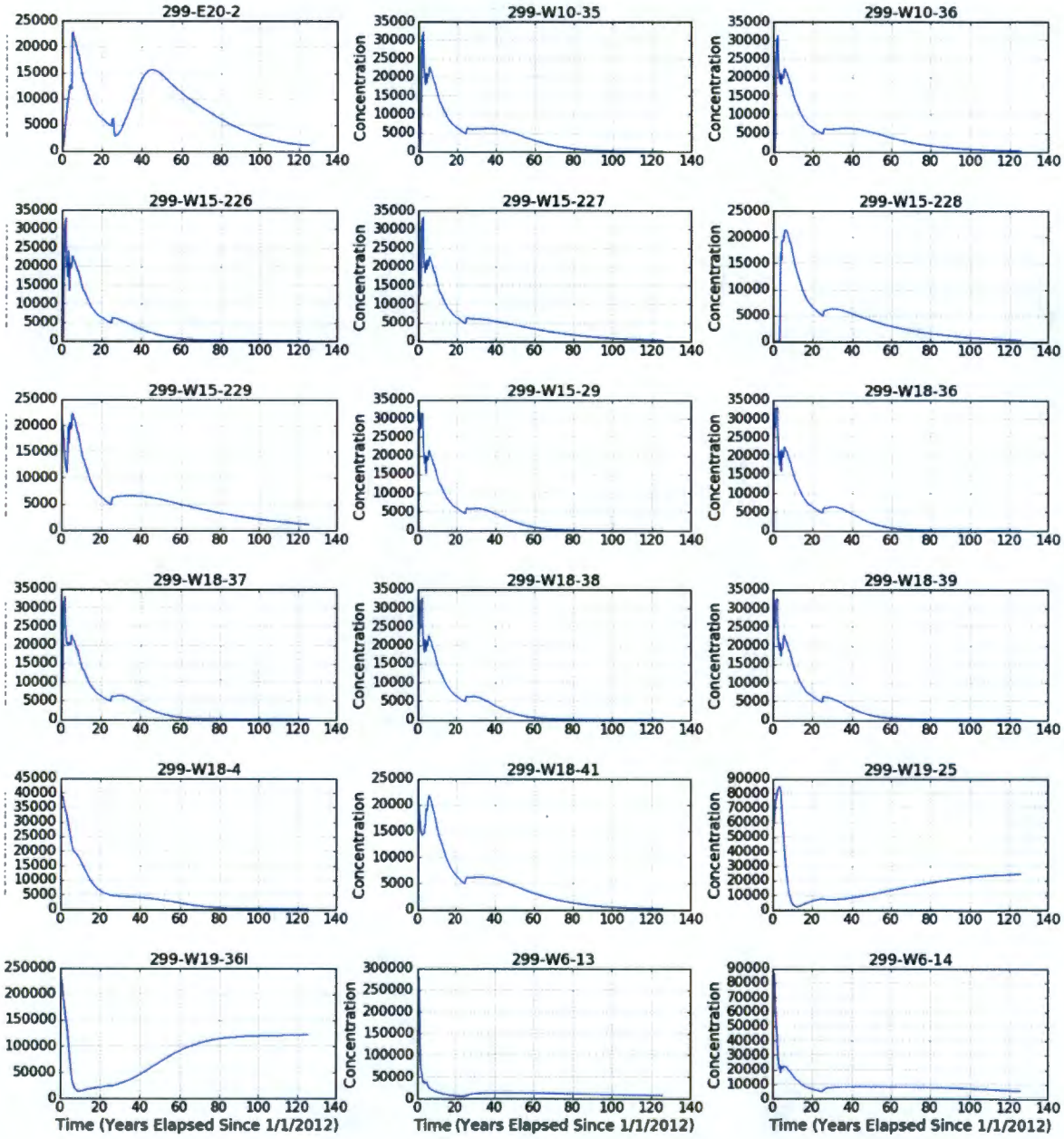
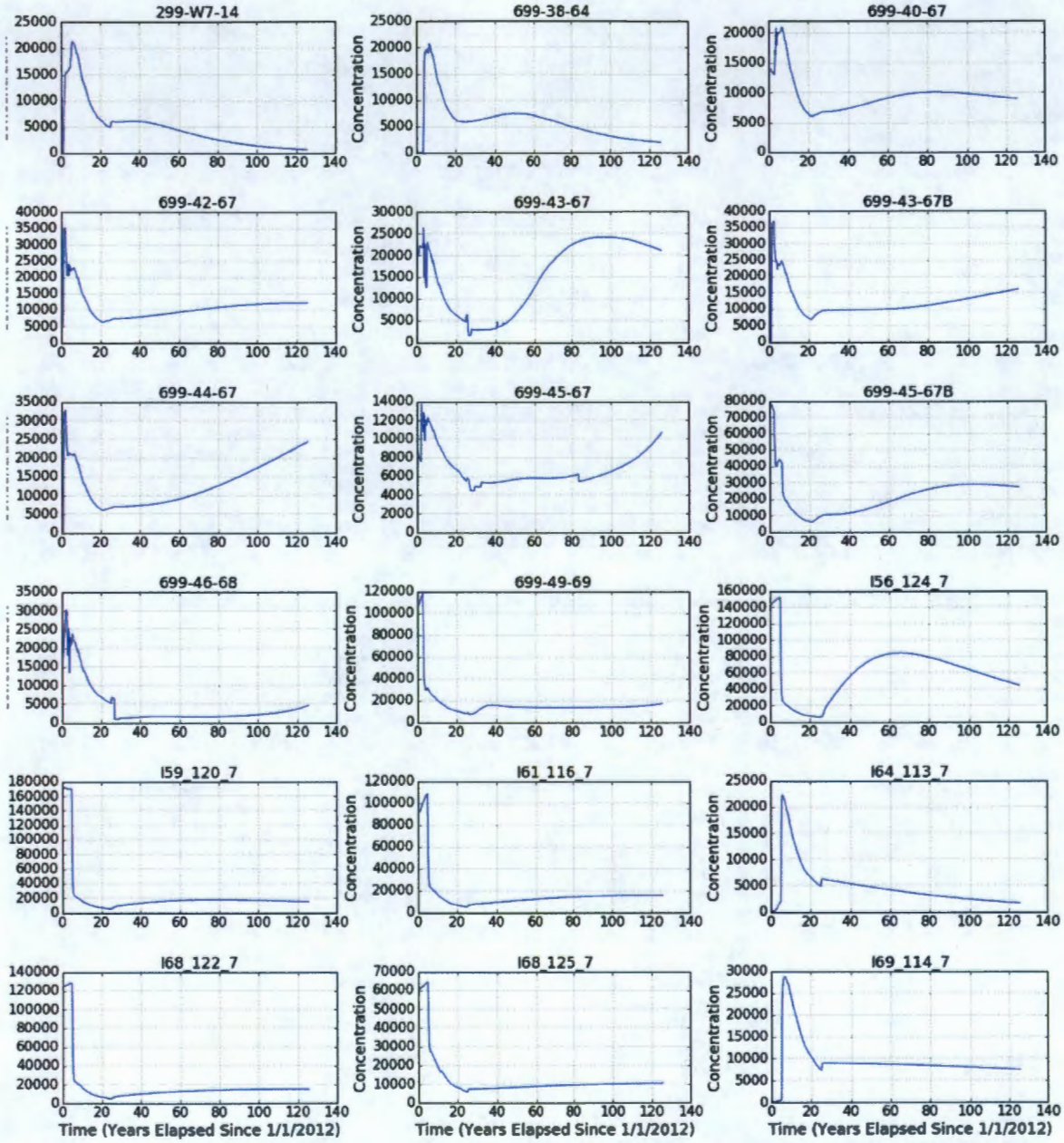
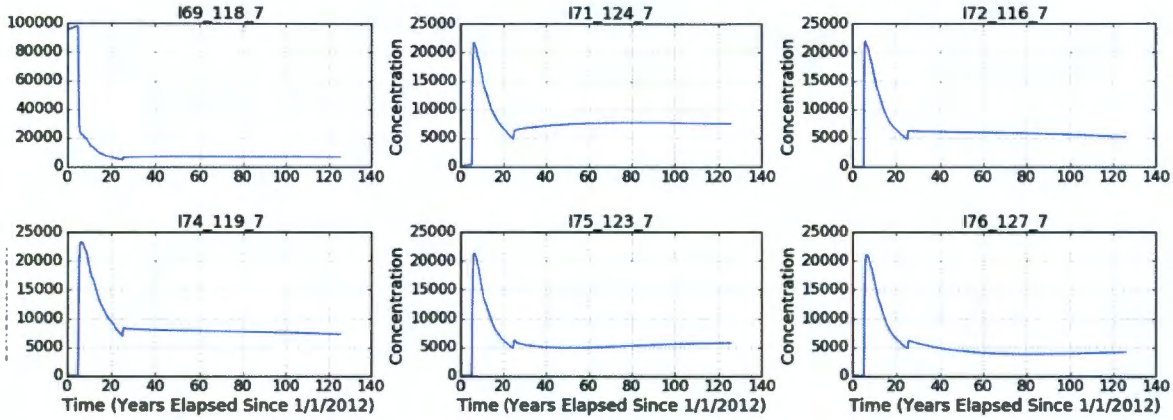


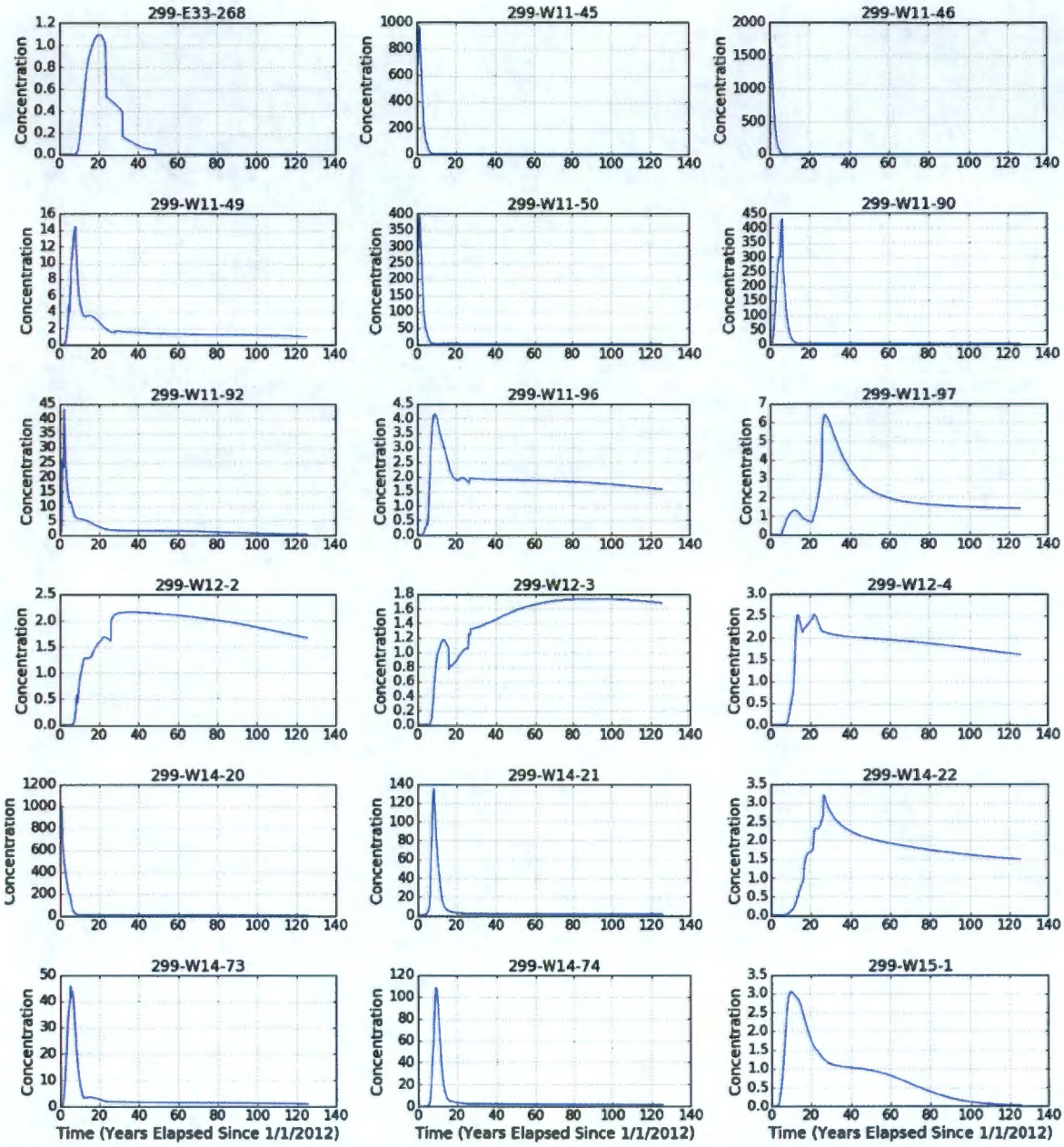
Simulated Extraction Concentrations in ug/L for Nitrate With Source for Optimization Case 13



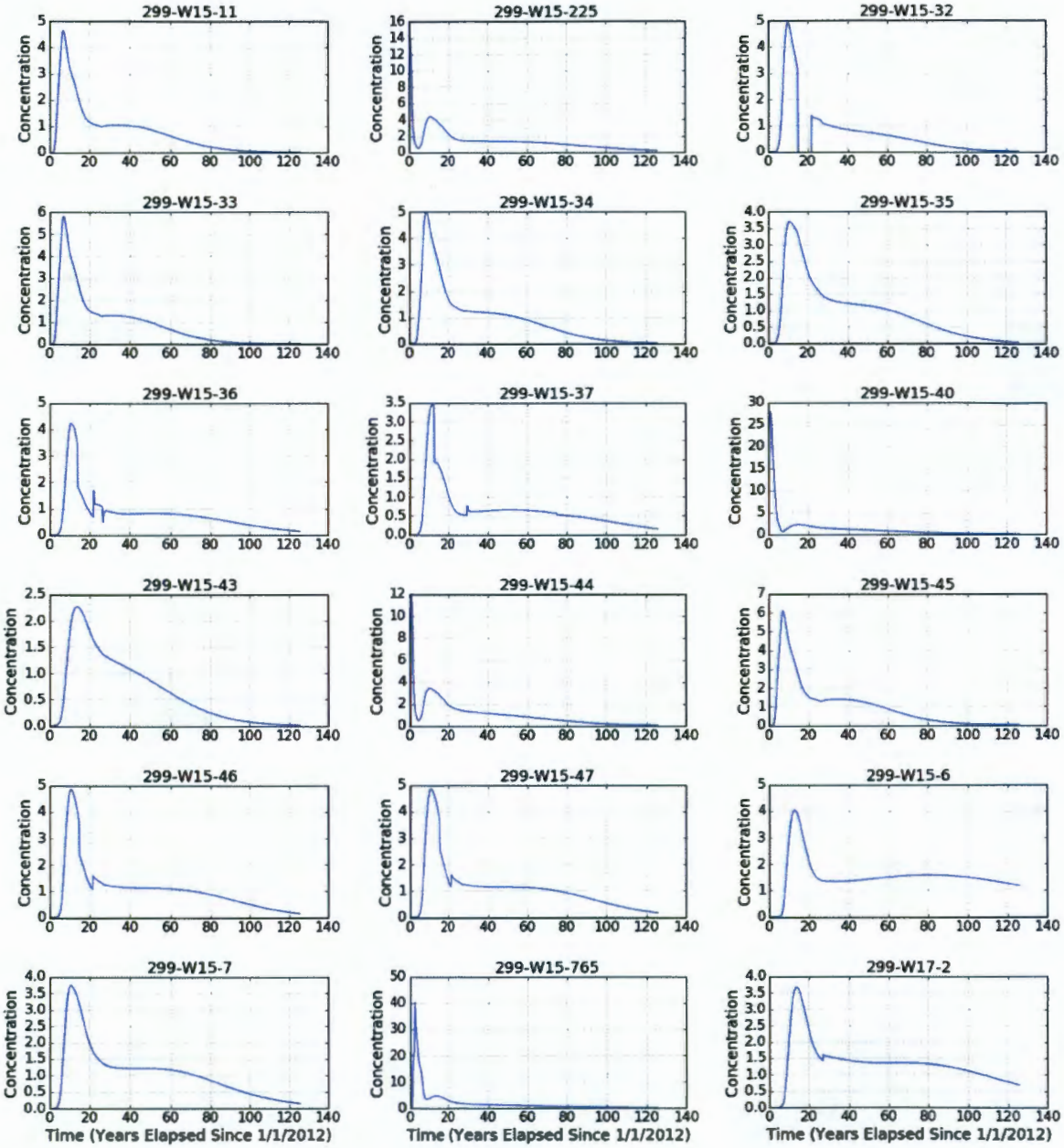
Simulated Extraction Concentrations in ug/L for Nitrate With Source for Optimization Case 13



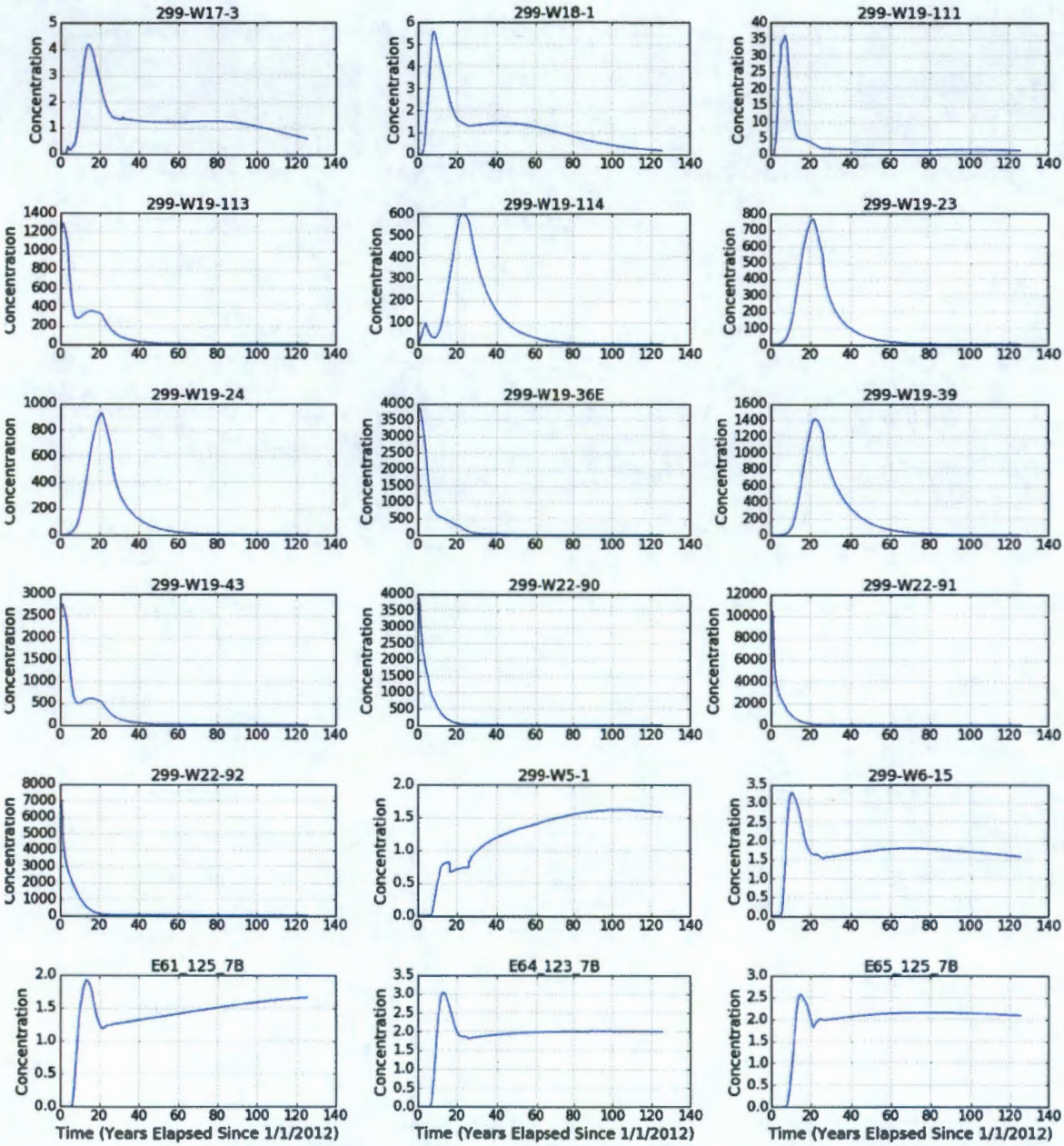
Simulated Extraction Concentrations in pCi/L for Tc-99 for Optimization Case 13



Simulated Extraction Concentrations in pCi/L for Tc-99 for Optimization Case 13



Simulated Extraction Concentrations in pCi/L for Tc-99 for Optimization Case 13



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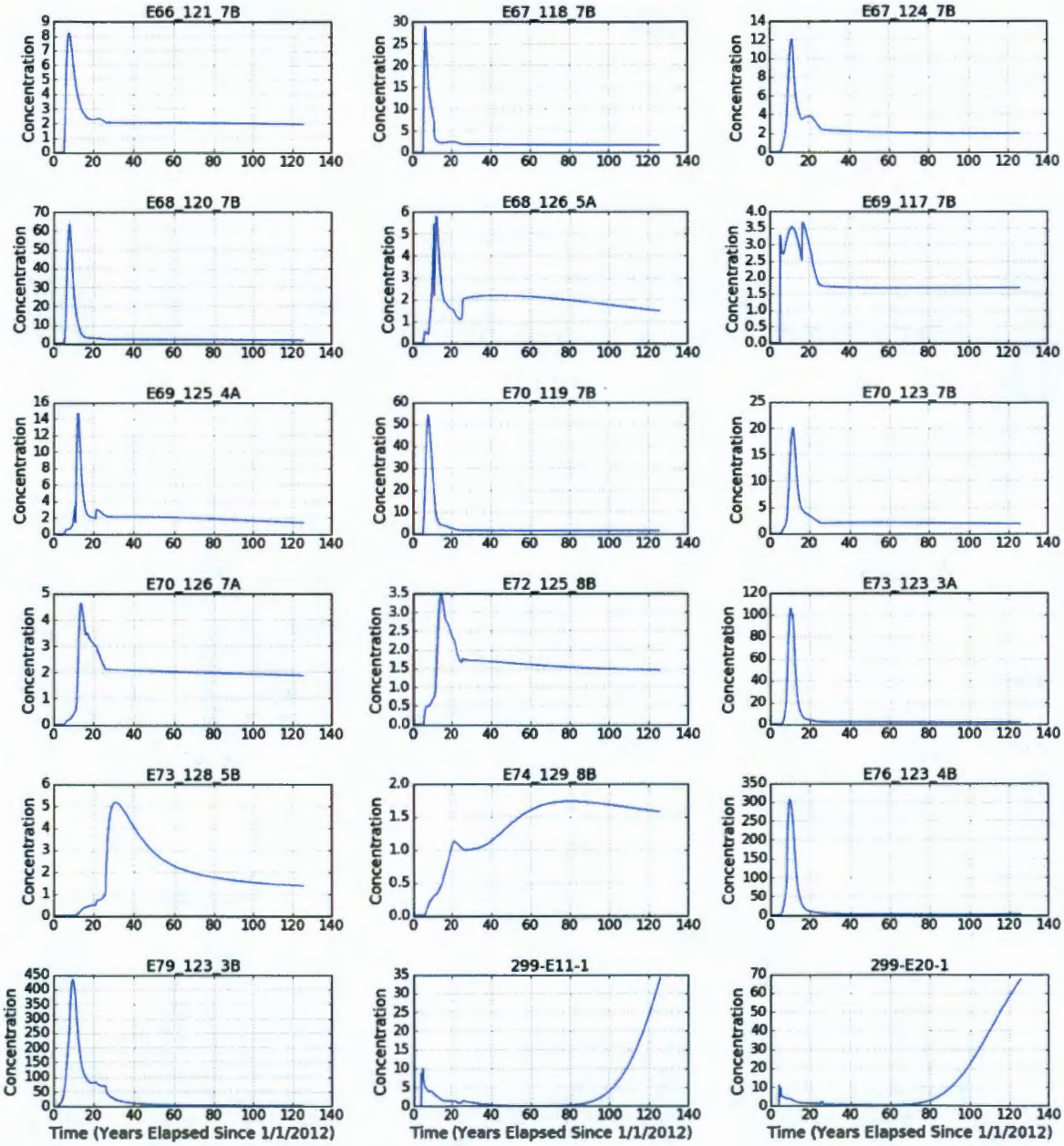

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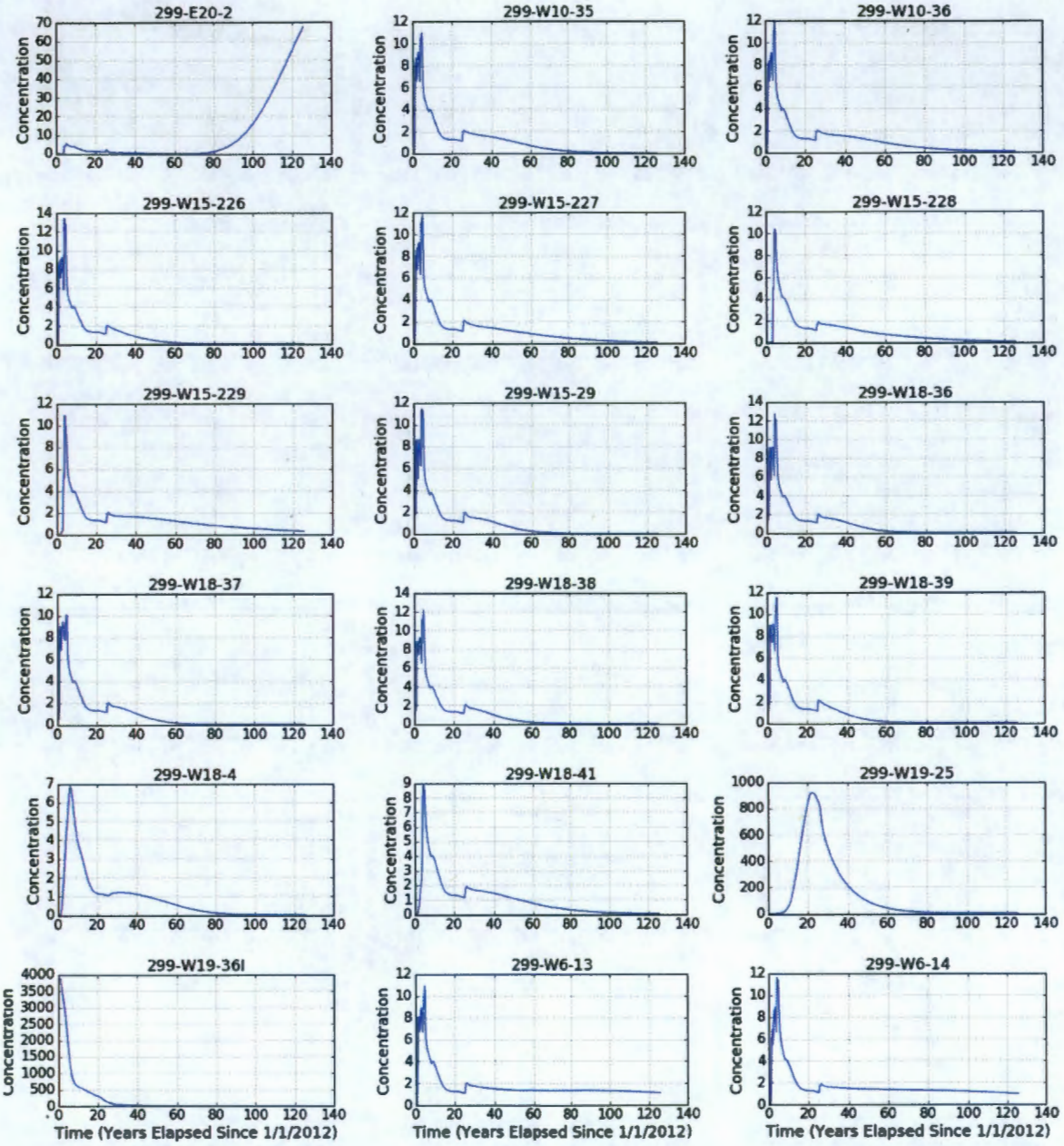
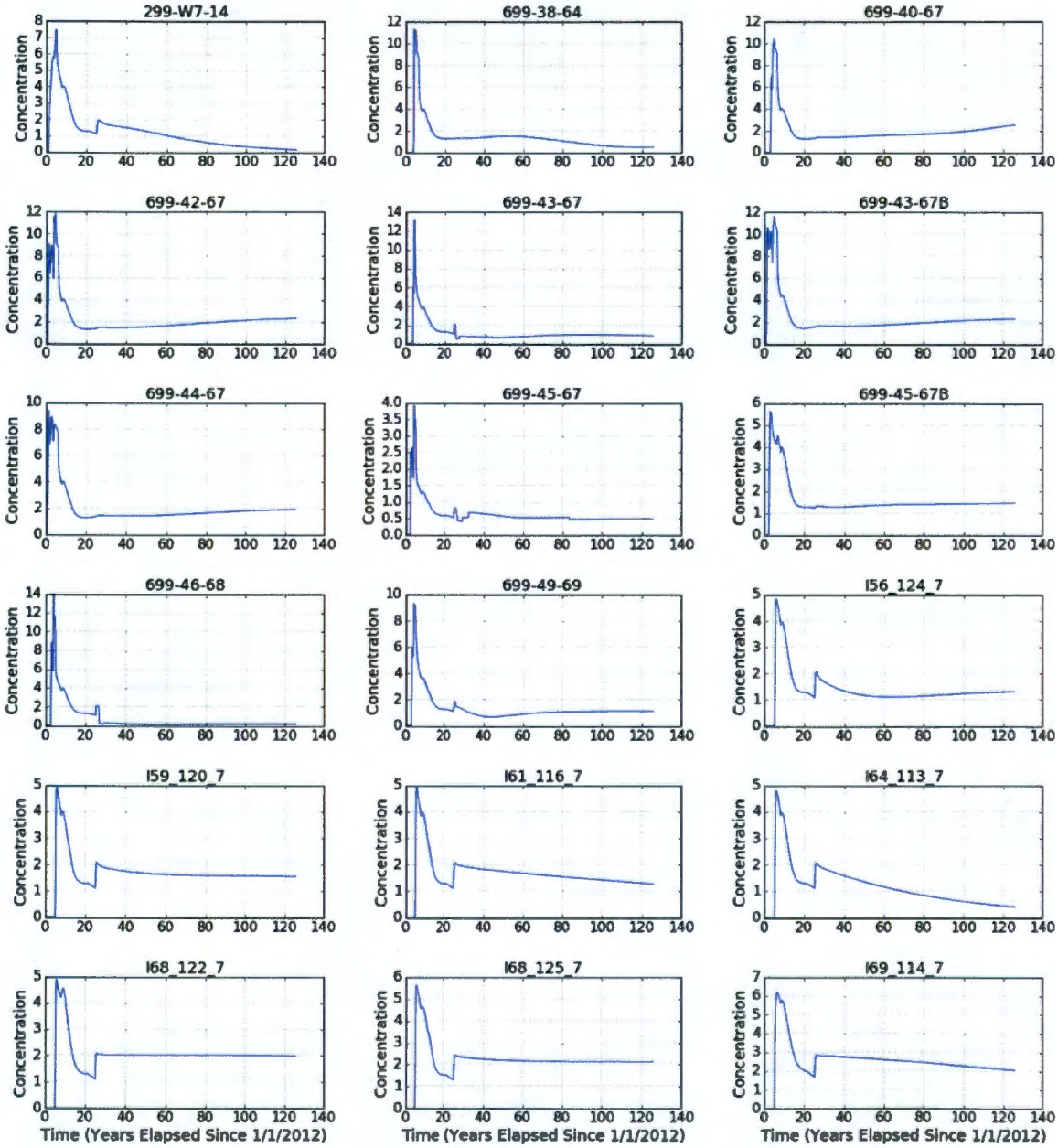
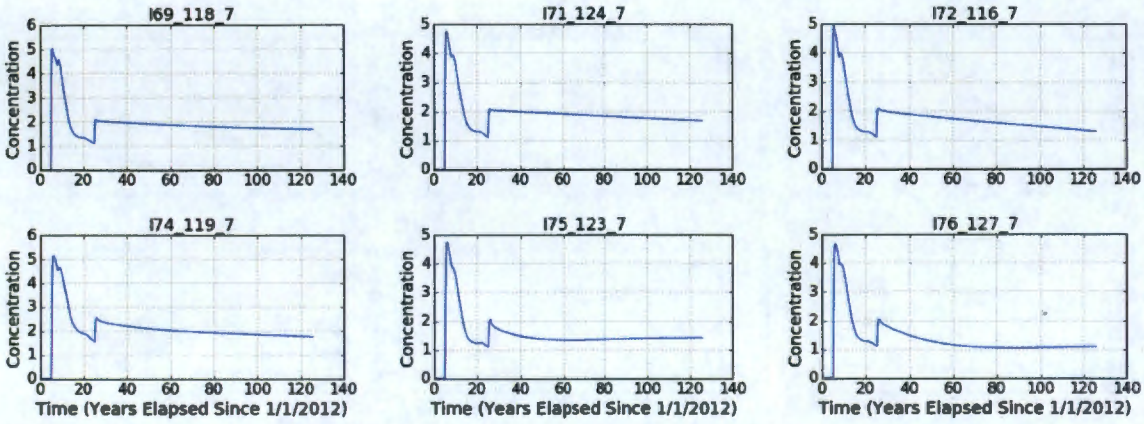


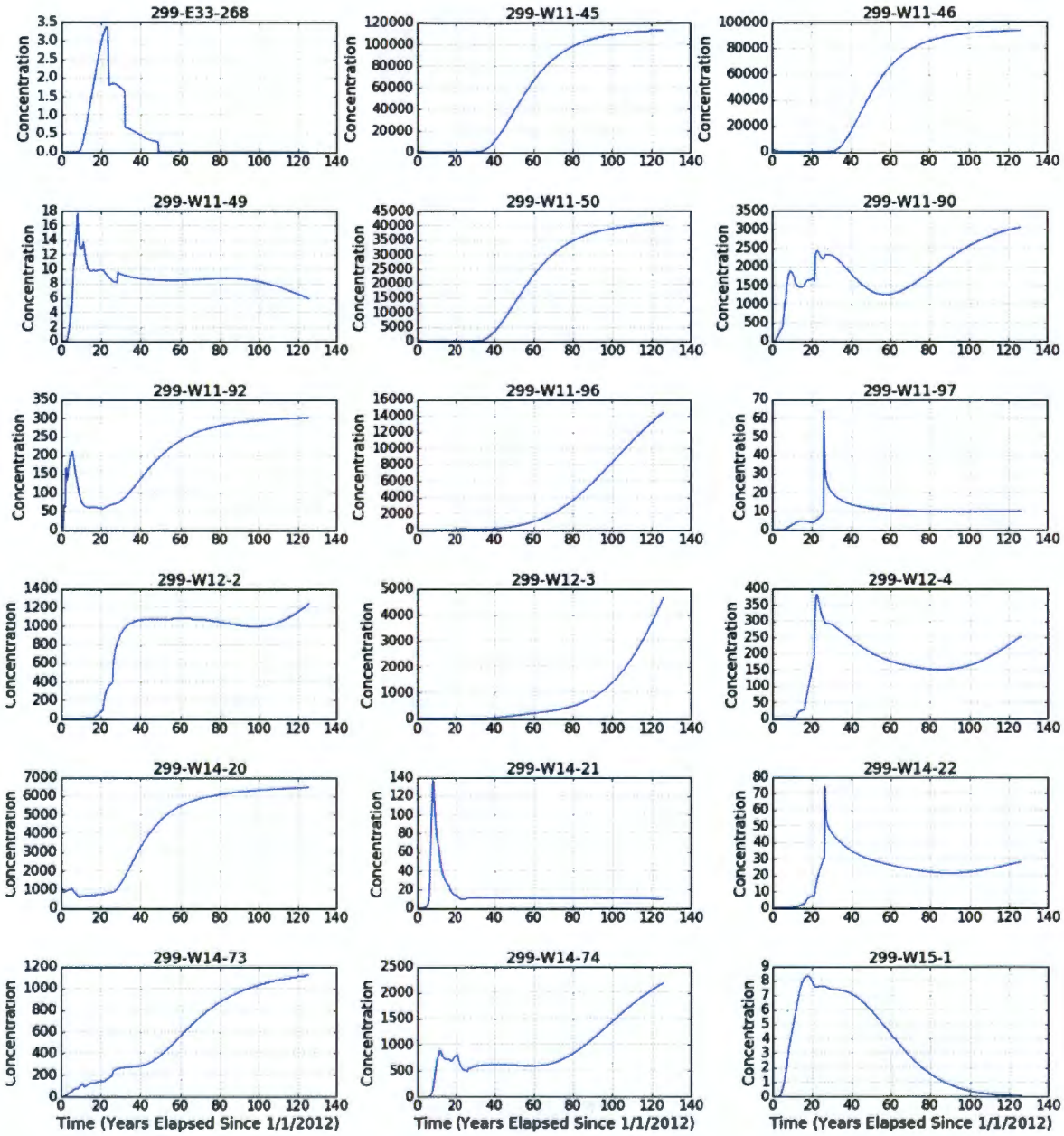
Simulated Extraction Concentrations in pCi/L for Tc-99 for Optimization Case 13



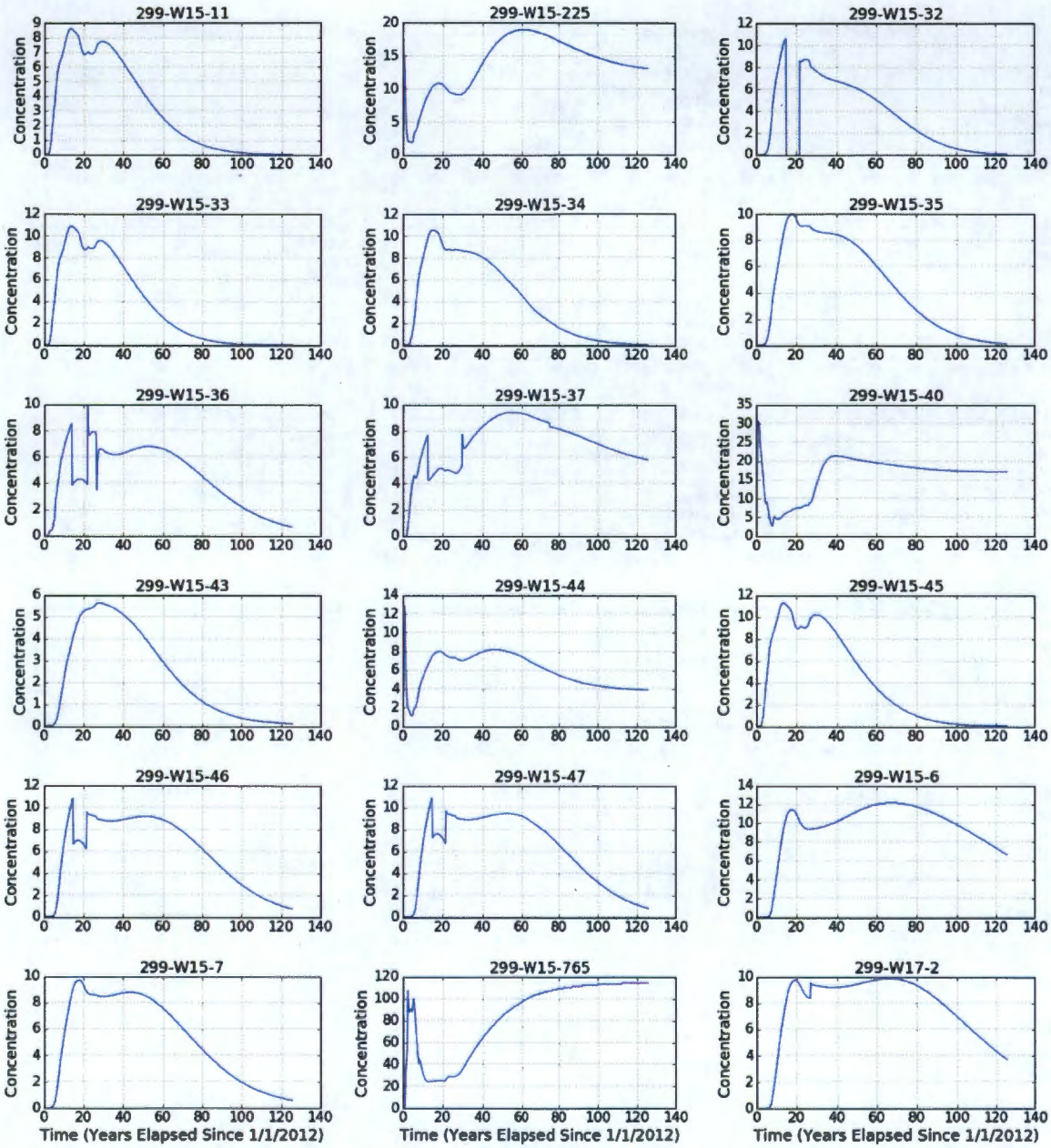
Simulated Extraction Concentrations in pCi/L for Tc-99 for Optimization Case 13



Simulated Extraction Concentrations in pCi/L for Tc-99 With Source for Optimization Case 13



Simulated Extraction Concentrations in pCi/L for Tc-99 With Source for Optimization Case 13



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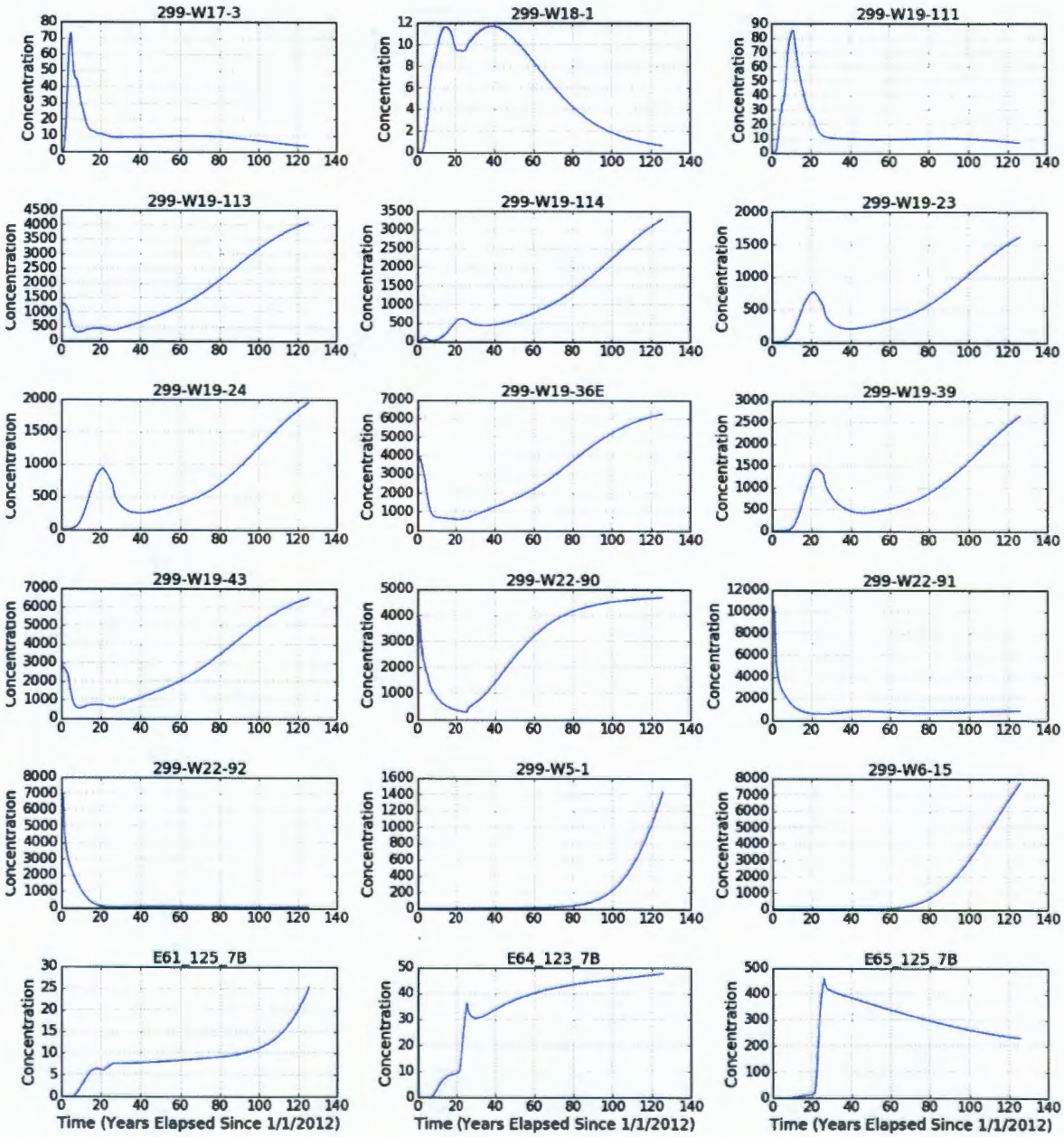
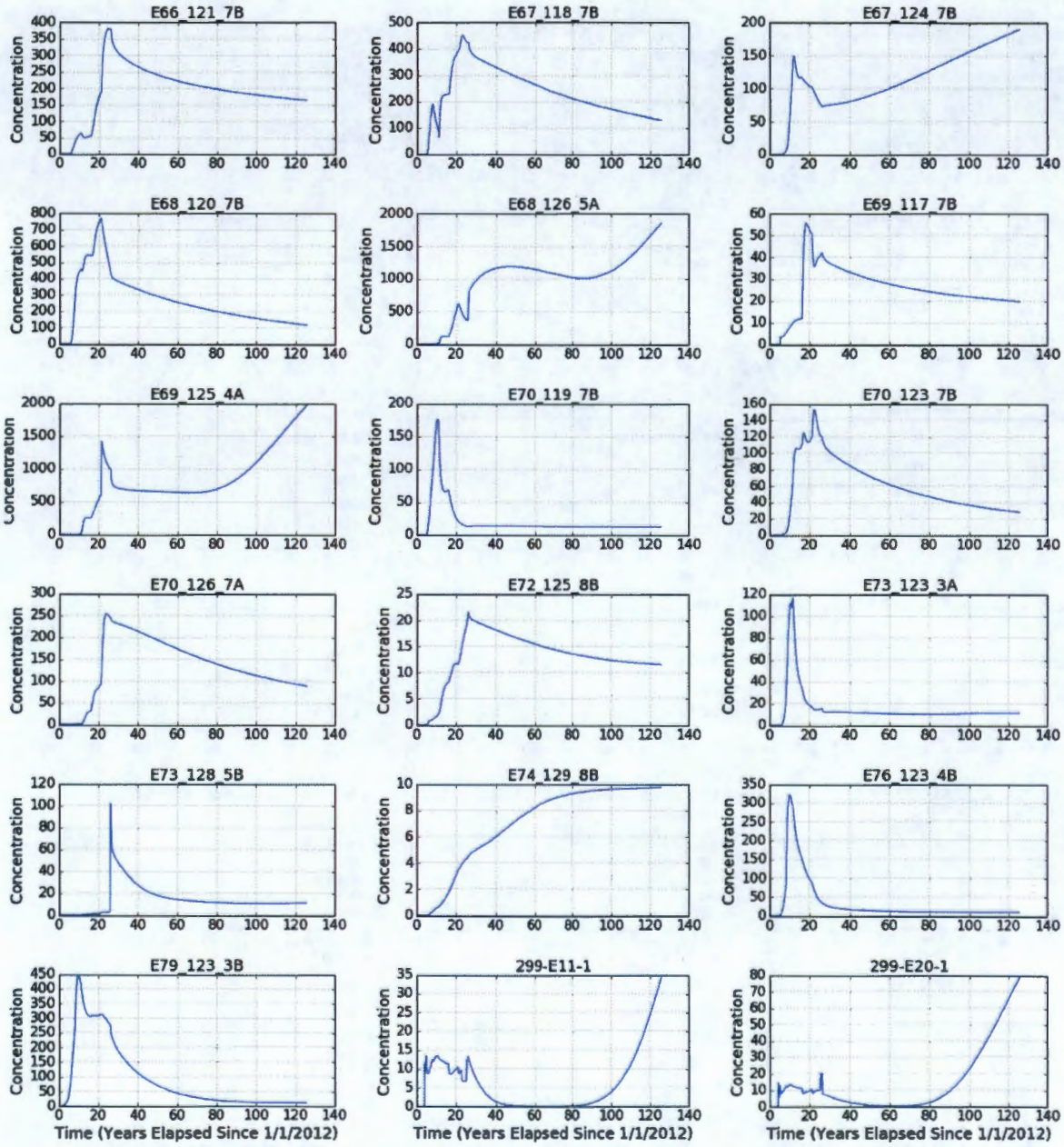


Simulated Extraction Concentrations in pCi/L for Tc-99 With Source for Optimization Case 13



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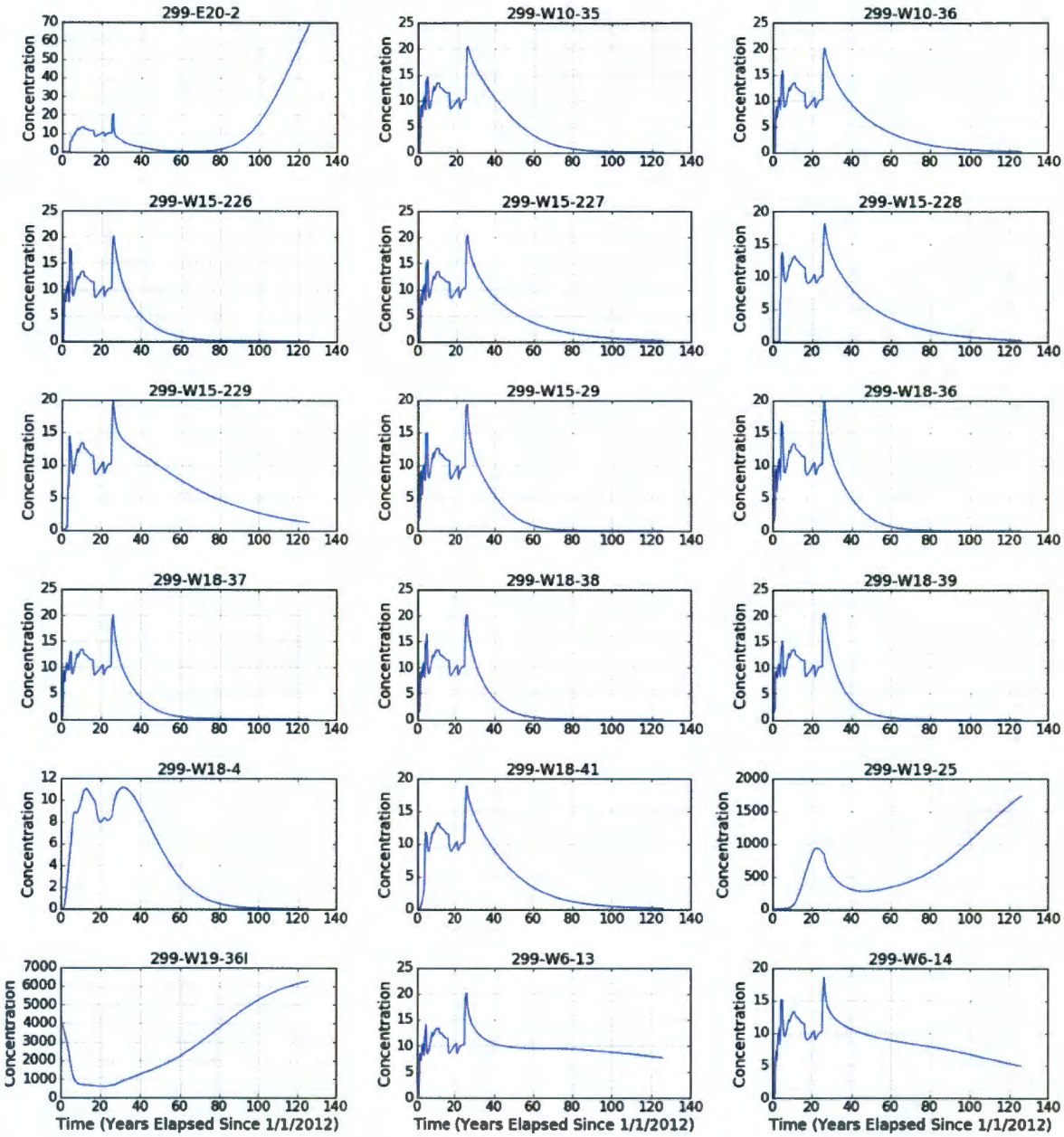

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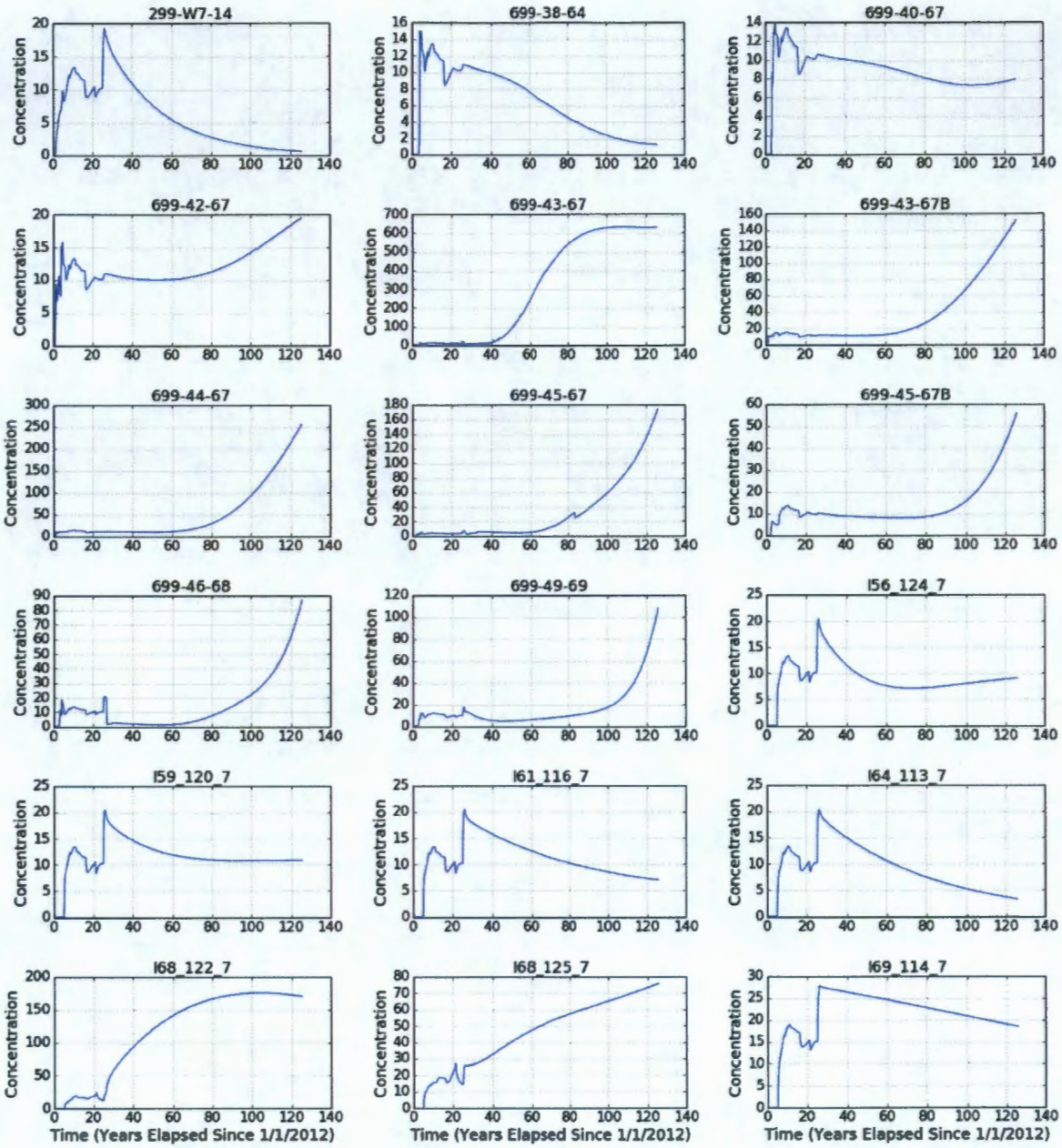

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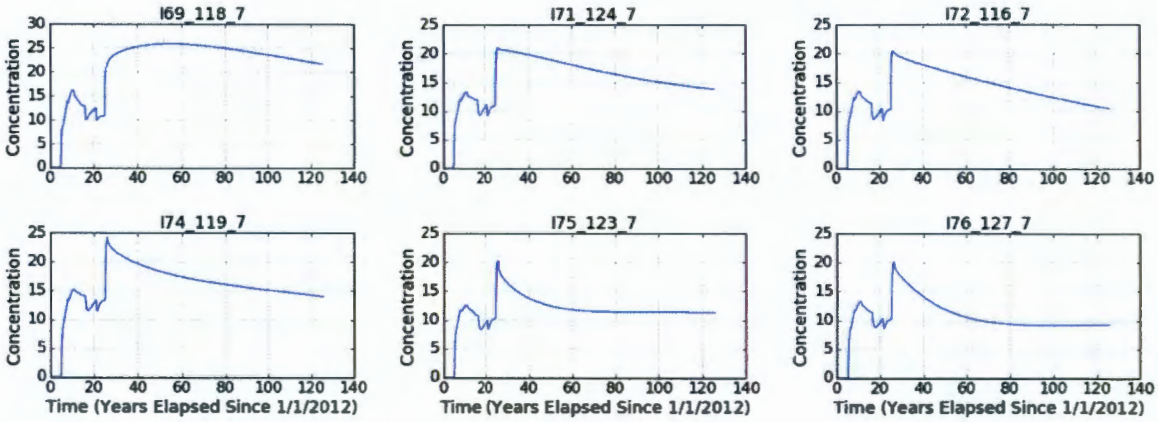
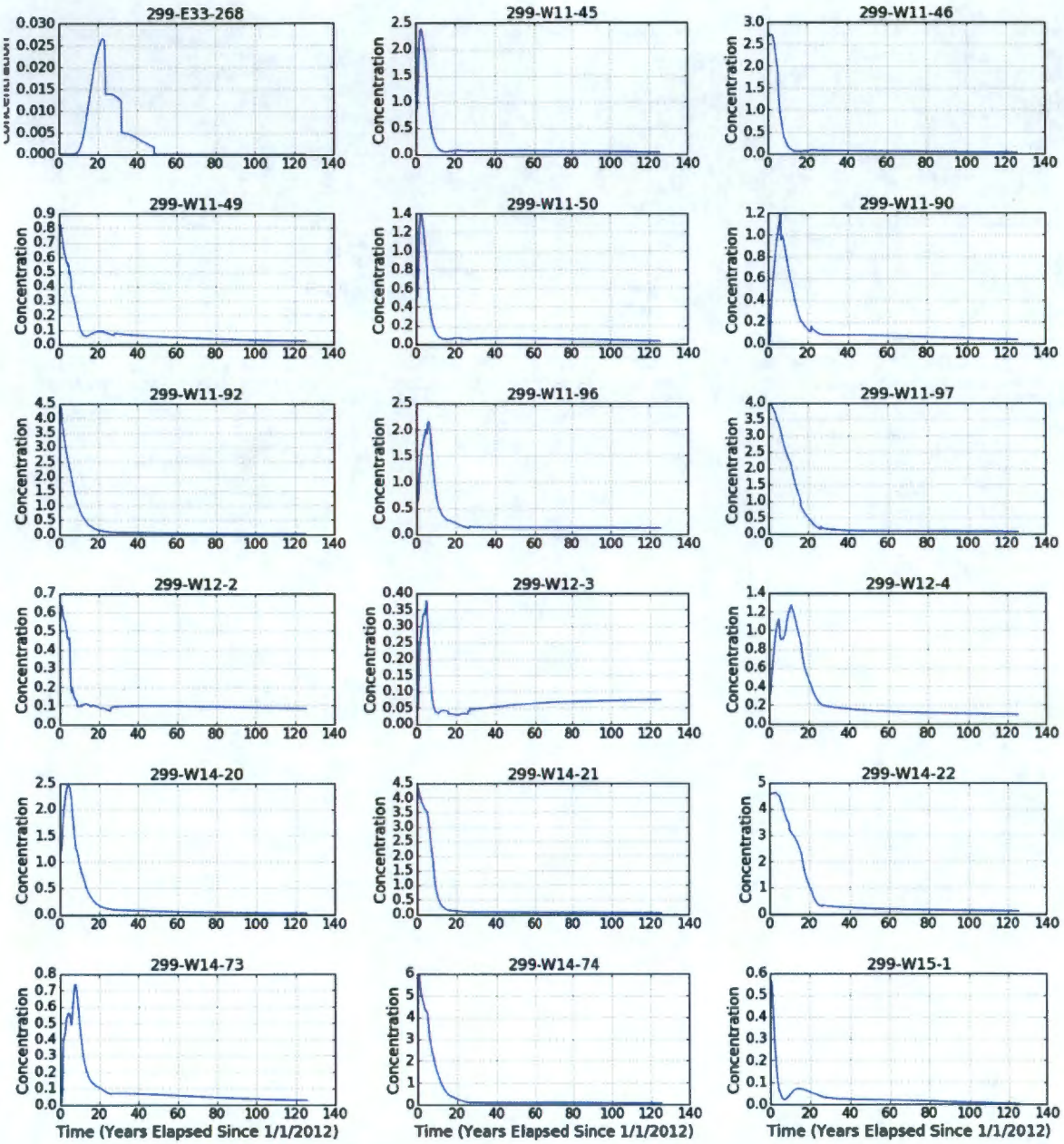
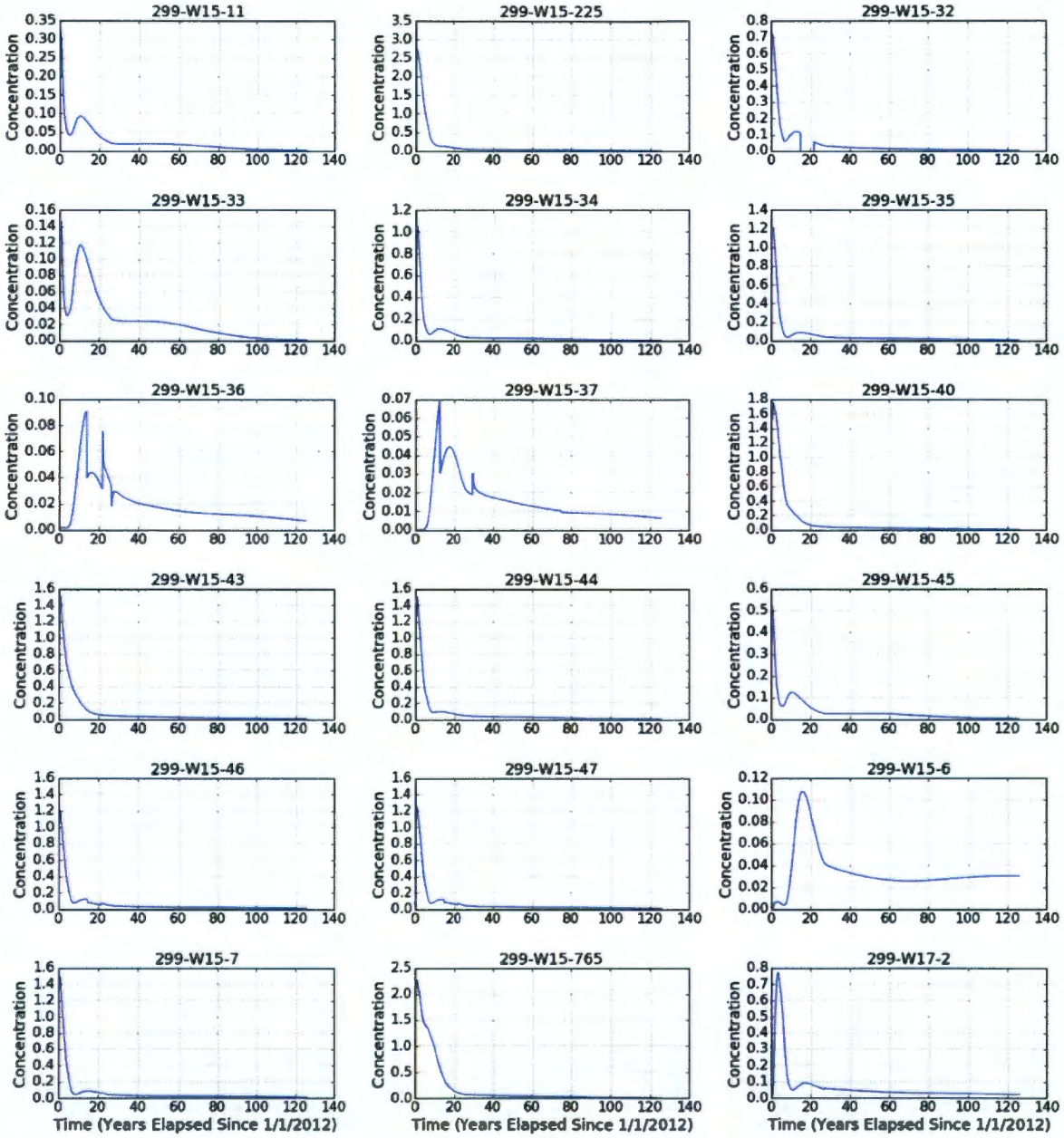


Simulated Extraction Concentrations in ug/L for TCE for Optimization Case 13



Simulated Extraction Concentrations in ug/L for TCE for Optimization Case 13



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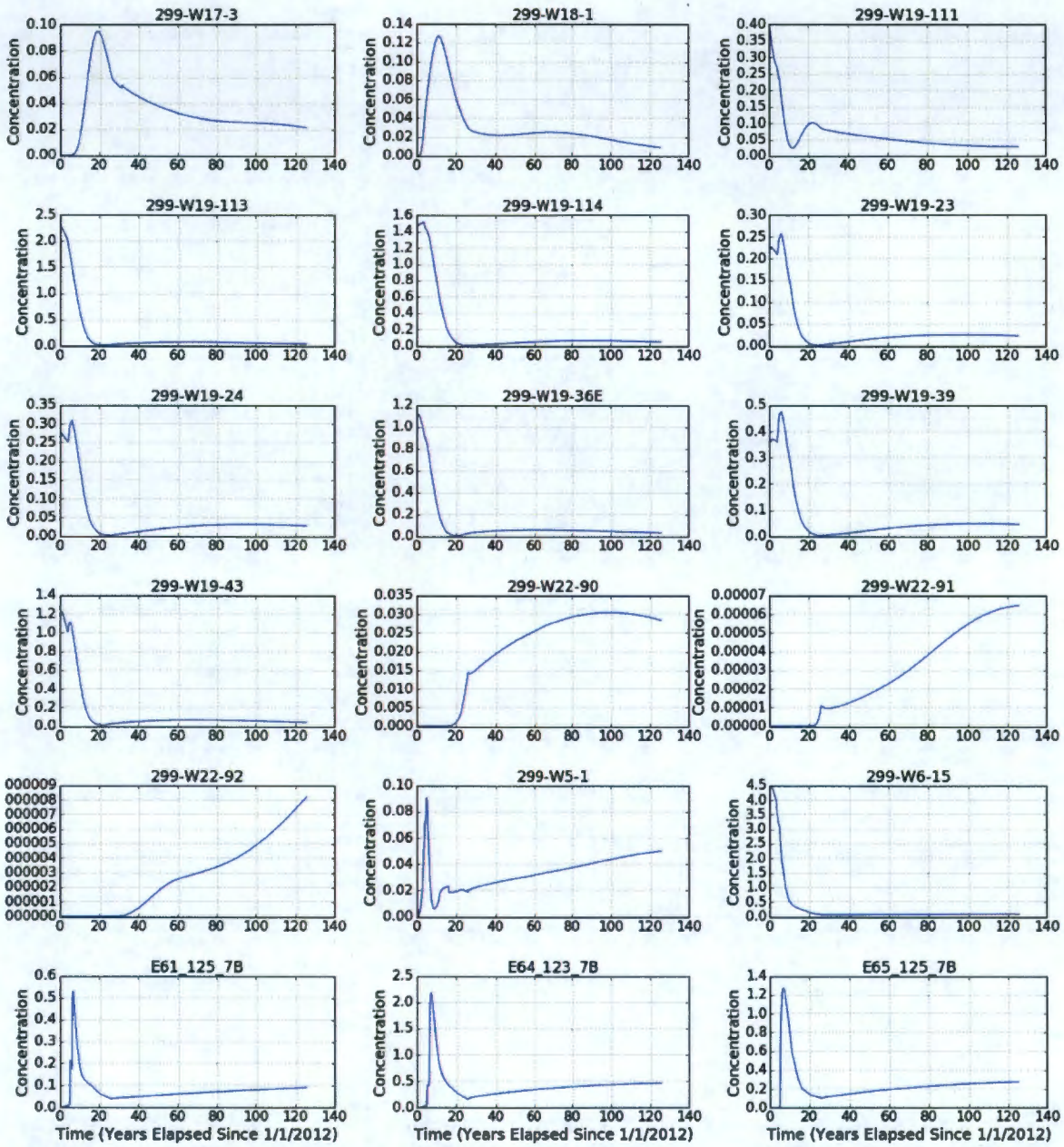

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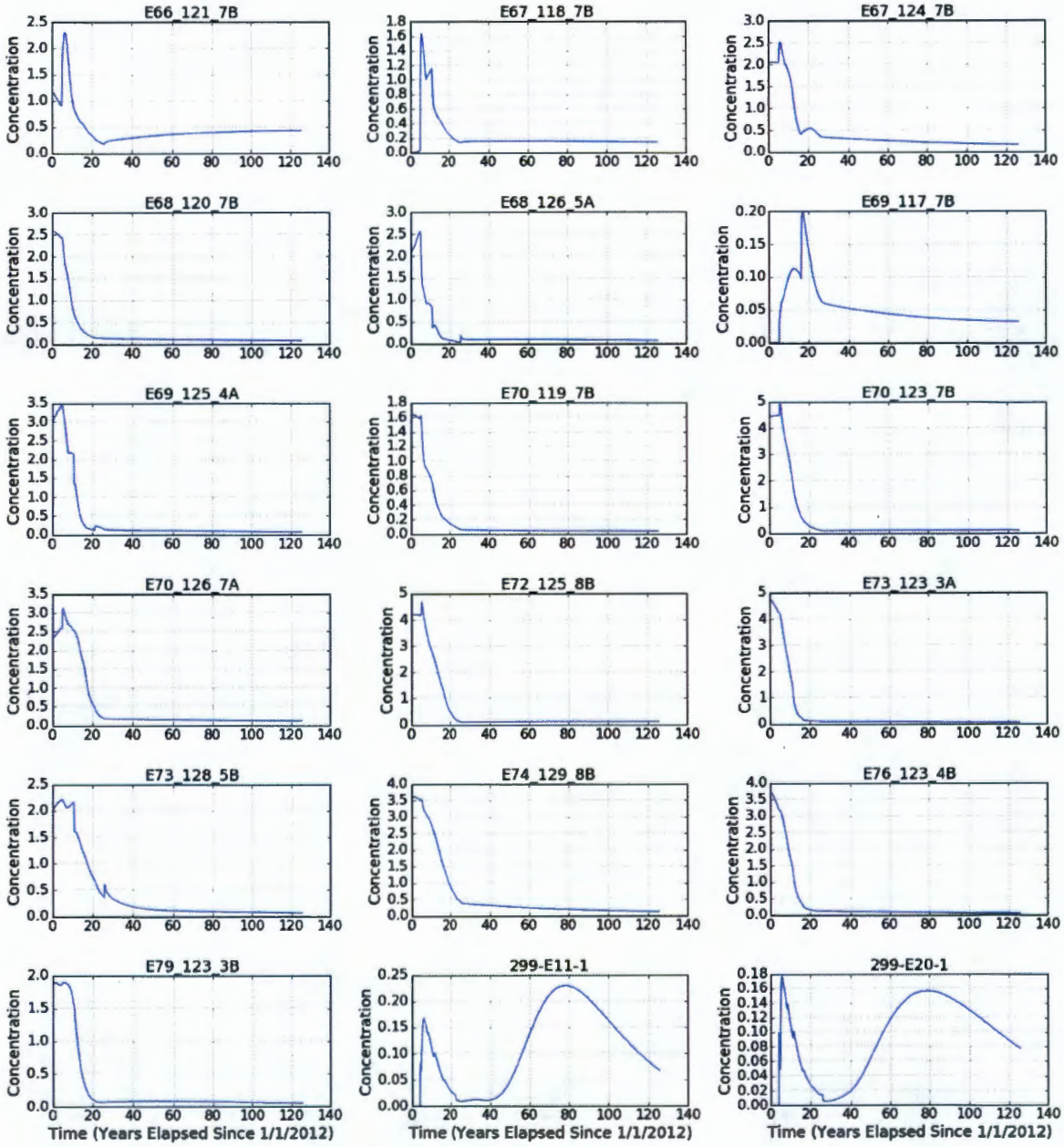

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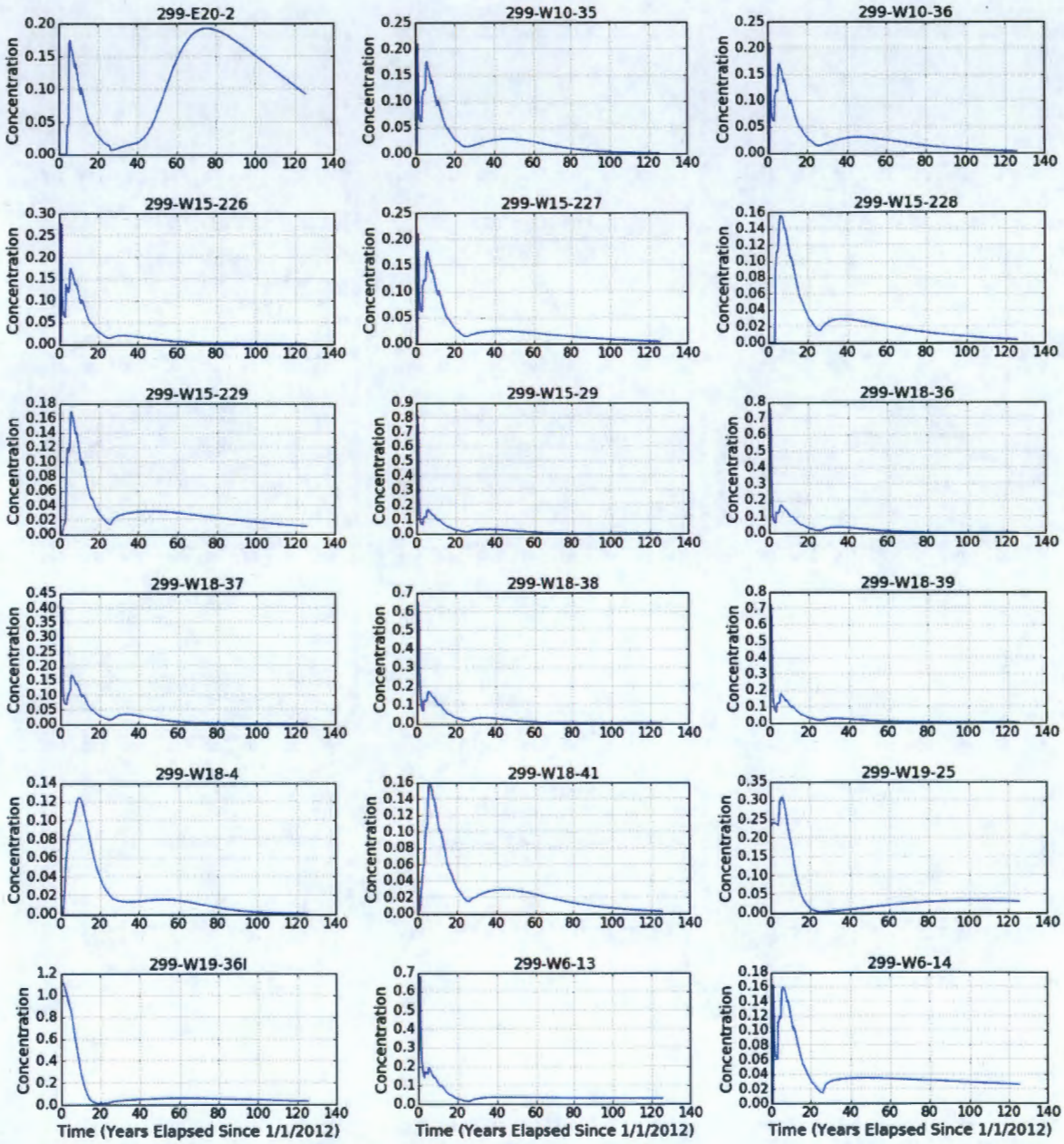
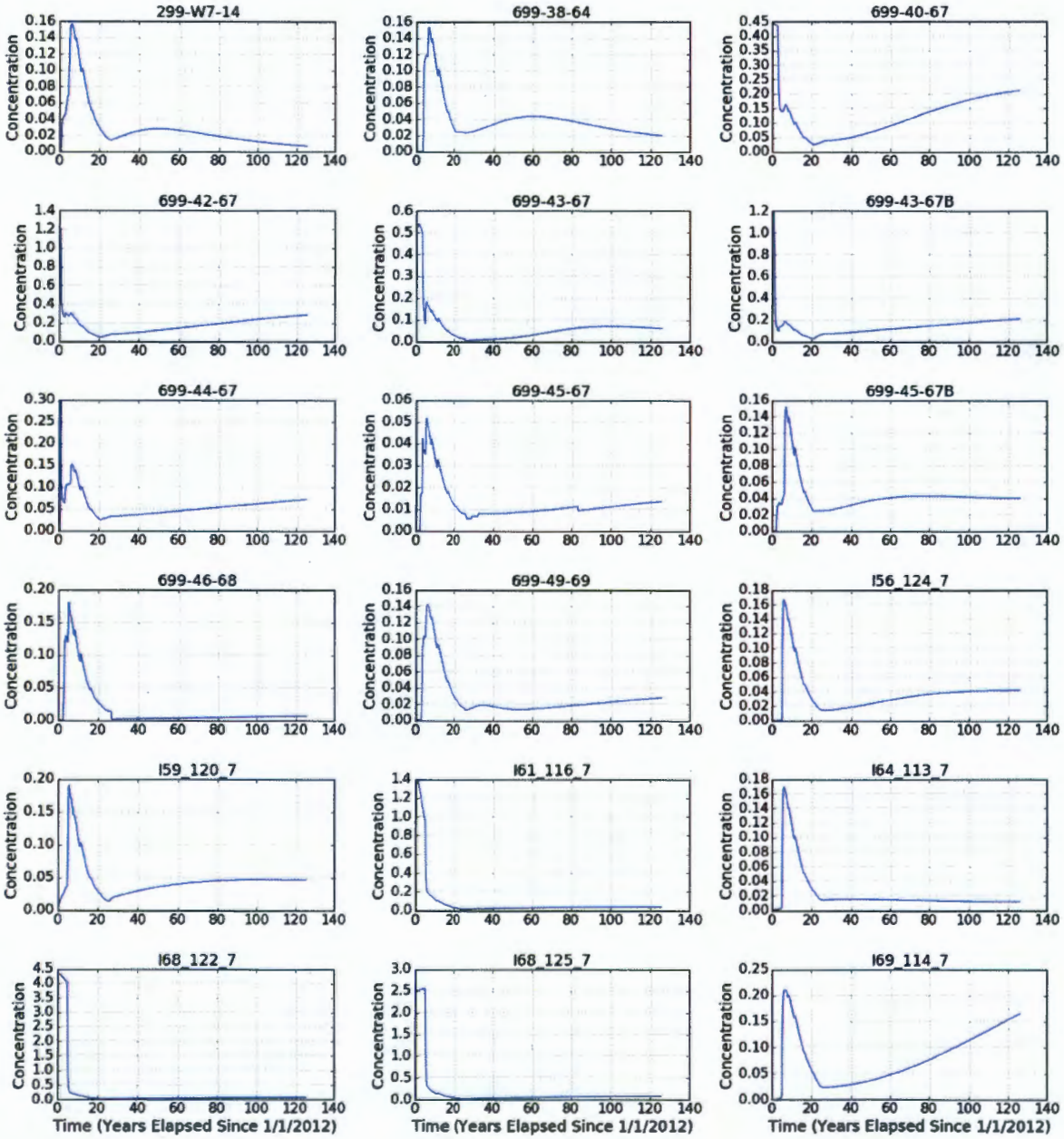


Simulated Extraction Concentrations in ug/L for TCE for Optimization Case 13



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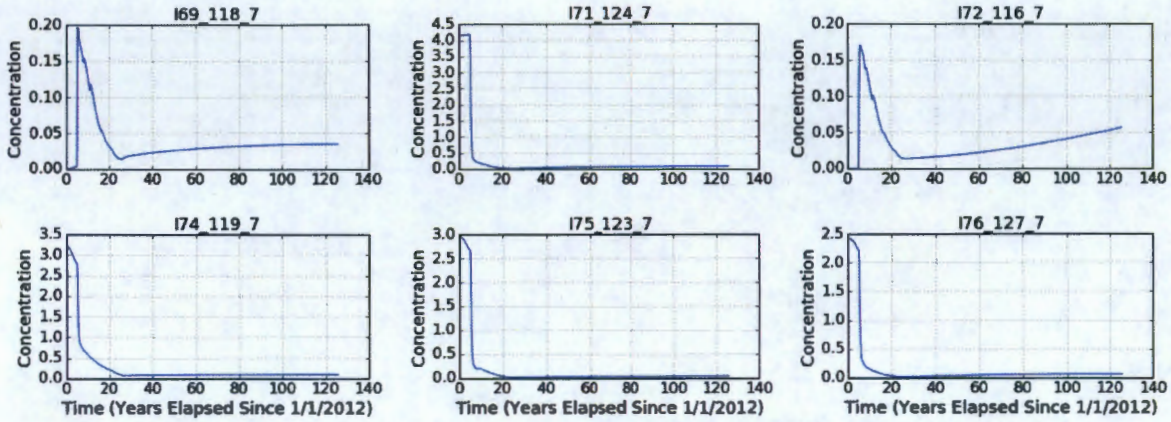
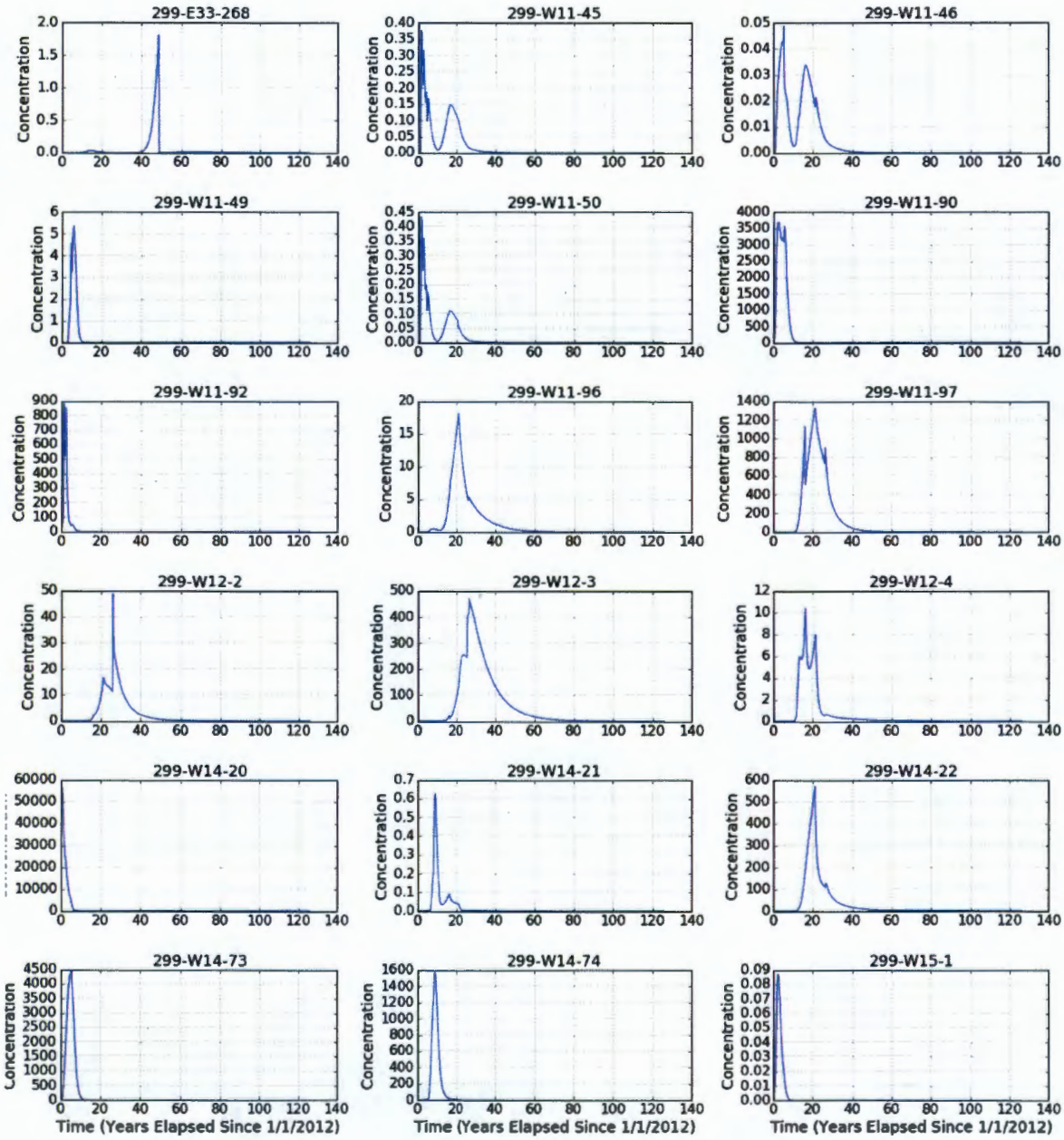
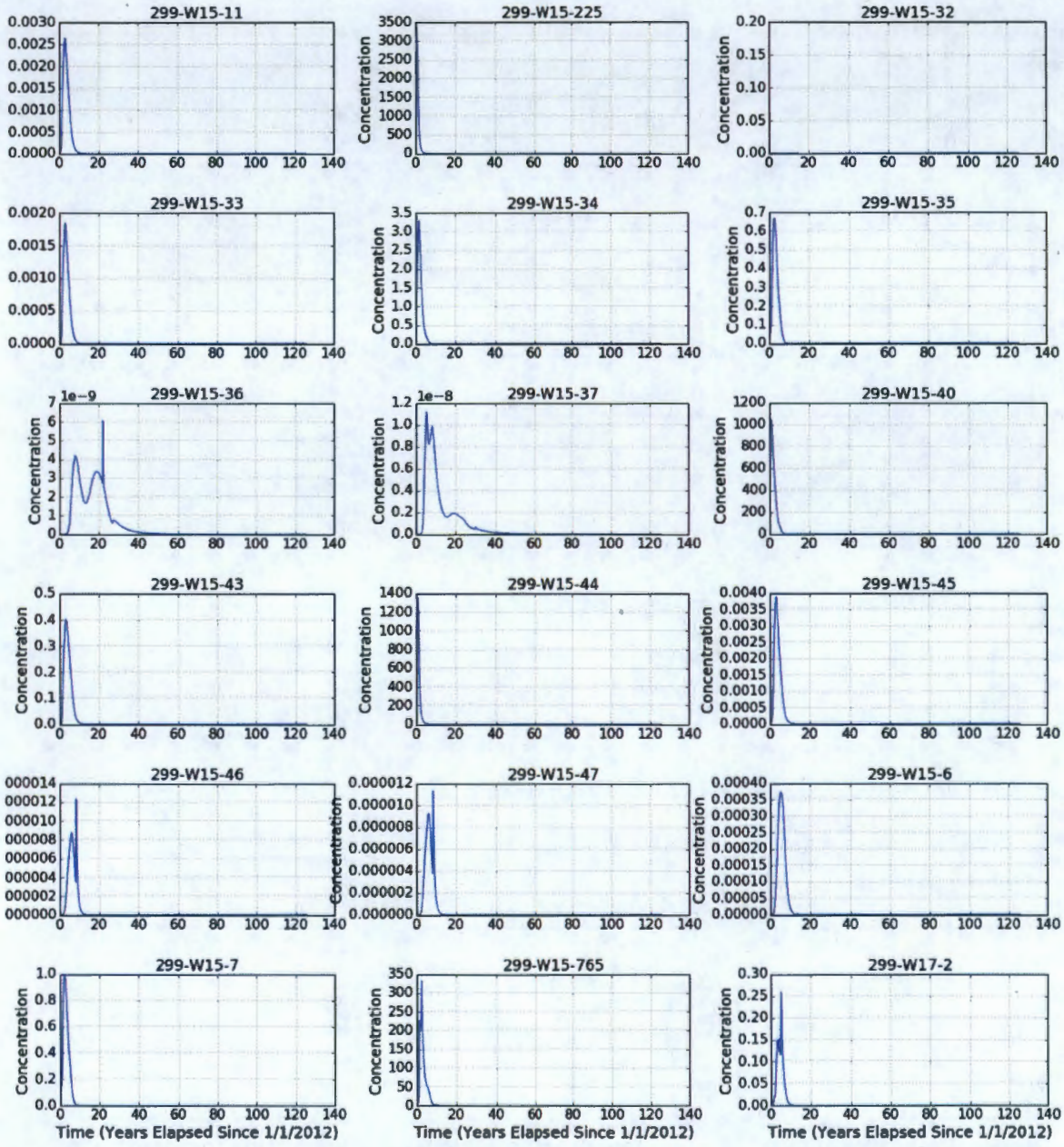


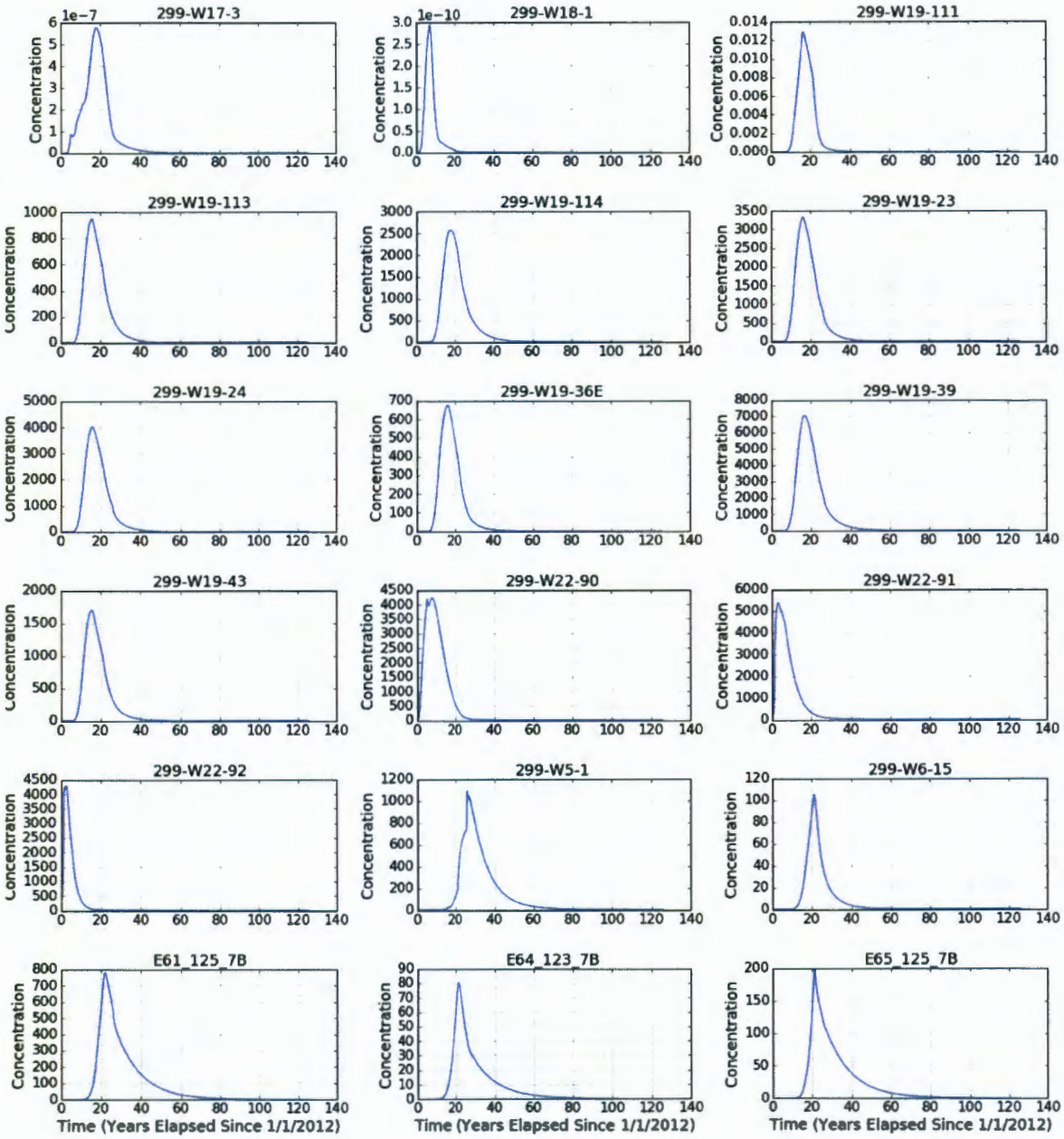
Simulated Extraction Concentrations in pCi/L for Tritium for Optimization Case 13



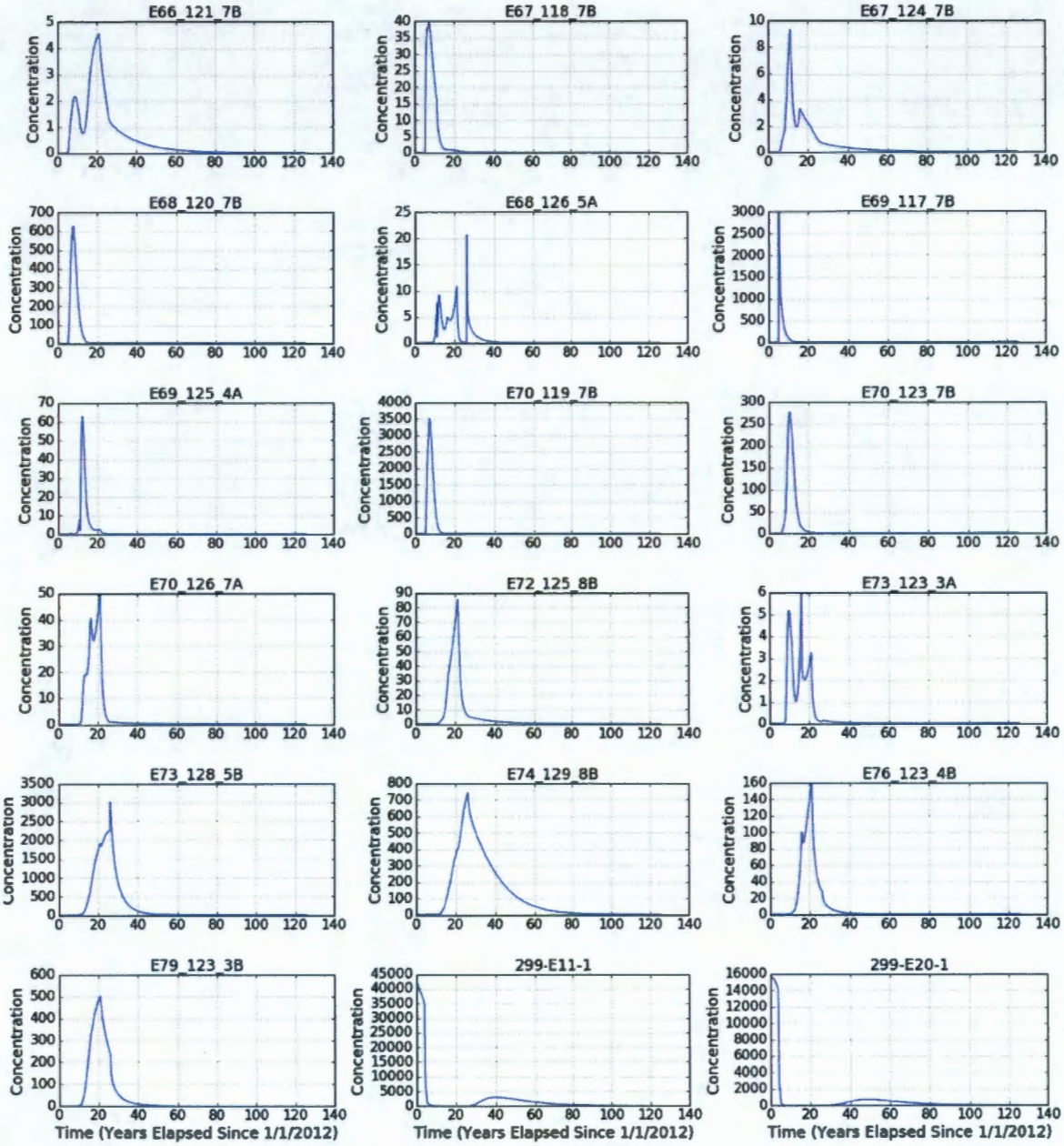
Simulated Extraction Concentrations in pCi/L for Tritium for Optimization Case 13



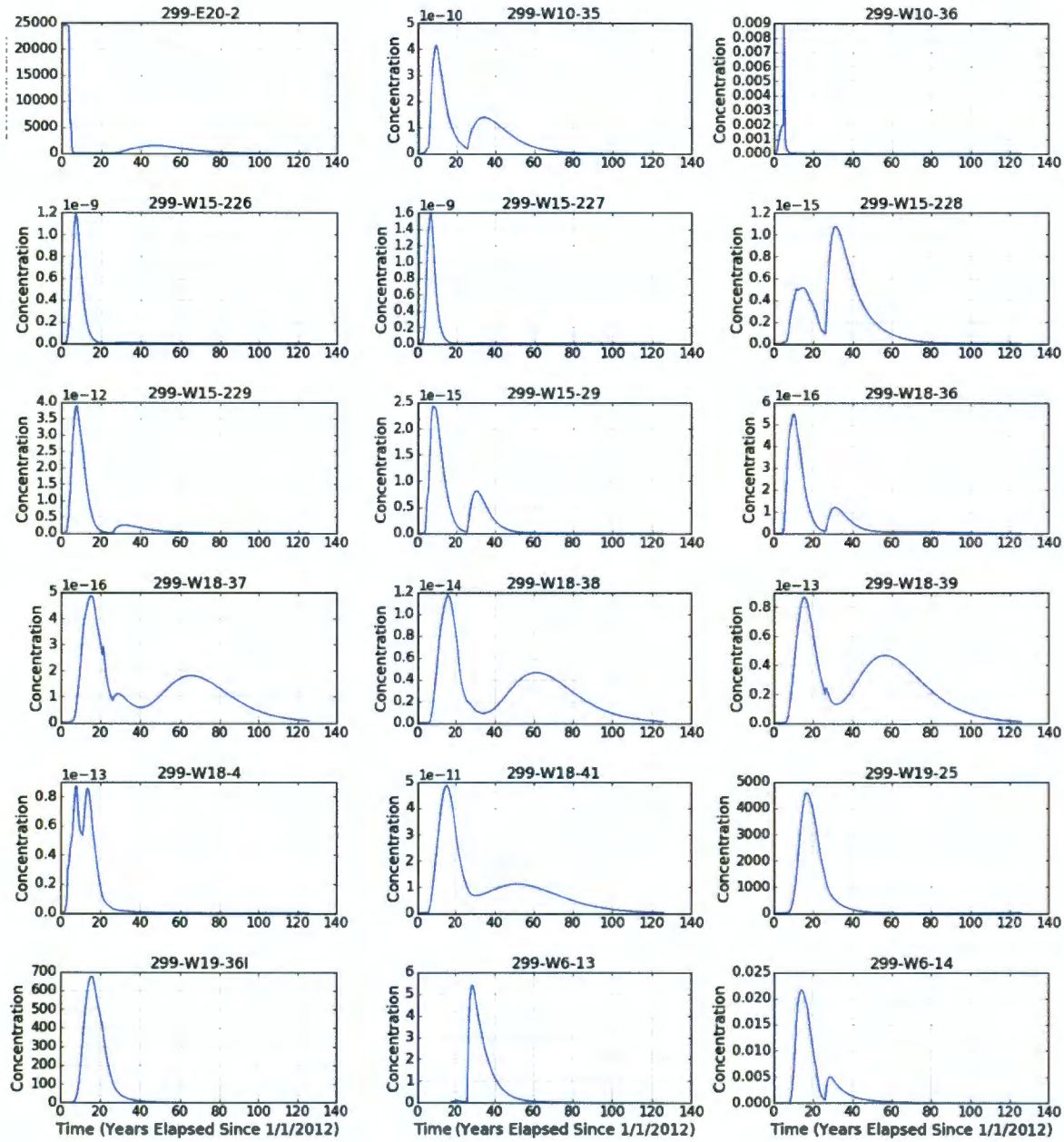
Simulated Extraction Concentrations in pCi/L for Tritium for Optimization Case 13



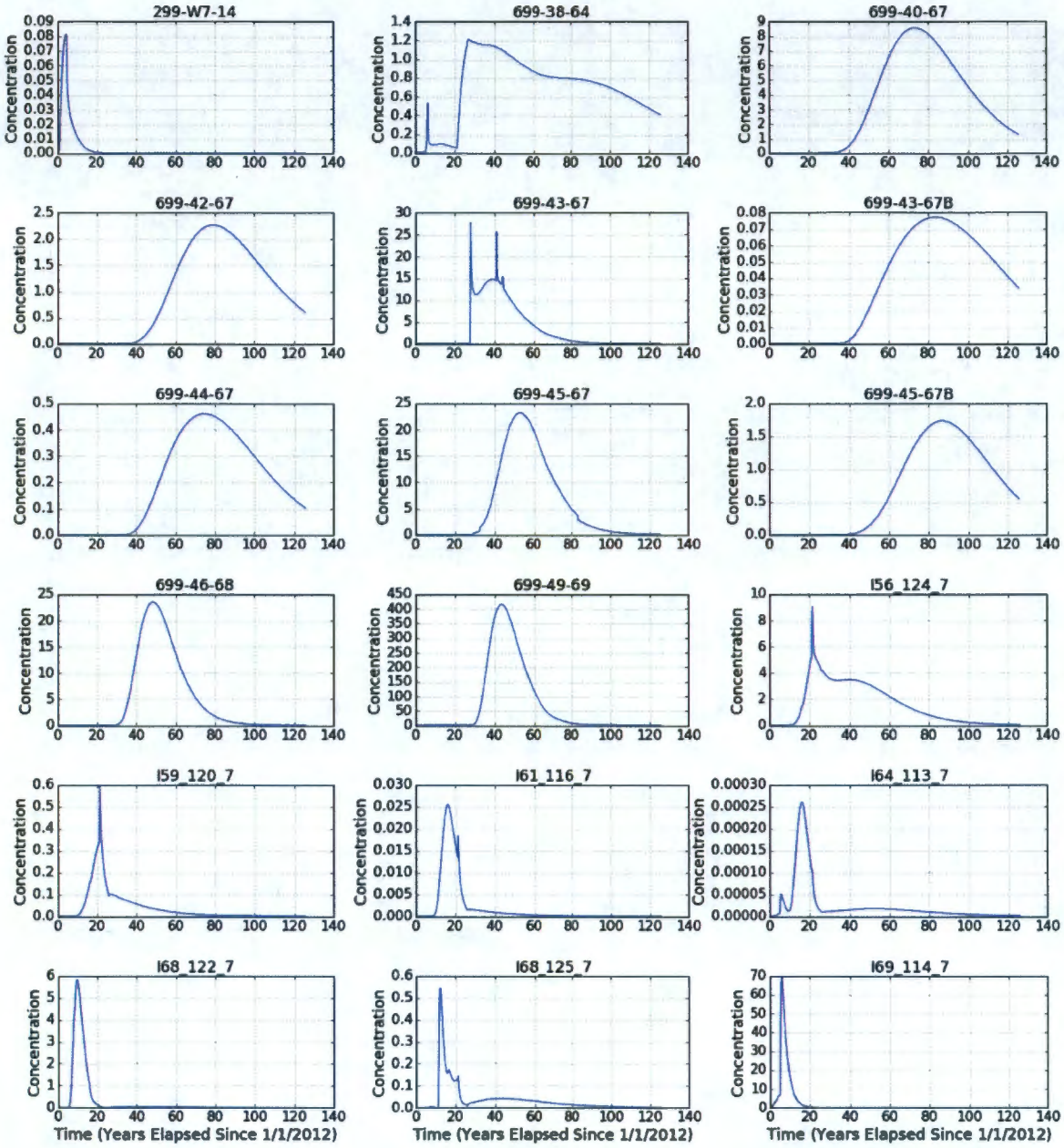
Simulated Extraction Concentrations in pCi/L for Tritium for Optimization Case 13



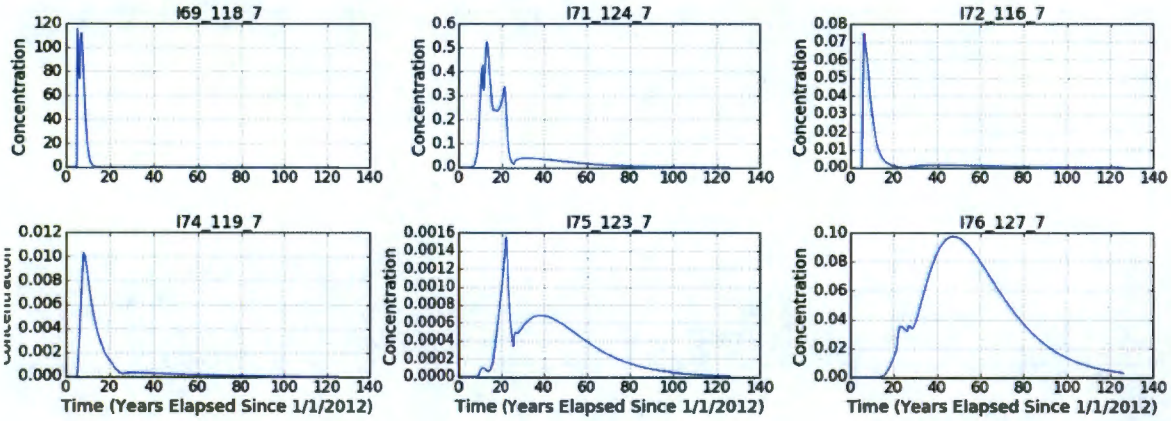
Simulated Extraction Concentrations in pCi/L for Tritium for Optimization Case 13



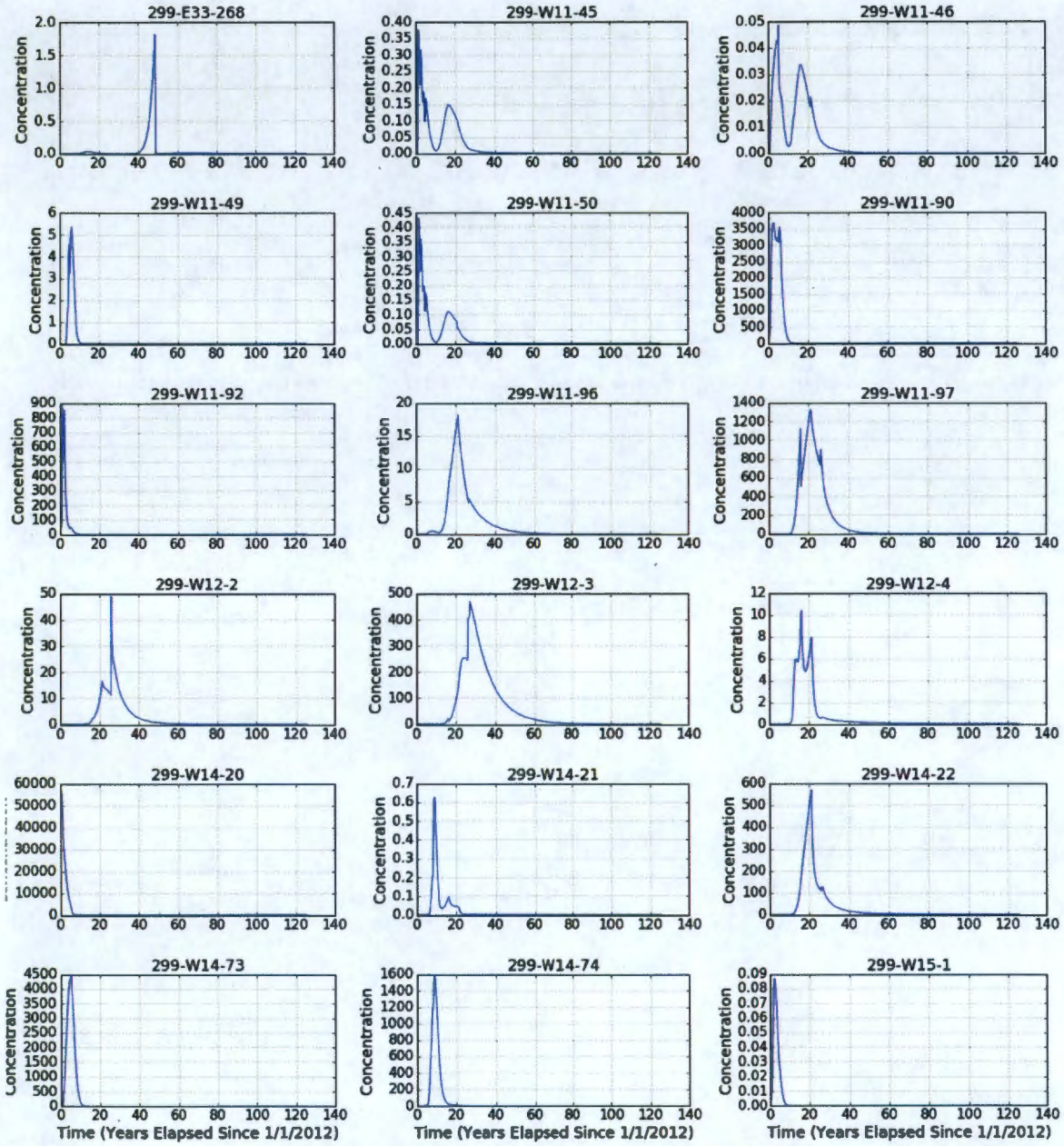
Simulated Extraction Concentrations in pCi/L for Tritium for Optimization Case 13



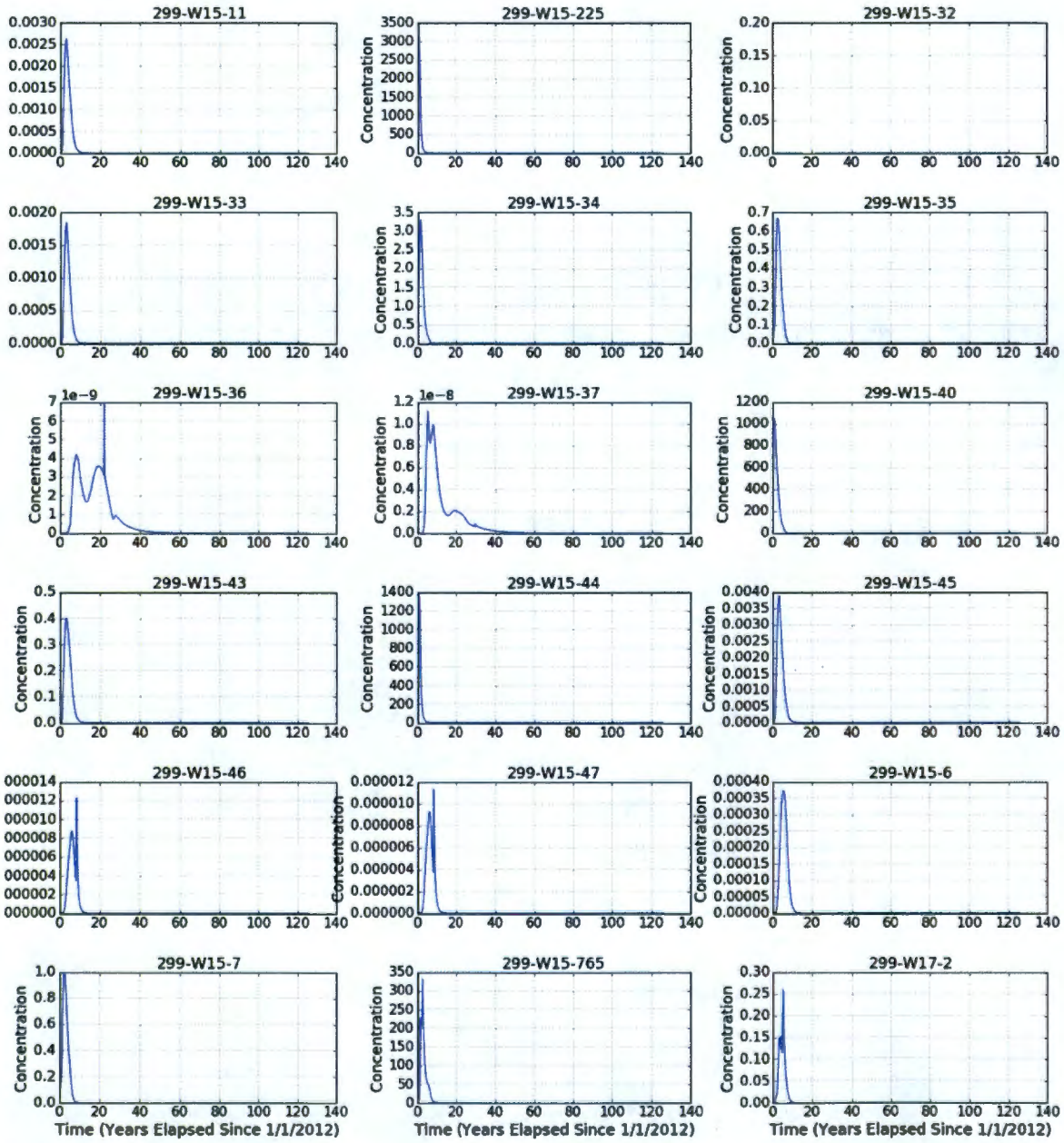
Simulated Extraction Concentrations in pCi/L for Tritium for Optimization Case 13



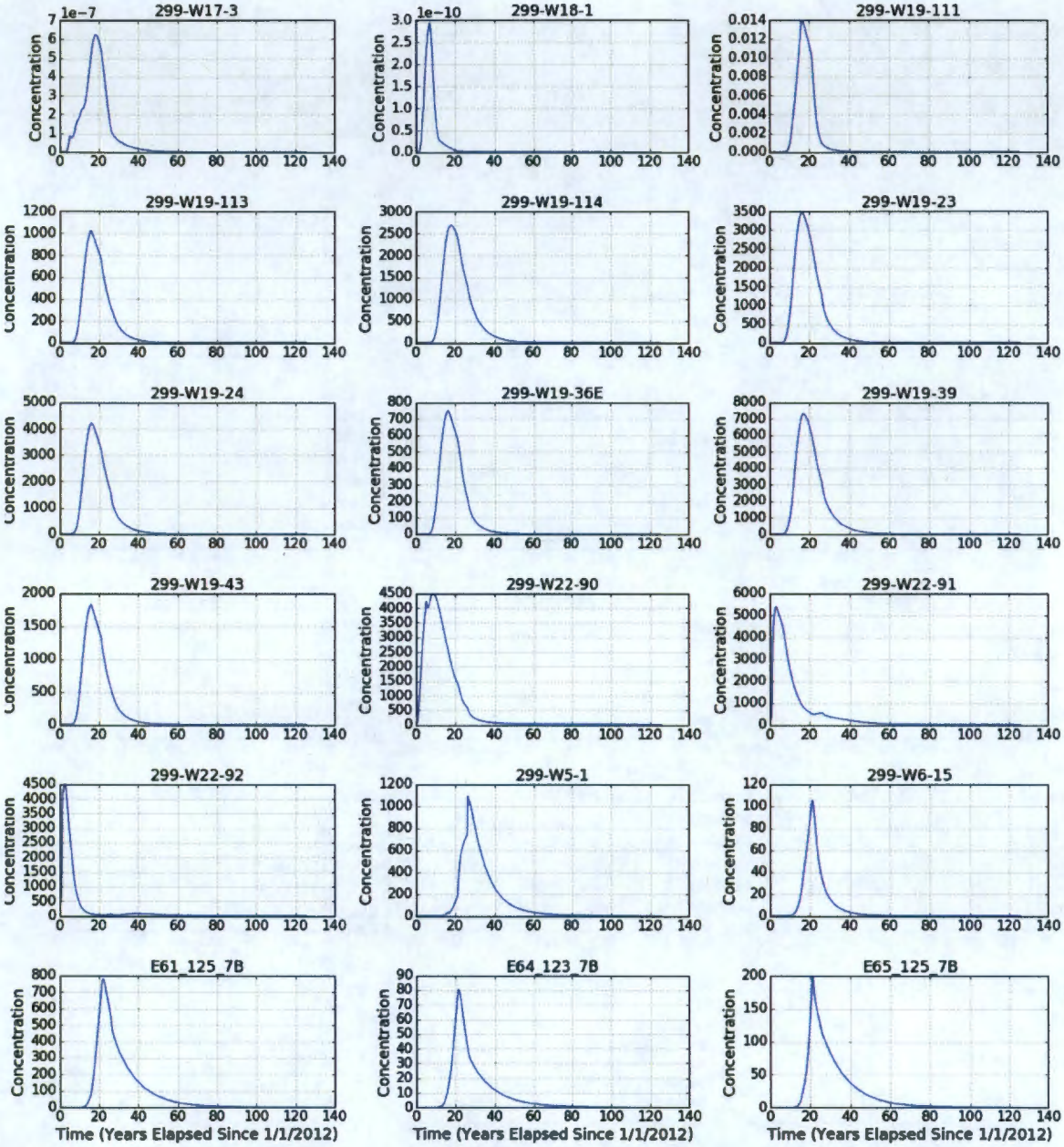
Simulated Extraction Concentrations in pCi/L for Tritium With Source for Optimization Case 13



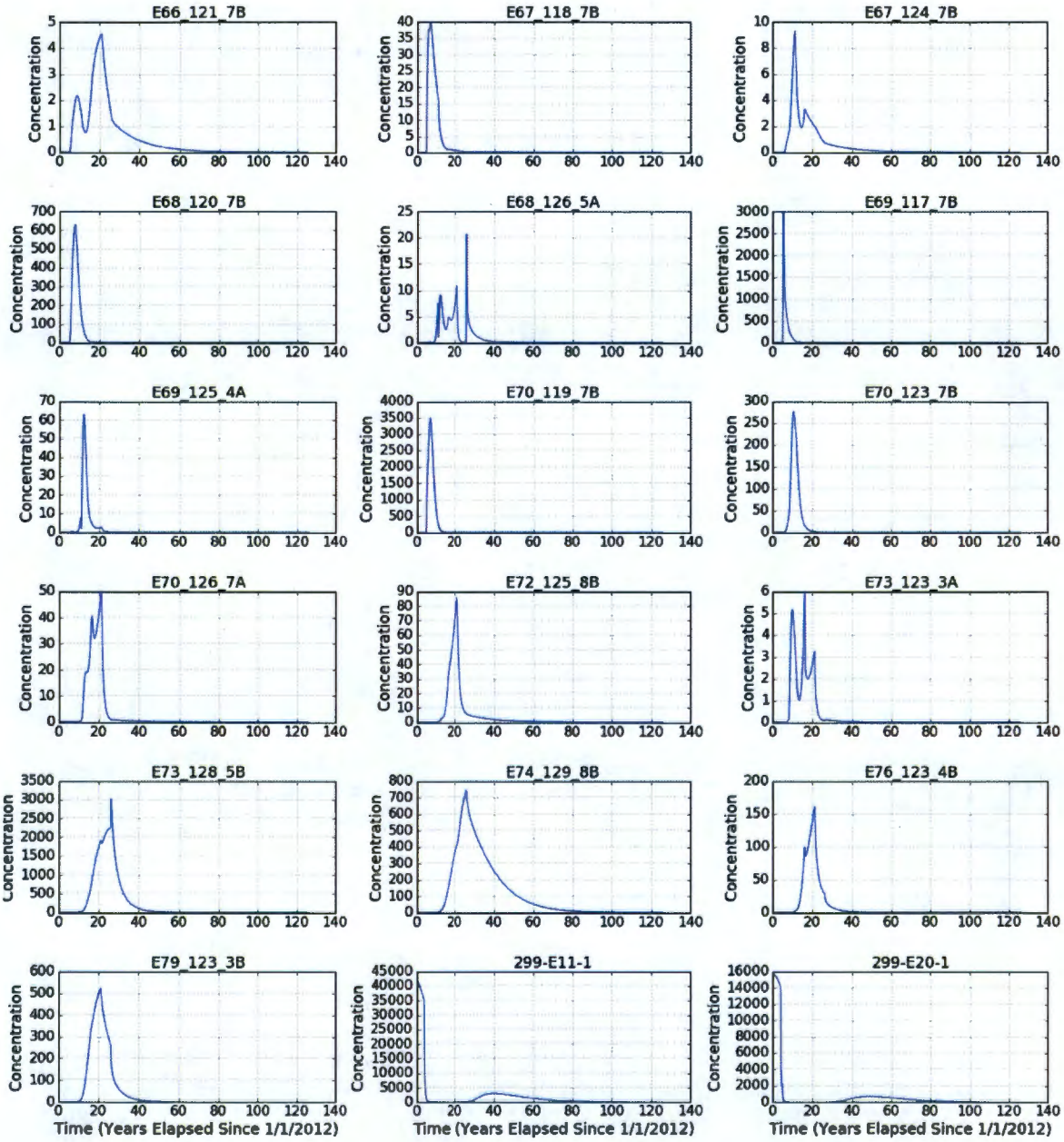
Simulated Extraction Concentrations in pCi/L for Tritium With Source for Optimization Case 13



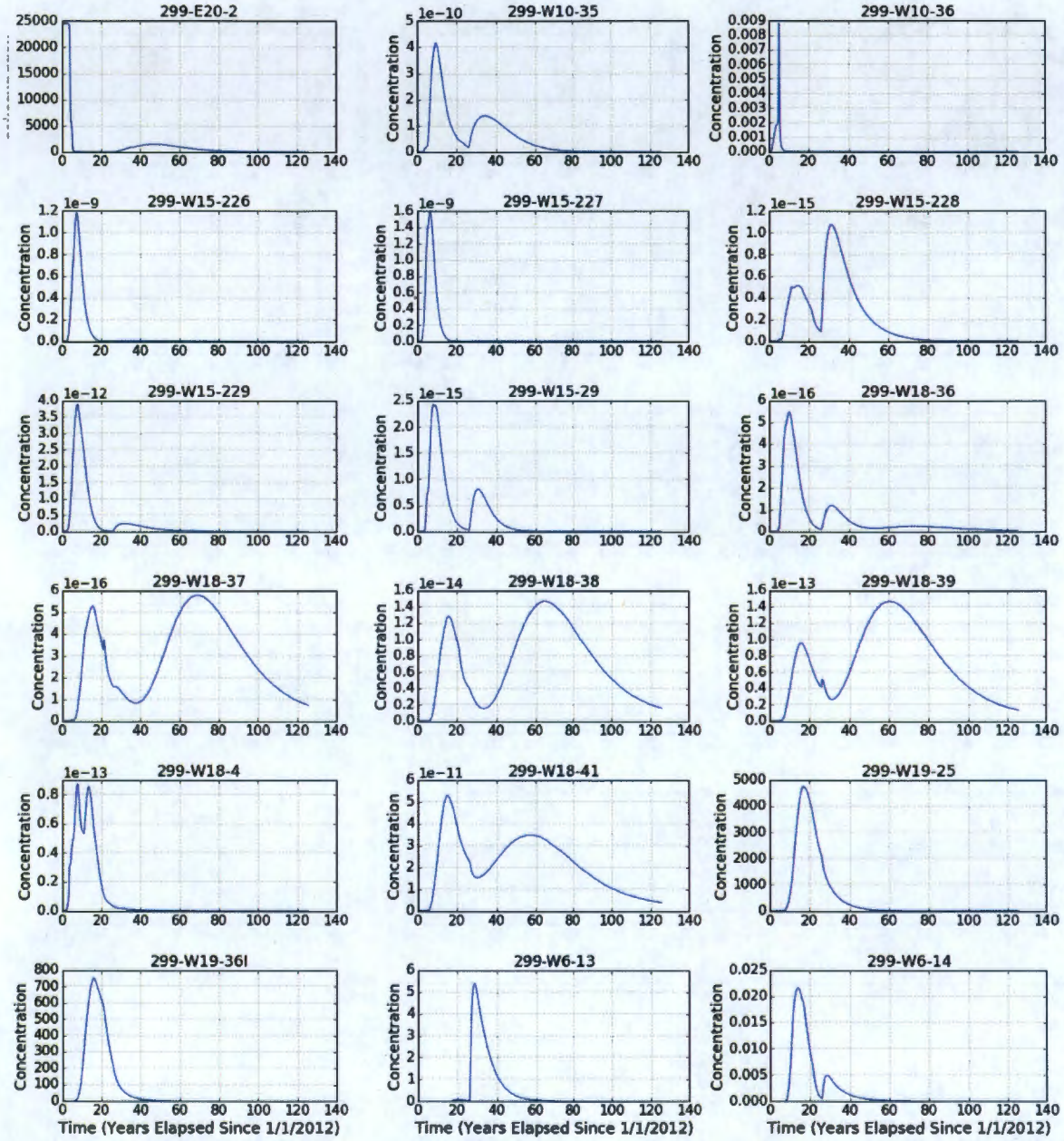
Simulated Extraction Concentrations in pCi/L for Tritium With Source for Optimization Case 13



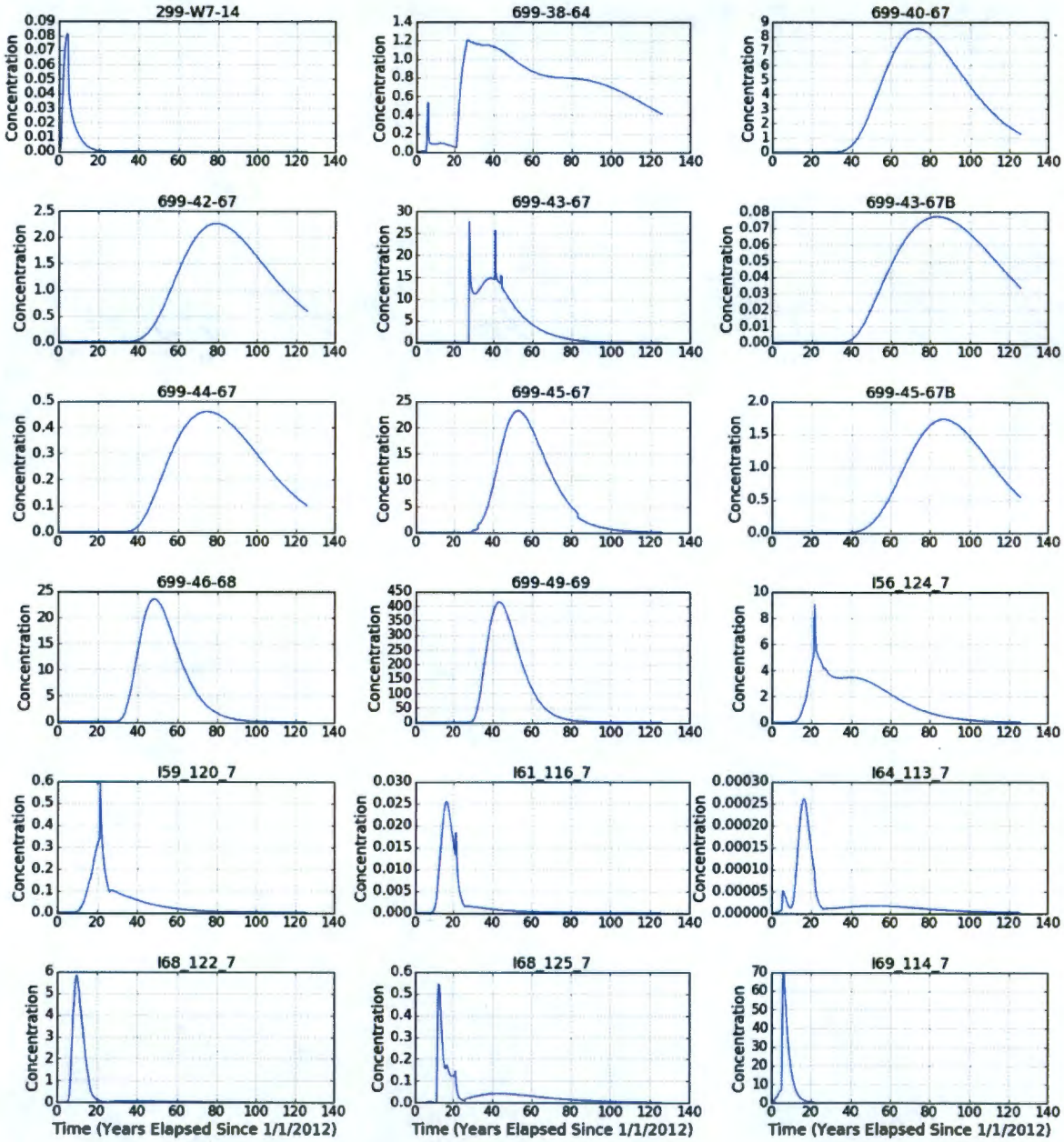
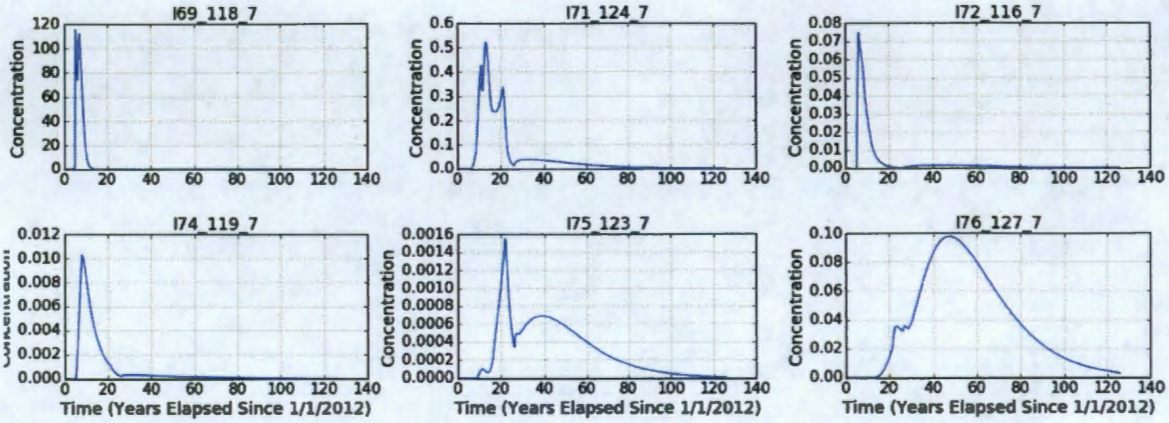
Simulated Extraction Concentrations in pCi/L for Tritium With Source for Optimization Case 13



Simulated Extraction Concentrations in pCi/L for Tritium With Source for Optimization Case 13



Simulated Extraction Concentrations in pCi/L for Tritium With Source for Optimization Case 13



Simulated Extraction Concentrations in pCi/L for Tritium With Source for Optimization Case 13