FINAL

OPTIMAL PUMPING STRATEGIES FOR TCE AND TNT PLUMES AT BLAINE NAVAL AMMUNITION DEPOT, HASTINGS, NEBRASKA

Presented to

Navy Facilities Engineering Command
NAVFACENGCOMDET-SLC

Per

Contract No. N47408-00-C-7153

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Dec 31, 2002

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Executive Summary

We present optimal pumping strategies to address TCE and TNT plumes at Blaine Naval Ammunition Depot (NAD). We provide strategies for three optimization problem formulations (Tables 1 and 2). Each strategy employs multiple five-year management periods (MPs). Each MP consists of 10 periods of time-varying background pumping, two per year. We completed these designs by the September 16 deadline. Per our contract, we performed some additional work on September 17, which is before a second deadline—the date of formally presenting results. We identify that additional work when discussing it.

The Formulation 1 problem is to minimize the present value of containing TCE and TNT plumes, and reducing them to cleanup levels (CLs) within thirty years. CLs are 5.0 ppb for TCE and 2.8 ppb for TNT. Presented Strategy USU1 costs $40.82M. Pumping rates gradually increase with time. USU1 requires constructing ten extraction wells -- 8 wells in the first management period (MP1), and two wells in period five (MP5). Of the ten wells, seven are in the northwestern contamination area and three are in the southeastern area. USU1 achieves CLs at year 30 for TCE and year 29 for TNT. Strategies that achieved cleanup within 20 years or less cost more than USU1, because they required more wells and higher pumping rates. The same is true for Formulation 2 strategies.

The Formulation 2 optimization problem is the same as Formulation 1, except that 2400 gpm of extracted water will not require treatment. Therefore, the cost will be less. Strategy USU2 is the same as USU1, and costs $18.88M.

The Formulation 3 goal is to minimize the maximum MP total pumping rate needed to contain all water contaminated at values exceeding the CLs. Containment must be achieved for 30 years. By the first deadline (September 16) USU developed strategy USU3A. USU3A satisfies Formulation 3 constraints, has time-varying pumping rates with a 2139 gpm maximum. The next day that strategy improved to 2123 gpm (termed strategy USU3A').

During September 17 we also reported preliminary draft strategies for alternative formulations 3B' and 3C'. These differ from Formulation 3 in the size of the containment area. In essence, Formulation 3 uses precisely the containment constraints posed by NAD. Formulation 3B' reduces the size of the area within which the plumes are to be contained by one cell in all directions. Thus Formulation 3B' is a more restrictive or constrained problem than Formulation 3. Formulation 3C' is even more restrictive. It lets the plume expand by a maximum of one cell in any direction. Strategies USU3B' and USU3C' require successively more pumping than USU3A, but were not vigorously optimized. USU reported all strategies mentioned above in its first draft report (SSOL, 2002).

For optimization, we used our SOMOS (Simulation/Optimization Modeling System) software. Employed SOMOS heuristic optimization methods include genetic algorithm (GA) and simulated annealing (SA), augmented by tabu search (TS) procedures. We also used SOMOS' coupled GA and artificial neural networks (ANN). We used the different techniques for different situations in the project.

Introduction

Blaine Naval Ammunition Depot (NAD), in Hastings, Nebraska, has significant contamination of groundwater by volatile hydrocarbons. Figure 1 shows the finite difference grid of flow and transport simulation models of the contaminated aquifer. Figures 2-4 and Figure 5, respectively, show TCE and TNT plumes as they are simulated to exist in January 2003.

NAD posed three optimization problem formulations. Each formulation consists of an objective function and a set of bounds and constraints. The objective function is an equation, the value of which is to be minimized, while satisfying all posed constraints. The objective function equations are functions of pumping and well construction in time. Contractee personnel that will later evaluate any developed pumping strategies indicated that evaluation would only include consideration of how good the objective function value is, and whether constraints are satisfied. Therefore, for this site, USU did not significantly include other considerations in creating the optimal pumping strategies.

We developed optimal groundwater extraction strategies using our SOMOS simulation/optimization model (SSOL and HGS, 2002). Procedures utilized in this project include genetic algorithm (GA), simulated annealing (SA), tabu search (TS) and artificial neural networks (ANN). SOMOS GA and SA codes include TS internally. When GA and SA are referred to below, the included use of TS should be assumed. Others have described procedures for GA (Aly and Peralta, 1999), SA (Shieh and Peralta, 1997), TS (Glover and Laguna, 1997), and linked ANN and GA (Aly and Peralta, 1999). SSOL or Hydrogeosystems Group have used a linked ANN-GA in developing pump and treat strategies for several other sites, including Massachusetts Military Reservation (HGS, 2000). The current SOMOS ANN-GA utilizes an innovative moving subspace or spacetube approach (SSOL and HGS, 2002).

Optimization Techniques

Formulations Addressed

We present optimal pumping strategies for three optimization problems posed by NAD, Formulations 1-3, and modifications thereof. NAD-specified requirements of the strategy development process are:

• The 30-year planning period is discretized into 6 five-year management periods (MPs), and 60 simulation model stress periods. There are two unequal stress periods (SPs) per year, corresponding to irrigation and non-irrigation seasons.

• Input data includes 60 SPs of time varying background irrigation pumping rates. These are not subject to optimization.

•To be optimized are timing and installation of extraction wells and pumping rates for each 5-year management period (MP). Remediation well pumping rates must be constant during a MP. New wells can be added only at the beginning of a MP.

A restriction for all formulations is that no developed pumping strategy can allow TCE or TNT to exceed cleanup levels (CLs) in the *forbidden zones* outside their *cleanup zones.* CLs are 5.0 ppb for TCE and 2.8 ppb for TNT. Polygons encircling the plumes in Figures 2-5 delineate the frontier between the *cleanup zones* and the surrounding *forbidden zones.*

The top part of Figure 6 summarizes mathematical constraints imposed in all three optimization problem formulations. The lower part of Figure 6 describes the additional constraint imposed on Formulations 1 and 2--forcing TCE and TNT concentrations to below CLs by the end of 30 years.

The Formulation 1 optimization problem is to minimize the value of the Figure 7a objective function equation, while satisfying all the Figure 6 constraints. The Figure 7a objective function is the sum of the present value of all manageable remediation costs.

Formulations 1 and 2 differ in how the extracted groundwater is managed. Hence, they differ in how the cost of treating or discharging the extracted water is computed. Formulation 2 does not incur treatment cost or discharge cost for up to 2400 gpm of extracted water. Figure 7b shows the Formulation 2 objective function.

Formulation 3 involves developing a pumping strategy that minimizes the maximum total remediation pumping rate in any management period over a 30-year simulation (Fig. 8). Cleanup need not be achieved within 30 years, but containment constraints must be satisfied (for TCE and TNT) at the end of each of the management periods. A Formulation 3 strategy cannot use more than 25 extraction wells. Since no cost is assigned to the wells, an optimization model will tend to use as many wells as possible. (Theoretically, in an absolute mathematical sense, reducing the number of wells cannot improve the objective function value. Therefore, optimization will tend to maximize the number of number of wells subject to restrictions.)

Between September 16 and September 17, we developed other strategies for the Formulation 3 family. These include USU3A', USU3B' and USU3C'. USU3A' resulted from continuing optimization of strategy USU3A. USU3B' and USU3C' are for alternative optimization problem formulations that restrict plume growth more than USU3 (A or A'). Figure 9 shows the USU3B' and USU3C' *forbidden zones* that prevent the contamination from migrating as far before capture as in the NAD-posed Formulation 3 optimization problem.

Optimization Process and Results

Overview

USU Formulation 1 results are supported by Figures 10-12, Appendix A, and Tables 1 and 3. USU proposes the same strategy for Formulation 2 as for Formulation 1. Therefore, USU Formulation 2 results are supported by the same figures, and also Appendix B and Tables 1 and 4. Formulation 3A is supported by Figures 13-16, Appendix C, and Tables 1 and 5. The Appendices are GeoTrans postprocessor outputs for the respective strategies.

USU developed additional strategies USU3A', USU3B' and USU3C' on September 17, the day between the above work was completed and the day we formally presented results. Strategy USU3A' is supported by Tables 2 and 6, and Appendix D. Formulation 3B' is supported by Figures 17-19, Table 2 and Appendix E. Formulation 3C' is supported by Figures 20-22, Appendix F and Table 2.

Tables 7-9 provide representative optimization solver input parameters. For Formulations 1 and 2 we primarily used the SOMOS GA and SA optimization solvers. For Formulation 3 we used the GA, SA and ANN-GA.

We began the optimization process by exploring candidate well locations for Formulation 3. That yielded a preliminary steady pumping strategy that would satisfy plume containment constraints, and the rest of those in the top part of Figure 6. Then, we pursued developing strategies for Formulations 1 and 3 simultaneously, on different computers.

Formulation 1 and least cost strategy USU1

Beginning with candidate wells and rates that could achieve plume containment, we identified candidate well locations that would likely also help achieve cleanup while satisfying the full set of Formulation 1 constraints (Figure 6). We made preliminary simulations in which we assumed that the managed (candidate) wells would pump steadily for 30 years (60 stress periods). The background (unmanaged) wells pumped at the NAD-specified unsteady rates.

After identifying reasonable sets of candidate wells we used GA to develop steady and transient 30-year pumping strategies. Table 7 shows representative GA input parameters.

We also used GA to develop 20-year pumping strategies that achieved cleanup within 20 years. However, pumping rates required to achieve 20-year cleanup were so great that it was unlikely that a 20-year strategy would be less costly than a 30-year strategy.

We continued Formulation 1 optimization for 30 years. Table 8 shows sample SA input parameters. Time-varying pumping strategy USU1 (Tables 1 and 3) yields the least cost, \$40,824,320. It requires constructing 10 wells – eight initially and two at the beginning of management period 5. The GeoTrans post-processor shows the present value cost (Appendix A).

Figures 10-12 show TCE and TNT plumes at year 25. TCE cleanup is achieved in year 30. TNT cleanup is achieved in year 29.

Formulation 2 and least cost strategy USU2

Evaluating the objective function showed that a least-cost strategy for Formulation 1 would also be a least-cost strategy for Formulation 2. Therefore our best Formulation 1 strategy, USU1 is also our best strategy for Formulation 2.

The Formulation 2 optimization problem differs from that of Formulation 1 in the objective function. Therefore, even though the pumping rates are the same for USU1 and USU2, their objective function values differ. Tables 1 and 4 and Appendix B show strategy USU2 and its results.

Formulation 3 mimimax management period pumping strategy USU3A

Formulation 3 deals with minimizing the maximum total pumping rate that occurs in any management period (Figure 8), subject to the containment and other constraints of the top part of Figure 6. Formulation 3 differs from the previous problem formulations in its objective function and because it has no cleanup constraint.

We initially addressed the 30-year problem by assuming steady pumping and using GA. Table 7 shows representative inputs. For different groups of candidate wells, SOMOS developed different pumping strategies that satisfied the constraints. These required constructing different numbers of wells and had different total steady pumping rates. Examples included: 2551 gpm and 11 wells; 2305 gpm and 13 wells. However, we felt we could develop strategies having a better objective function value.

We optimized time-varying pumping using GA, SA, and GA linked with ANN. Tables 7-9 show representative respective inputs. Strategy USU3A had the lowest objective function value (Tables 1 and 5). The USU3A maximum period pumping rate is 2139 gpm. USU3A requires constructing 25 wells. Appendix C shows post-processor output. Figures 13-16 show concentrations predicted to result after 30 years of pumping.

Next Day Strategies USU3A', USU3B' and USU3C'

Within less than 24 hours of the time we reported strategy USU3A, a slightly better strategy (USU3A') evolved. USU3A' uses the same wells as USU1A, but different transient pumping rates to yield an improved objective function value of 2123 gpm. During the same period, preliminary draft strategies USU3B' and USU3C' evolved. These use fewer wells than USU3A and larger forbidden zones.

Strategy USU3B' assumes an alternative forbidden zone for TCE. The forbidden zone boundary is located 1 cell inside the forbidden zone posed by NAD (Figure 9). This is a more restrictive problem than that of USU3A because the contamination is not allowed to move as far. We used GA and SA to develop feasible solutions for the more restrictive optimization problem, but only did a little optimization. The best of those strategies, only partially optimized, is strategy USU3B'. USU3B' steadily pumps 2697 gpm using 24 wells (Appendix E).

Figures 17-19 show the plumes resulting after 30 years pumping per USU3B'. These show that the contamination stays at least 1 cell away from the NAD-posed containment zone.

Strategy USU3C' is a no-plume-growth scenario. In it, the containment zone is only one cell beyond the initial plume. The zone is identical in all layers. GA and SA were used to develop feasible solutions for this problem. The resulting slightly optimized strategy USU3C' uses 3237 gpm of steady pumping. Relaxing the containment constraint a little can allow significantly less pumping.

Summary and Observations

Table 1 summarizes results from the pumping strategies developed during the primary modeling period for the several optimization problem formulations. Strategies USU1 and USU2, for Formulations 1 and 2 respectively, are identical transient pumping strategies. These yield least cost objective function values of $40.8M and $18.9M, respectively. Strategy USU3A has a mini-max pumping rate of 2139 gpm. Representative strategies USU developed for Formulation 3 employed from 11 to 25 wells and from 2551 to 2139 gpm, respectively.

During computational optimization, a solution might not improve for a while, and then might suddenly improve. By the day after we reported strategy USU3A, the objective function pumping rate had improved to the 2123 gpm of strategy USU3A'. From that same 24-hour period we also report strategies (USU3B' and USU3C') developed for problems using larger (more restrictive) forbidden zones. USU3B' and USU3C' were not intensely optimized, but nevertheless demonstrate the general trend of objective function value worsening as a constraint is tightened. Theoretically, as restrictions (constraints) are tightened, globally optimal solutions cannot improve.

This project is intended to demonstrate the power of using optimization techniques for plume remediation design. We believe it does so. Our contract specified that we were to address the three posed optimization problem formulations using only PC computers and without interacting with the client (NAD).

Normally, when using optimization to design a pumping strategy for a client, the developer and the client interact even after the optimization has begun (Peralta and Aly, 1994, 1995, 1996; Hegazy and Peralta, 1997; Peralta, 2001a,b). Interaction is helpful in refining a strategy so that it considers additional factors useful for design and construction.

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Table 1. Strategy summary for three formulations.

Formulation #	**1 (Strategy USU1)**	**2 (Strategy USU2)**	**3a (Strategy USU3a)**
Objective Function Value ($M or gpm)	**40.824320**	**18.879953**	**2138.7**
Number of New Extraction Wells Installed	**10**	**10**	**25**
Cleanup Time for TCE	**30**	**30**	**N/A**
Cleanup Time for TNT	**29**	**29**	**N/A**

Table 2. Executive summary of optimal strategies developed during the day after the primary modeling period.

Base Formulation	**3**		
Strategy Option	**USU3A'**	**USU3B'**	**USU3C'**
Containment Zone	**As posed**	**Smaller**	**Smallest**
Objective Function Value (gpm)	**2123**	**2692**	**3237**
Number of New Extraction Wells Installed	**25**	**24**	**24**
Elapsed Years Until Cleanup	**N/A**		

*** Notes:**
- **3A' is designed for the posed optimization problem.**
- **3B' is designed for a containment zone that is one cell smaller in all directions than the posed containment zone. It was not thoroughly optimized.**
- **3C' is designed for the smallest containment zone—a no-plume growth scenario. The containment zone was one cell beyond the initial plume. This design was not thoroughly optimized.**

Table 3. Thirty-year transient pumping strategy USU1 and results.

	Strategy name:	USU1					
		Strategy Pumping Rates (GPM) for each management period (MP)					
	Well Location (K,I,J)	MP1	MP2	MP3	MP4	MP5	MP6
1	(3,26,32), (4,26,32)	0	0	0	0	423	696
2	(3,26,52), (4,26,52)	0	0	0	0	198	147
3	(3,37,39)	299	297	295	350	350	350
4	(3,34,58), (4,34,58)	306	340	379	344	407	344
5	(3,35,81), (4,35,81)	502	476	471	482	482	570
6	(3,28,57), (4,28,57)	506	554	523	564	398	690
7	(3,48,117), (4,48,117)	281	287	285	270	278	183
8	(3,52,122)	257	258	265	242	257	0
9	(3,56,111)	107	140	119	107	135	0
10	(3,33,66), (4,33,66)	226	277	306	392	377	397
	Total extraction (gpm)	2486	2632	2644	2752	3306	3378
	Cleanup time for TCE (years)	30					
	Cleanup time for TNT (years)	29					
	Total cost present value ($M)	**40.82**					

Table 4. Thirty-year transient pumping strategy USU2 and results.

	Strategy name:	USU2					
		Strategy Pumping Rates (gpm) for each management period (MP)					
	Well Location (K,I,J)	MP1	MP2	MP3	MP4	MP5	MP6
1	(3,26,32), (4,26,32)	0	0	0	0	423	696
2	(3,26,52), (4,26,52)	0	0	0	0	198	147
3	(3,37,39)	299	297	295	350	350	350
4	(3,34,58), (4,34,58)	306	340	379	344	407	344
5	(3,35,81), (4,35,81)	502	476	471	482	482	570
6	(3,28,57), (4,28,57)	506	554	523	564	398	690
7	(3,48,117), (4,48,117)	281	287	285	270	278	183
8	(3,52,122)	257	258	265	242	257	0
9	(3,56,111)	107	140	119	107	135	0
10	(3,33,66), (4,33,66)	226	277	306	392	377	397
	Total extraction (gpm)	2486	2632	2644	2752	3306	3378
	Cleanup time for TCE (years)	30					
	Cleanup time for TNT (years)	29					
	Total cost present value ($M)	**18.88**					

Table 5. Thirty-year transient pumping strategy USU3A and results.

	Strategy name:	USU3A					
		Strategy Pumping Rates (gpm) for each management period (MP)					
	Well Location (K,I,J)	MP1	MP2	MP3	MP4	MP5	MP6
1	(4,48,114)	190	190	190	190	190	156
2	(3,47,110)	76	76	76	76	65	0
3	(3,53,116)	145	145	145	145	145	145
4	(3,53,121)	157	157	157	157	157	157
5	(3,57,111)	51	51	51	51	51	51
6	(3,37,39)	277	277	277	277	277	277
7	(4,26,58)	23	23	23	23	23	23
8	(4,27,59)	22	22	22	22	22	22
9	(4,28,60)	18	18	18	18	18	18
10	(4,29,61)	15	15	15	15	15	15
11	(3,30,62), (4,30,62)	53	53	53	53	53	53
12	(3,31,63), (4,31,63)	56	56	56	56	56	56
13	(3,32,64), (4,32,64)	128	128	128	128	128	128
14	(4,34,81)	146	146	146	146	146	146
15	(3,35,81), (4,35,81)	167	167	167	167	167	174
16	(3,36,81)	65	65	65	65	65	65
17	(4,36,81)	70	70	70	70	68	68
18	(3,25,58), (4,25,58)	87	87	87	87	88	114
19	(3,32,68), (4,32,68)	56	56	56	56	57	57
20	(4,33,81)	88	88	88	88	88	88
21	(3,28,60)	73	73	73	73	73	83
22	(3,29,61)	62	62	62	62	62	83
23	(3,26,58)	57	57	57	57	57	57
24	(3,27,59)	57	57	57	57	57	57
25	(3,28,65)	0	0	0	0	10	34
	Total extraction (gpm)	2139	2139	2139	2139	2139	2129
	Minimum maximum pumping rate (gpm)	**2139**					

Table 6. Thirty-year transient pumping strategy USU3A' and results.

	Strategy name:	USU3A'					
		Strategy Pumping Rates (gpm) for each management period (MP)					
	Well Location (K,I,J)	MP1	MP2	MP3	MP4	MP5	MP6
1	(4,48,114)	190	190	190	190	190	0
2	(3,47,110)	76	76	76	76	65	0
3	(3,53,116)	145	145	145	145	145	145
4	(3,53,121)	157	157	157	157	157	157
5	(3,57,111)	51	51	51	51	51	51
6	(3,37,39)	272	272	272	272	272	281
7	(4,26,58)	16	16	16	16	16	16
8	(4,27,59)	15	15	15	15	15	15
9	(4,28,60)	13	13	13	13	13	13
10	(4,29,61)	13	13	13	13	13	13
11	(3,30,62), (4,30,62)	58	58	58	58	58	58
12	(3,31,63), (4,31,63)	56	56	56	56	56	67
13	(3,32,64), (4,32,64)	102	102	102	102	102	102
14	(4,34,81)	146	146	146	146	146	146
15	(3,35,81), (4,35,81)	177	177	177	177	177	271
16	(3,36,81)	65	65	65	65	65	65
17	(4,36,81)	68	68	68	68	68	68
18	(3,25,58), (4,25,58)	84	84	84	84	84	134
19	(3,32,68), (4,32,68)	57	57	57	57	57	98
20	(4,33,81)	88	88	88	88	88	88
21	(3,28,60)	78	78	78	78	78	83
22	(3,29,61)	77	77	77	77	77	94
23	(3,26,58)	57	57	57	57	57	57
24	(3,27,59)	57	57	57	57	57	57
25	(3,28,65)	5	5	5	5	16	44
	Total extraction (gpm)	2123	2123	2123	2123	2123	2123
	Minimum maximum pumping rate (gpm)	**2123**					

Table 7. Representative GA input parameters.

1. Total number of simulations	800
2. Total number of generations	100
3. Generation size	8
4. Penalty coefficient	10
5. Crossover probability	0.8
6. Mutation probability	0.04

Notes:

1. Total number of simulations performed by end of the number of generations specified in item 2.
2. Total number of generations used in a GA optimization.
3. The number of individuals in a generation.
4. Within the objective function, this is the coefficient used to weight unit violations of constraints. The resulting penalty makes the objective function less desirable proportionally with respect to the degree of constraint violation.
5. Probability that a pair of individuals will mate. Usually, one maintains a high probability (i.e. 0.7 ~ 0.9), since without mating, only mutation will change a strategy. Aly and Peralta (1999) report that a probability less than 0.7 produces inferior results.
6. Probability that each bit of a chromosome will mutate. The rate of mutation should generally be low (smaller than 0.1). Mutation is performed after crossover.

Table 8. Representative SA input parameters.

1. Number of moves	6
2. Number of trials	15
3. Initial temperature	400
4. Adjustment parameter	0.01
5. Initial step length	500
6. Initial penalty coefficient	10

Notes:

1. The number of simulations (moves) within a trial.
2. The total number of trials. Within a trial, a particular temperature, penalty coefficient, and moving step size are used. After each trial the temperature is cooled.
3. Initial temperature. The temperature controls the probability that the code will accept a worse strategy.
4. The adjustment parameter for the movement generation function (Corana et. At, 1987). This is a value between 0 and 1.0. The product of the adjustment factor and the decision variable range is the maximum change in decision variable in a movement.
5. Initial step length (expressed in decision variable units). It is the largest step size of moves in the first trial.
6. Initial penalty coefficient used in the first trial. This is the largest penalty coefficient used in a run.

Table 9. Representative ANN-GA input parameters**.**

ANN input parameters	
1. number of cycles	4
2. min. no. of simulations per cycle	10
3. Number of ANN training sessions	4
4. Number of iterations per training session	4000
5. number of nodes in hidden layer	16
6. kappa	0.1
7. phi	0.5
8. theta	0.7
9. Initial learning rate	0.05
GA input parameters	
10. population size	50
11. number of generations	1500
12. crossover probability	0.8
13. mutation probability	0.04
14. penalty coefficient	10

Notes:

1. The number of cycles. A cycle is one process of developing strategies, training ANNs and optimizing. The ANNs represent substitute simulators or response surfaces. The process is continued untill the total number of cycles are completed.
2. The minimum number of real model simulations per cycle. Included within these simulations is the best strategy from the previous cycle.
3. The number of training sessions usually is less than 10, but more is possible. A larger number will require more time to train the ANN, but might improve the training and yield a more accurate ANN.
4. The number of iterations for each ANN training session. This is usually between 500 and 10000.
5. The number of nodes (neurons) in the hidden layer. This number determines the number of weights between the input and hidden layer and hidden layer and output layer. Increasing the number of nodes causes the ANN architecture to become more complex, and increases run time. The more nodes, possibly the better the ANN-prediction abilities—up to a point. Too many nodes can cause an ANN to memorize all inputs and reduce its ability to recognize new patterns.
6. Kappa parameter. Used internally to determine a learning rate. Kappa should have a value between 0 and 1. Normally kappa is 0.1. ANN performance is not very sensitive to this.
7. Phi parameter. Used internally to help determine a learning rate. Phi should have a value between 0 and 1. Normally phi ranges from 0.5 to 0.7.
8. Theta parameter. Used in the adaptive learning algorithm. Theta should have a value between 0 and 1. Normally, we use a theta of 0.1.
9. The initial learning rate. This usually ranges from 0.15 to 0.5. A frequently used value is 0.5. Higher values could lead to oscillation or saturated processing elements (nodes).

10-14. See Notes of Table 7.

Fig. 1. Blaine Naval Ammunition Depot base map.

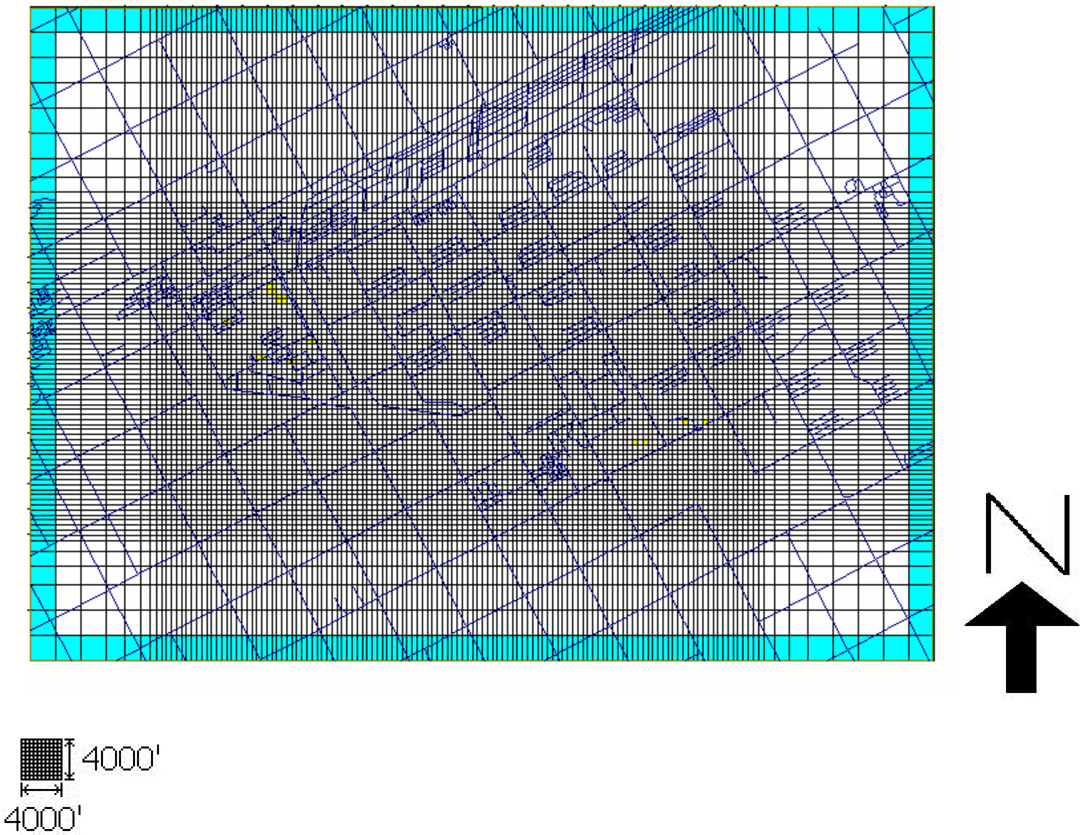


Fig. 2. Initial (Projected 1 Jan 2003) TCE concentrations exceeding 5.0 ppb in Layer 3, and part of finite difference grid with rows and columns numbered.

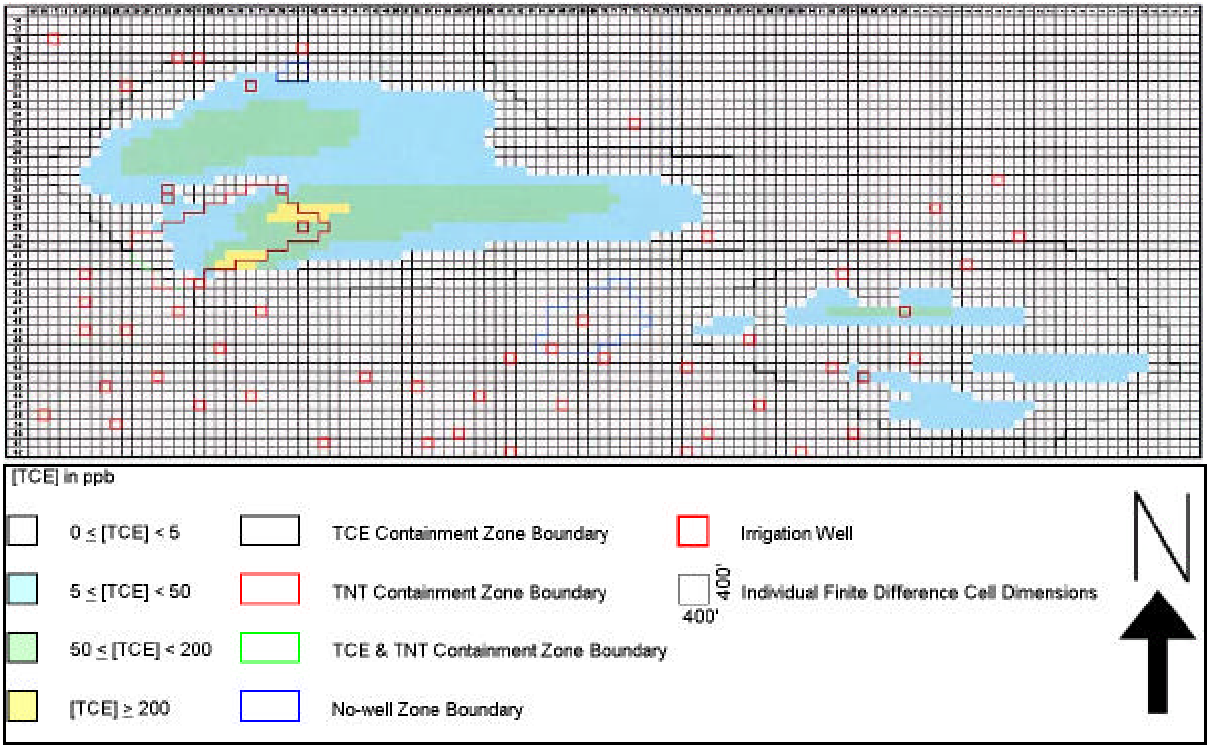


Fig. 3. Initial (Projected 1 Jan 2003) TCE concentrations exceeding 5.0 ppb in Layer 4, and part of finite difference grid with rows and columns numbered.

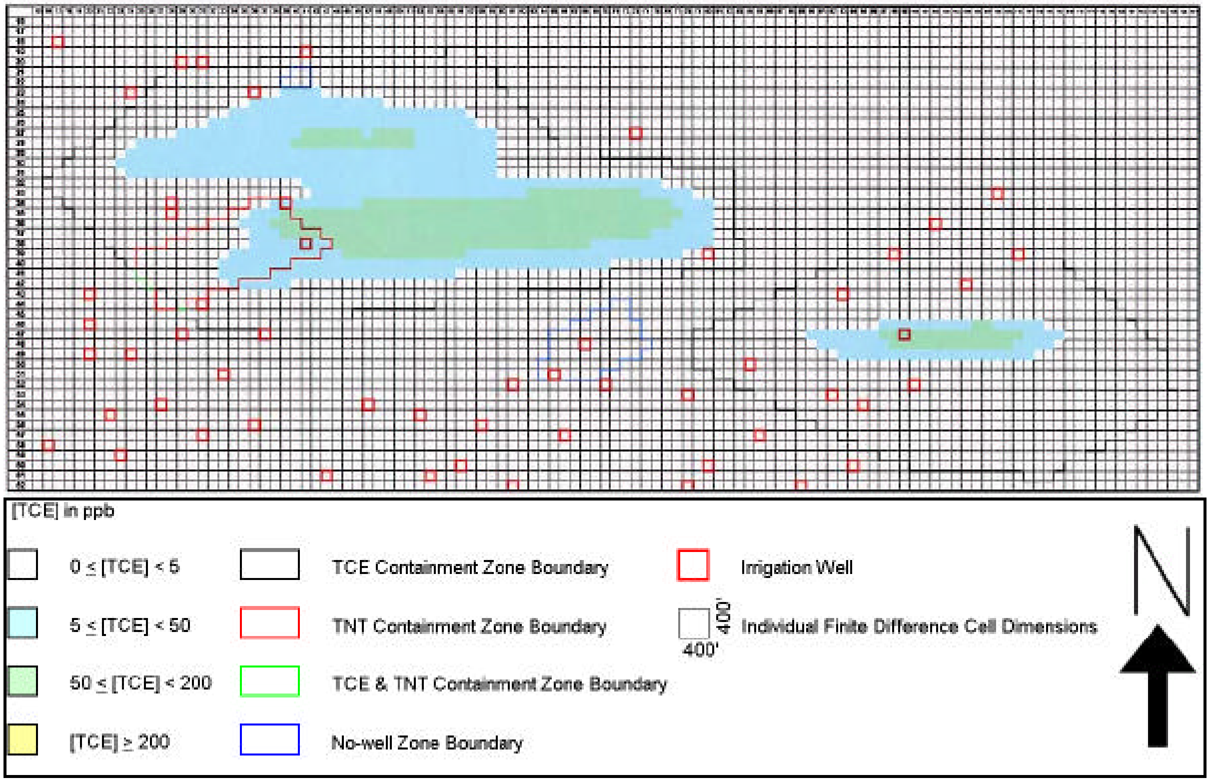


Fig. 4. Initial (Projected 1 Jan 2003) TCE concentrations exceeding 5.0 ppb in Layer 5, and part of finite difference grid with rows and columns numbered.

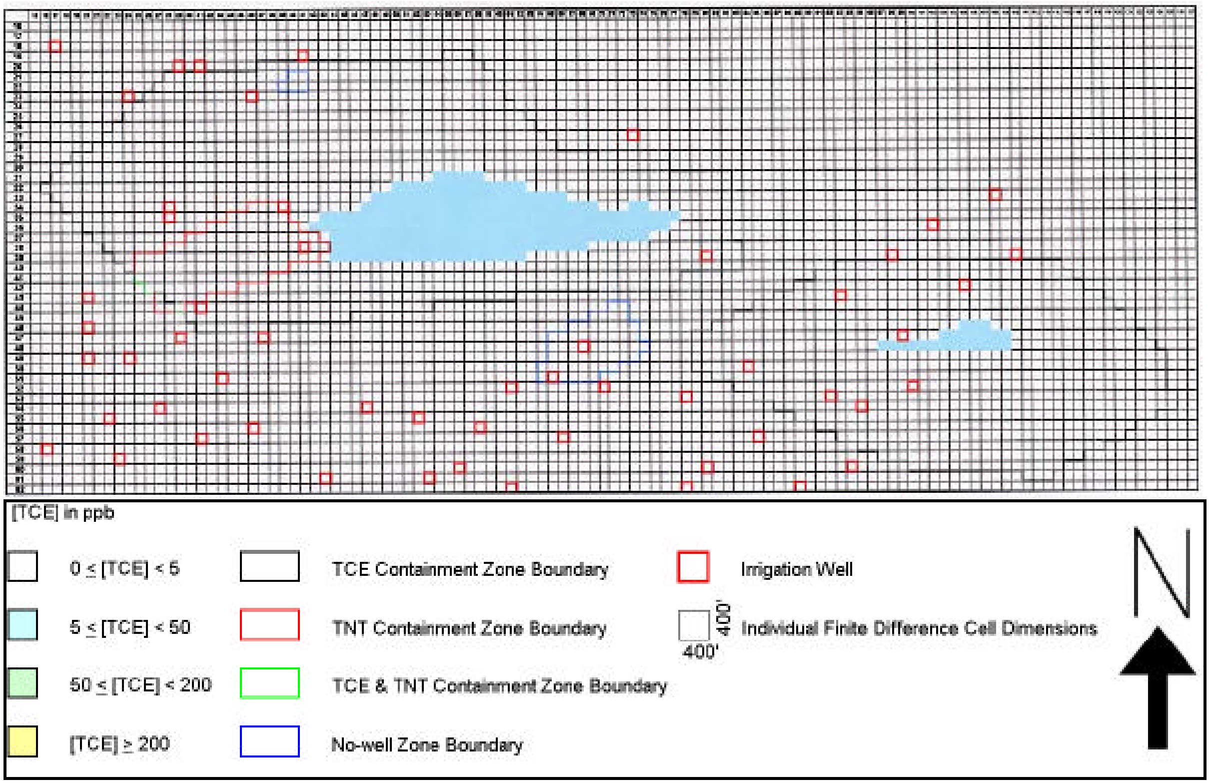


Fig. 5. Initial (Projected 1 Jan 2003) TNT concentrations exceeding 2.8 ppb in layer 3, and part of finite difference grid.

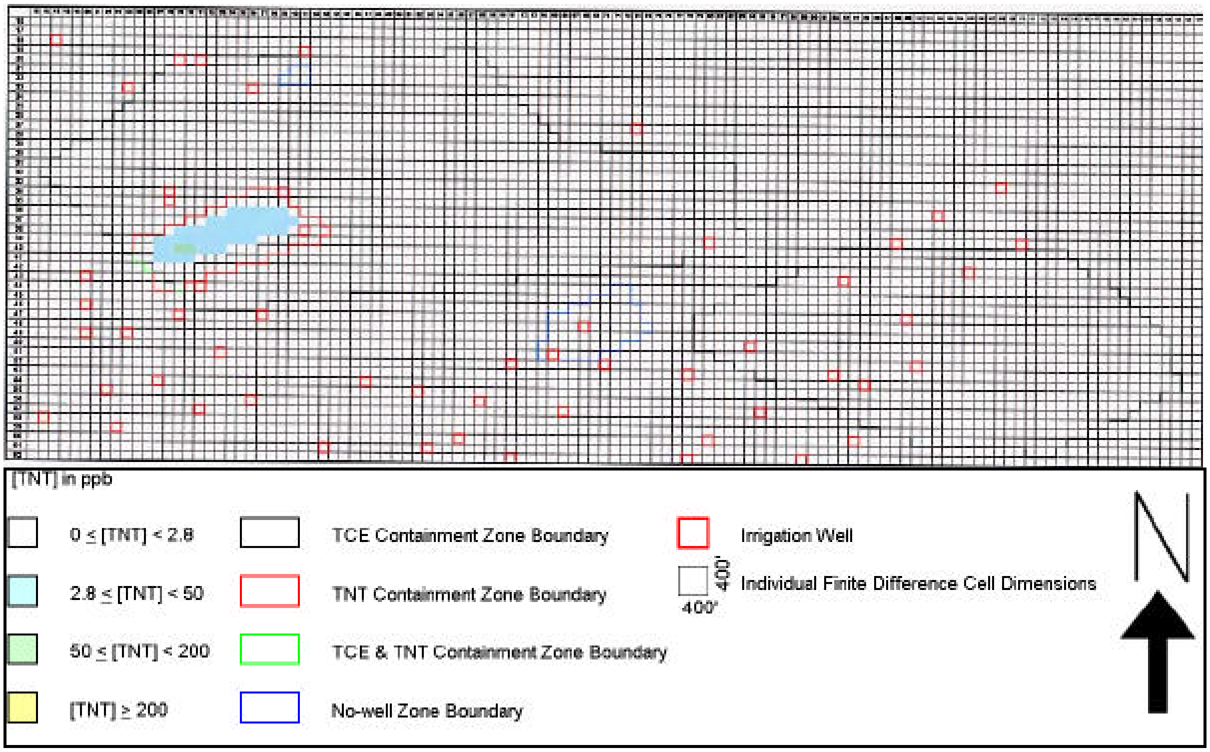


Fig. 6. Constraints for optimization problem formulations.

Constraints for all formulations

- Layer 1 and 2 cells not allowed to become dry
- Use of extraction wells, but no injection
- 350 gpm pumping limit on wells screened in 1 layer
- 700 gpm pumping limit on wells screened in 2 layers
- 1050 gpm pumping limit on wells screened in 3 layers
- No remediation well screening in layer 6
- No remediation wells in restricted areas.
- No remediation wells allowed in irrigation well cells
- Concentrations cannot exceed CLs in forbidden zones at end of any MP (CL_{TCE} = 5ppb, CL_{TNT} = 2.8 ppb)

Additional constraint for Formulations 1 and 2

- Cleanup to CLs within 30 years for Layers 3-6

Fig. 7a. Formulation 1 objective function: minimize present value of cost

MINIMIZE (CCE + CCT + CCD + FCM + FCS + VCE + VCT +VCD)

Evaluated at the end of every year to account for discounting of annual costs:

CCE **=** Capital Costs of new extraction wells($400K)

CCT **=** Capital Cost of Treatment($1.0K per gpm)

CCD **=** Capital Cost of Discharge Piping($1.5K per gpm)

FCM **=** Fixed Cost of Management($115K O&M)

FCS **=** Fixed Cost of Sampling ($300K annual sampling and analysis)

VCE **=** Variable cost of electricity for well operations($0.046K per gpm)

VCT **=** Variable cost of treatment ($0.283K per gpm)

VCD **=** Variable cost of discharge ($0.066K per gpm)

Fig. 7b. Formulation 2 objective function: minimize present value of cost

MINIMIZE (CCE + CCT + CCD + FCM + FCS + VCE + VCT +VCD)

Same as Formulation 1 but assume diversion of 2400 gpm of extracted water:

CCT **=** Capital Cost of Treatment

CCD **=** Capital Cost of Discharge Piping

VCT **=** Variable cost of treatment

VCD **=** Variable cost of discharge

If Qmax = 2400 then

$CCT = CCD = CT_i = CD_i = 0$

Else $CCT = 1.0x[Qmax-2400]$

$CCD = 1.5x[Qmax-2400]$

$CT_i = 0.2863x[Q_i-2400]$

$CD_i = 0.066x[Q_i-2400]$

Fig. 8. Formulation 3 objective function: minimizing maximum total pumping rate in any management period.

MINIMIZE MAXIMUM TOTAL PUMPING RATE IN ANY MANAGEMENT PERIOD

MINIMIZE (Q_{max})

Q_{max} is the maximum total pumping at remediation wells (Layers 3-6) in any management period over a 30-year simulation.

Fig. 9. Formulation 3 surrogate containment zones for Strategies USU3B' and USU3C'.

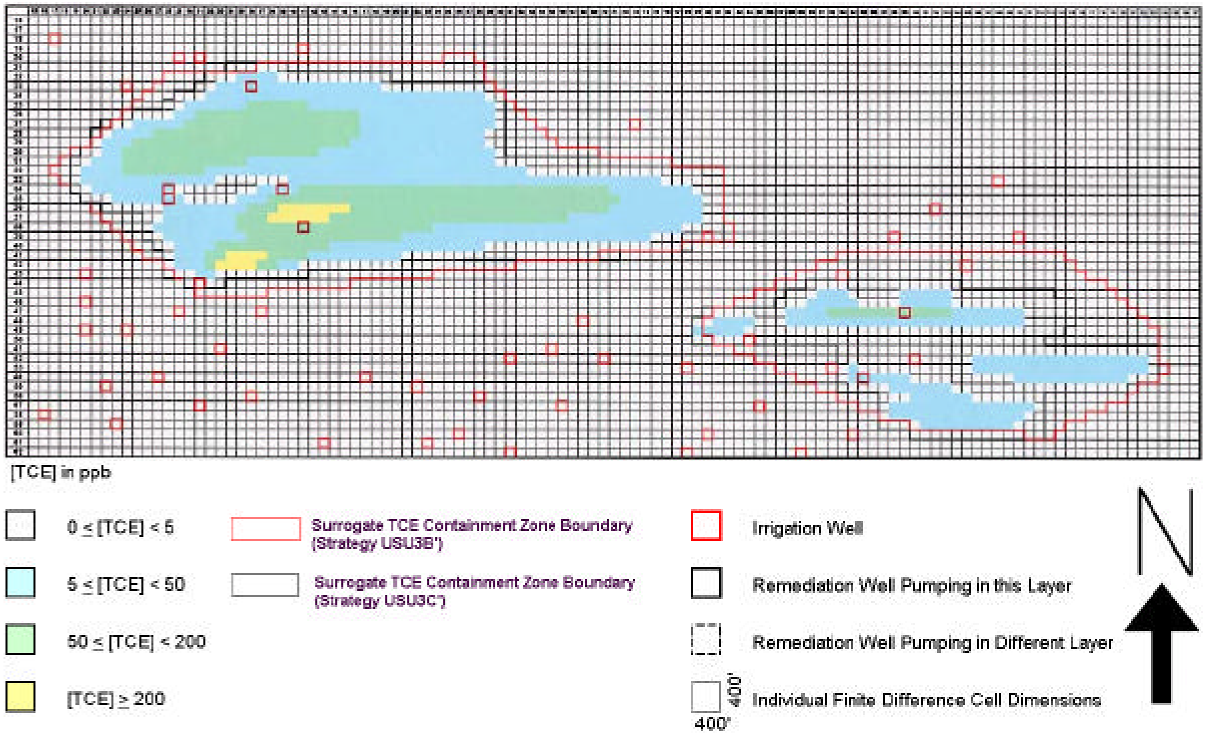


Fig. 10. Strategy USU1: TCE concentrations ≥ 5.0 ppb in Layer 3 after 25 years of pumping.

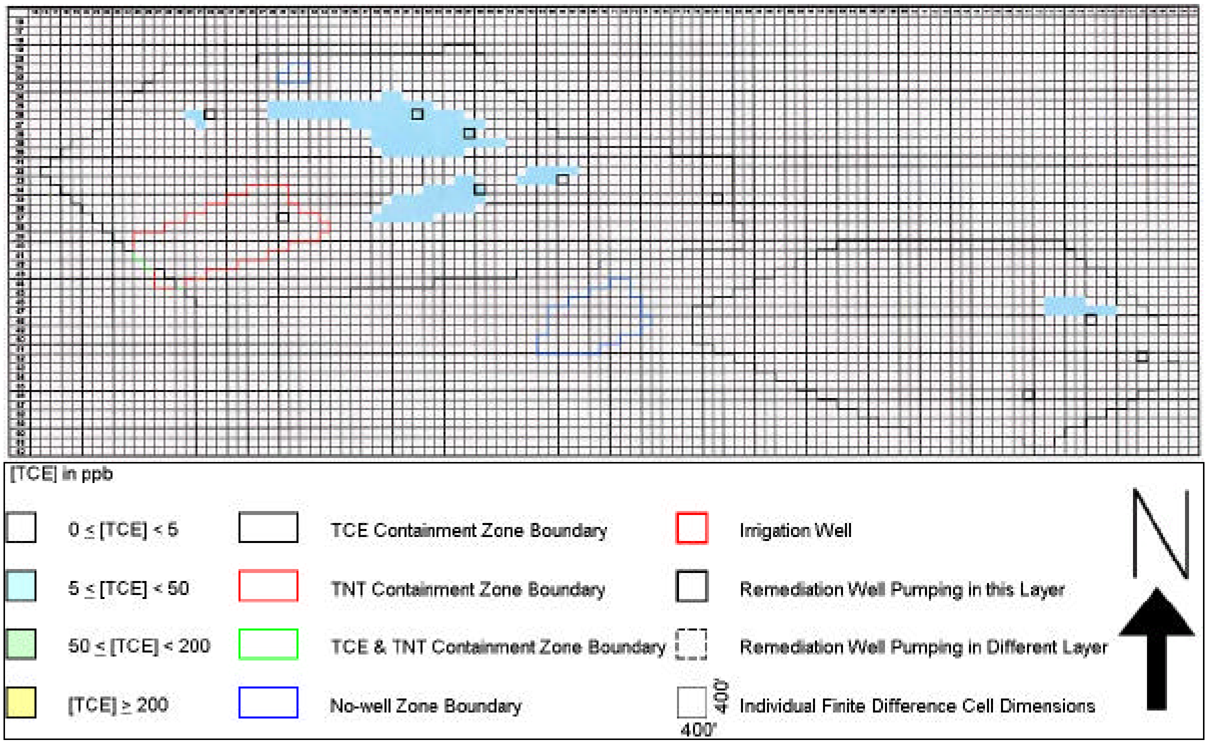


Fig. 11. Strategy USU1: TCE concentrations ≥ 5.0 ppb in Layer 4 after 25 years of pumping.

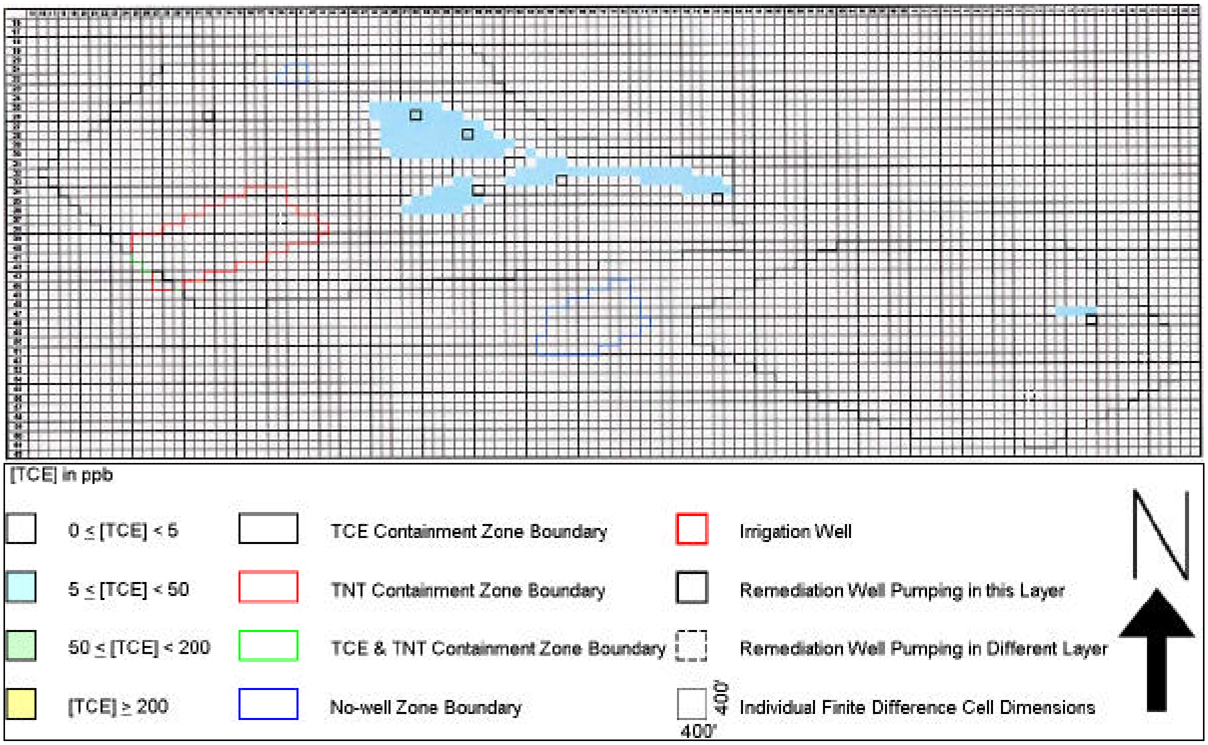


Fig. 12. Strategy USU1: TNT concentrations ≥ 2.8 ppb in Layer 3 after 25 years of pumping.

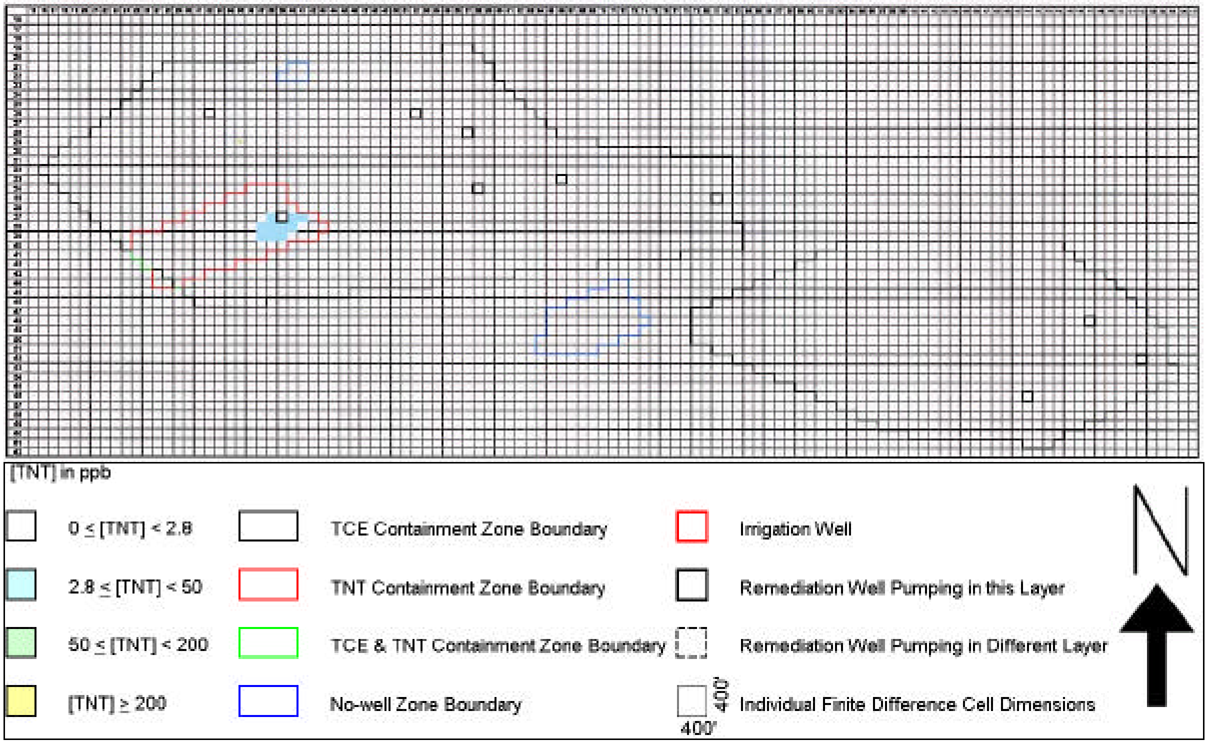


Fig. 13. Strategy USU3A: TCE concentrations ≥ 5.0 ppb in Layer 3 after 30 years of pumping.

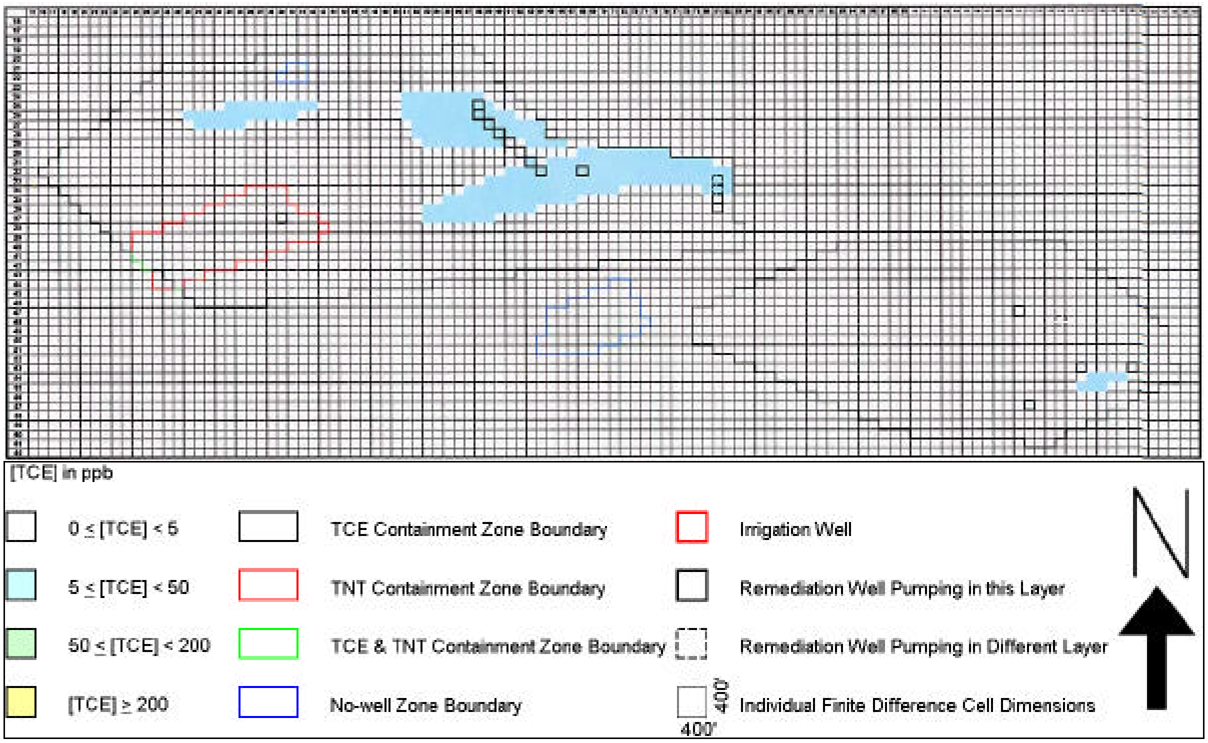


Fig. 14. Strategy USU3A: TCE concentrations ≥ 5.0 ppb in Layer 4 after 30 years of pumping.

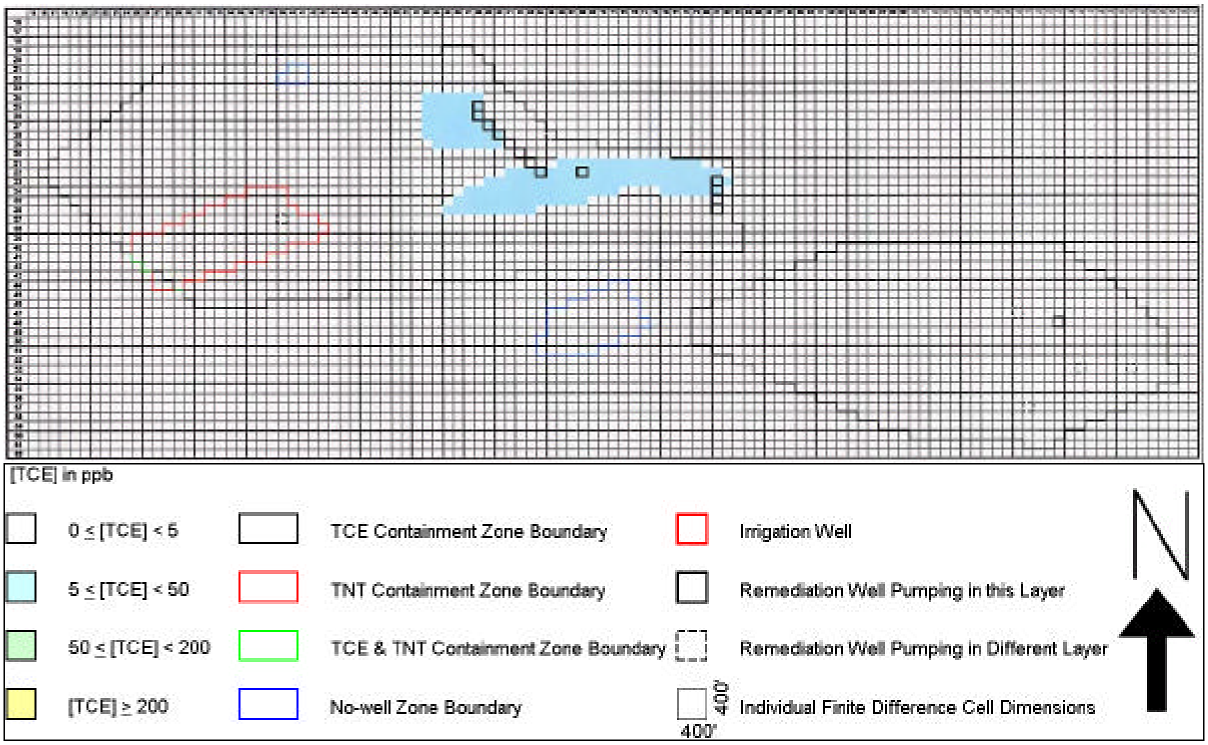


Fig. 15. Strategy USU3A: TCE concentrations $\geq$ 5.0 ppb in Layer 5 after 30 years of pumping.

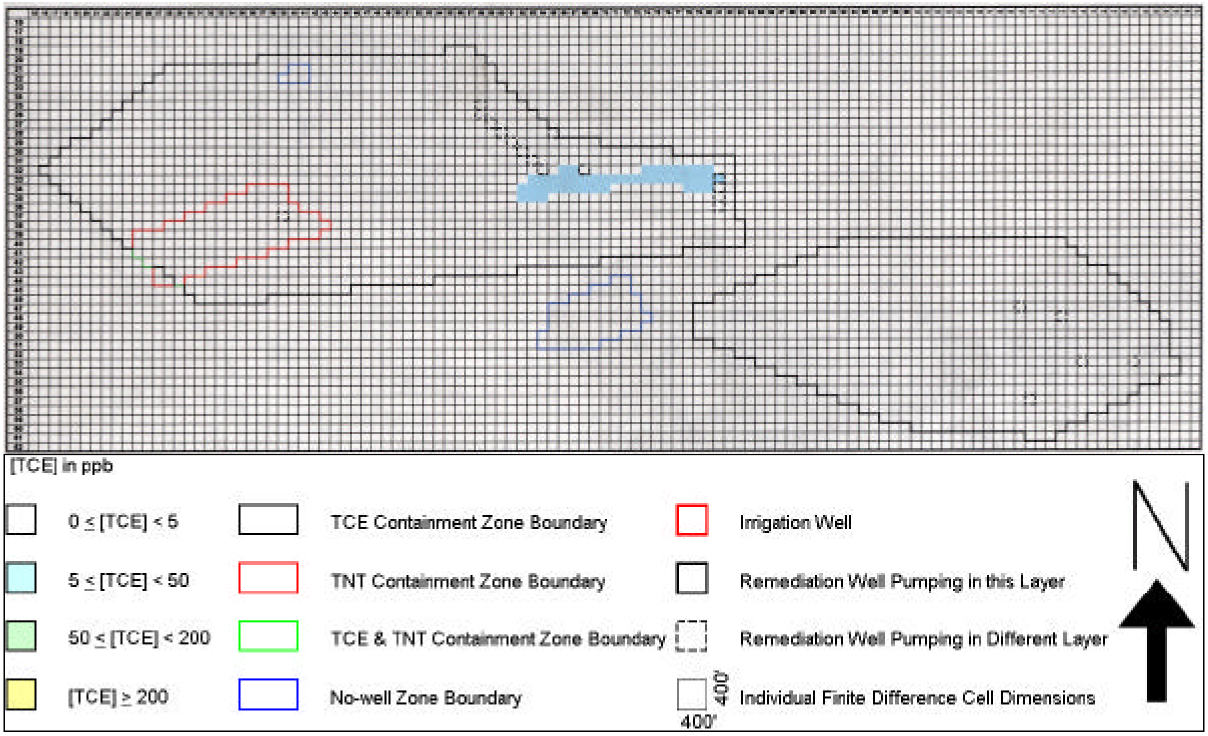


Fig. 16. Strategy USU3A: TNT concentrations > 2.8 ppb in Layer 3 after 30 years of pumping.

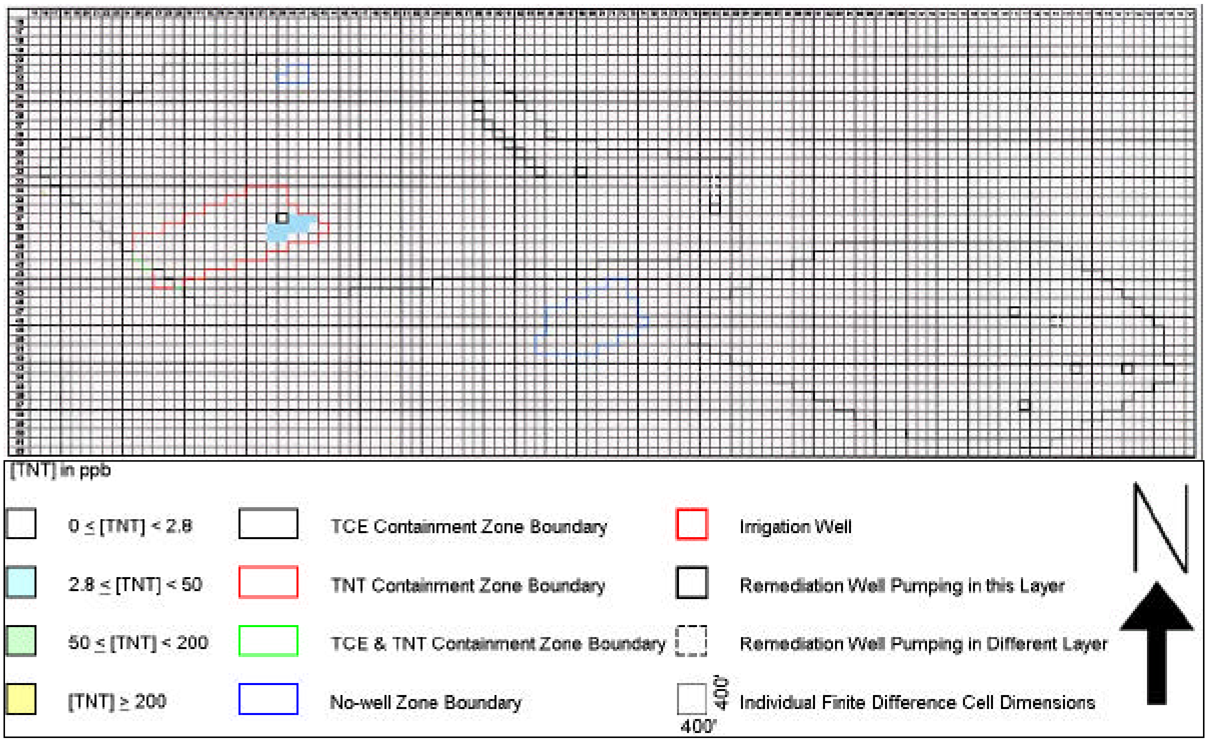


Fig. 17. Strategy USU3B’: TCE concentrations ≥ 5.0 ppb in Layer 3 after 30 years of pumping.

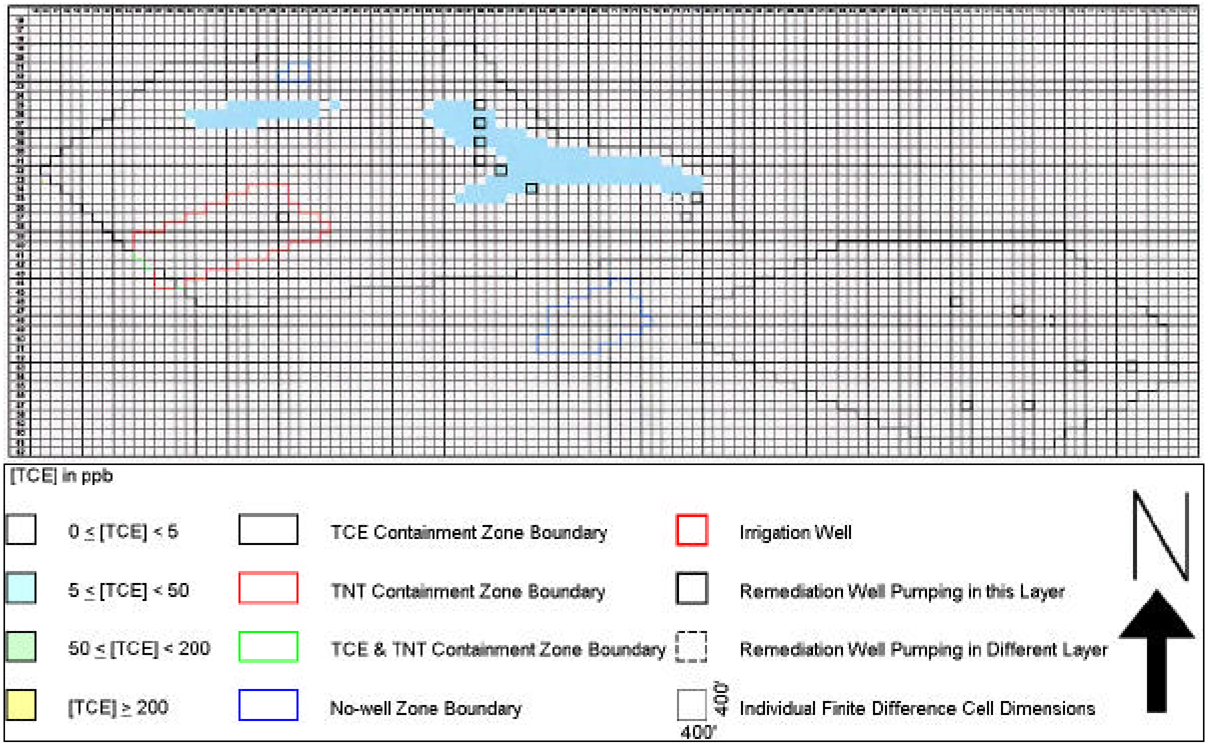


Fig. 18. Strategy USU3B': TCE concentrations ≥ 5.0 ppb in Layer 4 after 30 years of pumping.

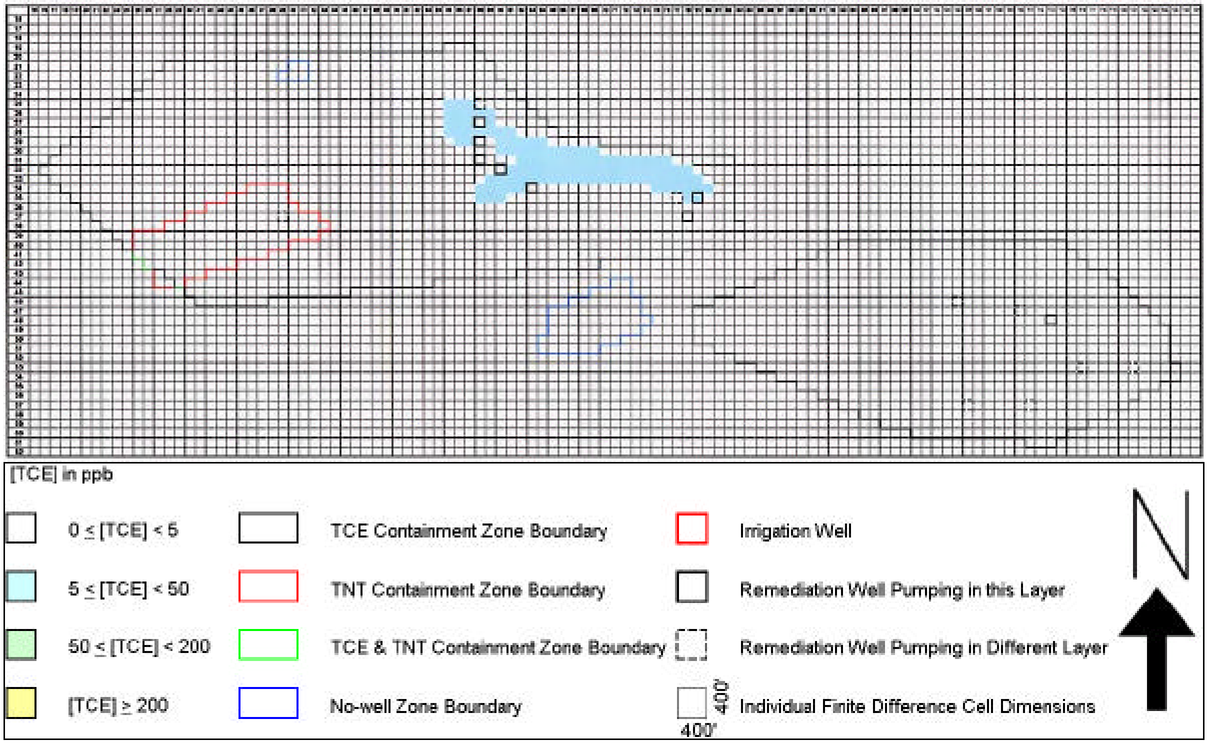


Fig. 19. Strategy USU3B’: TNT concentrations ≥ 2.8 ppb in Layer 3 after 30 years of pumping.

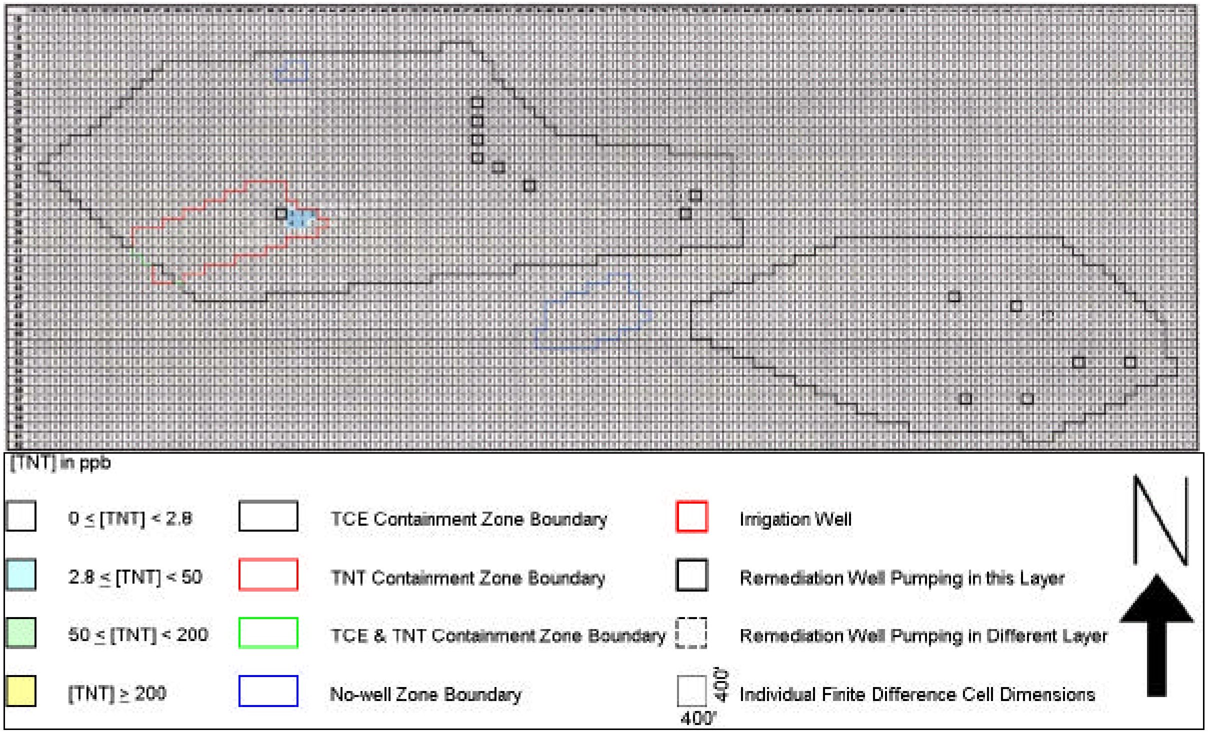


Fig. 20. Strategy USU3C’: TCE concentrations ≥ 5.0 ppb in Layer 3 after 30 years of pumping.

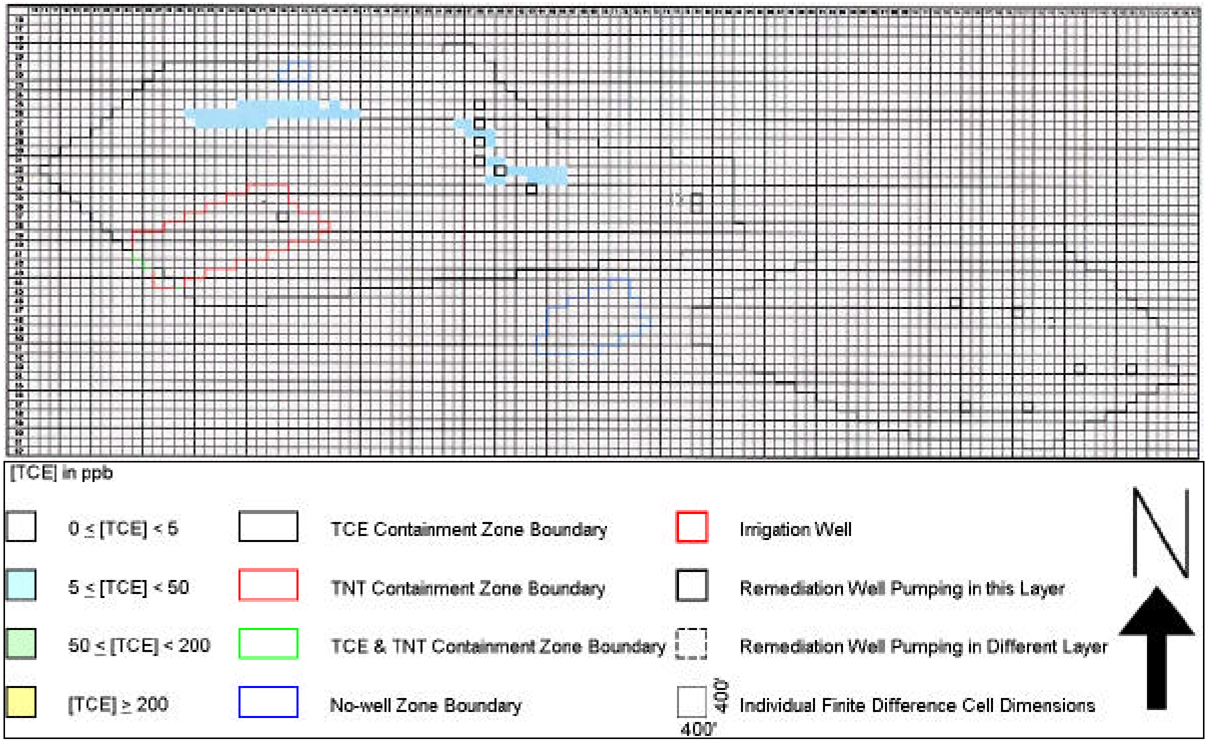


Fig. 21. Strategy USU3C': TCE concentrations ≥ 5.0 ppb in Layer 4 after 30 years of pumping.

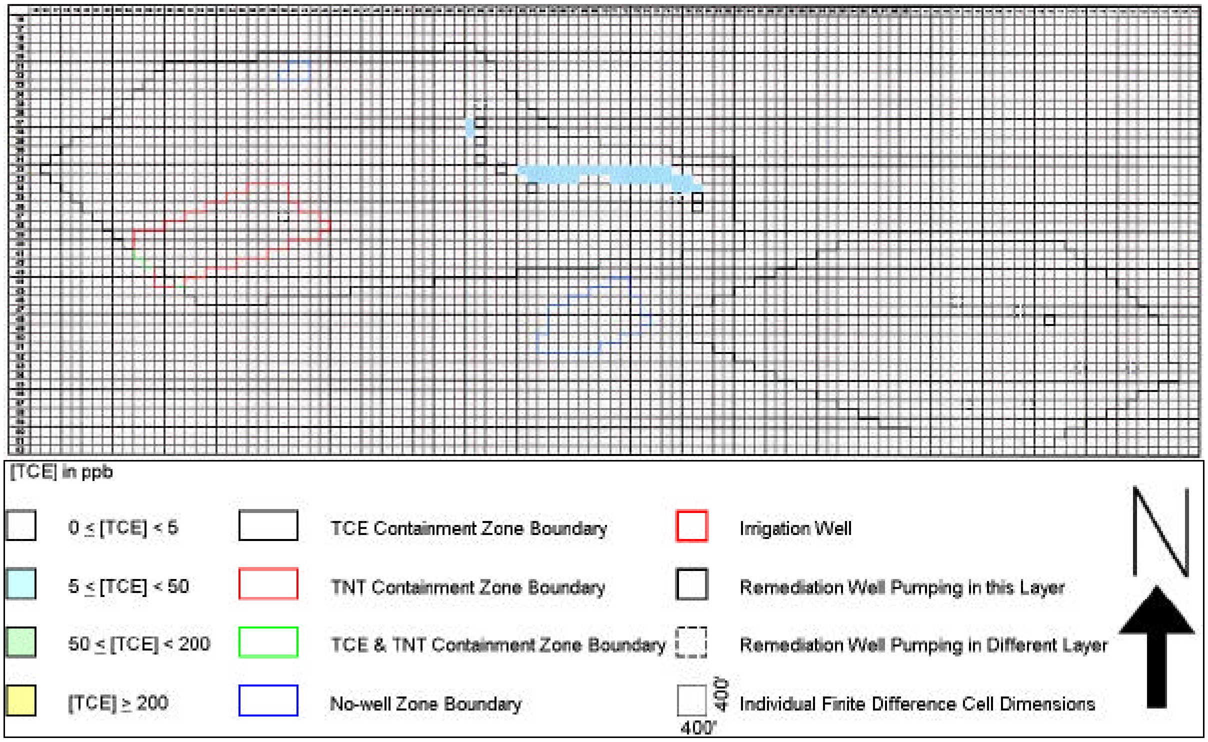
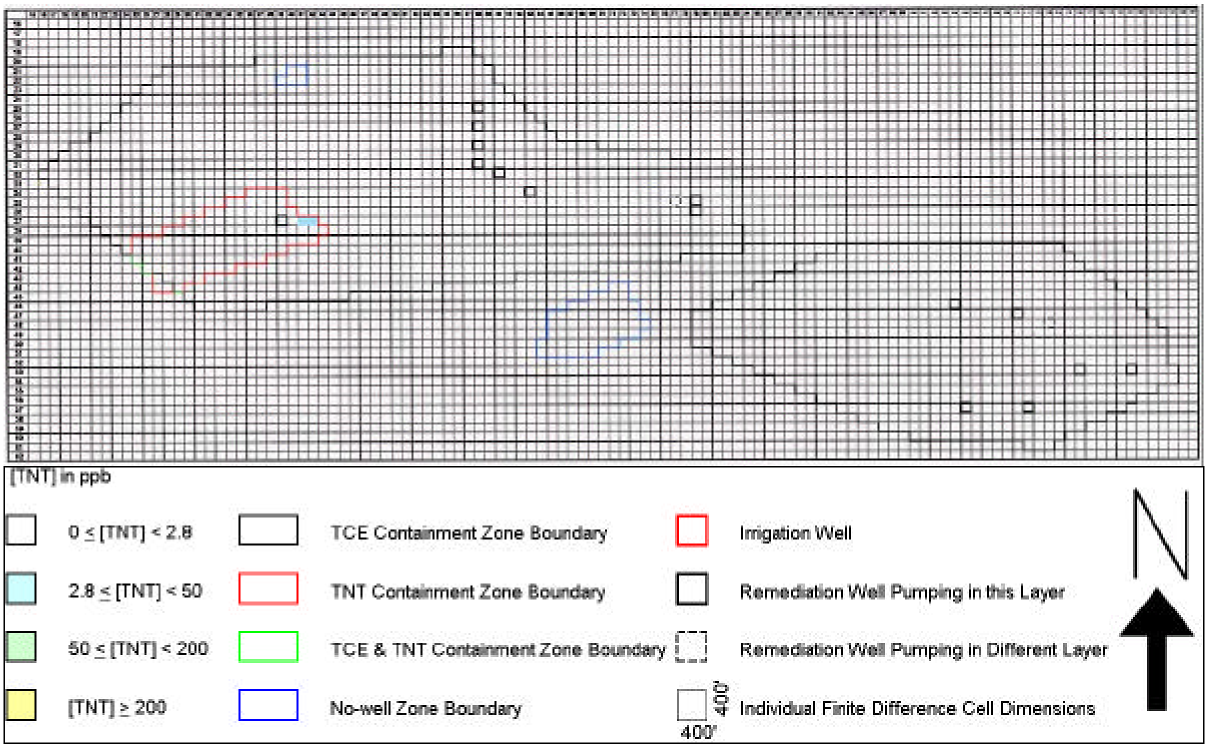


Fig. 22. Strategy USU3C': TNT concentrations ≥ 2.8 ppb in Layer 3 after 30 years of pumping.



Appendix A. Post processor evaluation of Strategy USU1.

```
                      Intermediate Variables Calculation
                      ----------------------------------

     Cleanup Year for TCE
             30
     Cleanup Year for TNT
             29
     Cleanup Year for Formulation  1
             30

     Number of Irrigation Wells and Total Rates
          Season          Number of Wells          Total Rate (gpm)
          ------          ---------------          ----------------
              1                  12                     2100.000
              2                 951                    54298.152

     Total Number of Wells In Each Stress Period
          Stress Period
          -------------
              1                   8
              2                   8
              3                   8
              4                   8
              5                  10
              6                   8

     Extraction Well Rates (Combining Multi-Aquifer Wells)
          Well Index        Well Rate (gpm)        Screen Layers
          ----------        ---------------        -------------
          Stress Period:   1
              3                301.293                   1
              5                305.995                   2
              6                501.766                   2
              7                506.161                   2
              8                280.873                   2
             10                257.029                   1
             11                106.675                   1
             12                226.452                   2
          Stress Period:   2
              3                299.906                   1
              5                340.447                   2
              6                476.291                   2
              7                553.506                   2
              8                287.169                   2
             10                258.369                   1
             11                139.636                   1
```

```
         12                276.945                   2
      Stress Period:   3
          3                296.473                   1
          5                378.909                   2
          6                471.190                   2
          7                522.951                   2
          8                285.247                   2
         10                264.722                   1
         11                118.956                   1
         12                305.694                   2
      Stress Period:   4
          3                350.000                   1
          5                344.374                   2
          6                481.870                   2
          7                563.751                   2
          8                270.223                   2
         10                242.447                   1
         11                107.055                   1
         12                392.073                   2
      Stress Period:   5
          1                423.055                   2
          2                198.286                   2
          3                350.000                   1
          5                407.335                   2
          6                482.275                   2
          7                397.610                   2
          8                277.517                   2
         10                257.210                   1
         11                134.971                   1
         12                377.257                   2
      Stress Period:   6
          1                696.104                   2
          2                147.429                   2
          3                350.000                   1
          5                344.031                   2
          6                569.756                   2
          7                690.192                   2
          8                183.397                   2
         12                397.195                   2

 Number of New Extraction Wells in Each Stress Period
          8
          0
          0
          0
          2
          0

 Total Pumping Rate in Each Stress Period (gpm)
      Pumping Rate
      ------------
        2486.244
```

```
            2632.270
            2644.140
            2751.792
            3305.517
            3378.104


                           Objective Function Calculation
                           ------------------------------

     The Capital Costs of New Wells (thousand of dollars)
          3602.053

     The Capital Costs of Treatment Plant (thousand of dollars)
          3378.104

     The Capital Costs of Discharge Piping (thousand of dollars)
          5067.156

     The Fixed Costs of O&M (thousand of dollars)
          2189.114

     The Fixed Costs of Sampling (thousand of dollars)
          5710.732

     The Variable Costs of Electricity for Operating Wells (thousand
of dollars)
          2431.264

     The Variable Costs of Treatment (thousand of dollars)
         14957.560

     The Variable Costs of Discharge (thousand of dollars)
          3488.336

     The Objective Function Value (thousands of dollars) for
Formulation #  1
         40824.320


                           Constraints Check-Out
                           ---------------------


     --- Modification Occurrence Constraint ---

     The Modification Occurrence Constraint Satisfied


     --- Cleanup Year Constraint ---

     The Cleanup Year
```

```
        30
The Cleanup Year Constraint Satisfied


--- Plume Containment Constraint ---

The Plume Containment Constraint Satisfied


--- Pumping Limit Constraint ---

The Pumping Limit Constraint Satisfied


--- Well Restricted Areas Constraint ---

The Well Restricted Areas Constraint Satisfied


--- Remediation Well Location Constraint ---

The Remediation Well Location Constraint Satisfied


--- Dry Cell Constraint ---

The Dry Cell Constraint Satisfied


--- Irrigation Well Constraint ---

The Irrigation Well Constraint Satisfied


--- Well Screen Constraint ---

The Well Screen Constraint Satisfied


Number of Constraints Not Satisfied
         0
```

Appendix B. Post processor evaluation of Strategy USU2.

```
                      Intermediate Variables Calculation
                      ----------------------------------

     Cleanup Year for TCE
             30
     Cleanup Year for TNT
             29
     Cleanup Year for Formulation  2
             30

     Number of Irrigation Wells and Total Rates
          Season          Number of Wells          Total Rate (gpm)
          ------          ---------------          ----------------
              1                 12                     2100.000
              2                951                    54298.152

     Total Number of Wells In Each Stress Period
          Stress Period
          -------------
              1                    8
              2                    8
              3                    8
              4                    8
              5                   10
              6                    8

     Extraction Well Rates (Combining Multi-Aquifer Wells)
          Well Index        Well Rate (gpm)        Screen Layers
          ----------        ---------------        -------------
          Stress Period:   1
              3                301.293                   1
              5                305.995                   2
              6                501.766                   2
              7                506.161                   2
              8                280.873                   2
             10                257.029                   1
             11                106.675                   1
             12                226.452                   2
          Stress Period:   2
              3                299.906                   1
              5                340.447                   2
              6                476.291                   2
              7                553.506                   2
              8                287.169                   2
             10                258.369                   1
             11                139.636                   1
             12                276.945                   2
          Stress Period:   3
```

```
           3                296.473                   1
           5                378.909                   2
           6                471.190                   2
           7                522.951                   2
           8                285.247                   2
          10                264.722                   1
          11                118.956                   1
          12                305.694                   2
       Stress Period:   4
           3                350.000                   1
           5                344.374                   2
           6                481.870                   2
           7                563.751                   2
           8                270.223                   2
          10                242.447                   1
          11                107.055                   1
          12                392.073                   2
       Stress Period:   5
           1                423.055                   2
           2                198.286                   2
           3                350.000                   1
           5                407.335                   2
           6                482.275                   2
           7                397.610                   2
           8                277.517                   2
          10                257.210                   1
          11                134.971                   1
          12                377.257                   2
       Stress Period:   6
           1                696.104                   2
           2                147.429                   2
           3                350.000                   1
           5                344.031                   2
           6                569.756                   2
           7                690.192                   2
           8                183.397                   2
          12                397.195                   2

  Number of New Extraction Wells in Each Stress Period
           8
           0
           0
           0
           2
           0

  Total Pumping Rate in Each Stress Period (gpm)
       Pumping Rate
       ------------
         2486.244
         2632.270
         2644.140
```

```
            2751.792
            3305.517
            3378.104


                           Objective Function Calculation
                           ------------------------------

     The Capital Costs of New Wells (thousand of dollars)
          3602.053

     The Capital Costs of Treatment Plant (thousand of dollars)
           978.104

     The Capital Costs of Discharge Piping (thousand of dollars)
          1467.156

     The Fixed Costs of O&M (thousand of dollars)
          2189.114

     The Fixed Costs of Sampling (thousand of dollars)
          5710.732

     The Variable Costs of Electricity for Operating Wells (thousand
of dollars)
          2431.264

     The Variable Costs of Treatment (thousand of dollars)
          2028.462

     The Variable Costs of Discharge (thousand of dollars)
           473.069

     The Objective Function Value (thousands of dollars) for
Formulation #  2
         18879.953


                           Constraints Check-Out
                           ---------------------


     --- Modification Occurrence Constraint ---

     The Modification Occurrence Constraint Satisfied


     --- Cleanup Year Constraint ---

     The Cleanup Year
             30
     The Cleanup Year Constraint Satisfied
```

```
--- Plume Containment Constraint ---

The Plume Containment Constraint Satisfied

--- Pumping Limit Constraint ---

The Pumping Limit Constraint Satisfied

--- Well Restricted Areas Constraint ---

The Well Restricted Areas Constraint Satisfied

--- Remediation Well Location Constraint ---

The Remediation Well Location Constraint Satisfied

--- Dry Cell Constraint ---

The Dry Cell Constraint Satisfied

--- Irrigation Well Constraint ---

The Irrigation Well Constraint Satisfied

--- Well Screen Constraint ---

The Well Screen Constraint Satisfied

Number of Constraints Not Satisfied
         0
```

Appendix C. Post processor evaluation of Strategy USU3A.

```
                          Intermediate Variables Calculation
                          ----------------------------------

     Cleanup Year for TCE
          > 30 years
     Cleanup Year for TNT
           > 30 years
     Cleanup Year for Formulation  3
           > 30 years

     Number of Irrigation Wells and Total Rates
          Season          Number of Wells          Total Rate (gpm)
          ------          ---------------          ----------------
              1                 12                      2100.000
              2                951                     54298.152

     Total Number of Wells In Each Stress Period
          Stress Period
          -------------
              1                   24
              2                   24
              3                   24
              4                   24
              5                   25
              6                   24

     Extraction Well Rates (Combining Multi-Aquifer Wells)
          Well Index        Well Rate (gpm)        Screen Layers
          ----------        ---------------        -------------
          Stress Period:   1
              1                 189.616                  1
              2                  75.740                  1
              3                 145.091                  1
              4                 156.800                  1
              5                  51.434                  1
              6                 277.403                  1
              7                  23.444                  1
              8                  21.652                  1
              9                  17.657                  1
             10                  15.361                  1
             11                  52.592                  2
             12                  56.395                  2
             13                 128.197                  2
             14                 146.213                  1
             15                 166.629                  2
             16                  65.164                  1
             17                  69.896                  1
             18                  86.691                  2
```

19	56.104	2
20	87.730	1
21	72.727	1
22	61.647	1
23	57.377	1
24	57.065	1
Stress Period: 2		
1	189.616	1
2	75.740	1
3	145.091	1
4	156.800	1
5	51.434	1
6	277.403	1
7	23.444	1
8	21.652	1
9	17.657	1
10	15.361	1
11	52.592	2
12	56.395	2
13	128.197	2
14	146.213	1
15	166.629	2
16	65.164	1
17	68.083	1
18	87.730	2
19	56.925	2
20	87.730	1
21	72.727	1
22	61.647	1
23	57.377	1
24	57.065	1
Stress Period: 3		
1	189.616	1
2	75.740	1
3	145.091	1
4	156.800	1
5	51.434	1
6	277.403	1
7	23.444	1
8	21.652	1
9	17.657	1
10	15.361	1
11	52.592	2
12	56.395	2
13	128.197	2
14	146.213	1
15	166.629	2
16	65.164	1
17	68.083	1
18	87.730	2
19	56.925	2
20	87.730	1

21	72.727	1
22	61.647	1
23	57.377	1
24	57.065	1
Stress Period: 4		
1	189.616	1
2	75.740	1
3	145.091	1
4	156.800	1
5	51.434	1
6	277.403	1
7	23.444	1
8	21.652	1
9	17.657	1
10	15.361	1
11	52.592	2
12	56.395	2
13	128.197	2
14	146.213	1
15	166.629	2
16	65.164	1
17	68.083	1
18	87.730	2
19	56.925	2
20	87.730	1
21	72.727	1
22	61.647	1
23	57.377	1
24	57.065	1
Stress Period: 5		
1	189.616	1
2	65.294	1
3	145.091	1
4	156.800	1
5	51.434	1
6	277.403	1
7	23.444	1
8	21.652	1
9	17.657	1
10	15.361	1
11	52.592	2
12	56.395	2
13	128.197	2
14	146.213	1
15	166.629	2
16	65.164	1
17	68.083	1
18	87.730	2
19	56.925	2
20	87.730	1
21	72.727	1
22	61.647	1

23	57.377	1
24	57.065	1
25	10.447	1
Stress Period: 6		
1	155.870	1
3	145.091	1
4	156.800	1
5	51.434	1
6	277.403	1
7	23.444	1
8	21.652	1
9	17.657	1
10	15.361	1
11	52.592	2
12	56.395	2
13	128.197	2
14	146.213	1
15	174.421	2
16	65.164	1
17	68.083	1
18	113.704	2
19	56.925	2
20	87.730	1
21	83.117	1
22	83.143	1
23	57.377	1
24	57.065	1
25	33.704	1

Number of New Extraction Wells in Each Stress Period

24
0
0
0
1
0

Total Pumping Rate in Each Stress Period (gpm)

Pumping Rate
2138.623
2138.670
2138.670
2138.670
2138.670
2128.540

Objective Function Calculation

The Objective Function Value (gpm) for Formulation # 3

```
      2138.670

                           Constraints Check-Out
                           ---------------------

  --- Modification Occurrence Constraint ---

  The Modification Occurrence Constraint Satisfied

  --- Plume Containment Constraint ---

  The Plume Containment Constraint Satisfied

  --- Pumping Limit Constraint ---

  The Pumping Limit Constraint Satisfied

  --- Well Restricted Areas Constraint ---

  The Well Restricted Areas Constraint Satisfied

  --- Remediation Well Location Constraint ---

  The Remediation Well Location Constraint Satisfied

  --- Dry Cell Constraint ---

  The Dry Cell Constraint Satisfied

  --- Irrigation Well Constraint ---

  The Irrigation Well Constraint Satisfied

  --- Well Screen Constraint ---

  The Well Screen Constraint Satisfied

  --- Maximum Number of New Wells Constraint ---

  Total Number of New Wells Ever Installed
          25
```

```
The Maximum Number of New Wells Constraint Satisfied


Number of Constraints Not Satisfied
         0
```

Appendix D. Post processor evaluation of Strategy USU3A'.

```
                           Intermediate Variables Calculation
                           ----------------------------------

     Cleanup Year for TCE
          > 30 years
     Cleanup Year for TNT
           > 30 years
     Cleanup Year for Formulation  3
           > 30 years

     Number of Irrigation Wells and Total Rates
          Season          Number of Wells          Total Rate (gpm)
          ------          ---------------          ----------------
              1                 12                     2100.000
              2                951                    54298.152

     Total Number of Wells In Each Stress Period
          Stress Period
          -------------
              1                   25
              2                   25
              3                   25
              4                   25
              5                   25
              6                   23

     Extraction Well Rates (Combining Multi-Aquifer Wells)
          Well Index        Well Rate (gpm)        Screen Layers
          ----------        ---------------        -------------
          Stress Period:   1
              1                189.616                  1
              2                 75.740                  1
              3                145.091                  1
              4                156.800                  1
              5                 51.434                  1
              6                272.208                  1
              7                 15.652                  1
              8                 14.899                  1
              9                 13.018                  1
             10                 12.764                  1
             11                 57.787                  2
             12                 56.395                  2
             13                102.223                  2
             14                146.213                  1
             15                177.018                  2
             16                 65.164                  1
             17                 68.083                  1
```

18	83.574	2
19	56.925	2
20	87.730	1
21	77.922	1
22	77.231	1
23	57.377	1
24	57.065	1
25	5.195	1
Stress Period: 2		
1	189.616	1
2	75.740	1
3	145.091	1
4	156.800	1
5	51.434	1
6	272.208	1
7	15.652	1
8	14.899	1
9	13.018	1
10	12.764	1
11	57.787	2
12	56.395	2
13	102.223	2
14	146.213	1
15	177.018	2
16	65.164	1
17	68.083	1
18	83.574	2
19	56.925	2
20	87.730	1
21	77.922	1
22	77.231	1
23	57.377	1
24	57.065	1
25	5.195	1
Stress Period: 3		
1	189.616	1
2	75.740	1
3	145.091	1
4	156.800	1
5	51.434	1
6	272.208	1
7	15.652	1
8	14.899	1
9	13.018	1
10	12.764	1
11	57.787	2
12	56.395	2
13	102.223	2
14	146.213	1
15	177.018	2
16	65.164	1
17	68.083	1

18	83.574	2
19	56.925	2
20	87.730	1
21	77.922	1
22	77.231	1
23	57.377	1
24	57.065	1
25	5.195	1
Stress Period: 4		
1	189.616	1
2	75.740	1
3	145.091	1
4	156.800	1
5	51.434	1
6	272.208	1
7	15.652	1
8	14.899	1
9	13.018	1
10	12.764	1
11	57.787	2
12	56.395	2
13	102.223	2
14	146.213	1
15	177.018	2
16	65.164	1
17	68.083	1
18	83.574	2
19	56.925	2
20	87.730	1
21	77.922	1
22	77.231	1
23	57.377	1
24	57.065	1
25	5.195	1
Stress Period: 5		
1	189.616	1
2	65.294	1
3	145.091	1
4	156.800	1
5	51.434	1
6	272.208	1
7	15.652	1
8	14.899	1
9	13.018	1
10	12.764	1
11	57.787	2
12	56.395	2
13	102.223	2
14	146.213	1
15	177.018	2
16	65.164	1
17	68.083	1

18	83.574	2
19	56.925	2
20	87.730	1
21	77.922	1
22	77.231	1
23	57.377	1
24	57.065	1
25	15.642	1
Stress Period: 6		
3	145.091	1
4	156.800	1
5	51.434	1
6	280.732	1
7	15.652	1
8	14.899	1
9	13.018	1
10	12.764	1
11	57.787	2
12	66.784	2
13	102.223	2
14	146.213	1
15	270.525	2
16	65.164	1
17	68.083	1
18	134.483	2
19	98.483	2
20	87.730	1
21	83.117	1
22	93.532	1
23	57.377	1
24	57.065	1
25	44.094	1

Number of New Extraction Wells in Each Stress Period

25
0
0
0
0
0

Total Pumping Rate in Each Stress Period (gpm)

Pumping Rate
2123.122
2123.122
2123.122
2123.122
2123.122
2123.049

```
                    Objective Function Calculation
                    ------------------------------

The Objective Function Value (gpm) for Formulation #  3
     2123.122

                    Constraints Check-Out
                    ---------------------


--- Modification Occurrence Constraint ---

The Modification Occurrence Constraint Satisfied


--- Plume Containment Constraint ---

The Plume Containment Constraint Satisfied


--- Pumping Limit Constraint ---

The Pumping Limit Constraint Satisfied


--- Well Restricted Areas Constraint ---

The Well Restricted Areas Constraint Satisfied


--- Remediation Well Location Constraint ---

The Remediation Well Location Constraint Satisfied


--- Dry Cell Constraint ---

The Dry Cell Constraint Satisfied


--- Irrigation Well Constraint ---

The Irrigation Well Constraint Satisfied


--- Well Screen Constraint ---

The Well Screen Constraint Satisfied
```

```
--- Maximum Number of New Wells Constraint ---

Total Number of New Wells Ever Installed
        25

The Maximum Number of New Wells Constraint Satisfied


Number of Constraints Not Satisfied
         0
```

Appendix E. Post processor evaluation of Strategy USU3B'.

```
                      Intermediate Variables Calculation
                      ----------------------------------

 Cleanup Year for TCE
      > 30 years
 Cleanup Year for TNT
       > 30 years
 Cleanup Year for Formulation  3
       > 30 years

 Number of Irrigation Wells and Total Rates
      Season          Number of Wells          Total Rate (gpm)
      ------          ---------------          ----------------
          1                  12                    2100.000
          2                 951                   54298.152

 Total Number of Wells In Each Stress Period
      Stress Period
      -------------
          1                    24
          2                    24
          3                    24
          4                    24
          5                    24
          6                    24

 Extraction Well Rates (Combining Multi-Aquifer Wells)
      Well Index        Well Rate (gpm)        Screen Layers
      ----------        ---------------        -------------
      Stress Period:   1
          1                 98.597                   1
          2                 75.590                   1
          3                 65.517                   1
          4                 93.834                   1
          5                180.265                   1
          6                 74.244                   1
          7                 73.366                   1
          8                118.732                   1
          9                 42.494                   1
         10                245.896                   1
         11                290.909                   1
         12                 76.686                   1
         13                 61.086                   1
         14                137.340                   1
         15                136.888                   1
         16                 88.306                   1
         17                 81.335                   1
```

```
        18              150.831                  1
        19              198.187                  1
        20               98.930                  1
        21               95.610                  1
        22               72.821                  1
        23              102.696                  1
        24               32.203                  1
    Stress Period:   2
         1               98.597                  1
         2               75.590                  1
         3               65.517                  1
         4               93.834                  1
         5              180.265                  1
         6               74.244                  1
         7               73.366                  1
         8              118.732                  1
         9               42.494                  1
        10              245.896                  1
        11              290.909                  1
        12               76.686                  1
        13               61.086                  1
        14              137.340                  1
        15              136.888                  1
        16               88.306                  1
        17               81.335                  1
        18              150.831                  1
        19              198.187                  1
        20               98.930                  1
        21               95.610                  1
        22               72.821                  1
        23              102.696                  1
        24               32.203                  1
    Stress Period:   3
         1               98.597                  1
         2               75.590                  1
         3               65.517                  1
         4               93.834                  1
         5              180.265                  1
         6               74.244                  1
         7               73.366                  1
         8              118.732                  1
         9               42.494                  1
        10              245.896                  1
        11              290.909                  1
        12               76.686                  1
        13               61.086                  1
        14              137.340                  1
        15              136.888                  1
        16               88.306                  1
        17               81.335                  1
        18              150.831                  1
        19              198.187                  1
```

20	98.930	1
21	95.610	1
22	72.821	1
23	102.696	1
24	32.203	1
Stress Period: 4		
1	98.597	1
2	75.590	1
3	65.517	1
4	93.834	1
5	180.265	1
6	74.244	1
7	73.366	1
8	118.732	1
9	42.494	1
10	245.896	1
11	290.909	1
12	76.686	1
13	61.086	1
14	137.340	1
15	136.888	1
16	88.306	1
17	81.335	1
18	150.831	1
19	198.187	1
20	98.930	1
21	95.610	1
22	72.821	1
23	102.696	1
24	32.203	1
Stress Period: 5		
1	98.597	1
2	75.590	1
3	65.517	1
4	93.834	1
5	180.265	1
6	74.244	1
7	73.366	1
8	118.732	1
9	42.494	1
10	245.896	1
11	290.909	1
12	76.686	1
13	61.086	1
14	137.340	1
15	136.888	1
16	88.306	1
17	81.335	1
18	150.831	1
19	198.187	1
20	98.930	1
21	95.610	1

```
         22                  72.821                  1
         23                 102.696                  1
         24                  32.203                  1
      Stress Period:   6
          1                  98.597                  1
          2                  75.590                  1
          3                  65.517                  1
          4                  93.834                  1
          5                 180.265                  1
          6                  74.244                  1
          7                  73.366                  1
          8                 118.732                  1
          9                  42.494                  1
         10                 245.896                  1
         11                 290.909                  1
         12                  76.686                  1
         13                  61.086                  1
         14                 137.340                  1
         15                 136.888                  1
         16                  88.306                  1
         17                  81.335                  1
         18                 150.831                  1
         19                 198.187                  1
         20                  98.930                  1
         21                  95.610                  1
         22                  72.821                  1
         23                 102.696                  1
         24                  32.203                  1

 Number of New Extraction Wells in Each Stress Period
         24
          0
          0
          0
          0
          0

 Total Pumping Rate in Each Stress Period (gpm)
      Pumping Rate
      ------------
        2692.364
        2692.364
        2692.364
        2692.364
        2692.364
        2692.364


                      Objective Function Calculation
                      ------------------------------

 The Objective Function Value (gpm) for Formulation #  3
```

```
      2692.364

                       Constraints Check-Out
                       ---------------------

--- Modification Occurrence Constraint ---

The Modification Occurrence Constraint Satisfied

--- Plume Containment Constraint ---

The Plume Containment Constraint Satisfied

--- Pumping Limit Constraint ---

The Pumping Limit Constraint Satisfied

--- Well Restricted Areas Constraint ---

The Well Restricted Areas Constraint Satisfied

--- Remediation Well Location Constraint ---

The Remediation Well Location Constraint Satisfied

--- Dry Cell Constraint ---

The Dry Cell Constraint Satisfied

--- Irrigation Well Constraint ---

The Irrigation Well Constraint Satisfied

--- Well Screen Constraint ---

The Well Screen Constraint Satisfied

--- Maximum Number of New Wells Constraint ---

Total Number of New Wells Ever Installed
        24
```

```
The Maximum Number of New Wells Constraint Satisfied


Number of Constraints Not Satisfied
         0
```

Appendix F. Post processor evaluation of Strategy USU3C'.

```
                          Intermediate Variables Calculation
                          ----------------------------------

     Cleanup Year for TCE
          > 30 years
     Cleanup Year for TNT
           > 30 years
     Cleanup Year for Formulation  3
           > 30 years

     Number of Irrigation Wells and Total Rates
          Season          Number of Wells          Total Rate (gpm)
          ------          ---------------          ----------------
              1                  12                     2100.000
              2                 951                    54298.152

     Total Number of Wells In Each Stress Period
          Stress Period
          -------------
              1                    24
              2                    24
              3                    24
              4                    24
              5                    24
              6                    24

     Extraction Well Rates (Combining Multi-Aquifer Wells)
          Well Index        Well Rate (gpm)        Screen Layers
          ----------        ---------------        -------------
          Stress Period:   1
              1                145.408                   1
              2                116.665                   1
              3                112.218                   1
              4                 95.455                   1
              5                228.883                   1
              6                 90.665                   1
              7                 79.034                   1
              8                135.829                   1
              9                 71.164                   1
             10                281.855                   1
             11                316.883                   1
             12                 80.213                   1
             13                 75.268                   1
             14                167.647                   1
             15                189.200                   1
             16                102.639                   1
             17                133.429                   1
```

```
      18            155.330            1
      19            178.592            1
      20            107.771            1
      21            132.810            1
      22             87.242            1
      23            126.587            1
      24             26.000            1
   Stress Period:   2
       1            145.408            1
       2            116.665            1
       3            112.218            1
       4             95.455            1
       5            228.883            1
       6             90.665            1
       7             79.034            1
       8            135.829            1
       9             71.164            1
      10            281.855            1
      11            316.883            1
      12             80.213            1
      13             75.268            1
      14            167.647            1
      15            189.200            1
      16            102.639            1
      17            133.429            1
      18            155.330            1
      19            178.592            1
      20            107.771            1
      21            132.810            1
      22             87.242            1
      23            126.587            1
      24             26.000            1
   Stress Period:   3
       1            145.408            1
       2            116.665            1
       3            112.218            1
       4             95.455            1
       5            228.883            1
       6             90.665            1
       7             79.034            1
       8            135.829            1
       9             71.164            1
      10            281.855            1
      11            316.883            1
      12             80.213            1
      13             75.268            1
      14            167.647            1
      15            189.200            1
      16            102.639            1
      17            133.429            1
      18            155.330            1
      19            178.592            1
```

20	107.771	1
21	132.810	1
22	87.242	1
23	126.587	1
24	26.000	1
Stress Period: 4		
1	145.408	1
2	116.665	1
3	112.218	1
4	95.455	1
5	228.883	1
6	90.665	1
7	79.034	1
8	135.829	1
9	71.164	1
10	281.855	1
11	316.883	1
12	80.213	1
13	75.268	1
14	167.647	1
15	189.200	1
16	102.639	1
17	133.429	1
18	155.330	1
19	178.592	1
20	107.771	1
21	132.810	1
22	87.242	1
23	126.587	1
24	26.000	1
Stress Period: 5		
1	145.408	1
2	116.665	1
3	112.218	1
4	95.455	1
5	228.883	1
6	90.665	1
7	79.034	1
8	135.829	1
9	71.164	1
10	281.855	1
11	316.883	1
12	80.213	1
13	75.268	1
14	167.647	1
15	189.200	1
16	102.639	1
17	133.429	1
18	155.330	1
19	178.592	1
20	107.771	1
21	132.810	1

```
          22                  87.242                  1
          23                 126.587                  1
          24                  26.000                  1
       Stress Period:   6
           1                 145.408                  1
           2                 116.665                  1
           3                 112.218                  1
           4                  95.455                  1
           5                 228.883                  1
           6                  90.665                  1
           7                  79.034                  1
           8                 135.829                  1
           9                  71.164                  1
          10                 281.855                  1
          11                 316.883                  1
          12                  80.213                  1
          13                  75.268                  1
          14                 167.647                  1
          15                 189.200                  1
          16                 102.639                  1
          17                 133.429                  1
          18                 155.330                  1
          19                 178.592                  1
          20                 107.771                  1
          21                 132.810                  1
          22                  87.242                  1
          23                 126.587                  1
          24                  26.000                  1

  Number of New Extraction Wells in Each Stress Period
          24
           0
           0
           0
           0
           0

  Total Pumping Rate in Each Stress Period (gpm)
       Pumping Rate
       ------------
         3236.784
         3236.784
         3236.784
         3236.784
         3236.784
         3236.784


                      Objective Function Calculation
                      ------------------------------

  The Objective Function Value (gpm) for Formulation #  3
```

```
          3236.784

                          Constraints Check-Out
                          ---------------------


     --- Modification Occurrence Constraint ---

     The Modification Occurrence Constraint Satisfied


     --- Plume Containment Constraint ---

     The Plume Containment Constraint Satisfied


     --- Pumping Limit Constraint ---

     The Pumping Limit Constraint Satisfied


     --- Well Restricted Areas Constraint ---

     The Well Restricted Areas Constraint Satisfied


     --- Remediation Well Location Constraint ---

     The Remediation Well Location Constraint Satisfied


     --- Dry Cell Constraint ---

     The Dry Cell Constraint Satisfied


     --- Irrigation Well Constraint ---

     The Irrigation Well Constraint Satisfied


     --- Well Screen Constraint ---

     The Well Screen Constraint Satisfied


     --- Maximum Number of New Wells Constraint ---

     Total Number of New Wells Ever Installed
             24
```

```
The Maximum Number of New Wells Constraint Satisfied


Number of Constraints Not Satisfied
         0
```