FINAL

# OPTIMAL PUMPING STRATEGIES

# FOR

# TOOELE ARMY DEPOT MAIN TCE PLUME

Presented to

Navy Facilities Engineering Command
NAVFACENGCOMDET-SLC

Per

Contract No. N47408-00-C-7153

Prepared by

Systems Simulation/Optimization Laboratory
Dept. of Biological and Irrigation Engineering
Bldg EC-216
Utah State University
Logan, UT  84322-4105

**23 Dec  2002**

**TABLE OF CONTENTS**



**TABLES**

**FIGURES**

## Executive Summary

Utah State University (USU) was to develop pumping strategies for the main TCE plume (MP) at Tooele Army Depot (TAD). Strategies were to minimize the present value cost of satisfying posed optimization problems for a 21-year period. Three pump and treat (PAT) optimization problems were posed to USU. Formulation 1 addresses plume containment at the Point of Enforcement (POE), along the TAD boundary. Formulation 2 addresses plume containment at a Point of Compliance (POC), in addition to all Formulation 1 constraints. The POC is along an internal operable unit boundary. Formulation 3 includes all Formulation 1 and 2 constraints, a cleanup constraint, and limits on the numbers of extraction wells (EW) and injection wells (IW) that can be constructed. Formulations 1 and 2 assume contaminant source cells having temporally constant concentrations. Formulation 3 assumes temporally decreasing concentration at source cells.

Per its contract, USU here reports and distinguishes between work performed during two periods. These periods are: from project commencement through March 1, 2002; and from that first deadline to March 18, the date of USU's formal presentation and draft final report (SSOL, Mar 18, 2002). Table 1 summarizes results.

While addressing Formulation 1, USU intended to lay the groundwork for Formulation 3. Therefore, USU developed alternative Formulation 1 strategies that use different numbers of wells and their placements. In its approach to Formulation 1, USU assumed that a pumping strategy would need to extract the contaminated flux moving northward toward the POE boundary.

The first two strategies (USU1A and USU1B), require constructing only two extraction wells (EW), but require extracting from many existing wells. Because of the annual cost associated with pumping at an EW, the twenty-one year costs of USU1A and USU1B were larger than that of a strategy requiring constructing three EWs (USU1C). It seemed unlikely that we could reduce USU1A and USU1B costs enough to make them competitive with USU1C. Therefore, we only slightly optimized Strategies USU1A and USU1B before ceasing work on them.

Both new EWs required by USU1A and USU1B would have to pump near the maximum allowed by the posed optimization problem. If TAD can significantly relax that limit, possibly only one new EW would need to be constructed to address the Formulation 1 POE containment constraint.

Strategy USU1C has a present value cost of about $14.14 M and requires constructing 3 EW. The most northern of those three wells is needed because of sharp angle between the facility boundary and the flow direction, and is needed only in the first stress period.

An IW costs less than an EW. Therefore, USU developed another strategy by substituting an IW for the northernmost EW of USU1C. The resulting Strategy USU1D costs slightly less than USU1C, but is less robust and spreads contamination laterally. Therefore for Formulation 1 USU recommended strategy USU1C. USU did not try other applications of

injection for Formulation 1. An alternative solution might suffice if regulators allow TAD to delay containment until four or five years (i.e. until after the end of the current first three-year period). In such case, no EW or IW well might be needed to the north, and only two EWs (or one well pumping at a greater rate than is currently allowed by Formulation 1) might economically provide a solution.

USU began addressing Formulation 2 by considering that Strategy USU1C EW positions were appropriate to address the POE constraint, and by adding 4 IWs and no EWs to address the POC constraint. However, one week before the March 1st due date, USU realized that strategy eventually caused high TCE concentrations to bypass the POC to the west. The strategy satisfied all TAD Formulation 2 constraints, but was unacceptable to USU. Environmental regulators do not usually accept strategies that cause much clean aquifer material to become contaminated.

Thus, without vigorous optimization, on 1 Mar 2002 USU presented strategy USU2A for a Formulation 2 problem that was somewhat more restrictive than that posed by TAD. That modified Formulation 2 problem includes what USU terms a Zone 4 constraint in column 29, rows 106-140. This constraint prevents TCE concentrations of 5 ppb or greater from moving to the west of the POC into previously uncontaminated aquifer.

USU2A costs $17.110 M. USU2A involved constructing 4EW and 4IW. Of these, new injection well UI4 aids robustness in the field, and would only be constructed if needed at the beginning of year 2011 (stress period 3). UI4 is in an area having source concentration cells, competing hydraulic stresses in multiple layers, and time varying concentration constraints. UI4 could help assure that flows and resulting concentrations can be tailored to management needs even if the physical system differs from the modeled system.

In the computer model, one can decrease Formulation 2 lifetime cost by screening the adjacent Layer 1 well (UI3) in two layers, instead of one, when it is constructed. Thus strategy USU2B (developed 5-17 March) requires one fewer IW than USU2A (it does not use UI4). USU2B involves constructing 4EW and 3IW and costs $15.731 M. It also satisfies the additional Zone 4 constraint. Because it builds one less IW (near the eastern POC), it provides a little less control over flows in that area than USU2A.

Formulation 3 as posed to USU was infeasible. USU invoked its contractual option of not preparing a substitute formulation by March 1. As allowed, USU developed an alternative during March 5-17. Strategy USU3-1 costs $17.928 M and requires constructing 9 EW and 3 IW. USU3-1 is a compromise between minimizing westward TCE spread and minimizing cost. In addition to applying TAD concentration constraints it applies Zone 4 constraints for the first three stress periods only. In period 4 USU3-1 turns off one new EW to reduce cost. The consequence is that concentration almost reaches 10 ppb in the northernmost Zone 4 cell in period 4. After that the maximum Zone 4 concentration is below 4 ppb. Alternatively, to satisfy the Zone 4 constraint for all stress periods requires less than $0.060M more—merely continuing pumping in the westernmost new EW through period 4.

## Introduction

We present optimal pumping strategies to address the Tooele Army Depot (TAD) TCE plume as it is projected to exist in January 2003 (Figures 1 and 2). We developed these strategies ``using the heuristic optimization capabilities of the SOMOS simulation/optimization model (SSOL and HGS, 2001). We tried to balance the desire for mathematical optimality with practicality. We verified the concentration constraint feasibility of our pumping strategies using the Geotrans postprocessor.

We submitted strategies USU1A-1D and 2A by March1, 2002. We were not obligated to submit a Formulation 3 strategy by then. Between March 5th and the March 18th draft due date, we did additional evaluation, resulting in strategies USU2B and USU3-1. (In that period USU also developed strategy USU1E using the same wells as USU1C and costing a slightly improved $14.132M).

## Optimization Technique

### Formulations Addressed

We present optimal pumping strategies for three optimization problems (Formulations 1-3 posed by TAD or modifications thereof). All three involve minimizing present value of the cost of operating a PAT system for 21 years. They differ in the applied constraints. For Formulations 1 and 2 contaminant source concentrations are constant in time. For Formulation 3, contaminant source concentrations decline with time.

A Formulation 1 strategy must cause concentrations in POE cells in all layers to not exceed 5 ppb by the end of year 3. Figure 3A shows the line of cells included in this POE constraint.. A Formulation 2 strategy must satisfy the POE constraint and prevent concentrations in POC cells (Layers 1 and 2) from exceeding time varying limits. Figure 3B shows the cells in rows 106, 107 and 108 included in the POC constraint.

USU added a line of concentration constraint cells (Zone 4) to assure the plume did not expand into previously uncontaminated aquifer to the west (Figure 3B, Column 24). Such expansion could otherwise result from injection along the POC.

A Formulation 3 strategy includes POE and POC constraints and requires that all cells (except for excluded cells) must be below 50 ppb by the end of year 9. Excluded cells include: all those in model columns 56 and greater; and cells having high source concentrations or extremely low conductivity.

## The Optimization Process

USU developed optimal pumping strategies for Tooele Army Depot (TAD) using the SOMO3 module of SOMOS (SSOL and HGS, 2001). The SOMO3 optimization module uses heuristic optimization and artificial intelligence capabilities. SOMO3 heuristic optimization modules include genetic algorithm (GA) and simulated annealing (SA). In its spacetube or ANN-GA Moving System (AGMS) mode, it trains artificial neural networks (ANN) for state variables and uses a GA for optimization. For Tooele optimization we employed GA without artificial intelligence.

For each optimization problem formulation, our computer runs are generally partitionable into two phases:

- Exploratory simulation and optimization. We began this phase by performing exploratory flow and transport simulation. Then we tested and evaluated several candidate well locations using transport optimization.
- Optimization. We performed transport optimization for limited sets of candidate well locations.

Formulation 1 is supported by Figures 3A, and 4-7 and Appendix B. Formulation 2 is supported by Figures 3B and 8-13 and Appendix B. Formulation 3 is supported by Figures 14-17 and Appendix B. Appendix B contained postprocessor outputs for those respective strategies.

### *Formulation 1*

After considering the optimization problem and the site boundary, USU decided its ultimately proposed strategy should extract all the contaminated water approaching the POE boundary constraint. Doing otherwise could cause the contamination to move into undesirable locations, and possibly to ultimately escape the facility. This meant that USU emphasized extraction, rather than injection, for this problem.

Preliminary optimization runs revealed that the cost objective function value (OFV) was most significantly affected by he number of EWs that pump and the cost of installing any new wells. Therefore USU's general approach was to try to use as few existing EWs and to install as few new wells as possible.

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To initially evaluate candidate well locations, USU simplified the optimization problem by addressing only the first stress period. Runs included:

- Installing 2 EWs, and pumping at those and existing EWs. (Because of the bounds on pumping at individual wells, we had to install at least 2 wells to satisfy the POE containment constraint.
- Installing 3 EWs.

USU optimized for both situations, using different combinations of candidate well locations. Table 2 lists representative GA optimization input parameters. After identifying a desirable batch of candidate well locations, USU performed sequential optimization for all stress periods. Then, USU tried to reduce cost further. For a strategy requiring constructing 3 EWs, USU replaced the northernmost EW with an IW, and optimized. However, using injection spread the contamination laterally. Although the strategy with injection was less expensive, it was not desirable, and was neither recommended nor used further.

### *Formulation 2*

Because the Formulation 2 problem includes the Formulation 1 constraints, USU began strategy design using the wells employed for the best Formulation 1 strategy (one that required constructing 3 EWs). Thus, USU focused on determining how to best address the additional POC constraints.

After making some simulations, USU judged that it would not be physically practical to satisfy the POC constraints via extraction. Then USU made optimization runs exploring candidate IW locations upstream of the POC zones. USU concluded that satisfying the POC constraints would require installing at least 4 IWs, if installing no EWs.

To reduce computational effort, initial optimizations focused on the first three stress periods (the most crucial periods with respect to satisfying the various POC constraints). After USU obtained satisfactory candidate wells for the first three periods, it optimized for all seven periods. Those strategies required constructing 4 IWs.

One week before the deadline for submitting the strategies, USU noticed what it considered a major problem. As a result of the injection, TCE moved significantly to the west around POC-mp1 (Fig. 3B), contaminating formerly clean aquifer. Although allowed by the problem formulation, this seemed unacceptable.

USU then replaced the westernmost IW with an EW, but even this change was insufficient to keep the plume from moving into formerly clean aquifer during optimization. Thus USU added a zonal concentration constraint on concentration moving to the west. At first the zonal constraint was a line of cells diagonal with respect to flow direction (roughly running from the western end of the POC-mp1 to the southwest). However, that orientation made it more difficult to get feasible solutions for all periods).

Thus USU added a constraint on the maximum concentration allowed in a specified line of cells running roughly to the south from the western end of the POC-mp1 (Zone 4 in Fig. 3B). Figure 9 shows the revised optimization problem. At that moment there was insufficient time to optimize much, but the result was strategy USU2A.

In the two weeks between the first deadline, and the time of formal results presentation, USU optimized for the 7 stress periods, reducing cost significantly (Strategy USU2B). Table 3 displays representative GA parameters.

**Formulation 3**

The TAD-posed Formulation 3 problem included all the Formulation 2 constraints, plus cleanup constraints and limits on the numbers of EWs and IWs that could be constructed. Experience with Formulation 2 and exploratory evaluations led USU to believe Formulation 3 was infeasible as posed. As contractually permitted for an infeasible strategy, USU did not present a strategy by the first deadline.

Before March 18, USU developed a strategy that satisfied all TAD concentration constraints and Zone 4 constraints for all stress peiods, but used more wells than TAD allowed. To develop that strategy, USU used as candidates all Formulation 2 wells, existing wells and EWs at high-concentration locations that would otherwise not be remediated. USU did not report this $18M strategy after noticing that the source concentrations near the western edge of POC-mp1 dropped significantly by the end of period 3. This means that in the later periods, there is less need for the Zone 4 constraint.

After developing the above strategy, USU faced a dilemma. As with previous formulations, there was a conflict—increasing strategy desirability increases costs. Because the Zone 4 constraints were conceived and imposed solely by USU, USU chose to remove the Zone 4 constraints after period 3 to reduce cost from that of the above strategy. Figure 14B shows the optimization problem formulation.

In essence, USU tried to 'straddle the fence' in developing strategy USU3-1--a compromise between minimizing westward TCE spread and minimizing cost. This action is particularly appropriate because Formulation 3 source concentrations decrease in time. This means that with time, the need for a western extraction well to satisfy the Zone 4 constraints decreases. It made sense to evaluate the extent to which relaxing the Zone 4 constraint with time reduces cost.

USU only briefly optimized USU3-1. There was no time to thoroughly explore alternative candidate well locations. Table 4 shows GA input parameters. As seen later, USU3-1 cost less than $18M and resulted in only a little westward spread of TCE.

## Optimization Results

### Strategies USU1A and USU1B (Formulation 1)

Figure 4 shows the formal Formulation 1 cost minimization optimization problem objective function. Figure 5 shows the total optimization problem. USU presents four strategies for Formulation 1 in Table 1. The first two (USU1A and USU1B), require constructing only two EWs, but require extracting from many existing wells. Because of the annual cost associated with pumping at an EW, the twenty-one year costs of USU1A and USU1B are larger than those of strategies that require constructing an additional well but extract via fewer wells.

USU1A and USU1B cost more than USU1C and USU1D because they extract at more wells and extract more water. This also means that USU1A and USU1B remove more contaminant mass. We only slightly optimized Strategies USU1A and USU1B before ceasing work on them.

Strategies USU1A and USU1B differ in locations of the new EW and in pumping rates. USU1A costs less than USU1B (Table 1), but USU1B uses the same locations as USU1C. Therefore USU1B could be ungraded to USU1C more easily. This can be useful if TAD budget restrictions prevent constructing three EW in the first year.

### Strategies USU1C, USU1D, and USU1E (Formulation 1)

Strategy USU1C requires constructing 3 EW, and clearly satisfies the POE constraint (Fig. 6). USU1C costs slightly more than USU1D, (which requires only 2 EW and 1 IW). However, Figure 7 shows that USU1D pushes some contamination laterally, potentially leading to eventual escape from hydraulic capture.

For Formulation 1 and subsequent formulations, USU chose the well locations of USU1C over those of USU1D. Figures 10-13 show results of applying the three USU1C EW wells within strategy USU2A.

After March 1st, USU very slightly improved its Formulation 1 pumping strategy. The well locations of this USU1E strategy are the same as USU1C, but the OFV improved slightly to $ 14.132 M.

**Strategy USU2A (A More Restrictive Version of Formulation 2)**

Strategy USU2A, developed by March 1st, includes an additional concentration constraint zone (Zone 4) in column 29, rows 106-140. This prevents water of 5 ppb or greater from moving to the left (west) of the POC, preventing clean aquifer from becoming contaminated. USU added this constraint about February 25th when noting that our preliminary Formulation 2 strategies caused contaminated water to bypass the POC. USU2A constructs 4 EW and 4 IW and costs $17.11M (Table 2). Figures 10-13 show the resulting plume.

**Strategy USU2B (A More Restrictive Version of Formulation 2)**

USU2B, developed from March 5-17, is the result of optimization refinement of USU2A. USU2B employs the Zone 4 constraint. USU2B constructs 4EW and 3IW and costs $15.731M (Table 1). Resulting plumes are similar to those of Figures 10-13.

**Strategy USU3-1 (Formulation 3 Alternative)**

USU3-1 was developed from March 5-17. Of the TAD-posed Formulation 3 constraints, USU3-1 satisfies all except the limit on EWs. It requires constructing 9 EW and 3 IW (Table 1, Figures 15-17). USU3-1 also constrains western TCE migration. It costs $17.928 M.

USU3-1 is a compromise between preventing contamination from moving to the west around the POC and reducing cost. USU3-1 applies the additional 5 ppb limit in Zone 4 for the first three stress periods. As a result, optimization can turn off the new EW near Zone 4 to reduce cost to $17.928M. The tradeoff is that maximum Zone 4 concentration almost reaches 10 ppb (in the northernmost cell) in period 4. After that the maximum Zone 4 concentration is below 4 ppb.

The cost is about $0.060M greater if applying the Zone 4 constraint for all stress periods. To prevent zone 4 concentrations from exceeding 5 ppb in period 4, extraction must continue at well UE4 during period 4. Possibly the Zone-4-period-4 constraint can alternatively be satisfied by decreasing injection at UI1 and UI2.

In reality, TAD might not need to construct all the wells that US3-1 says are needed. For example, TAD might prefer not to construct well UE9. UE9 extracts water that is moving to the Northeast. Instead of using UE9, one might let a future Northeastern plume system address that contamination. UE9 is used here to satisfy the 50 ppb constraint after year 9.

TAD might also not need to construct all of the USU3-1 wells located in source cells. If the source concentration degrades more quickly or if the 50 ppb constraint is relaxed, regulators might concur with not building wells UE8 or UE5.

## Conclusions and Recommendations

USU has presented least-cost pumping strategies for three optimization problem formulations. The recommended strategies, present value, and numbers of new wells needed for each are:

Formulation 1: USU1E; $ 13.132 M ; 3 EW, 0 IW.
Formulation 2: USU2B; $ 15.731 M ; 4 EW, 3 IW.
Formulation 3: USU3-1; $ 17.928 M ; 9 EW, 3 IW.

Minimum-cost strategies might not be as robust as strategies that pump more water. Robustness is the assurance that a pumping strategy will achieve in the field what the model says its will. The economic benefit of minimizing pumping or other cost might be offset by reduced robustness.

To the extent possible, design projects should include interaction between the client and the designer (Hegazy and Peralta, 1997; Peralta and Aly, 1994, 1995, 1996; Peralta 2001a,b). Such interaction was not possible in this effort. Interaction can help determine whether modifications should be made to the Formulations to improve benefit to the client.

Not being able to communicate with the client cost USU a great deal of time on this project. USU sometimes had to decide whether to try to reduce cost versus trying to maintain strategy quality in other ways. Trying to do both took time and effort. Weighing noncommensurate goals without interaction is challenging.

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Table 1. Executive summary of USU pumping strategies for TAD.

| **Formulation #** | **1** | | | | **2 modified with extra constraint #** | | **3 with relaxed constraint and extra constraint # @** |
|---|---|---|---|---|---|---|---|
| **Option and Notes (These differ in initial cost, expandability, contamination removal, etc. )** | **1A*** | **1B*** | **1C** | **1D** | **2A #** | **2B #, %** | **3-1 %** |
| **Objective Function Value ($M)** | 16.058 | 16.216 | 14.137 | 14.136 | 17.110 | 15.731 | $17. 928M |
| **Number of New Extraction Wells Installed** | 2 | 2 | 3 | 2 | 4 | 4 | 9 |
| **Number of New Injection Wells Installed** | 0 | 0 | 0 | 1 | 4 | 3 | 3 |
| **Elapsed Years Until Cleanup** | N/A | | | | N/A | | 9 |

Notes:
- * 1A was designed for expansion into a Formulation III design. Therefore, optimization was not completed.
- * 1B was designed for expansion into a Formulation II or III design. Therefore, optimization was not completed.
- # 2A and 2B employed an additional constraint preventing TCE from exceeding 5 ppb in any column west of the POC.
- % 2B and 3-1 were developed during 5-17 March.
- @ 3-1 required relaxing the posed Formulation 3 constraint on number of extraction wells that could be constructed. 3-1 employed an additional constraint restricting TCE movement to the west of the POC.

Table 2. GA input parameters for Formulation 1.

| | |
|---|---|
| 1. total number of simulations | 400 |
| 2. total number of generations | 9 |
| 3. generation size (gen. 1) | 80 |
| 4. generation size (later generations) | 40 |
| 5. penalty coefficient | 100 |
| 6. crossover probability | 0.85 |
| 7. mutation probability | 0.05 |

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 generation 1.
4. The number of individuals in all generations after generation 1.
5. 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.

6. 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.

7. 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.

8.

Table 3. GA input parameters for Formulation 2.

| | |
|---|---|
| total number of simulations | 260 |
| total number of generations | 12 |
| generation size (gen. 1) | 40 |
| generation size (later generations) | 20 |
| penalty coefficient | 100 |
| crossover probability | 0.85 |
| mutation probability | 0.05 |

Table 4. GA input parameters for Formulation 3-1.

| | |
|---|---|
| total number of simulations | 100 |
| total number of generations | 5 |
| generation size (gen. 1) | 20 |
| generation size (later generations) | 20 |
| penalty coefficient | 100 |
| crossover probability | 0.85 |
| mutation probability | 0.05 |

Fig. 1. Initial (Projected 1 Jan 2003) Layer 1 TCE concentrations exceeding 5 ppb, and lines identifying hydraulic conductivity changes.

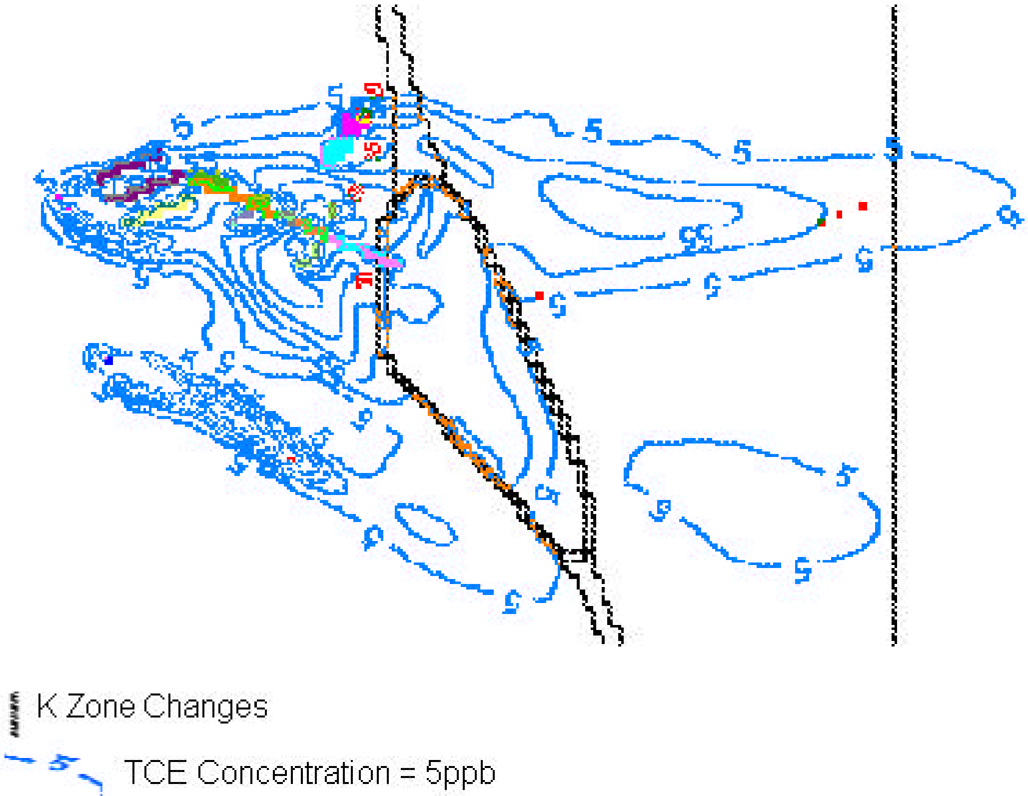

Fig. 2. Initial (Projected 1 Jan 2003) Layer 2 TCE concentrations exceeding 5 ppb, and lines identifying hydraulic conductivity changes.

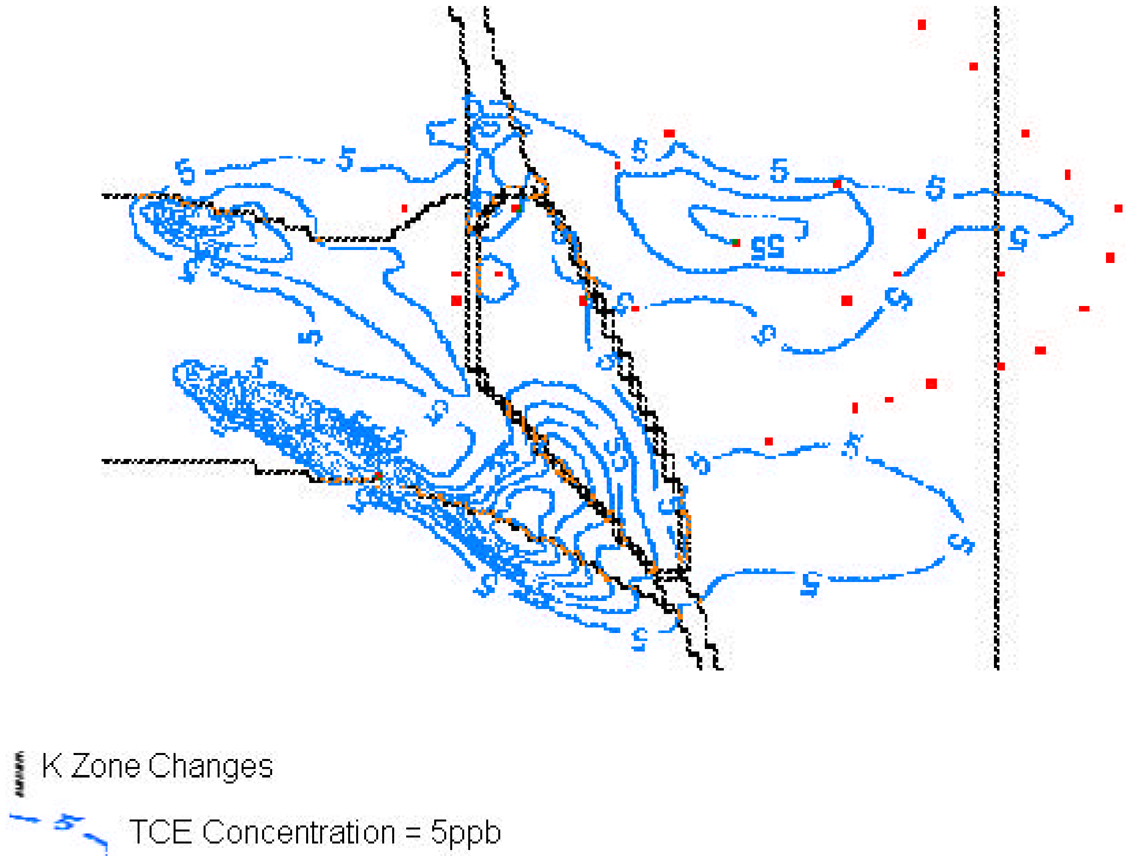

Fig. 3a. POE Constraint cells and Layer 1 TCE concentrations > 5 ppb after three years of pumping per USU2A.

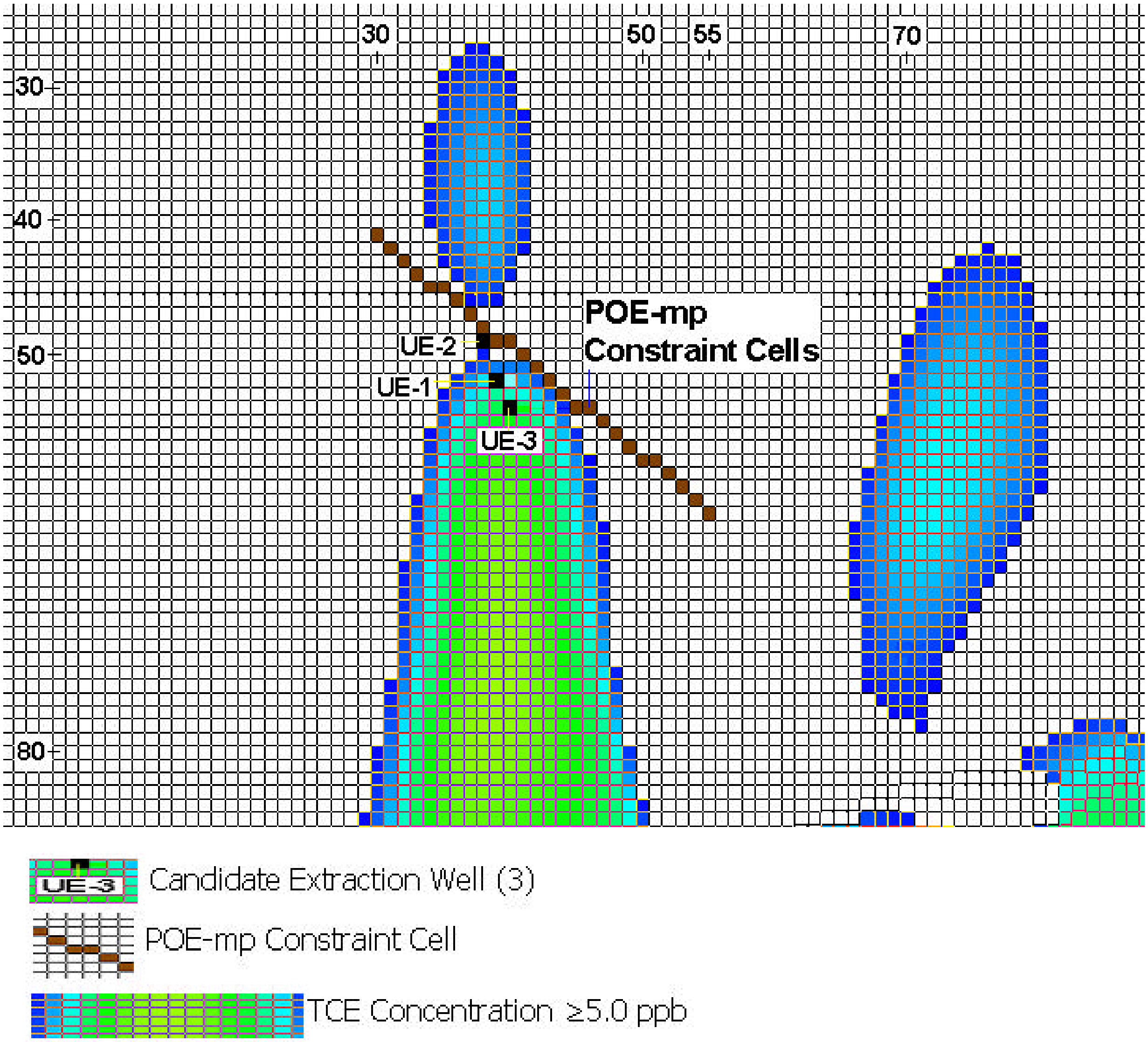

Fig. 3b. POC Constraint and Zone 4 Constraint cells and Layer 1 TCE concentrations ≥ 5 ppb after three years of pumping per USU2A.

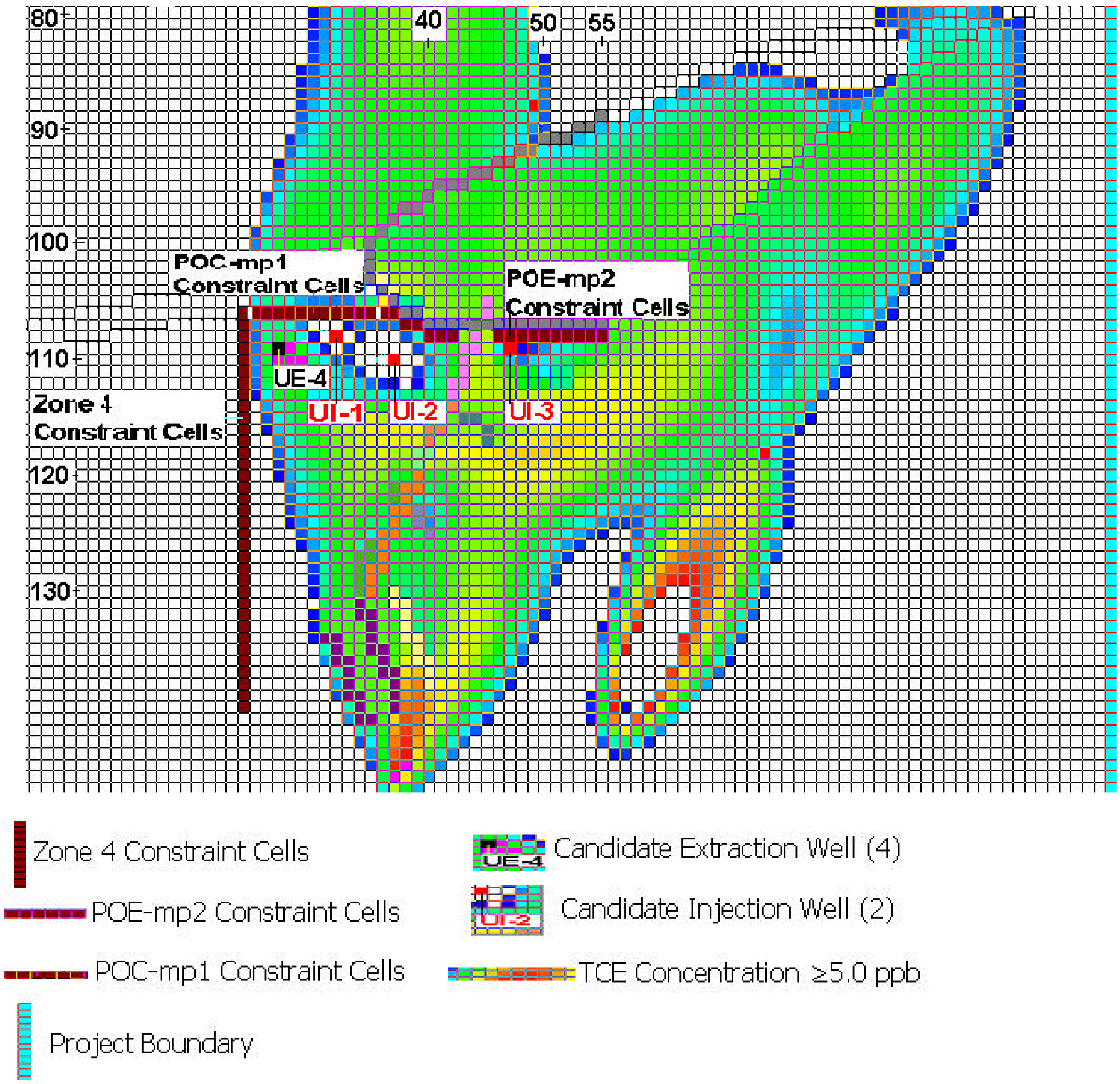


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Fig. 4. Formulation 1 objective function: minimize present value of cost.

**MINIMIZE (CCE + CCI + FCO + VCE + VCS+VCC)**

Where all below costs must be discounted to present value (none include proposed NE plume well at 118,69):

**CCE =** New well capital cost ($307K)

**CCI =** New recharge basin capital cost ($223K)

**FCO =** Fixed annual cost of O&M each year of operation ($525K)

**VCE =** Variable annual electrical cost ($34.5K*number of extraction wells that pump in a year)

**VCC =** Variable annual Chemical Cost($0.02K/gpm extraction)

**VCS =** Variable annual sampling cost {($208K)*plume area at beginning of a stress period/ Jan 2003 plume area}

Fig. 5. Formulation 1 optimization problem.

**MINIMIZE (CCE + CCI + FCO + VCE + VCS+VCC)**

Subject to:

- At year / 3 , for all POE-MP cells in all layers,TCE concentration ≤ 5 ppb
- Σ Extraction(including fixed NE plume well) ≤ (8000 gpm)*95 = 7600 gpm
- | Σ Extraction - Σ Injection | ≤ 1gpm
- Bounds on Pumping at Individual Wells
- Temporally constant TCE concentration source cells

Fig. 6. USU1C: Layer 1 TCE concentrations > 5 ppb after 3 years of pumping.

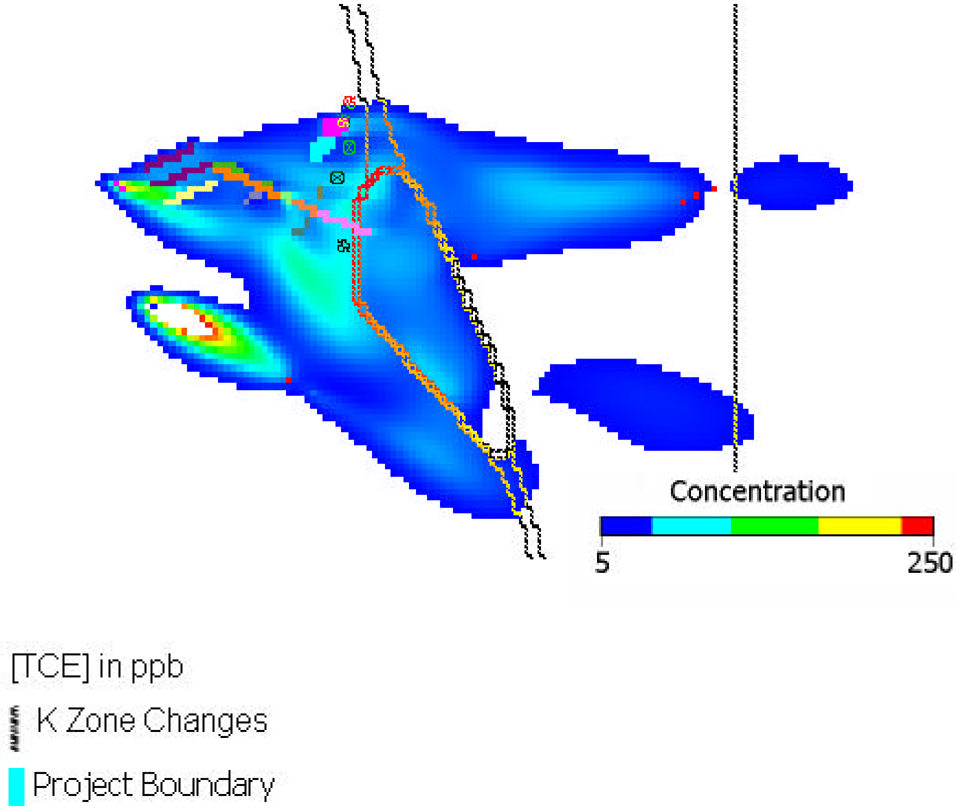

Fig. 7. USU1D: Layer 1 TCE concentrations > 5 ppb after 3 years of pumping.

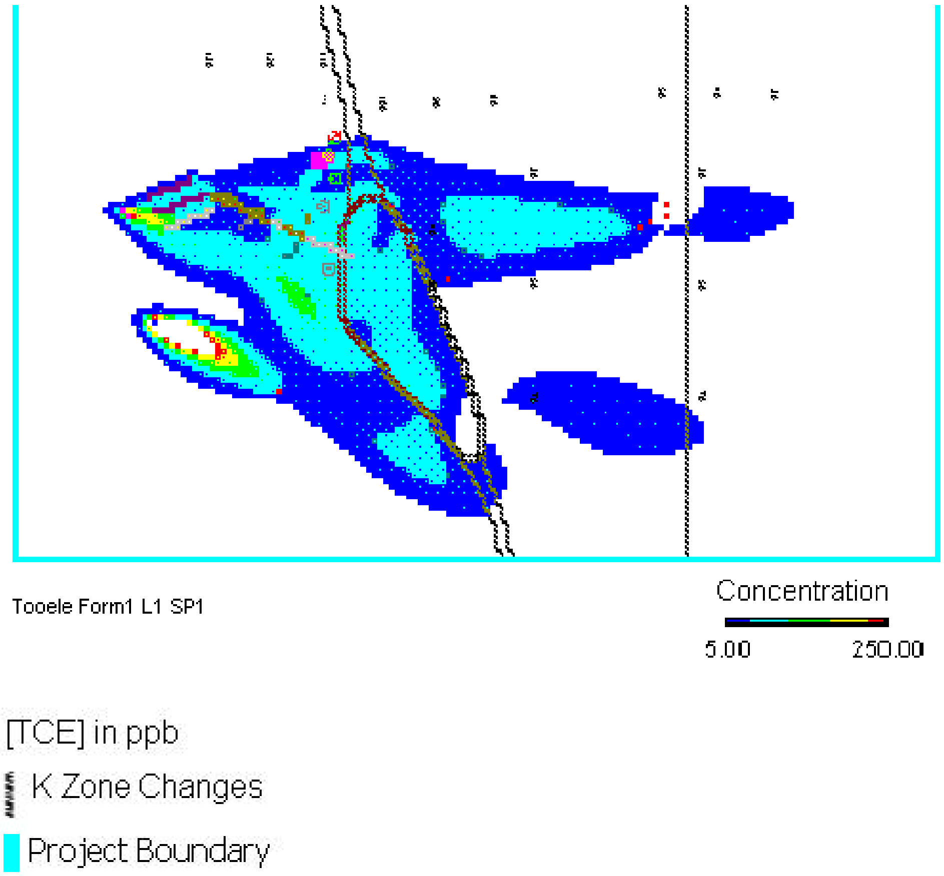

Fig. 8. Formulation 2 optimization problem.

**MINIMIZE (CCE + CCI + FCO + VCE + VCS+VCC)**

Subject to:

- All previous Formulation 1 constraints
- At year ≥ 3, layers 1 & 2, POC-MP1,
  TCE ≤ Max (20 ppb, ½ initial conc.)
- At year 3-8, layers 1 & 2, POC-MP2,
  TCE ≤ 50 ppb
- At year ≥ 9, layers 1 & 2, POC-MP2,
  TCE ≤ 20 ppb

Fig. 9. A more restrictive version of Formulation 2 optimization problem.

**MINIMIZE (CCE + CCI + FCO + VCE + VCS+VCC)**

Subject to:

- All previous Formulation 1 constraints
- At year ≥ 3, layers 1 & 2, POC-MP1, TCE ≤ Max (20 ppb, ½ initial conc.)
- At year 3-8, layers 1 & 2, POC-MP2, TCE ≤ 50 ppb
- At year ≥ 9, layers 1 & 2, POC-MP2, TCE ≤ 20 ppb
- At year ≥ 3, all layers, Zone 4 TCE ≤ 5 ppb

Fig. 10. USU2A: Layer 1 TCE concentrations > 5 ppb after 3 years of pumping.

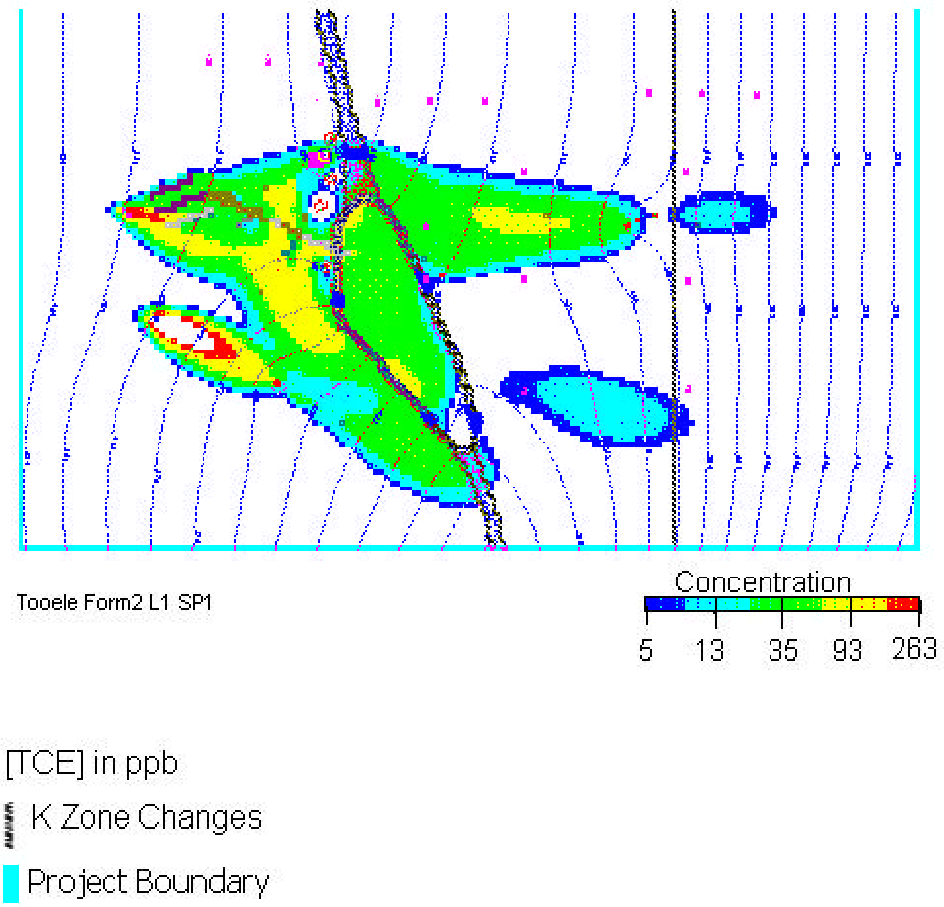

Fig. 11. USU2A: Layer 2 TCE concentrations > 5 ppb after 3 years of pumping.

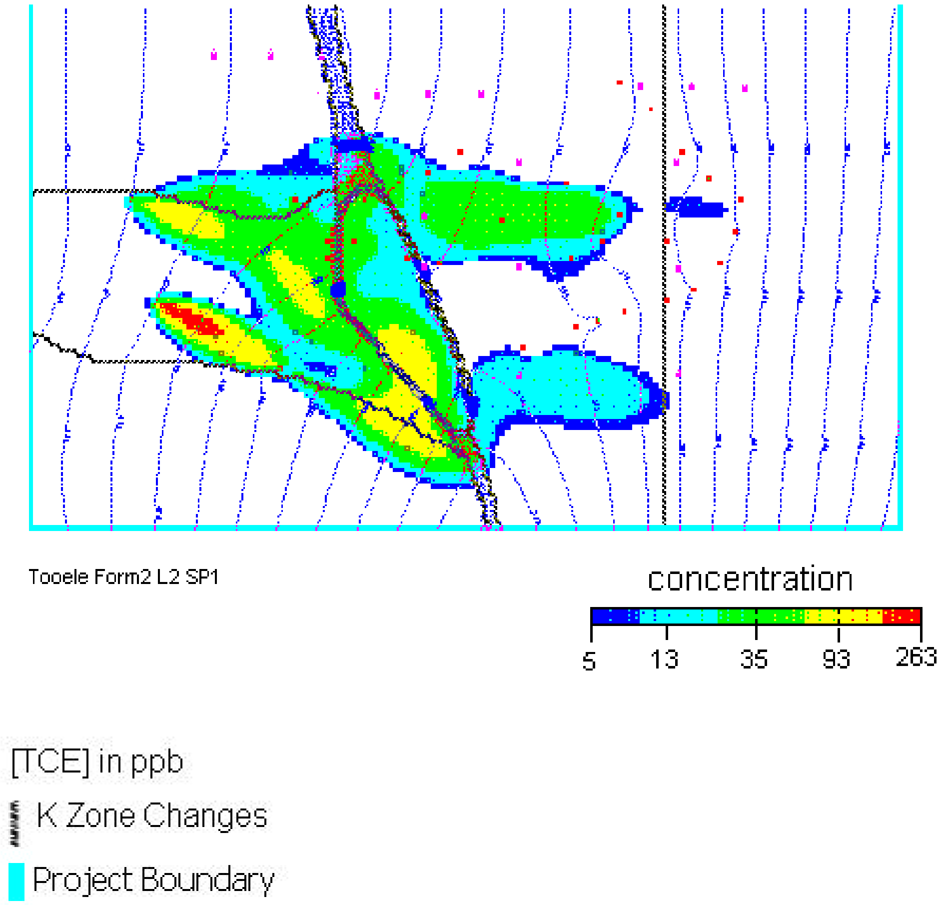

Fig. 12. USU2A: Layer 1 TCE concentrations > 5 ppb after 9 years of pumping.

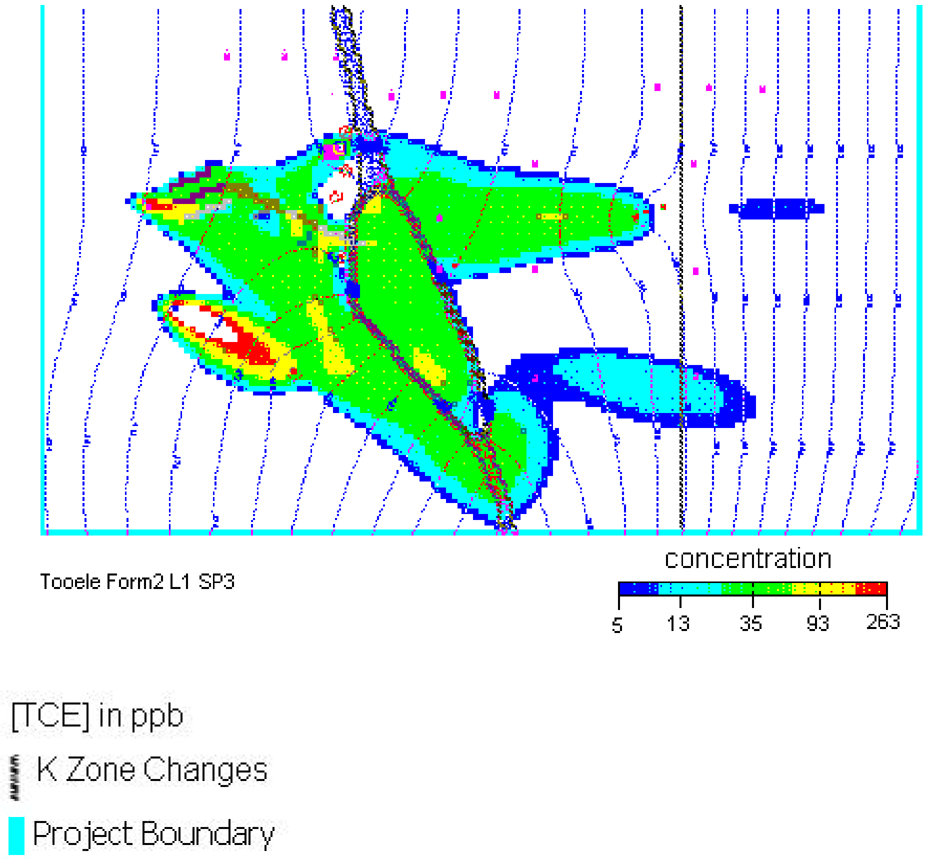

Fig. 13. USU2A: Layer 2 TCE concentrations ≥ 5 ppb after 9 years of pumping.

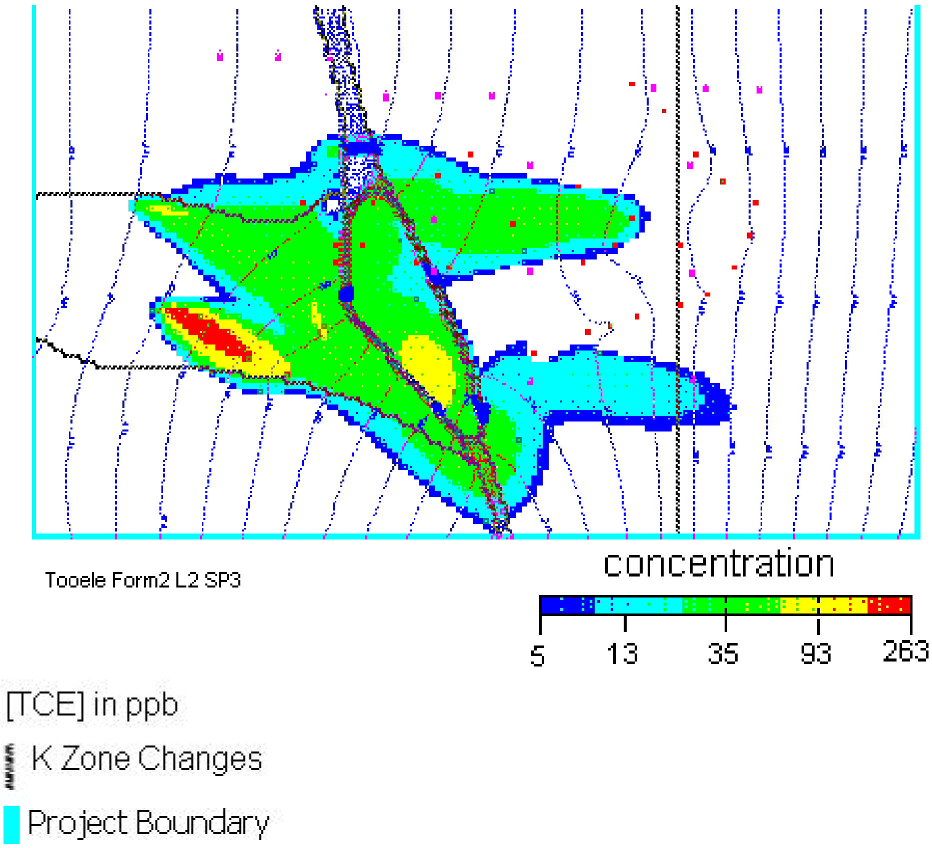

Fig. 14A. Posed infeasible Formulation 3 optimization problem.

**MINIMIZE (CCE + CCI + FCO + VCE + VCS+VCC)**

Subject to:

- All previous formulation 1&2 constraints and,in layer 1 and 2:
- Number of new extraction wells ≤ 4(for entire period of 21 years)
- Number of new injection wells ≤ 4 (for entire period of 21 years)
- At year ≥ 9 , cleanup zone in all layers:
  TCE ≤ 50ppb

Fig. 14B. Optimization problem for Formulation USU3-1

**MINIMIZE (CCE + CCI + FCO + VCE + VCS+VCC)**

Subject to:

- All Formulation 1&2 constraints
- At year $\geq$ 9 , cleanup zone in all layers:
  TCE $\leq$ 50ppb
- Temporally decreasing TCE concentration sources
- Zone 4, all layers, TCE $\leq$ 5 for periods 1-3

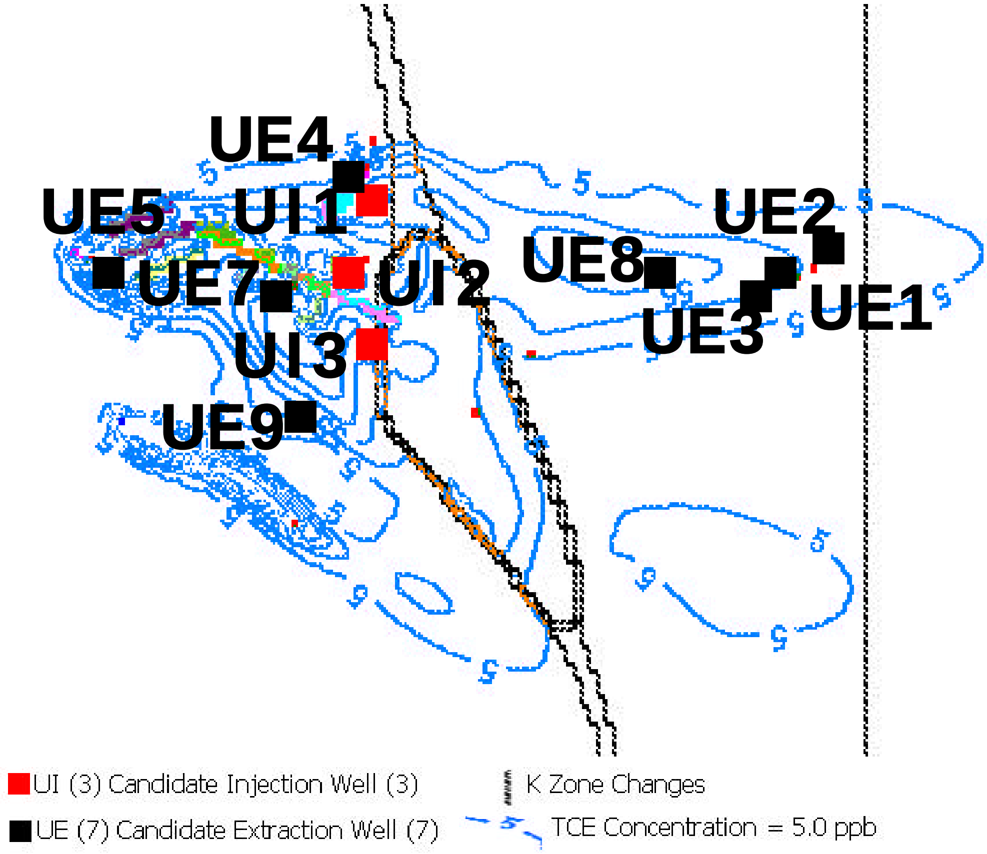


Fig15. Initial Layer 1 TCE ≥ 5 ppb concentration and Formulation 3 alternative Strategy USU3-1 new wells required.

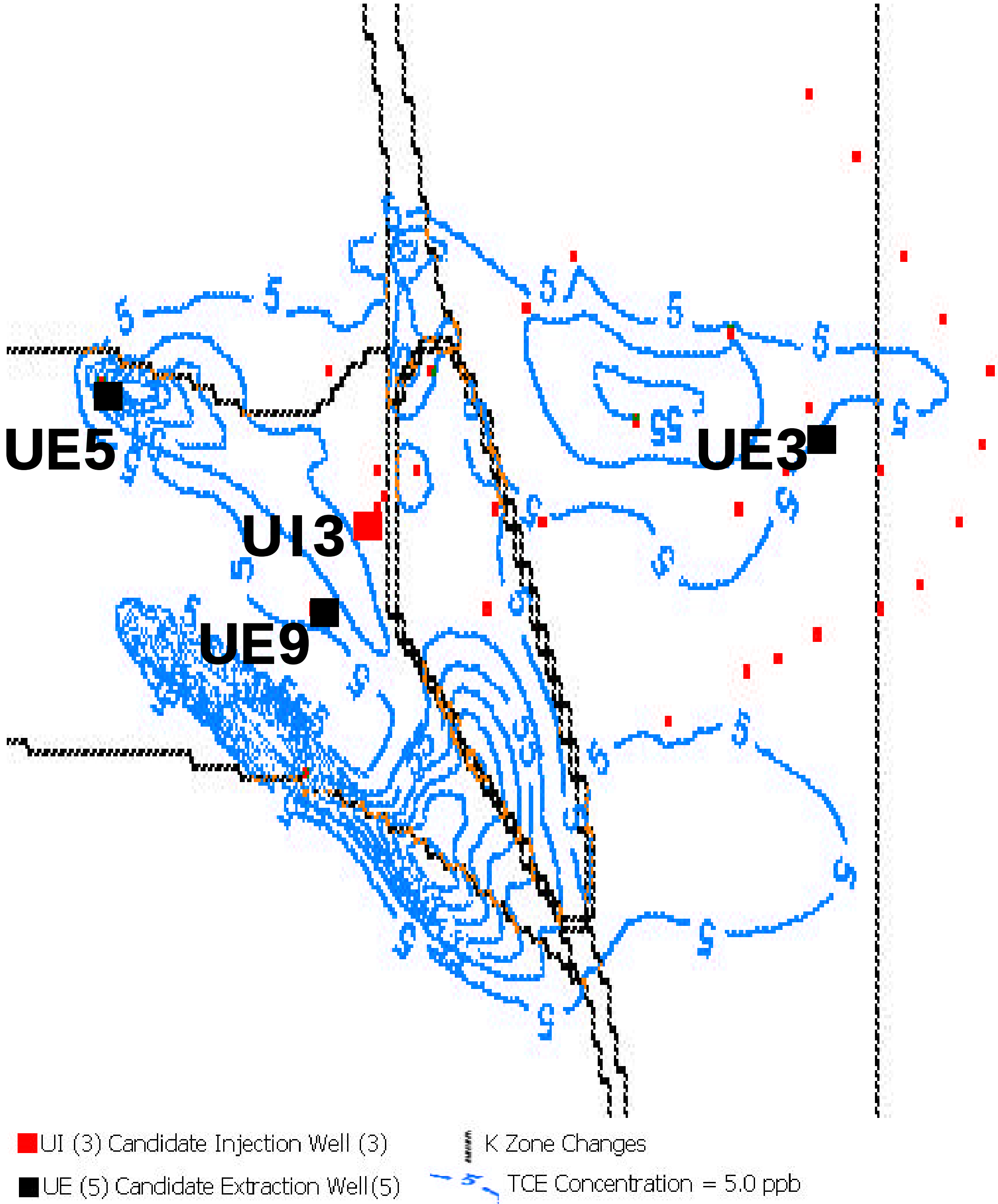


Fig16. Initial Layer 2 TCE ≥ 5 ppb concentration and Formulation 3 alternative Strategy USU3-1 new wells required.

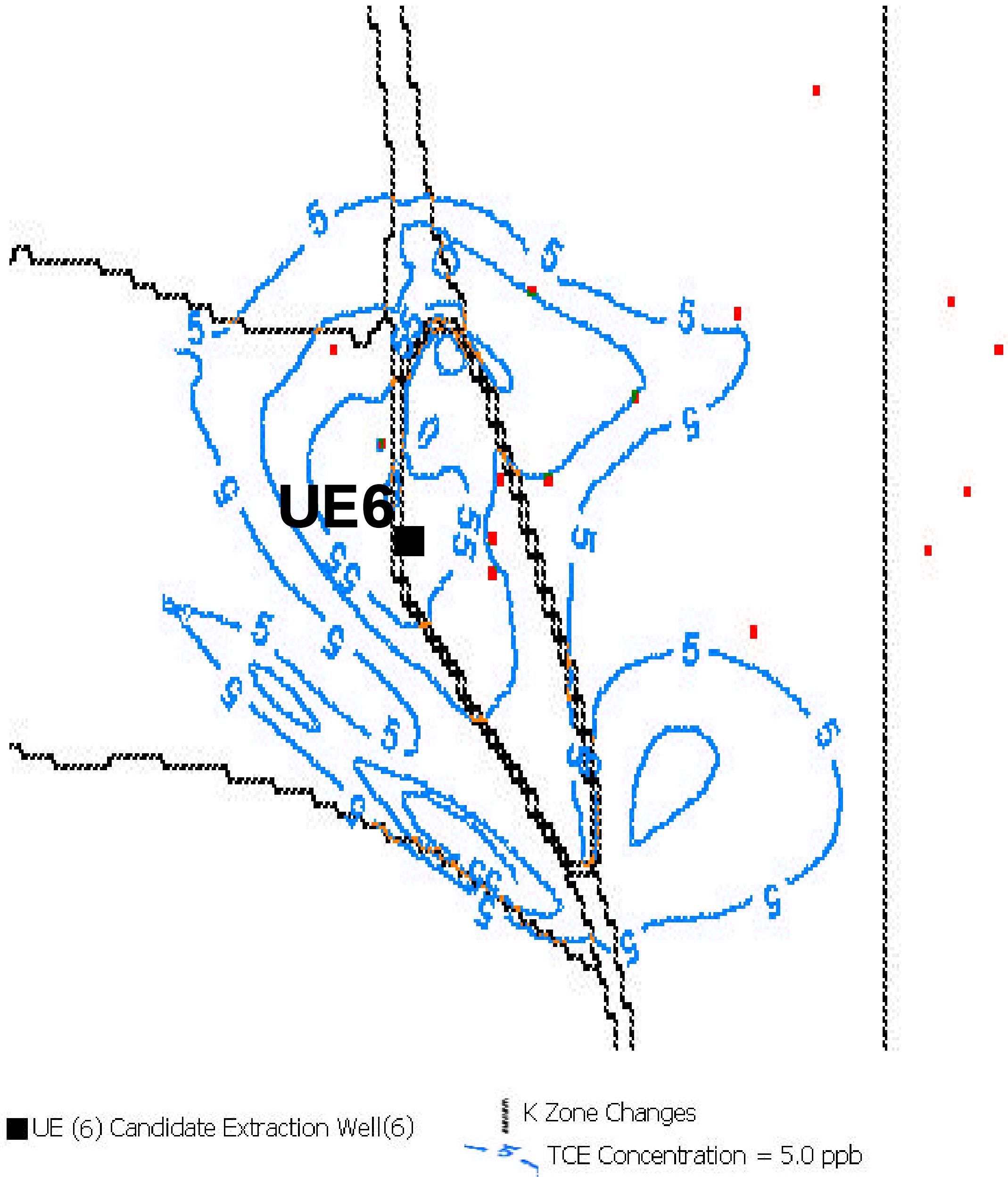


Fig17. Initial Layer 3 TCE ≥ 5 ppb concentration and Formulation 3 alternative Strategy USU3-1 new wells required.

# Appendix A.

## Edited Post Processor Output for Formulation 1, USU1E

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

Total Number of Wells In Each Stress Period

| Stress Period | Extraction Wells | Injection Wells |
|---|---|---|
| 1 | 5 | 7 |
| 2 | 4 | 6 |
| 3 | 5 | 7 |
| 4 | 5 | 7 |
| 5 | 5 | 7 |
| 6 | 5 | 4 |
| 7 | 5 | 5 |

Extraction Well Rates (Combining Multi-Aquifer Wells)

| Well Index | Well Rate (gpm) |
|---|---|
| Stress Period: 1 | |
| 12 | 608.023 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 32 | 374.445 |
| 33 | 380.009 |
| Stress Period: 2 | |
| 12 | 581.185 |
| 30 | 1353.796 |
| 31 | 356.263 |
| 33 | 380.009 |
| Stress Period: 3 | |
| 12 | 602.828 |
| 16 | 608.023 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |
| Stress Period: 4 | |
| 12 | 287.221 |
| 16 | 413.730 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 376.695 |
| Stress Period: 5 | |
| 12 | 617.519 |
| 16 | 282.322 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |
| Stress Period: 6 | |
| 12 | 617.519 |
| 16 | 466.085 |
| 30 | 1353.796 |

| | |
|---|---|
| 31 | 378.367 |
| 33 | 326.568 |
| Stress Period: 7 | |
| 12 | 617.519 |
| 16 | 599.373 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |

Injection Well Rates (Combining Multi-Aquifer Wells)

| Well Index | Well Rate (gpm) |
|---|---|
| ---------- | --------------- |
| Stress Period: 1 | |
| 19 | 181.061 |
| 20 | 65.987 |
| 21 | 702.073 |
| 22 | 129.807 |
| 23 | 1128.640 |
| 25 | 813.412 |
| 26 | 75.811 |
| Stress Period: 2 | |
| 19 | 42.448 |
| 22 | 746.724 |
| 23 | 83.354 |
| 25 | 427.143 |
| 26 | 757.763 |
| 27 | 614.314 |
| Stress Period: 3 | |
| 18 | 276.197 |
| 21 | 701.948 |
| 22 | 409.756 |
| 23 | 108.435 |
| 25 | 522.191 |
| 26 | 763.826 |
| 27 | 542.820 |
| Stress Period: 4 | |
| 18 | 165.840 |
| 22 | 709.990 |
| 23 | 384.549 |
| 24 | 55.945 |
| 25 | 827.932 |
| 26 | 599.155 |
| 28 | 68.044 |
| Stress Period: 5 | |
| 18 | 95.484 |
| 19 | 236.170 |
| 20 | 672.753 |
| 21 | 43.882 |
| 22 | 714.957 |
| 23 | 1082.825 |
| 27 | 167.596 |
| Stress Period: 6 | |
| 22 | 713.544 |
| 23 | 1082.550 |
| 25 | 877.576 |
| 26 | 469.166 |

Stress Period: 7

| | |
|---|---|
| 18 | 350.927 |
| 22 | 707.549 |
| 23 | 1097.704 |
| 24 | 383.583 |
| 25 | 791.276 |

Number of New Extraction Wells in Each Stress Period

3
0
0
0
0
0
0

Number of New Injection Wells in Each Stress Period

0
0
0
0
0
0
0

Total Pumping and Injection Rates in Each Stress Period (gpm)

| Pumping Rate | Injection Rate |
|---|---|
| 3096.288 | 3096.792 |
| 2671.253 | 2671.747 |
| 3324.670 | 3325.174 |
| 2811.456 | 2811.456 |
| 3013.661 | 3013.666 |
| 3142.336 | 3142.835 |
| 3330.712 | 3331.039 |

Plume Area at the Beginning of Each Stress Period

| Stress Period | Plume Area (ft*ft) |
|---|---|
| 1 | 0.118720E+09 |
| 2 | 0.170400E+09 |
| 3 | 0.175320E+09 |
| 4 | 0.178600E+09 |
| 5 | 0.181200E+09 |
| 6 | 0.186520E+09 |
| 7 | 0.192160E+09 |

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

The Capital Costs of New Wells (thousand of dollars)
921.000

The Capital Costs of New Recharge Basins (thousand of dollars)
0.000

The Fixed Costs of O&M (thousand of dollars)
7067.663

The Variable Costs of Electricity for Operating Wells (thousand of dollars)
1772.568

The Variable Costs of Sampling (thousand of dollars)
3919.310

The Variable Costs of Chemicals (thousand of dollars)
451.611

The Objective Function Value (thousands of dollars) for Formulation # 1
14132.152

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

--- Maximum Treatment Capacity Constraint ---

The Maximum Treatment Capacity Constraint Satisfied

--- Pumping/Injection Limit Constraint ---

The Pumping/Injection Limit Constraint Not Satisfied
Stress Period Extraction Wells Injection Wells
*This is caused by the format of our well package. This constraint is not violated.*

--- Pumping-Injection Balance Constraint ---

The Pumping-Injection Balance Constraint Satisfied

--- POE_MP Constraint ---

The POE_MP Constraint Satisfied

Number of Constraints Not Satisfied
0

## Edited Post Processor Output for Formulation 2, USU2B

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

Total Number of Wells In Each Stress Period

| Stress Period | Extraction Wells | Injection Wells |
|---|---|---|
| 1 | 6 | 13 |
| 2 | 5 | 10 |
| 3 | 6 | 12 |
| 4 | 6 | 15 |
| 5 | 6 | 13 |
| 6 | 6 | 10 |
| 7 | 6 | 14 |

Extraction Well Rates (Combining Multi-Aquifer Wells)

| Well Index | Well Rate (gpm) |
|---|---|
| Stress Period: 1 | |
| 12 | 539.589 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 32 | 380.014 |
| 33 | 380.009 |
| 38 | 380.014 |
| Stress Period: 2 | |
| 12 | 617.519 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |
| 38 | 380.014 |
| Stress Period: 3 | |
| 12 | 607.134 |
| 16 | 517.874 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |
| 38 | 380.014 |
| Stress Period: 4 | |
| 12 | 561.746 |
| 16 | 422.483 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |
| 38 | 379.599 |
| Stress Period: 5 | |
| 12 | 517.531 |
| 16 | 588.723 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |
| 38 | 379.084 |
| Stress Period: 6 | |
| 12 | 617.504 |

| | |
|---|---|
| 16 | 356.361 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |
| 38 | 332.511 |

Stress Period: 7

| | |
|---|---|
| 12 | 607.477 |
| 16 | 605.649 |
| 30 | 1353.796 |
| 31 | 380.014 |
| 33 | 380.009 |
| 38 | 368.138 |

Injection Well Rates (Combining Multi-Aquifer Wells)

| Well Index | Well Rate (gpm) |
|---|---|
| ---------- | --------------- |

Stress Period: 1

| | |
|---|---|
| 17 | 41.004 |
| 19 | 71.000 |
| 20 | 293.258 |
| 21 | 373.385 |
| 22 | 451.601 |
| 23 | 326.973 |
| 25 | 222.689 |
| 26 | 296.614 |
| 28 | 52.999 |
| 29 | 54.890 |
| 35 | 464.075 |
| 36 | 559.408 |
| 37 | 205.873 |

Stress Period: 2

| | |
|---|---|
| 19 | 134.987 |
| 22 | 323.389 |
| 24 | 141.086 |
| 25 | 914.876 |
| 26 | 234.175 |
| 27 | 269.054 |
| 28 | 51.534 |
| 35 | 412.530 |
| 36 | 303.154 |
| 37 | 326.573 |

Stress Period: 3

| | |
|---|---|
| 18 | 64.595 |
| 19 | 240.383 |
| 21 | 417.377 |
| 23 | 291.954 |
| 24 | 65.909 |
| 25 | 776.507 |
| 26 | 407.459 |
| 27 | 351.405 |
| 29 | 184.012 |
| 35 | 239.604 |
| 36 | 292.058 |
| 37 | 287.590 |

Stress Period: 4

| | |
|---|---|
| 18 | 154.203 |

| | |
|---|---|
| 19 | 68.709 |
| 20 | 71.390 |
| 21 | 164.001 |
| 22 | 74.429 |
| 23 | 852.526 |
| 24 | 74.912 |
| 25 | 694.146 |
| 26 | 157.679 |
| 27 | 372.305 |
| 28 | 74.491 |
| 29 | 155.429 |
| 35 | 136.026 |
| 36 | 215.265 |
| 37 | 212.263 |
| Stress Period: | 5 |
| 17 | 158.915 |
| 18 | 262.649 |
| 20 | 158.562 |
| 22 | 312.858 |
| 23 | 836.473 |
| 24 | 296.422 |
| 25 | 300.198 |
| 26 | 514.206 |
| 27 | 117.688 |
| 28 | 61.311 |
| 35 | 201.228 |
| 36 | 173.201 |
| 37 | 205.452 |
| Stress Period: | 6 |
| 17 | 121.833 |
| 19 | 329.425 |
| 20 | 601.410 |
| 21 | 532.462 |
| 22 | 369.463 |
| 25 | 410.395 |
| 26 | 290.681 |
| 27 | 156.390 |
| 35 | 478.080 |
| 37 | 130.062 |
| Stress Period: | 7 |
| 17 | 70.356 |
| 18 | 56.459 |
| 19 | 422.686 |
| 20 | 352.247 |
| 21 | 67.197 |
| 22 | 577.216 |
| 23 | 613.270 |
| 24 | 373.682 |
| 25 | 181.882 |
| 26 | 191.155 |
| 27 | 269.117 |
| 35 | 142.327 |
| 36 | 206.449 |
| 37 | 171.045 |

Number of New Extraction Wells in Each Stress Period

4
0
0
0
0
0
0

Number of New Injection Wells in Each Stress Period

3
0
0
0
0
0
0

Total Pumping and Injection Rates in Each Stress Period (gpm)

| Pumping Rate | Injection Rate |
|---|---|
| 3413.437 | 3413.770 |
| 3111.353 | 3111.359 |
| 3618.842 | 3618.853 |
| 3477.647 | 3477.772 |
| 3599.158 | 3599.164 |
| 3420.196 | 3420.201 |
| 3695.084 | 3695.089 |

Plume Area at the Beginning of Each Stress Period

| Stress Period | Plume Area (ft*ft) |
|---|---|
| 1 | 0.118720E+09 |
| 2 | 0.172760E+09 |
| 3 | 0.177720E+09 |
| 4 | 0.181560E+09 |
| 5 | 0.184600E+09 |
| 6 | 0.188560E+09 |
| 7 | 0.193880E+09 |

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

The Capital Costs of New Wells (thousand of dollars)
1228.000

The Capital Costs of New Recharge Basins (thousand of dollars)
669.000

The Fixed Costs of O&M (thousand of dollars)
7067.663

The Variable Costs of Electricity for Operating Wells (thousand of dollars)
2237.015

The Variable Costs of Sampling (thousand of dollars)
3966.035

The Variable Costs of Chemicals (thousand of dollars)
563.549

The Objective Function Value (thousands of dollars) for Formulation # 2
15731.262

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

--- Maximum Treatment Capacity Constraint ---

The Maximum Treatment Capacity Constraint Satisfied

--- Pumping/Injection Limit Constraint ---

The Pumping/Injection Limit Constraint Not Satisfied
Stress Period     Extraction Wells     Injection Wells
-------------     ----------------     ---------------

*This is caused by the format of our well package. This constraint is not violated.*

--- Pumping-Injection Balance Constraint ---

The Pumping-Injection Balance Constraint Satisfied

--- POE_MP Constraint ---

The POE_MP Constraint Satisfied

--- POC_MP1 Constraint ---

The POC_MP1 Constraint Satisfied

--- POC_MP2 Constraint ---

The POC_MP2 Constraint Satisfied

Number of Constraints Not Satisfied
0

# Edited Post Processor Output for Formulation 3, USU3

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

Total Number of Wells In Each Stress Period

| Stress Period | Extraction Wells | Injection Wells |
|---|---|---|
| 1 | 10 | 15 |
| 2 | 9 | 14 |
| 3 | 11 | 15 |
| 4 | 5 | 9 |
| 5 | 5 | 11 |
| 6 | 4 | 10 |
| 7 | 4 | 6 |

Extraction Well Rates (Combining Multi-Aquifer Wells)

| Well Index | Well Rate (gpm) |
|---|---|
| Stress Period: 1 | |
| 7 | 208.751 |
| 10 | 355.452 |
| 12 | 617.519 |
| 30 | 1353.796 |
| 31 | 379.760 |
| 32 | 377.967 |
| 33 | 380.009 |
| 38 | 380.014 |
| 40 | 380.014 |
| 43 | 380.014 |
| Stress Period: 2 | |
| 12 | 461.669 |
| 30 | 1353.796 |
| 31 | 364.429 |
| 33 | 374.897 |
| 38 | 259.750 |
| 40 | 363.650 |
| 41 | 363.650 |
| 43 | 207.800 |
| 44 | 363.650 |
| Stress Period: 3 | |
| 10 | 760.023 |
| 12 | 561.850 |
| 30 | 1353.796 |
| 31 | 374.170 |
| 33 | 380.009 |
| 38 | 350.740 |
| 40 | 377.973 |
| 41 | 380.009 |
| 43 | 378.466 |
| 44 | 202.002 |

45 380.014
Stress Period: 4
12 617.114
30 1353.796
31 380.014
33 380.009
40 281.657
Stress Period: 5
12 527.760
30 1353.796
31 380.014
33 380.009
40 216.533
Stress Period: 6
12 409.719
30 1353.796
31 380.014
33 380.009
Stress Period: 7
12 617.519
30 1353.796
31 380.014
33 379.516

Injection Well Rates (Combining Multi-Aquifer Wells)

Well Index Well Rate (gpm)
---------- ---------------
Stress Period: 1
17 54.870
18 365.686
19 315.892
20 448.121
21 217.826
22 399.137
23 901.779
24 97.115
25 391.682
26 151.294
27 196.303
29 132.550
35 383.105
36 486.938
37 271.496
Stress Period: 2
17 70.834
19 139.730
21 239.510
22 121.469
23 466.807
24 56.428
25 824.192
26 467.254
27 543.880
28 62.065
29 43.420
35 369.598

| | |
|---|---|
| 36 | 383.173 |
| 37 | 324.942 |
| Stress Period: 3 | |
| 17 | 154.385 |
| 18 | 100.051 |
| 20 | 169.118 |
| 21 | 295.476 |
| 22 | 693.761 |
| 23 | 418.442 |
| 24 | 232.139 |
| 25 | 343.099 |
| 26 | 670.534 |
| 27 | 615.488 |
| 28 | 54.958 |
| 29 | 170.957 |
| 35 | 551.932 |
| 36 | 550.940 |
| 37 | 478.267 |
| Stress Period: 4 | |
| 17 | 210.346 |
| 20 | 43.233 |
| 21 | 207.192 |
| 24 | 379.048 |
| 25 | 708.203 |
| 26 | 754.969 |
| 35 | 288.852 |
| 36 | 207.800 |
| 37 | 213.463 |
| Stress Period: 5 | |
| 17 | 188.158 |
| 19 | 555.559 |
| 20 | 75.650 |
| 21 | 100.321 |
| 23 | 477.758 |
| 25 | 207.961 |
| 26 | 759.722 |
| 27 | 83.156 |
| 29 | 156.292 |
| 36 | 76.652 |
| 37 | 176.890 |
| Stress Period: 6 | |
| 17 | 59.571 |
| 18 | 255.236 |
| 20 | 71.177 |
| 21 | 44.183 |
| 22 | 648.284 |
| 23 | 321.087 |
| 24 | 60.974 |
| 25 | 900.361 |
| 26 | 41.679 |
| 35 | 121.153 |
| Stress Period: 7 | |
| 17 | 54.392 |
| 19 | 562.135 |
| 23 | 974.598 |
| 24 | 336.013 |

| | |
|---|---|
| 25 | 708.723 |
| 29 | 95.484 |

Number of New Extraction Wells in Each Stress Period

6
2
1
0
0
0
0

Number of New Injection Wells in Each Stress Period

3
0
0
0
0
0
0

Total Pumping and Injection Rates in Each Stress Period (gpm)

| Pumping Rate | Injection Rate |
|---|---|
| 4813.297 | 4813.796 |
| 4113.292 | 4113.303 |
| 5499.053 | 5499.546 |
| 3012.591 | 3013.105 |
| 2858.112 | 2858.118 |
| 2523.539 | 2523.705 |
| 2730.845 | 2731.344 |

Plume Area at the Beginning of Each Stress Period

| Stress Period | Plume Area (ft*ft) |
|---|---|
| 1 | 0.118720E+09 |
| 2 | 0.170400E+09 |
| 3 | 0.173800E+09 |
| 4 | 0.175320E+09 |
| 5 | 0.177800E+09 |
| 6 | 0.180440E+09 |
| 7 | 0.182720E+09 |

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

The Capital Costs of New Wells (thousand of dollars)
2601.485

The Capital Costs of New Recharge Basins (thousand of dollars)
669.000

The Fixed Costs of O&M (thousand of dollars)
7067.663

The Variable Costs of Electricity for Operating Wells (thousand of dollars)
3045.144

The Variable Costs of Sampling (thousand of dollars)
3859.248

The Variable Costs of Chemicals (thousand of dollars)
685.018

The Objective Function Value (thousands of dollars) for Formulation # 3
17927.557

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

--- Maximum Treatment Capacity Constraint ---

The Maximum Treatment Capacity Constraint Satisfied

--- Pumping/Injection Limit Constraint ---

The Pumping/Injection Limit Constraint Not Satisfied

| Stress Period | Extraction Wells | Injection Wells |
| --- | --- | --- |

*This is caused by the format of our well package. This constraint is not violated.*

--- Pumping-Injection Balance Constraint ---

The Pumping-Injection Balance Constraint Satisfied

--- POE_MP Constraint ---

The POE_MP Constraint Satisfied

--- POC_MP1 Constraint ---

The POC_MP1 Constraint Satisfied

--- POC_MP2 Constraint ---

The POC_MP2 Constraint Satisfied

--- Cleanup Year Constraint ---

The Cleanup Year Constraint Satisfied

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

Total Number of New Wells Ever Installed
9

The Maximum Number of New Wells Constraint Not Satisfied

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

Total Number of New Injection Wells Installed
3

The Maximum Number of New Injection Wells Constraint Satisfied

Number of Constraints Not Satisfied
1