Transport Optimization Tooele Army Depot
Draft Mathematical Formulations
10/31/01

INTRODUCTION

Tooele Army Depot (TEAD) was established in 1942 to provide storage, maintenance and demilitarization of troop support equipment especially wheeled vehicles and conventional weapons. From 1942-1966, large quantities of hazardous materials were used and generated in these operations in the industrial area. During this time period, the waste chemicals were piped through the industrial complex into a set of four unlined drainage ditches. These ditches ended at a set of natural depressions that were used as evaporation (and infiltration) ponds. These ponds have been called the Old Industrial Waste Lagoon (Old IWL). In 1966, a collector ditch was constructed to intercept the four existing ditches. This interceptor ditch ran north approximately 1.5 miles to an abandoned gravel pit, called the Industrial Wastewater Lagoon (IWL), which was used as an evaporation pond until its closure in 1988 when an industrial wastewater plant was brought on line. The primary contaminant of concern was TCE used as a solvent in the repair operations of military equipment.

In 1983, the Army began investigating sources of contamination contributing to a plume of TCE (the "Main Plume") that originated in the southeast portion of the Industrial Area and extends approximately 3.3 miles to the northwest. This plume was believed to have originated in the wastewater discharge through the unlined ditches to the original and then new evaporation ponds. A groundwater pump and treat system was put in place to treat this plume and prevent TCE concentrations greater than MCLs from crossing the property boundary. By the mid-1990's however it became apparent that there was contamination associated with the Main Plume that could not have originated in the IWL system and must therefore have originated somewhere in the industrial area or perhaps in the Defense Reutilization ad Marketing Office (DRMO) yard. Therefore, The Main Plume originates from several source areas within the industrial area and the IWL.

More recently, an additional plume (the "Northeast Plume") has also been identified. The Northeast Plume is originating from a recently identified point source in the industrial area, the oil/water separator at Building 679. The Northeast Plume extends beyond the property boundary, and the offsite extent is not fully characterized.

Groundwater flow trends in a northwest direction across TEAD. Uplifted, fractured bedrock in the central area of the Depot is a controlling hydrogeological feature. In general, the Depot can be divided into three separate hydrogeologic regimes, 1) the steep flow gradients of the fractured bedrock and adjoining low conductive alluvium in the central area of TEAD; 2) the highly transmissive alluvium in the northern part of the Depot and 3) the shallow alluvium at the southern upgradient end of the site. The uplifted bedrock block and adjoining low conductive alluvium are the hydraulically controlling features of the study area due to the steep gradients required for flow across this area. The uplifted bedrock block strikes roughly east-northeast and dips north–northwest. On the local scale the bedrock block exhibits strongly heterogeneous hydrogeology typical of fractured flow environments. Flow through the bedrock block consists of a steep gradient when entering the bedrock, a flatter gradient through the bedrock core and a steep gradient when exiting the bedrock.

A recent Independent Technical Review (ITR), Final Draft dated December 2000, at TEAD suggests that a risk-based approach be implemented. According to the ITR, the reissued Postclosure Permit (the principal legal driver for the site) will allow for the application of alternate concentration limits (ACL) via petition if:

> "The corrective action described … fails to meet the groundwater protection standard… and after the Permittee has demonstrated that all other feasible methods have been used to meet the groundwater protection standard, or (emphasis added) if in accordance with R315-101, a risk assessment concludes that a contaminant concentration greater than the concentration limits specified … poses no unacceptable risk to human health or the environment".

According to the ITR, the Utah RCRA Regulations at R315 also known as "the Risk Rule", upon which the Postclosure Permit is based, will also be legally applicable requirements for remediation. Under the Risk Rule, the magnitude of the level of risk present at a site determines the degree to which actions must be taken (i.e., no further action versus institutional controls versus active remediation). Two separate requirements are set out in the Risk Rule, which apply regardless of the presence or absence of risk at the site. First, the Risk Rule requires the responsible party to "take appropriate action to stabilize the site either through source removal or source control" [R315-101-2]. Referred to as stabilization, the agency will require in part that, all continuing sources be removed or contained as a part of remediation. Secondly, the Risk Rule requires "when closing or managing a contaminated site, the responsible party shall not allow levels of contamination in groundwater, surface water, soils, and air to increase beyond the existing levels of contamination at a site when site management commences" (referred to as the principle of non-degradation) [R315-101-3].

The ITR recommends that, for the Main Plume, the IWL and the industrial area should be considered one waste management area with the circumscribing line as the Point of Compliance (POC), and the downgradient property boundary considered as the Point of Exposure (POE). Using this approach, an Alternate Concentration Limit (ACL) is determined by establishing a contaminant concentration at the POC that will attain a concentration at the POE that is protective of human health and the environment taking into consideration the attenuation of contaminants between the POC and the POE. For the IWL/Industrial waste management area, the ACL would be the concentration of TCE at the POC that will result in a concentration of 5 ug/l of TCE at the POE.

Based on the ESTCP site visit at Tooele on May 31, 2001, the Northeast Plume is not well-defined, and for the purpose of our study, all formulations will include a specified well in the NE plume @ 1500 gpm (implemented as 1425 gpm in the well package to account for downtime of 5%, discussed later), to represent a general containment solution in that area.

DEFINITIONS SPECIFIC TO TOOELE FORMULATIONS

POE-MP — "Point of Exposure-Main Plume": TCE concentrations cannot exceed 5 ug/L for TCE at the POE-MP, evaluated in all model layers. POE-MP will be the property boundary, specifically at the cells in Table 1 (located at end of the formulation document).

POC-MPx — "Point of Compliance – Main Plume": POC-MP1 is defined as the southern boundary of the displaced sediments near Well P-3. It is in row106 and extends between model columns 25 and 36. POC-MP2 is defined as the boundary along the upstream edge of the low permeability gouge surrounding the bedrock, beginning at r106, c37 and ending at r103, c55 *with exception of three model cells which are one source cell and two adjacent cells*. These evaluations will be made in model layers 1 and 2. Specific cells for POC-MP1 and POC-MP2 are listed in Table 2 (located at the end of the formulation document).

PROPOSED FORMULATIONS

Each formulation consists of an objective function (to be maximized or minimized) and a set of constraints that must be satisfied. The formulations are provided in detail in the following pages and can be summarized as follows:

<u>Formulation 1</u>: Seven management periods, each 3 years. The objective function is to minimize a cost function, subject to: 1) POE-MP of 5ppb is achieved at the end of 1st management period (3 yrs) and all years thereafter; 2) a specified well location and pumping rate for addressing the NE plume is included; and 3) current capacity of the treatment plant is held constant and includes the specified pumping for the NE plume.

<u>Formulation 2</u>: Same as Formulation 1 (including the POE-MP constraint), but also add POC constraints: 1) POC-MP1 is 50% of the initial concentrations or ≤ 20 ug/l at the end of 1st management period (year 3) and thereafter; (2) POC-MP2 is 50ppb at the end of the 1st management period (3 yrs), and 20ppb at the end of 3rd management period (9 yrs) and thereafter.

<u>Formulation 3</u>: Same as Formulation 2 but with the following changes/additions: 1) source concentrations decline 25% each management period (i.e., source term in period 2 is 25% less than source term in period 1, source term in period 3 is 25% less than source term in period 2, etc.); 2) in addition to point-of-exposure and point-of-compliance constraints, cleanup (TCE ≤ 50 ppb) must also be achieved at a specified group of cells associated with the main plume in layers 1 to 4 within 3 management periods (9 yrs); and 3) maximum of 4 new extraction wells and 4 new injection wells can be installed for Main Plume not including the specified new well used for the NE Plume.

SPECIAL NOTES

Fixed Well, NE Plume

All formulations include a specified well in the NE plume @ 1500 gpm (implemented as 1425 gpm in the well package to account for downtime of 5%, discussed later). The fixed pumping for the NE plume will be implemented at one well location (row117, column 68, apportioned between layers 1 and 2 as weighted by transmissivity), to represent a generalized containment solution in that area without specifically developing an "optimal management solution" for the NE plume. *The fixed NE well will be counted towards total plant capacity, and included in the constraint balancing extraction and injection, but will not be included in any objective function terms based on number of wells and/or pumping rate (CCE, VCE, VCC) because it is common to all solutions. This new well for NE plume will also not be subject to the maximum well rate limit for new wells, since it is conceptual and not part of the management solution*.

Treatment of Multi-Aquifer Wells

Many of the existing wells in the model are "multi-aquifer", i.e., they screened in multiple model layers and therefore have multiple entries in the MODFLOW well package (one per model layer screened by the well). This is often done in models, and the rate specified in each model layer for a multi-aquifer well is usually calculated according to the weighted average of transmissivity in each layer.

For new wells in our study this becomes quite complicated, because new wells specified in the same row and column, but different layers, can represent either of the following two cases:

- Case 1: the multiple wells specified in the same cell but different layers represent one multi-aquifer well (i.e., capital cost is for only one well, limit on the maximum well rate applies to the combined well, and the ratio of rates between model layers must be consistent with the transmissivity of each layer).

  Since layer 1 in the model is defined as an unconfined aquifer, thus the transmissivity in layer 1 is calculated as a multiplier of hydraulic conductivity and saturated thickness that varies with time. The saturated thickness ranges 49.1-52.2ft based on simulated heads at the beginning of optimization simulation, i.e., 1/1/2003. To simplify the calculation, 50ft saturated thickness is used to calculate the transmissivity in layer 1 for the purpose of establishing ratios for multi-aquifer wells.

- Case 2: the multiple wells specified in the same cell but different layers represents a different new well in each layer (i.e., capital cost are incurred for more than one well, the limit on maximum rate applies separately to each well, and the well rate in each layer need not conform to transmissivity ratios between layers).

Our optimization problem allows for either type of new well (if not, the formulation would be unrealistically restrictive). However, the user will need to keep track of which case is being employed for situations where new wells are specified in the same row and column, but different layers, so that the objective function and constraints can be properly evaluated.

Well Numbers Must Be Specified in Well Package

To differentiate between Case 1 and Case 2 described above, an additional column (after layer, row, column, and rate) is needed in the WEL package for each cell to indicate well number for extraction wells or injection wells. There are 16 extraction wells and 13 injection wells in the current system, and the fixed NE plume well is counted as extraction well #17, thus any new extraction well has to start at number 18 and in ascending order thereafter, e.g., 18, 19, 20, ……, and any new injection well has to start at number 14 and in ascending order thereafter, e.g., 14, 15, 16, ……Use the same number more than once to indicate a multi-aquifer well.

The FORTRAN postprocessor being provided by GeoTrans will calculate the number of new extraction wells and number of new injection wells based on well numbers assigned by users. The FORTRAN postprocessor will also check the transmissivity ratios for multi-aquifer wells and output the error messages if the rates don't obey the transmissivity ratio rule.

Different MT3D Model for Formulation 3

Note that formulation 3 has a different source term than the other formulations to account for declining source strength over time. Therefore, two versions of the MT3d source/sink file will be distributed, one for the first two formulations, and the other for the third formulation.

Feasible Solutions

GeoTrans has determined feasible (though certainly sub-optimal) solutions for formulations 1 and 2. Each involves a large number of new extraction and injection wells (there is no specific limits on new wells in Formulations 1 and 2, although it is likely sub-optimal to have so many new wells). Well packages for those runs will be provided to each modeling group. For formulation 3, there is a limit of 4 new extraction wells and 4 new injection wells, plus a constraint on cleanup. GeoTrans found a solution that satisfies the cleanup constraints, but does not satisfy the constraint on # of new wells (that well package will also be provided to each modeling group). If a modeling group feels Formulation 3 as stated is infeasible after trying to solve it, they report that result. Additionally, if they choose to (but not required) they can determine and report the minimum number of new wells (extraction and injection) they determine is necessary to meet all the other constraints including the cleanup constraint (i.e., by relaxing the limits on number of new extraction and injection wells).

Formulation #1

This formulation includes

- 7 management period of 3 years, total 21 years
- POE-MP = 5 ppb at end of 1st management period
- Specified well location and rate to address NE Plume (detailed earlier)
- No capital cost limits
- Continuous source
- Existing limits on existing extraction well rates and treatment plant rates (no limit on # added extraction/injection wells as long treatment plant capacity not exceeded)
- Limit of 400 gpm on new pumping wells, 600 gpm on new injection wells

Formulation 1 -- Definitions

year – the modeling year defined by

$$year = \text{Roundup}(elapsed\ modeling\ years)$$

- January 1, 2003 corresponds to zero elapsed modeling years
- 2003 corresponds to *year* =1
- The end of June 2004 corresponds to about 1.5 elapsed modeling years and *year* =2
- **Roundup**() is a function to convert a real number into an integer by rounding up (i.e., 1.0 → 1 but 1.1 → 2).

d – use 5%, this represents the conversion of capital and annual costs incurred to present value (i.e., discounted) with the following discount function:

$$PV = \frac{cost}{(1 + rate)^{year-1}}$$

- PV is the present value of a *cost* incurred in *year* with a discount rate of *rate*
- No discounting is done for all costs for *year*=1(i.e., 2003)
- All costs in subsequent years are discounted at the ends of those years
- Example 1: Assuming a discount rate of 5% and a $1000 cost incurred at any time during 2003 (*year*=1) the present value of the cost is $1000
- Example 2: Assuming a discount rate of 5% and a $1000 cost incurred in 2004 (*year*=2), the present value of that cost is $1000/1.05=$952.38.

management period – 3-year periods during which the pumping rates cannot be modified. Modifications may only be made during the initial time step of each management period.

Formulation 1-- Objective Function

This function minimizes total cost over 21 years. This function must be evaluated at the end of every year, rather than after every management period, to properly account for discounting of annual costs. All costs are in thousands of dollars.

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

CCE: Capital costs of new extraction wells (does not include fixed well in NE plume)

$$\text{CCE} = \sum_{i=1}^{ny} (307 \times NW_i)^d$$

ny is total number of the modeling years, i.e., 21 years
NW_i is the total number of new extraction wells installed in year *i*. New wells may only be installed in years corresponding to the beginning of a 3-yr management period. Capital costs are not incurred for operating a well that previously has been in service (i.e., already installed).
$307K is cost of installing a new extraction well.
d indicates application of the discount function to yield Net Present Value (NPV).

****note: see discussion regarding "Treatment of Multi-Aquifer Wells" with respect to how the number of new wells is determined*

CCI: Capital costs of new injection wells

$$\text{CCI} = \sum_{i=1}^{ny} (223 \times NIW_i)^d$$

ny is total number of the modeling years, i.e., 21 years
NIW_i is the total number of new injection wells installed in year *i*. New wells may only be installed in years corresponding to the beginning of a 3-yr management period. Capital costs are not incurred for operating a well that previously has been in service (i.e., already installed).
$223K is cost of installing a new injection well.
d indicates application of the discount function to yield Net Present Value (NPV).

****note: see discussion regarding "Treatment of Multi-Aquifer Wells" with respect to how the number of new wells is determined*

FCO: Fixed cost of O&M any year system operates

$$\text{FCO} = \sum_{i=1}^{ny} (525)^d$$

ny is total number of the modeling years, i.e., 21 years
$525K is the fixed annual O&M cost.
d indicates application of the discount function to yield Net Present Value (NPV).

VCE: Variable electrical costs of operating wells (based on fixed electric cost per well, does not include fixed well in NE plume)

$$VCE = \sum_{i=1}^{ny} \sum_{j=1}^{nwel} \left(34.5 \times IW_{ij}\right)^d$$

ny is total number of the modeling years, i.e., 21 years
nwel is the total number of extraction wells.
$34.5K is the electrical cost operating an extraction well
IW_{ij} is a flag indicator; 1 if the extraction well *j* is on in year *I* (do not include fixed well in NE plume), 0 otherwise.
d indicates application of the discount function to yield Net Present Value (NPV).

VCS: Variable cost of sampling

$$VCS = \sum_{i=1}^{ny} \left[208 \times (A_i / IA)\right]^d$$

ny is total number of the modeling years, i.e., 21 years
IA is the initial plume area (118,720,000 sq. ft.) as determined from the model in January 2003, based on TCE > 5.0 μg/l in any of the model layers, within the property boundary (calculated this way based on installation request, so that future sampling off the base property will account for scaled up costs relative to current sampling appropriately)
$208K is the sampling cost (as of January 2001) and considers both labor and analysis.
d indicates application of the discount function to yield Net Present Value (NPV).
A_i is the plume area during year *I*, including on-site and off-site. The plume area is only measured at the beginning of a management period; therefore, A_i can only change during years corresponding to the beginning of a management period. A_i is measured as the composite summed area of all model grid cells in all four layers that are not "clean" at the beginning of the management period, where "clean" is less than or equal to 5.0 μg/l.

$$A_i = \sum_{j=1}^{m} \sum_{k=1}^{n} \left[\Delta x_j \Delta y_k \times IC_{jk}\right]$$

m is the number of grid cells in the *x* direction
n is the number of grid cells in the *y* direction
Δx_j is length of the *j*th grid space in the *x* direction.
Δy_k is the length of the *k*th grid space in the *y* direction.

IC_{jk} is a flag

$$If \ (C_{jk}^{l} > 5.0 \text{ ug/L}, \quad l = 1,2,3, \text{or } 4)$$
$$\text{then } IC_{jk} = 1,$$
$$\text{else } IC_{jk} = 0$$

C_{jk}^{l} is the concentration of TCE of layer l in the grid cell with indices j and k.

VCC: Variable cost of chemicals (does not include fixed well in NE plume)

$$\text{VCC} = \sum_{i=1}^{ny} (0.02 \times Q_i)^d$$

ny is total number of the modeling years, i.e., 21 years
Q_i is the total pumping rate in year *I (not including fixed well in NE plume).*
$0.02K is unit cost of chemical per pumping rate, based on $109K/yr.
d indicates application of the discount function to yield Net Present Value (NPV).

Formulation 1 – Constraints

1) Modifications to the system may only occur at the beginning of each management period (i.e., the beginning of modeling years 1, 4, 7, 10, 13, 16, and 19).

2) The total modeled pumping rate (including fixed well for NE Plume), when adjusted for the average amount of uptime, cannot exceed 8000gpm, the current maximum treatment capacity of the plant.

$$Q^* / \alpha \leq 8000 \text{ gpm}$$

α: 0.95, a coefficient that accounts for the amount of average amount of uptime (i.e., model assumes up-time of 95% with α=0.95).
Q^*: the modeled flow rate in the well package (including 1425 gpm for NE plume).

When Evaluated: The beginning of each 3-year management period

3) POE-MP = 5ppb in each layer at the end of 1st management period and thereafter

At $year \geq 3$, and for each POE-MP location,

$$C_k \leq 5 \, ppb$$

C_k : the TCE concentration at the kth POE-MP cell

When Evaluated: End of each year beginning with end of year 3.

4) Individual limits on rate at each extraction/injection well, as follows:

$$Q_i/\alpha \leq L_i$$

Q_i: Extraction or injection rate at well i
α: 0.95, a coefficient that accounts for the amount of average amount of uptime (i.e., model assumes up-time of 95% with α=0.95).
L_i: Limit on extraction/injection rate at well i

Extraction Well	*Limit L_i (gpm)*	*Well Number*	*Layers*	*Injection Well*	*Limit L_i (gpm)*	*Well Number*	*Layers*
E-1	*220*	*1*	*2*	*I-1*	*204*	*1*	*2*
E-2-1	*310*	*2*	*2*	*I-2*	*95*	*2*	*2,3*
E-2-2	*520*	*3*	*3*	*I-3*	*653*	*3*	*2*
E-3-1	*450*	*4*	*1,2*	*I-4*	*804*	*4*	*2*
E-3-2	*500*	*5*	*3*	*I-5*	*963*	*5*	*2*
E-4	*800*	*6*	*2*	*I-6*	*413*	*6*	*2,3*
E-5	*690*	*7*	*2*	*I-7*	*1188*	*7*	*2,3*
E-6	*320*	*8*	*2,3*	*I-8*	*786*	*8*	*2*
E-8	*220*	*9*	*2,3*	*I-9*	*739*	*9*	*2,3*
E-9	*850*	*10*	*2,3,4*	*I-10*	*728*	*10*	*2,3*
E-10	*850*	*11*	*3*	*I-11*	*603*	*11*	*2*
E-11	*650*	*12*	*2*	*I-12*	*402*	*12*	*2*
E-12	*211*	*13*	*2*	*I-13*	*229*	*13*	*2,3*
E-13	*580*	*14*	*2*				
E-14	*530*	*15*	*2,3*				
E-15	*640*	*16*	*2,3*				

The maximum extraction rate for new wells is 400 gpm. The maximum injection well flow rate for new injection wells is 600 gpm.

When Evaluated: The beginning of each 3-year management period

5) To balance pumping and reinjection (including pumping for NE plume):

ABS(Total simulated pumping - total simulated injection) ≤ 1 gpm

When Evaluated: The beginning of each 3-year management period

Formulation #2

This formulation includes

- 7 management period of 3 years, total 21 years
- POE-MP = 5 ppb at end of 1st management period
- Concentrations at POC-MP1 (Table 2) are 50% of initial concentrations or ≤ 20 ug/l at end of 1st management period (3 yrs).
- Concentrations at POC-MP2 (table 2) are reduced to 50 ppb by end of 1st management period (3 yrs) and further reduced to 20ppb by end of 3rd management period (9 yrs).
- Specified well location and rate to address NE Plume (discussed earlier)
- No capital cost limits
- Continuous source
- Existing limits on existing extraction well rates and treatment plant rates (no limit on # added extraction/injection wells as long treatment plant capacity not exceeded)
- Limit of 400 gpm on new pumping wells, 600 gpm on new injection wells

Formulation 2-- Definitions

Same as Formulation 1

Formulation 2-- Objective Function

Same as Formulation 1

Formulation 2 – Constraints

Same as Formulation 1 (five constraints), plus:

6) Concentrations at POC-MP1 in layers 1 & 2 are either 50% of initial concentrations or ≤ 20ppb at end of 1st management period (3 yrs) and thereafter.

   At $year \geq 3$, and for each POC-MP1 location,

$$CC_k \leq MAX\,(\,(SC_k/2),\ 20\,ppb)$$

   CC_k : the TCE concentration at the *k*th POC-MP1 cell
   SC_k : the TCE initial concentration at the *k*th POC-MP1 cell

   When Evaluated: End of each year beginning with end of year 3.

7) Concentrations at POC-MP2 in layers 1 & 2 are reduced to 50 ppb by end of 1st management period and further reduced to 20ppb by end of 3rd management period.

At $year \geq 3$, and for each POC-MP2 location,

$$CC_k \leq 50\,ppb$$

CC_k : the TCE concentration at the kth POC-MP2 cell

When Evaluated: End of each year beginning with end of year 3

At $year \geq 9$, and for each POC-MP2 location,

$$CC_k \leq 20\,ppb$$

CC_k : the TCE concentration at the kth POC-MP2 cell

When Evaluated: End of each year beginning with end of year 9

Formulation #3

This formulation includes elements of formulation 2:

- 7 management period of 3 years, total 21 years
- POE-MP = 5 ppb at end of 1st management period
- Concentrations at POC-MP1 (Table 2) are 50% of initial concentrations or ≤ 20 ug/l at end of 1st management period (3 yrs).
- Concentrations at POC-MP2 (Table 2) are reduced to 50 ppb by end of 1st management period (3 yrs) and further reduced to 20ppb by end of 3rd management period (9 yrs).
- Specified well location and rate to address NE Plume (discussed earlier)
- Existing limits on existing extraction and treatment plant rates
- Limit of 400 gpm on new pumping wells, 600 gpm on new injection wells

The following additions/modifications also apply
- Only up to 4 new extraction wells are allowed to be installed for the Main Plume (in addition to the new well specified for NE Plume)
- Only up to 4 new injection wells are allowed to be installed for the Main Plume
- Cleanup, defined as all specified cells (exempted cells from this constraint are specified in the FORTRAN postprocessor input file, and illustrated on Figure 2 and 3) must have TCE ≤ 50 ppb achieved within 9 years in layers 1-4
- Source reduction with 25% decline each management period relative to the previous period

Note that formulation 3 has a different source term than the other formulations. Therefore, two versions of the MT3d source/sink file will be distributed, one for the first two formulations, and the other for the third formulation.

Formulation 3-- Definitions

Same as Formulation 1, except the definition for *CLEANUP locations:*

CLEANUP locations - located in columns 1-55 (at request of installation, to represent main plume but not NE plume), and excepting specific locations immediately adjacent to source areas (see Figures 2 and 3 for exempted cells), these locations in layers 1-4 must be cleaned up (i.e., $TCE \leq 50\, ppb$) within 9 years

EXECEPTED locations - exempted cells are all locations in columns 56 and higher (layers 1-4), plus cells where the bedrock low-K zone is located (layers 1-4), plus cells where the source strength exceeds 50 ug/l at the end of year 9 (layer1 only), plus additional cells (layer 1 only) surrounding several high-concentration source cells (exempted cells from this constraint are specified in the FORTRAN postprocessor input file, and illustrated on Figures 2 & 3)

Formulation 3-- Objective Function

Same as Formulation 1

Formulation 3 – Constraints

Same as formulation 2 (seven constraints), plus:

8) Limit on number of new extraction wells is 4, at request of installation (in addition to the new well specified for NE Plume)

$$NEW \leq 4$$

NEW is the total number of new extraction wells (not including the NE plume well) installed over the entire management period of 21 years.

When Evaluated: The beginning of each 3-year management period

9) Limit on number of new injection wells is 4, at request of installation

$$NIW \leq 4$$

NIW is the total number of new injection installed over the entire management period of 21 years.

When Evaluated: The beginning of each 3-year management period

10) Cleanup constraints for the main plume.

At $year \geq 9$, and for each CLEANUP location (in each model layer),

$$C_k \leq 50\,ppb$$

C_k : the TCE concentration at the kth CLEANUP cell

When Evaluated: End of each year beginning with end of year 9.

Table 1. Cell Locations for POE-MP:

ROW	COL
41	30
42	31
43	32
44	33
45	34
45	35
46	36
47	37
48	38
49	39
49	40
50	41
51	42
52	43
53	44
54	45
54	46
55	47
56	48
57	49
58	50
58	51
59	52
60	53
61	54
62	55

Table 2. Locations for POC-MP1 and POC-MP2

POC-MP1:

ROW	COL
106	25
106	26
106	27
106	28
106	29
106	30
106	31
106	32
106	33
106	34
106	35

POC-MP2:

ROW	COL
106	36
106	37
107	38
107	39
108	40
108	41
108	42
{gap for source cell and two adjacent cells}	
108	46
108	47
108	48
108	49
108	50
108	51
108	52
108	53
108	54
108	55

Figure 1. Location of POE-MP, POC-MP1, and POC-MP2

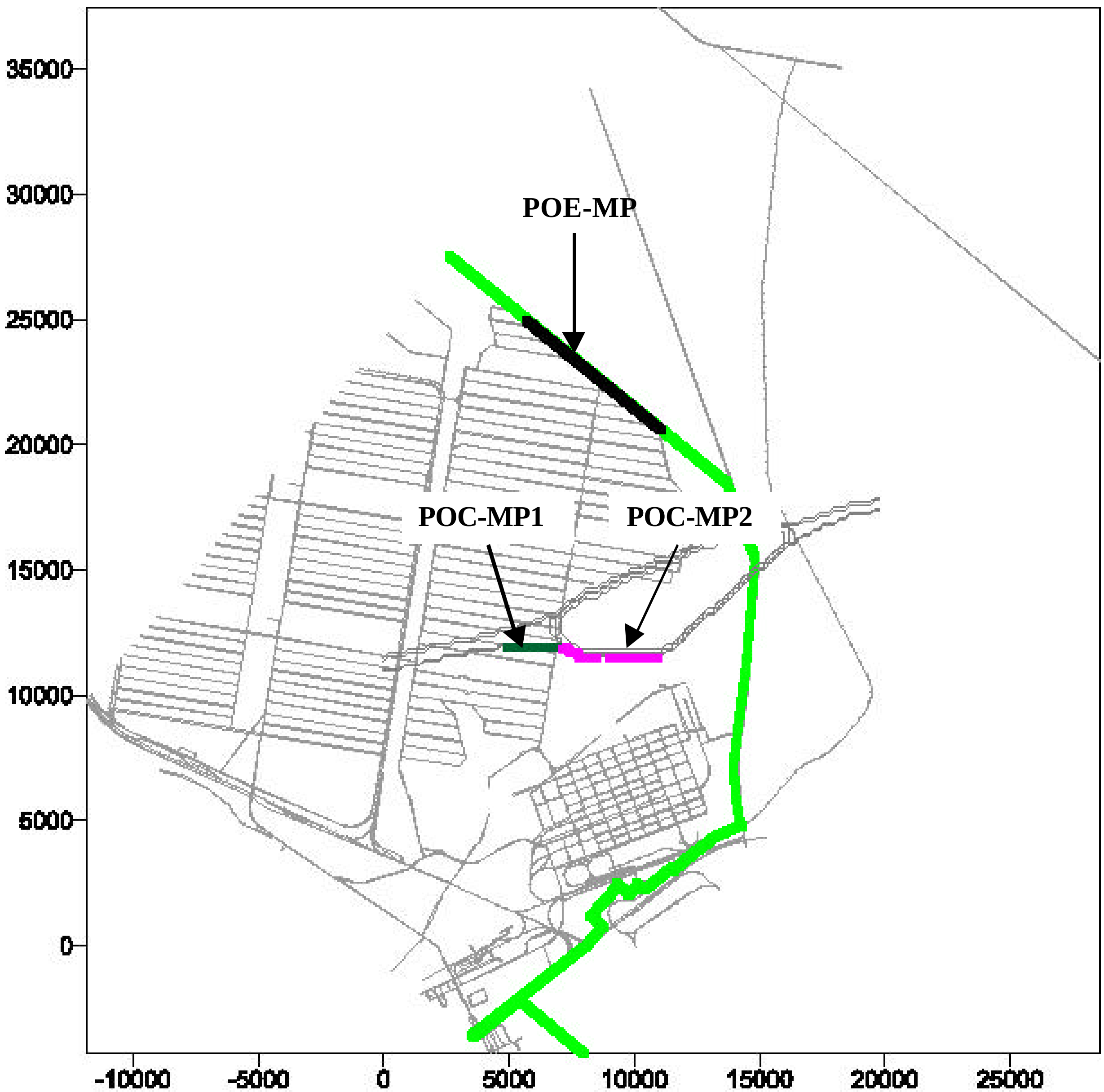
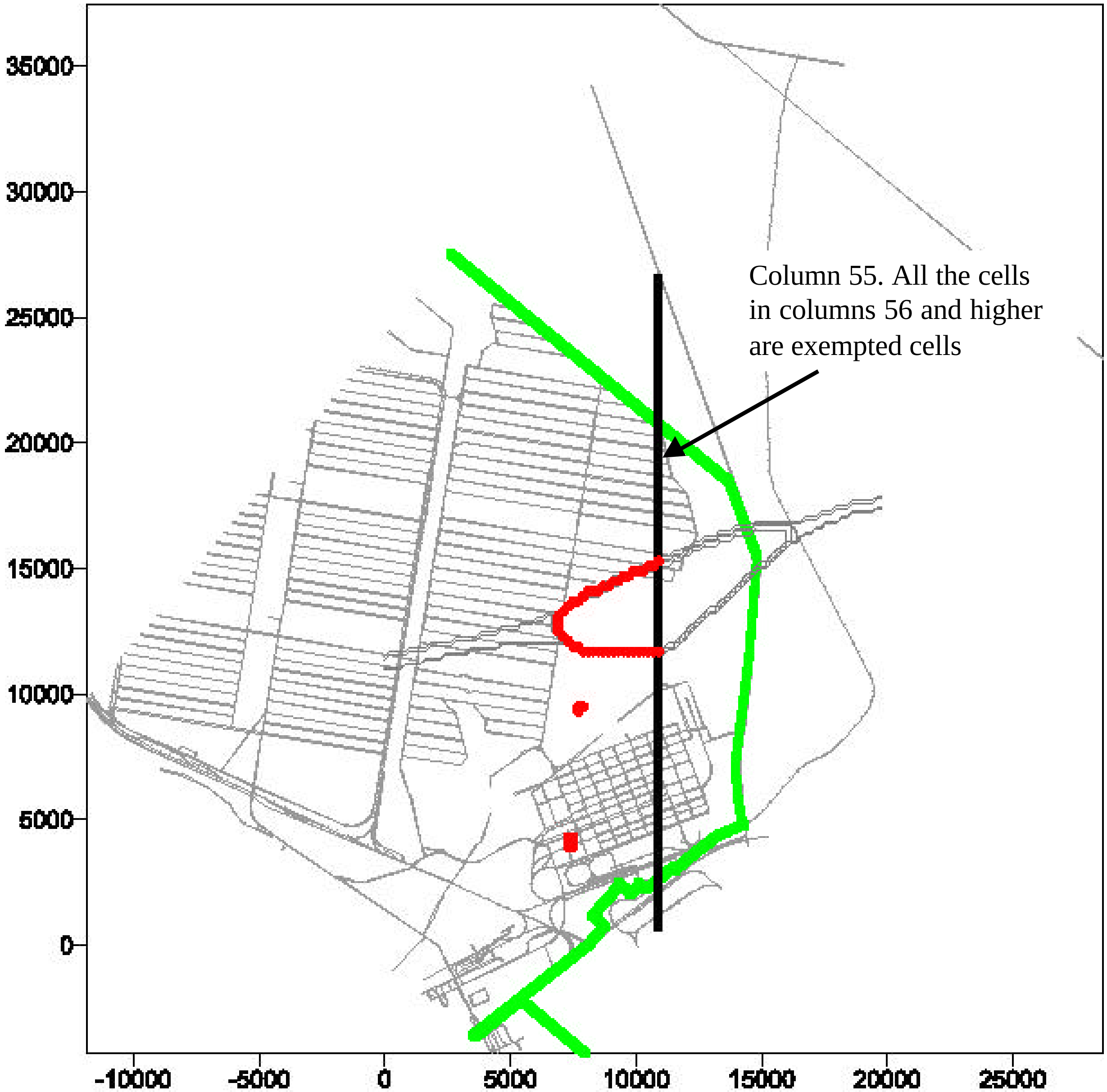


Figure 2. Location of Cells Exempted From Cleanup Constraint in Layer 1, Used in Formulation #3



Exempted   Property Boundary

Figure 3. Location of Cells Exempted From Cleanup Constraint in Layers 2-4, Used in Formulation #3