# Transport Optimization Hastings Naval Ammunition Depot
# Draft Mathematical Formulations
# 5/15/02

## INTRODUCTION

Hastings Naval Ammunition Depot (NAD) consists of 48,800 acres located immediately east of Hastings, Nebraska in eastern Adams County and western Clay County. Hastings is located 25 miles south of Grand Island, Nebraska and 105 miles west of Lincoln, Nebraska.

Hastings NAD was built in the early 1940s as an active "load, assemble, and pack" ammunition facility during World War II and the Korean Conflict. The NAD was responsible for producing nearly one-half of the ordnance used by the Navy during WWII. During the World War II, the Korean Conflict, and the subsequent decommissioning process (1958-1967), waste materials were generated through discharge of wastewater to surface impoundments and natural drainage areas of the facility, and disposal of solid waste and explosives.

Beginning in the mid-1960s, large tracts of the former NAD were either sold to various individuals, businesses, and municipalities or transferred to other governmental agencies. Much of the region's economy is based on agriculture. With sale and transfer of the NAD to the U.S. Department of Agriculture (USDA) and area farmers, over 100 irrigation wells have been installed on the former NAD.

As a result of findings of groundwater contamination at the NAD in the mid-1980s, the EPA included portions of the former NAD as part of the Hastings Groundwater Contamination Site (HGCS), a regional area of groundwater contamination in south-central Nebraska. The HGCS was added to EPA's National Priorities List (NPL) in 1986.

Five operable units (OUs) have been established for restoration of the former NAD: OU4 consists of shallow soil (less than 10 feet in depth) at the Hastings East Industrial Park (HEIP); OU8 consists of vadose zone soil that separates OU4 and groundwater at the HEIP; OU14 is groundwater which typically encountered across the former NAD at a depth of approximately 95 to 115 feet; OU16 consists of three production areas of the former NAD: the Explosives Disposal Area (EDA), the Naval Yard Dump (YD), and the Bomb and Mine Complex (BMC); OU15 is comprised of those remaining former NAD areas that were not included as part of the other Operable Units.

Groundwater was first characterized during RI/FS activities from 1987 to 1990. A Supplemental RI of the Hastings East Industrial Park (HEIP) was conducted in 1990/1991 that included additional characterization of groundwater contamination. The data from the RI annual groundwater program, and the 1999 groundwater sampling event show that the VOC plumes encompass nearly six and one-half square miles beneath the former NAD. Additionally, explosives groundwater contamination extends over an area of approximately three square miles and is commingled with the VOC plume(s) in several areas.

Groundwater is encountered in the study area approximately 100 feet below ground surface. The three saturated hydrogeologic units of primary interest of this study are, in descending order:

- The unconfined aquifer (model layer 1)
- The upper confining layer (model layer 2), and
- The semi-confined aquifer (model layers 3-6)

The unconfined aquifer is comprised of sand and gravel and clayey or silty sand. It is relatively thin, with a thickness of about 10 to 15 feet. The upper confining layer is comprised of silty clay, clayey silt and clayey sand. Although this confining layer is present under most of the region, it is absent or discontinuous in a significant part of the study are. The semi-confined aquifer has a thickness of 100 to 150 feet in the study area, and consists of sand and gravel with discontinuous layers of silty clay and clayey sand. The semi-confined aquifer is the major water supply aquifer in the region, and supports municipal, industrial, and particularly, irrigation needs.

The groundwater flow directions for both the unconfined and semi-confined aquifers are predominantly to the east and southeast during non-irrigation seasons with an average hydraulic gradient of 0.001. During irrigation season, which lasts about two and half months, heavy pumping from extensive irrigation wells dramatically alters the groundwater flow direction. The present extent of the plumes indicates that groundwater contaminant migration is also influenced by the seasonal irrigation pumping.

Groundwater contamination at the former NAD is primarily due to chemical spills and/or discharge of wastewater to surface impoundments, wastewater systems, and natural drainages, mainly in production areas of the former NAD. The contaminants of concern in groundwater are VOCs and explosives.

## GOUNDWATER FLOW AND TRANSPORT MODEL

Groundwater flow is simulated with the MODFLOW code. The model grid covers 134 square miles. Variable cell dimensions range from 400 ft by 400 ft in the center of the model, to 2000 ft by 2000 ft near the model edges. There are six model layers. Layer 1 is the unconfined aquifer. Layer 2 is the upper confining layer. Layers 3-6 are the semi-confined aquifer, split evenly into 4 layers with the equal thickness and properties. The groundwater flow model was calibrated to both steady-state and transient conditions, and included particle tracking to calibrate based on historical plume shape and plume length. Calibrated horizontal hydraulic conductivities range from 10 to 80 ft/day in the unconfined aquifer, and 150 to 250 ft/day in the semi-confined aquifer. Hydraulic conductivity of the upper confining bed is much lower.

Groundwater contaminant transport is simulated with MT3DMS. In the FS, the following six parameters were simulated:

- TCE (VOC)
- PCE (VOC)
- 1,1,1-TCA ("TCA") (VOC)
- 1,1-DCE ("DCE") (VOC)
- TNT (Explosive)
- RDX (Explosive)

The optimization project is restricted to simulation of two parameters. Site managers selected TCE and TNT as the parameters most important to remedial design. However, site managers also indicated a preference to not ignore the other parameters. Therefore, an approach was developed (discussed later) to incorporate the distribution of the other constituents.

## SPECIAL NOTES

***Stress Periods in the Model***

The FS flow and transport model was set up to run one year at a time manually. The head solution and concentration solution from the end of the previous year was used as the initial condition for the following year. Each calendar year was divided into 3 stress periods in the FS model with the temporal discretization scheme as shown below:

**FS Model (3 Stress Periods Per Year)**

| Stress Period | Length (days) | # Time Steps | Time Step Multiplier |
|---|---|---|---|
| 1 | 76 | 10 | 1.5 |
| 2 | 136 | 10 | 1.5 |
| 3 | 152 | 5 | 1.5 |

The 76-day period refers to the irrigation season, which occurs in summer months.

For this project, it is important to reduce execution time for the model as much as possible. Dr. Chunmiao Zheng accomplished this by converting the model to one complete simulation containing multiple years (rather than year-by-year as different simulations), and by reducing the number of stress periods per year from 3 to 2. This could be done because stress periods 2 and 3 contained identical external stresses (e.g., pumping, recharge, and general-head boundaries). Dr. Zheng also determined the number of time steps within each stress period could be reduced without any noticeable loss of accuracy. Thus, in the revised model, the temporal discretization scheme is modified as follows:

**Revised Model For This Project (2 Stress Periods Per Year)**

| Stress Period | Length (days) | # Time Steps | Time Step Multiplier |
|---|---|---|---|
| 1 | 76 | 5 | 1.5 |
| 2 | 289 | 5 | 1.5 |

Since two stress periods are required for one year, there are 60 stress periods for a 30-year simulation, with the above temporal discretization scheme repeated once per year.

***Initial Time For Optimization Simulations***

The model used for the FS was run forward in time to September 2003, under non-remediation conditions. It is assumed that a remedy will not be in place prior to September 2003. The simulation period for the optimization simulations therefore begins in September 2003. The first stress period each year is the non-irrigation season, and the second period each year is the irrigation season.

***Simulated Time Period For Optimization Runs***

For formulations 1 and 2, cleanup time must be less than 30 years. Thus the maximum simulated time period is 30 years. However, in Formulations 1 and 2, the objective function and constraints are only evaluated until "cleanup" is achieved (see "Definitions" section regarding the definition of cleanup). Therefore, simulated time periods shorter than 30 years are possible, depending on the pumping solution being simulated. GeoTrans determined a solution with cleanup time of 27 years during development of the formulations, but cannot specifically conclude that optimal solutions have cleanup time of 27 years or less (because of potential tradeoffs between capital costs, annual costs, and cleanup time).

For formulation 3, the simulation period is 30 years, since the plume containment constraint (based on concentrations) is evaluated after each year for 30 years.

***Discounting of Future Costs***

Site managers indicate that there is some question as to whether or not it is appropriate to use discounting to convert future costs to "net present value". They sometimes use a term called "Sum of Committed Cost Analysis", which accounts for the fact that they get just the funds needed to get through the following year's (i.e., cannot invest money not spent). However, it was ultimately decided to use a discount rate consistent with OMB guidance (3.5% was selected).

***Simplifications Regarding Cost Coefficients***

The FS provides extremely detailed unit costs for many items, as functions of design parameters such as flow rate. There are also many variables in the FS costs, such as type of treatment (e.g., GAC versus air stripping), which were not firmly established. For the purpose of this project, the cost terms and coefficients must be simplified. Simplifications to be made include the following (based on cost coefficients provided by ACOE and their contractor):

Capital Cost Items:

1) Treatment System: $1,000/gpm
2) New Extraction Well: $400,000/well
3) Discharge Piping: $1,500/gpm
4) Infiltration Basins: not being simulated as per site managers

Variable Annual O&M Cost Items:

1) Pumping Costs (Electrical): $46/gpm/yr
2) Treatment Costs: $283/gpm/yr
3) Discharge Costs: $66/gpm/yr

Fixed Annual O&M Cost Items:

1) Fixed Monitoring Costs: $300,000/yr
2) Fixed Management Costs: $115,000/yr

The goal of the simplifications is to create optimization problems that incorporate the tradeoff of higher pumping rate and/or increased number of wells (each of which increases capital or annual costs) versus reductions in cleanup time (which can lower life-cycle costs). These costs coefficients are not a rigorous accounting of costs. It is assumed that the optimization will provide solutions that incorporate to a reasonable degree these trade-offs, and that detailed design will then be performed on the basis of pumping strategies (i.e., well locations and rates) developed by the optimization procedures.

***Constituents Being Simulated***

GeoTrans test runs show that the cleanup of TCE and TNT cannot ensure the cleanup of other constituents, i.e., DCE, TCA, and RDX. This is because those constituents have extents that do not completely overlap with TCE or TNT (note that site managers feel PCE will be addressed by remediating TCE, due to it's extent and relative low concentrations). Due to limitations of this project, the optimization formulations can only consider up to 2 constituents. Site managers suggested that, since the project is restricted to simulating two parameters, that perhaps it would be reasonable to use TCE as a surrogate parameter for DCE, TCA, and RDX, because the retardation factors are similar to TCE (relative to TNT):

| | **Retardation Factor*** | **Cleanup Level (ppb)** | **Approach** |
|---|---|---|---|
| TCE | 1.14 | 5 | Simulate as TCE |
| DCE | 1.06 | 7 | Use TCE as surrogate |
| RDX | 1.243 | 2.1 | Use TCE as surrogate |
| TCA | 1.364 | 200 | Use TCE as surrogate |
| PCE | 1.635 | – | Do not simulate |
| TNT | 2.885 | 2.8 | Simulate as TNT |

*for layer 1 and layers 3-6, different values are assigned for model layer 2

The approach to generate combined initial concentration is described as follows:

- Simulate DCE, TCA, and RDX independently from 6/1999 to 9/2003 to get the initial concentration distribution of each constituent for the optimization runs 9/2003;

- Normalize the concentration of each constituent in 9/2003 to a representative TCE level according to the ratio of the cleanup levels (CL), to properly account for cleanup levels of the other constituents (since the model is evaluating TCE based on the TCE cleanup level of 5 ppb):

- $Conc^S(DCE) = Conc(DCE) *CL(TCE)/CL(DCE)$
- $Conc^S(TCA) = Conc(TCA) *CL(TCE)/CL(TCA)$
- $Conc^S(RDX) = Conc(RDX) *CL(TCE)/CL(RDX)$

- Assign the initial concentration for the combined parameters in each cell as the maximum concentration of TCE, DCE, TCA, and RDX at that cell:

$$Conc^{Comb} = Max(TCE, DCE, TCA, RDX)$$

This last step is done to address areas where multiple constituents overlap. If constituent concentrations were added in areas of overlap, mass would be preserved, but comparing simulated concentrations to the cleanup level of TCE would be inappropriate. Using the maximum concentration, while it does not properly account for total mass of all constituents, is the appropriate method to compare simulated concentrations to the TCE cleanup level.

It should also be noted that the individual transport models have a decay term for TCE only (not DCE, TCA, or RDX). The half-life for TCE is simulated as 65 years. Given the approximations being made for this surrogate parameter approach, the fact that the other parameters are now being simulated with this half life is not a concern, since the half life is so long relative to the simulation period (30 years or less).

***MODFLOW Code Modification to Improve "Dry Cell" Conditions***

Starting from the hydraulic containment scenario in the FS report, GeoTrans performed some test simulations with added/modified pumping rates in high concentration areas, focusing only on model layers 3-6. GeoTrans noted that the simulation suffered from many "dry cells" in model layers 1 and 2, indicating that at some point during the flow simulation the head dropped below the bottom elevation of the layer (that cell is then set to inactive for the rest of the flow and transport simulation). GeoTrans applied a procedure developed by Dr. Zheng for MODFLOW which assigns a user-specified value of saturated thickness for cells where head is below layer bottom (i.e., the head is still below the layer bottom, but the cell remains active and transmissivity is calculated based on the minimum saturated thickness that is specified). This fixes the problem of cells going dry just because of the solution iteration process in the flow simulation, or as a result of a domino effect caused by nearby cells going dry. While this procedure allows the cells that are not truly supposed to be dry to stay active in MODFLOW, in MT3D if a cell is truly supposed to be dry (head below bottom of layer) then concentration will still be assigned a special value by MT3D as an inactive cell, which is an indicator that the solution has too much pumping. However, for the test runs GeoTrans performed, it was determined that the dry cells were being caused by the iteration process (i.e., they were not really supposed to be dry) and Dr. Zheng's procedure allowed the model to ultimately reach a more appropriate solution (i.e., without the dry cells).

***Treatment of Model Layer 1***

Model layer 1 is a thin, unconfined aquifer. It was noted during development of the formulations that wells placed in layer 1, in conjunction with the code modification discussed above, caused instabilities in the flow model (causing the flow model to not converge). It was empirically determined that the flow model had no convergence problems when wells in layer 1 were represented with the MODFLOW drain package rather than the MODFLOW well package. The "drains" actually represent wells with a low-level shutoff (specified as the drain elevation). Water is removed from the aquifer as long as the water level in the aquifer exceeds the drain elevation (i.e., the low-level shutoff elevation).

In the FS solutions, the vast majority of pumping at remediation wells occurs in layers 3-5. For instance, for the hydraulic containment solution in the FS, the following remediation well rates are specified:

- Layer 1: 18 gpm
- Layer 3-5: 4050 gpm

Based on discussions with site managers, it was decided that the majority of the management problem is associated with model layers 3-6. This is partly due to the ratio of pumping from layer 1 versus layers 3-6 (presented above) and also because the FS assumes individual treatment units for those shallow wells (versus centralized treatment for the deeper wells). Therefore, in the optimization formulations, drains will be fixed in model layer 1 to provide mass reduction associated with future remedial action in that layer, but the drain locations and/or parameters will not be "optimized" as part of the formulations. The items to be optimized will be well locations and rates in model layers 3-6.

***Treatment of Model Layer 2***

Because layer 2 is a low permeability layer, remediation wells were not included in model layer 2 in the FS. That restriction applies to the optimization project as well.

In the modeling done for the FS, the model was run for 1 year at a time. At the beginning of each year, the concentration of model layer 2 was set to the concentration of model layer 1. For the optimization project, the simulation model was modified to simulate the entire simulation period as one model run, and the concentrations in model layer 2 are not set to equal the concentrations in model layer 1 after each year. Because all simulations include mass reductions in layer 1 (discussed above), layer 2 has higher concentrations in the optimization runs than would be present if the FS approach was utilized. Thus, the approach for the optimization runs is conservative.

***Discharge of Treated Water***

The FS does not explicitly detail the plan for discharge of treated water. It may be discharged to surface water, or may be discharged via ponds. In the FS, recharge of treated water into the aquifer was not considered. Project managers indicate that, for the optimization project, recharge of treated water to the aquifer should not be simulated.

A unit cost for discharge ($/gpm/yr) is assigned for formulations 1 and 2. For formulation 2, it is assumed that up to 2400 gpm of extracted water can be discharged to a local utility, with no treatment or discharge costs.

***Treatment of Multi-Aquifer Wells***

Remediation wells may be "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.

New wells in this project are limited to layers 3-5. We will assume that a remediation well in the in the same row and column, but different layers, represent one multi-aquifer well:

- capital cost is for only one well
- maximum well rate applies to the combined well
- ratio of rates between model layers must be consistent with the transmissivity of each layer.

In this model the transmissivity for a given row/column is the same in layers 3, 4 and 5. Therefore, if the well is in multiple layers, the rate must be the same in each layer.

Site managers used specific capacity assumptions, in conjunction with the thickness of model layer 3, to determine the following well rate limits for remediation wells specified in layers 3-5:

- well screens one model layer: 350 gpm limit
- well screens two model layers: 700 gpm limit
- well screens three model layers: 1050 gpm limit

These limits are intended to provide at least 10-15 feet of saturated thickness in model layer 3 in the cell containing the well (such water elevation limits are not included as actual constraints).

***Well Numbers Must Be Specified in Well Package***

To help identify multi-aquifer wells, 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. Use the same number more than once to indicate a multi-aquifer well. All irrigation wells are indicated with either negative number or 0 for well number.

The FORTRAN postprocessor being provided by GeoTrans will calculate the number of new extraction wells based on well numbers assigned by users. The FORTRAN postprocessor will also check the transmissivity ratios and combined well rates for multi-aquifer wells, and output the error messages if the rates don't obey the transmissivity ratio rule or maximum well rate constraints. It will also check if the correct non-remediation pumping (number of wells and total rates) is specified.

## DEFINITIONS

*year* – the modeling year defined by

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

- September, 2003 corresponds to zero elapsed modeling years
- *year* =1 corresponds consists of 2 stress periods
- Any timestep within stress periods 3 and 4 are in *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).

*ny* – the modeling year in which cleanup is achieved. That is the modeling year when

$$\text{For layers 3-6, } \left\| C_{TCE} \right\|_\infty \leq 5.0\ \mu\text{g/L} \quad \text{and} \quad \left\| C_{TNT} \right\|_\infty \leq 2.8\ \mu\text{g/L}$$

- $\left\| C_{TCE} \right\|_\infty$ is the infinity-norm, which returns the maximum value of two-dimensional array $C_{TCE}$, which is the two-dimensional concentration array in layers 3-6 for TCE. For example, if during the 17$^{th}$ year of the simulation "cleanup" is achieved, then costs are incurred for 17 full years.

*d* – indicates discounting using 3.5% discount rate to represent the conversion of capital and annual costs incurred in the future 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 (stress periods 1 and 2)
- All costs in subsequent years are discounted at the ends of those years
- Example 1: Assuming a discount rate of 3.5% and a $1000 cost incurred at any time during *year*=1, the present value of the cost is $1000
- Example 2: Assuming a discount rate of 3.5% and a $1000 cost incurred in *year*=2, the present value of that cost is $1000/1.035=$966.18.

management period – 5-year periods (consisting of 10 simulation stress periods) during which the pumping locations/rates for remediation wells cannot be modified. Modifications may only be made during the initial time step of each management period.

## FORMULATION #1

**<u>Formulation 1 – Objective Function</u>**

This function minimizes total cost up to and including *ny* (i.e., the year of cleanup). 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 + CCT + FCM + FCS + VCE + VCT + VCD)**

**CCE**: Capital Costs of new extraction wells

$$\text{CCE} = \sum_{i=1}^{ny} (400 \times NW_i)^d$$

*ny* is the modeling year when cleanup occurs.
$NW_i$ 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 5 -yr management period.
$400K is cost of installing a new extraction well.
*d* indicates application of the discount function to yield Net Present Value (NPV).

**CCT**: Capital Cost of Treatment (applied at beginning of simulation)

$$\text{CCT} = 1.0 \times Q_{\max}$$

$Q_{\max}$ is the maximum total pumping rate at remediation wells (layers 3-6) in any management period
$1.0K is the cost per gpm of installing a treatment unit of sufficient capacity at the beginning of the simulation for all subsequent management periods

**CCD**: Capital Cost of Discharge Piping (applied at beginning of simulation)

$$\text{CCD} = 1.5 \times Q_{\max}$$

$Q_{\max}$ is the maximum total pumping rate at remediation wells (layers 3-6) in any management period
$1.5K is the cost per gpm of installing discharge piping of sufficient capacity at the beginning of the simulation for all subsequent management periods

**FCM**: Fixed Cost of Management

$$\text{FCM}=\sum_{i=1}^{ny}(115)^{d}$$

$ny$ is the modeling year when cleanup occurs.
\$115K is the fixed annual O&M management cost.
$d$ indicates application of the discount function to yield Net Present Value (NPV).

**FCS**: Fixed Costs of sampling

$$\text{FCS}=\sum_{i=1}^{ny}(300)^{d}$$

$ny$ is the modeling year when cleanup occurs.
\$300K is the fixed annual cost of sampling and analysis
$d$ indicates application of the discount function to yield Net Present Value (NPV).

**VCE:** Variable Costs of Electricity for operating wells

$$\text{VCE}=\sum_{i=1}^{ny}\left(0.046\times Q_i\right)^{d}$$

$ny$ is the modeling year when cleanup occurs.
\$0.046K is the electrical cost per gpm
$Q_i$ is the total pumping rate in year $i$
$d$ indicates application of the discount function to yield Net Present Value (NPV).

**VCT**: Variable Cost of Treatment

$$\text{VCT}=\sum_{i=1}^{ny}\left(0.283\times Q_i\right)^{d}$$

where

$ny$ is the modeling year when cleanup occurs.
\$0.283K is the treatment cost per gpm
$Q_i$ is the total pumping rate in year $i$
$d$ indicates application of the discount function to yield Net Present Value (NPV).

**VCD**: Variable Cost of Discharge

$$\text{VCD}=\sum_{i=1}^{ny}\left(0.066\times Q_i\right)^{d}$$

where

*ny* is the modeling year when cleanup occurs.
\$0.066K is the discharge cost per gpm
$Q_i$ is the total pumping rate in year $i$
*d* indicates application of the discount function to yield Net Present Value (NPV).

**Formulation 1 – Constraints**

1) Modification Occurrence Constraint: Modifications to the system may only occur at the beginning of each management period (i.e., the beginning of modeling years 1, 6, 11, 16, 21, 26).

2) Cleanup must be achieved in model layers 3-6 within the modeling period (by the end of year 30).

$$ny \leq 30$$

3) Plume containment constraint: TCE and TNT concentration levels must not exceed their respective cleanup levels in locations beyond areas specified by the Hastings (Figures 1 & 2), i.e. plume cannot spread above cleanup levels to any cell adjacent to specified areas.

   At time, $t$, and for all grid indices $i$ and $j$ in layers 3-6,

$$\begin{aligned}
&\text{If BTCE}(i,j) = 0 \\
&\quad \text{then } C_{TCE}^{ij} \leq 5.0\ \mu\text{g/L} \\
&\text{and} \\
&\text{If BTNT}(i,j) = 0 \\
&\quad \text{then } C_{TNT}^{ij} \leq 2.8\ \mu\text{g/L}
\end{aligned}$$

   BTCE($i,j$): a function of model grid indices $i$ and $j$ that returns 1 if ($i,j$) corresponds to a location within the buffer zone for TCE and 0 if ($i,j$) corresponds to a location outside of the buffer zone for TCE

   BTNT($i,j$): a function of model grid indices $i$ and $j$ that returns 1 if ($i,j$) corresponds to a location within the buffer zone for TNT and 0 if ($i,j$) corresponds to a location outside of the buffer zone for TNT

   $C_{TCE}^{ij}$ : the concentration of TCE at grid location ($i,j$)

   $C_{TNT}^{ij}$ : the concentration of TNT at grid location ($i,j$)

   Location of these zones is provided in matrix form with the FORTRAN post-processor

   **When Evaluated:** The end of each 5-year management period.

4) Limits on individual extraction well rates: Site managers used specific capacity assumptions, in conjunction with the thickness of model layer 3, to determine the following well rate limits for remediation wells specified in layers 3-5:

   - well screens one model layer: 350 gpm limit
   - well screens two model layers: 700 gpm limit
   - well screens three model layers: 1050 gpm limit

5) Restricted area constraint: No remediation wells are allowed in specified restricted areas (Figure 3 and Table 1).

   At any time, *t*, and for all grid indices *i* and *j*,

$$\text{If } NoWelZon(i,j) = 1 \quad \text{then } \textit{No Well Allowed}$$

   *NoWelZon(i,j)*: a function of model grid indices *i* and *j* that returns 1 if (*i,j*) corresponds to a location within the restricted area and 0 if (*i,j*) corresponds to a location outside of the restricted area. Zones are provided in matrix form with the FORTRAN post-processor.

   **When Evaluated:** The beginning of each 5-year management period

6) Remediation well location constraint: No remediation wells are allowed in cells with irrigation wells to prevent excessive dewatering in irrigation wells and/or at remediation wells.

$$Location\ (Remediation\ Wells) \neq Location\ (Irrigation\ Wells)$$

   **When Evaluated:** The beginning of each 5-year management period

7) Dry cell constraint: This means that MT3D concentration array does not indicate an inactive cell due to dry conditions.

   At end of simulation, and for all grid indices *i* and *j*,

$$C_{ij} = active$$

   **When Evaluated:** The end of simulation.

8) Irrigation Well Constraint: Modeler cannot change well rates on irrigation wells in any stress period.

**When Evaluated:** The beginning of each simulation period.

9) Well Screen Constraint: No well is allowed screened in model layer 6

   **When Evaluated:** The beginning of each simulation period.

FORMULATION #2

Same as formulation 1, but assume diversion of 2400 gpm of extracted water (i.e., do not incur treatment cost or discharge cost for up to 2400 gpm of extracted water). Changes to formulation are:

**CCT**: Capital Cost of Treatment (applied at beginning of simulation)

If $\left(Q_{\max} \leq 2400\right)$ then

$$CCT = 0,$$

else

$$CCT = 1.0 \times \left[Q_{\max} - 2400\right]$$

where

$Q_{\max}$ is the maximum total pumping rate at remediation wells (layers 3-6) in any management period

\$1.0K is the cost per gpm of installing a treatment unit of sufficient capacity at the beginning of the simulation for all subsequent management

**CCD**: Capital Cost of Discharge Piping (applied at beginning of simulation)

If $\left(Q_{\max} \leq 2400\right)$ then

$$CCD = 0,$$

else

$$CCD = 1.5 \times \left[Q_{\max} - 2400\right]$$

where

$Q_{\max}$ is the maximum total pumping rate at remediation wells (layers 3-6) in any management period

\$1.5K is the cost per gpm of installing discharge piping of sufficient capacity at the beginning of the simulation for all subsequent management

**VCT**: Variable Cost of Treatment

$$\text{VCT} = \sum_{i=1}^{ny} CT_i^{\,d}$$

where

If $\left(Q_i \leq 2400\right)$ then

$$CT_i = 0,$$

else

$$CT_i = 0.283 \times \left[Q_i - 2400\right]$$

*ny* is the modeling year when cleanup occurs.
*nwel* is the total number of extraction wells.
\$0.283K is the treatment cost per gpm
$Q_i$ is the total rate in year *i*
*d* indicates application of the discount function to yield Net Present Value (NPV).

**VCD**: Variable Cost of Discharge

$$\text{VCD} = \sum_{i=1}^{ny} CD_i^{\,d}$$

where

*If* $\left(Q_i \leq 2400\right)$ then

$$CD_i = 0,$$

else

$$CD_i = 0.066 \times \left[Q_i - 2400\right]$$

*ny* is the modeling year when cleanup occurs.
*nwel* is the total number of extraction wells.
\$0.066K is the discharge cost per gpm
$Q_i$ is the total rate in year *i*
*d* indicates application of the discount function to yield Net Present Value (NPV).

FORMULATION #3

**Formulation 3 – Objective Function**

This function minimizes the maximum total remediation pumping rate in any management period over a 30-year simulation.

$$\textbf{MINIMIZE } (Q_{\max})$$

$Q_{\max}$: the maximum total pumping rate at remediation wells (layers 3-6) in any management Period over a 30 year simulation.

**Formulation 3 – Constraints**

Same as formulation 1, except:

- delete the second constraint (i.e., cleanup need not be achieved within 30 years in formulation 3)
- add limit of 25 on total number of new remediation wells over the entire modeling period

$$\#\ RemediationWells \leq 25$$

**Figure 1. TCE Containment Zone in Layers 3-6**

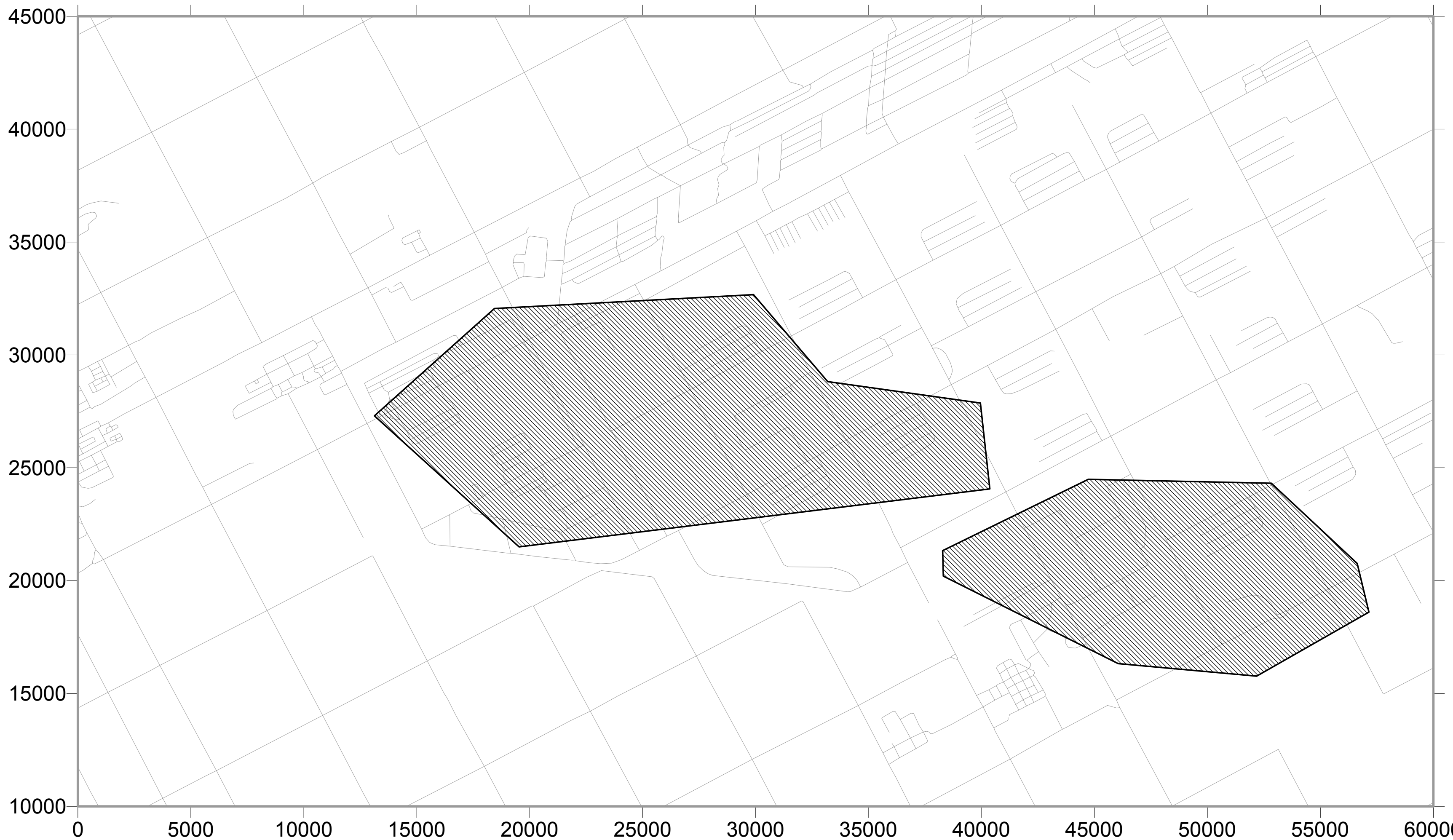

**Figure 2. TNT Containment Zone in Layers 3-6**

**Figure 3.  Restricted Areas Where No Remediation Wells Allowed**

**Table 1. Model Row and Column of Restricted Areas For New Wells**

| Row | Column |
|---|---|
| 21 | 40 |
| 21 | 41 |
| 22 | 39 |
| 22 | 40 |
| 22 | 41 |
| 44 | 71 |
| 44 | 72 |
| 45 | 69 |
| 45 | 70 |
| 45 | 71 |
| 45 | 72 |
| 46 | 67 |
| 46 | 68 |
| 46 | 69 |
| 46 | 70 |
| 46 | 71 |
| 46 | 72 |
| 46 | 73 |
| 47 | 65 |
| 47 | 66 |
| 47 | 67 |
| 47 | 68 |
| 47 | 69 |
| 47 | 70 |
| 47 | 71 |
| 47 | 72 |
| 47 | 73 |
| 48 | 65 |
| 48 | 66 |
| 48 | 67 |
| 48 | 68 |
| 48 | 69 |
| 48 | 70 |
| 48 | 71 |
| 48 | 72 |
| 48 | 73 |
| 48 | 74 |
| 49 | 65 |
| 49 | 66 |
| 49 | 67 |
| 49 | 68 |
| 49 | 69 |
| 49 | 70 |

| | |
|---|---|
| 49 | 71 |
| 49 | 72 |
| 49 | 73 |
| 50 | 64 |
| 50 | 65 |
| 50 | 66 |
| 50 | 67 |
| 50 | 68 |
| 50 | 69 |
| 50 | 70 |
| 50 | 71 |
| 51 | 64 |
| 51 | 65 |
| 51 | 66 |
| 51 | 67 |
| 51 | 68 |
| 51 | 69 |

***note: in addition, new wells may not be placed in cells with existing irrigation wells