OPTIMIZATION RESULTS: GEOTRANS

ESTCP TRANSPORT OPTIMIZATION PROJECT
SITE #1: UMATILLA ARMY DEPOT

Prepared By:

Yan Zhang and Rob Greenwald
GeoTrans, Inc.
2 Paragon Way
Freehold, New Jersey 07728

NOTICE

This work was performed for the U.S. Environmental Protection Agency (U.S. EPA) under Dynamac Contract No. 68-C-99-256, Task # WA-1-ST-1. The technical work was performed by GeoTrans under Subcontract No. AD01-106M.

PREFACE

The goal of the ESTCP Transport Optimization project (“the project”) is to evaluate the effectiveness and cost/benefit of transport optimization software for pump and treat system optimization. When coupled with a site-specific solute transport model, transport optimization software implements complex mathematical algorithms to determine optimal site-specific well locations and pumping rates. This demonstration project is intended to address the following scientific questions:

1) Do the results obtained from these optimization software packages (e.g. recommended optimal pump and treat scenarios) differ substantially from the optimal solutions determined by traditional "trial-and-error" optimization methods?

2) Do the results obtained from these optimization software packages warrant the additional effort and costs when compared to traditional "trial-and-error" optimization methods?

The project involves the determination of optimal extraction and pumping well scenarios at three Department of Defense (DoD) pump and treat systems. The installations are encouraged (but not required) to implement optimization suggestions resulting from the demonstration.

For each of the three sites, three site-specific optimization problems (“formulations”) will be defined. Each of three modeling groups will independently attempt to determine the optimal solution for each of the optimization formulations. Two of the modeling groups will use their own independently developed transport optimization software, and the other group (GeoTrans) will use a traditional "trial-and-error" optimization method. Thus, the optimization recommendations from two separate transport optimization software programs will be compared to each other and to the recommendations from an experimental control.

This report presents the “trial-and-error” results determined by GeoTrans for Site #1, which is the Umatilla Army Depot in Hermiston, Oregon. The three formulations for this site are described in detail in a separate document.

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1.0 OPTIMIZATION TECHNIQUE

GeoTrans applied "trial-and-error" optimization for each of the three formulations. The simulation period consisted of four 5-year management periods (20 years total), beginning January 2003. Each trial-and-error simulation involved modifying pumping wells (locations and rates) and recharge of treated water (represented as injection well locations and rates) in the MODFLOW/MT3D well package. Pumping and recharge could be modified at the beginning of each of the 5-year management periods within a specific simulation.

The general optimization approach utilized by GeoTrans is described below.

Step 1: Program FORTRAN Postprocessor

For each simulation, it was necessary to evaluate the objective function value, to determine if that simulation produced an improved solution relative to previous simulations. For each simulation it was also necessary to determine if all constraints were satisfied. For "trial-and-error" optimization, it was essential that the evaluation of objective function and constraints be done efficiently. Therefore, GeoTrans coded a FORTRAN program to read specific components of model input and output, and then print out the objective function value (broken into individual components) and all constraints that were violated. GeoTrans provided this FORTRAN code to the other modeling groups, to allow those groups to check their solutions (i.e., to make sure they had not made any errors in programming associated with their methods that would invalidate their results).

Step 2: Develop "Animation" approach for RDX and TNT

The purpose of the animations was to clearly illustrate the plume movement over time, for both RDX and TNT, based on simulation results. The animations for each constituent were developed by creating a concentration contour map for model layer 1 at the end of each year in the simulation, using SURFER, and then compiling those into a Microsoft PowerPoint file to allow the plume movement over time to be displayed as an "animation". This was only done for model layer 1 because the components of the optimization formulations only apply to model layer 1 at this site.

Step 3: Modify Pumping/Recharge, Run FORTRAN Code, and Create/Evaluate Animation

This is the classic "trial-and-error" method. After the simulation, the FORTRAN code allowed immediate determination regarding the objective function value, and whether or not the run was feasible (i.e., all constraints satisfied). Based on evaluation of the animations for RDX and TNT, modified pumping/recharge strategies were selected for one or more subsequent simulations, to better address areas of relatively high concentrations and/or areas where cleanup was not progressing fast enough.

2.0 OPTIMIZATION RESULTS

2.1 Current System

2.1.1 Layout of Wells and Recharge Basins for Current System

Pre-remediation concentration distributions for RDX and TNT are illustrated on Figure 2-1. The remedial design configuration for the current system is also shown in Figure 2-1. The current pump-and-treat system has 4 extraction wells installed (EW-1, EW-2, EW-3, and EW-4) and 3 recharge basins (IF1, IF2, and IF3). Wells EW-1, EW-3 and EW-4 have pumps and piping, and are being used to extract groundwater. Well EW-2 is located approximately 100 feet northwest of EW-4 and does not have a pump or any associated piping. Groundwater remediation at the site began with official plant startup on 15 January 1997. The system has operated since that time with the exception of an extended period of shutdown for treatment system adjustment during the first quarter of operation, intermittent power outages, and periodic granular active carbon (GAC) replacement events.

Contaminants (RDX and TNT) are removed in th treatment plant by GAC, and treated water is discharged to the infiltration basins. The current GAC capacity is 1300gpm. The representative extraction rates and recharge rates for the current system, as specified in the model provided by the installation, are listed below (these rates in the model account for 10% system downtime, such that actual rates when pumping are approximately 10% higher).

Well	Recharge Basin	Rate (gpm)
EW-1		128.23
EW-2		0
EW-3		105.05
EW-4		887.24
	IF1	232.80
	IF2	405.27
	IF3	482.40

2.1.2 Cleanup Time and Mass Removal for Current System

Based on the modeling results for the current system, RDX cleanup (2.1 ug/l) in the alluvial aquifer is predicted to take 8 years, and TNT cleanup (2.8 ug/l) in the alluvial aquifer is predicted to take 17 years. These times are based on simulations that begin in January, 2003, which is specified as the initial time for the transport optimization simulations.

Formulation 3 is based on minimizing the combined mass of RDX and TNT remaining in model layer 1 after 20 years, starting in January 2003. Based on the modeling results for the current system, the remaining mass of RDX and TNT in layer 1, after 20 years, is as follows:

	Time = 20 yrs
RDX Mass (kg)	0.204
TNT Mass (kg)	1.561
Total Mass (kg)	1.765

A plot of mass versus time, for the current system, is included as Figure 2-2.

2.1.3 Costs for Current System

For formulations 1 and 2, a cost function to be minimized was developed (in conjunction with the installation) that combines the “Up-Front Costs” with the “Total of Annual Costs” over the time it takes to reach cleanup for both RDX and TNT, assuming a discount rate of 5%. The components of cost are:

MINIMIZE (CCW + CCB + CCG + FCL + FCE + VCE + VCG + VCS)

where

CCW: Capital costs of new wells
CCB: Capital costs of new recharge basins
CCG: Capital cost of new GAC unit (formulation 2 only)
FCL: Fixed cost of labor
FCE: Fixed costs of electricity (lighting, heating, etc.)
VCE: Variable electrical costs of operating wells
VCG: Variable costs of changing GAC units
VCS: Variable cost of sampling

The specifics of the cost function are provided in the detailed problem formulation (separate document). All costs are in thousands of dollars.

Based on the modeling results, the value of the cost function for the current system (over the 17 years until both RDX and TNT are cleaned up) is 3836.285 (i.e., $3.836 million).

2.2 Formulation 1: Minimize Cost to Cleanup, Current Plant Capacity

2.2.1 Objective Function and Constraints

The objective function is to minimize the cost function over the time until cleanup levels are achieved for both RDX and TNT (see Section 2.1.3), subject to the following constraints:

- The modeling period consists of four 5-year management periods (20 years total) beginning January 2003;

- Modifications to the system may only occur at the beginning of each management period;

- Cleanup, for both RDX and TNT, must be achieved within modeling period (by the end of year 20);

- The total modeled pumping rate, when adjusted for the average amount of uptime, cannot exceed 1300gpm, the current maximum treatment capacity of the plant;

- The extraction system must account for limits imposed by the hydrogeology of the site (limit of 400 gpm or 1000 gpm, depending on location, adjusted for system downtime);

- RDX and TNT concentration levels must not exceed their respective cleanup levels in locations beyond a specified area;

- The total pumping rate and total recharge rate have to be balanced.

The specifics of the cost function are provided in the detailed problem formulation (separate document).

2.2.2 Optimal Solution

A total of 39 simulations were performed by GeoTrans for Formulation 1. The best solution was found in simulation 28, and has the following details:

	Current System	Optimal Solution
RDX Cleanup	8 yrs	6 yrs
TNT Cleanup	17 yrs	6 yrs
Objective Function (Total)	$3,836,285	$2,230,905
Objective Function (Components)		
CCW: Capital costs of new wells	$0	$133,764
CCB: Capital costs of new recharge basins	$0	$19,588
CCG: Capital cost of new GAC unit	$0	$0
FCL: Fixed cost of labor	$2,805,552	$1,263,086
FCE: Fixed costs of electricity	$42,616	$19,186
VCE: Variable electrical costs of operating wells	$251,405	$91,952
VCG: Variable costs of changing GAC units	$16,338	$14,301
VCS: Variable cost of sampling	$720,374	$689,028

Two new wells and one recharge basin are included in the optimal solution. Extraction rates and recharge rates are listed below:

Well or Recharge Basin	New or Existing	Current System (gpm)	Optimal Solution Period 1 (gpm)	Optimal Solution Period 2 (gpm)
EW-1	Existing	128.23	280	350
EW-2	Existing	0	0	0
EW-3	Existing	105.05	0	360
EW-4	Existing	887.24	660	0
NW-1	New		0	100
NW-2	New		230	360
Total Extraction		**1120.52**	**1170**	**1170**
IF1	Existing	232.80	282.33	585
IF2	Existing	405.27	405.27	0
IF3	Existing	482.40	482.40	0
RCH4	New		0	585
Total Injection		**1120.47**	**1170**	**1170**

Locations of wells and recharge basins are presented in Figure 2-3. A chart illustrating objective function value versus simulation number is provided in Figure 2-4. Note that the optimal solution (simulation 28) is only about 10 percent better than the solution found in simulations 2, 3, and 4. A chart illustrating mass remaining after each year is provided in Figure 2-5.

2.2.3 General Approach to Determining the Optimal Solution

It was evident from the cost function that total cost could be reduced substantially by shortening the cleanup horizon (which is also a component of the objective function that can be easily attacked via trial-and-error). The current system had a cleanup time of 8 years for RDX and 17 years for TNT. Therefore, the focus by GeoTrans was to reduce the total cleanup time. The general approach to finding the optimal solution via trial-and-error can be summarized as follows:

<u>Simulations 1-4</u>

Since RDX was largely cleaned up after Period 1, pumping was accelerated within the TNT plume starting in Period 2. By the end of 4 simulations, total cleanup time was reduced to 7 years (6 years for RDX, 7 years for TNT).

<u>Simulations 5-7</u>

The goal of these simulations was to accelerate RDX cleanup to 5 years or less, by adding new recharge basins. TNT cleanup was not a focus of these runs. By the end of simulation 7, RDX cleanup within 5 years was achieved.

Simulations 8-17

Combine the RDX strategy from simulations 5-7 with the TNT strategy from simulations 1-4. By simulation 17, solutions were achieved with RDX cleanup of 5 years and TNT cleanup of 8 years.

Simulations 18-19

Increase pumping within TNT plume in Period 1, with corresponding reduction in pumping beyond TNT plume. By the end of simulation 19, cleanup time was again reduced to 7 years (6 years for RDX, 7 years for TNT).

Simulations 20-22

Add new well locations at various locations within the TNT plume, in attempt to reduce TNT cleanup to 6 years or less. By the end of simulation 22, cleanup time was still 7 years (6 years for RDX, 7 years for TNT).

Simulations 23-28 (***Optimal Solution, Simulation 28***)

In addition to new wells in TNT plume, shift additional pumping from RDX plume (EW-4) to within TNT plume, in attempt to reduce TNT cleanup to 6 years or less. By the end of simulation 28, cleanup time was reduced to 6 years (6 years for RDX, 6 years for TNT). This was the best solution found by GeoTrans. No attempt was made to optimize the individual components of the objective function, because GeoTrans felt that the most significant management variable was cleanup time and variations in other components of the cost function would be minor.

Simulations 29-39

Attempt to find reduced cleanup time by adding recharge basins in center of TNT plume (dilution) and extraction wells at edge of TNT plume. However, this tended to cause unintended spreading of the TNT and/or RDX plume, and no improved solutions were found.

2.3 Formulation 2: Minimize Cost to Cleanup, Increased Plant Capacity Allowed

2.3.1 Objective Function and Constraints

The objective function is to minimize the cost function over the time until cleanup levels are achieved for both RDX and TNT (see Section 2.1.3), subject to the same constraints as Formulation 1, except that treatment plant capacity could be increased in steps of 325 gpm, from the current capacity of 1300 gpm to a maximum capacity of 1950 gpm.

2.3.2 Optimal Solution

A total of 25 simulations were performed by GeoTrans for Formulation 2. The best solution was found in simulation 25, and has the following details:

	Current System	Optimal Solution
RDX Cleanup	8 yrs	4 yrs
TNT Cleanup	17 yrs	4 yrs
Objective Function (Total)	$3,836,285	$2,015,909
Objective Function (Components) CCW: Capital costs of new wells CCB: Capital costs of new recharge basins CCG: Capital cost of new GAC unit FCL: Fixed cost of labor FCE: Fixed costs of electricity VCE: Variable electrical costs of operating wells VCG: Variable costs of changing GAC units VCS: Variable cost of sampling	 $0 $0 $0 $2,805,552 $42,616 $251,405 $16,338 $720,374	 $150,000 $0 $300,000 $882,410 $13,404 $98,329 $13,279 $558,487

Two new wells are included in the optimal solution (no new recharge basins are included). Extraction rates and recharge rates are listed below:

Well or Recharge Basin	New or Existing	Current System (gpm)	Optimal Solution (gpm)
EW-1	Existing	128.23	305
EW-2	Existing	0	0
EW-3	Existing	105.05	360
EW-4	Existing	887.24	774.565
NW-1	New		190.435
NW-2	New		125
Total Extraction		**1120.52**	**1755**
IF1	Existing	232.80	715
IF2	Existing	405.27	520
IF3	Existing	482.40	520
Total Injection		**1120.47**	**1755**

Locations of wells and recharge basins are presented in Figure 2-6. A chart illustrating objective function value versus simulation number is provided in Figure 2-7. Note that the optimal solution (simulation 25) is only about 10 percent better than the solution found in simulation 3. A chart illustrating mass remaining after each year is provided in Figure 2-8.

2.3.3 General Approach to Determining the Optimal Solution

The general approach was to increase pumping according to the increased capacity allowed, in an attempt to lower cleanup time to either 5 or 4 years (since 6 years had been achieved with Formulation 1).

<u>Simulations 1-2</u>

Increase pumping of three existing wells to their full individual capacities (each run had different distribution of recharge). Achieved cleanup time of 7 years (5 years for RDX and 7 years for TNT).

<u>Simulation 3</u>

Additionally add a new well in TNT plume, to reach full capacity of new plant. Achieved cleanup time of 5 years (5 years for RDX and 5 years for TNT).

<u>Simulation 4</u>

Same as Simulation 3, but attempt to speed TNT cleanup with new recharge basin at southern edge of TNT plume. Achieved cleanup time of 6 years (6 years for RDX and 5 years for TNT).

<u>Simulations 5-6</u>

Attempt to get cleanup in 5 years with only one new GAC unit (i.e., capacity only increased to 1625 gpm rather than 1950 gpm). Achieved cleanup time of 6 years (6 years for RDX and 6 years for TNT).

<u>Simulations 7-23</u>

Starting from Simulation 2, try various combinations of pumping/recharge, including addition of a second new well in TNT plume, in attempt to reduce cleanup time to 4 years. Achieved cleanup time of 5 years (4 years for RDX and 5 years for TNT).

<u>Simulation 24</u>

Add a new recharge basin closer to TNT plume to try to reduce TNT cleanup to 4 years. Achieved cleanup time of 5 years (5 years for RDX and 5 years for TNT).

<u>Simulation 25 (***Optimal Solution, Simulation 25***)</u>

Noticed that Simulation 20 was 1 gpm below capacity. Added the 1 gpm to NW-1 inside the TNT plume. Achieved cleanup time of 4 years (4 years for RDX and 4 years for TNT). Decided going after cleanup time of 3 years was not worth the effort (could not be accomplished). No attempt was made to optimize the individual components of the objective function, because GeoTrans felt that the most significant management variable was cleanup time and variations in other components of the cost function would be minor.

2.4 Formulation 3: Minimize Combined Mass of RDX and TNT Remaining After 20 Years

2.4.1 Objective Function and Constraints

The objective function is to minimize the total mass remaining (RDX plus TNT) in layer 1 at the end of 20 years. The constraints are the same as Formulation 1, except the maximum number of new wells cannot exceed 4, and the maximum number of new recharge basins cannot exceed 3.

2.4.2 Optimal Solution

A total of 24 simulations were performed by GeoTrans for Formulation 3. The best solution was found in simulation 9, and has the following details:

	Current System	Optimal Solution
Total Mass Remaining After 20 Years	RDX: 0.204 kg TNT: 1.561 kg Total: 1.765 kg	RDX: 0.231 kg TNT: 0.145 kg Total: 0.376 kg
RDX Cleanup	8 yrs	7 yrs
TNT Cleanup	17 yrs	7 yrs

Two new wells are included in the optimal solution (no new recharge basins are included). Extraction rates and recharge rates are listed below:

Well or Recharge Basin	New or Existing	Current System (gpm)	Optimal Solution Period 1 (gpm)	Optimal Solution Period 2 (gpm)	Optimal Solution Period 3 (gpm)	Optimal Solution Period 4 (gpm)
EW-1	Existing	128.23	110	0	0	0
EW-2	Existing	0	0	0	0	0
EW-3	Existing	105.05	0	210	210	210
EW-4	Existing	887.24	600	600	600	600
NW-1	New		360	0	0	0
NW-2	New		100	360	360	360
Total Extraction		**1120.52**	**1170**	**1170**	**1170**	**1170**
IF1	Existing	232.80	282.33	282.33	282.33	282.33
IF2	Existing	405.27	405.27	405.27	405.27	405.27
IF3	Existing	482.40	482.40	482.40	482.40	482.40
Total Injection		**1120.47**	**1170**	**1170**	**1170**	**1170**

Locations of wells and recharge basins are presented in Figure 2-9. A chart illustrating objective function value versus simulation number is provided in Figure 2-10. A chart illustrating mass remaining after each year is provided in Figure 2-11.

On Figure 2-10, two different "optimal solutions" are actually indicated. Simulation 23 actually has a slightly better objective function value than Simulation 9 (0.332 kg versus 0.376 kg), but was considered sub-optimal by GeoTrans because it required 4 new wells (as opposed to two), and two of the locations are in the bottom right corner of the modeled area and do not make sense with respect to future implementation..

2.4.3 General Approach to Determining the Optimal Solution

Simulation 1

Start with the optimal solution for Formulation 1 in stress period 1, keep same pumping for the entire 20 year simulation. That achieves total mass remaining of 0.645 kg.

Simulations 2-5

Try different combinations of pumping to lower mass remaining. Achieved total mass remaining of 0.465 kg.

Simulations 6-7

Add several new recharge basins at edge of RDX plume, makes objective function worse.

Simulation 8

Similar to Simulations 2-5, but add 2 extraction wells within RDX plume. Achieved total mass remaining of 0.466 kg.

Simulation 9 (***Optimal Solution, Simulation 9***)

Similar to Simulation 4, but slightly different combination of pumping rates. Achieved total mass remaining of 0.376 kg.

Simulations 10-16

Attempt various combinations of new wells and/or recharge basins, and varying combinations of rates. No improvement achieved.

Simulations 17-24

Add 2 new wells in lower right corner of active area where mass is determined. It was noted that some mass was accumulating there in the model, apparently moving up from layers 2 and 3. All of these solutions represented mathematical improvements (0.332 kg to 0.371 kg), but GeoTrans considers these sub-optimal because they include two extra wells, and do not make sense with respect to potential implementation.

3.0 COMPUTATIONAL PERFORMANCE

Preliminary Items

Development of the three formulations, and development of the FORTRAN postprocessing code, were considered separate tasks from the actual solution of the problems, and are not described herein (since each of the other optimization groups started after the formulations and FORTRAN postprocessor were provided to them). However, those costs should be accounted for when evaluating the cost of the overall optimization process.

Solution of the Three Formulations

GeoTrans worked within a pre-specified budget of approximately $32,000 for developing optimal solutions for each of the three formulations. Development of the SURFER/PowerPoint animation technique accounted for approximately $2000 of this $32,000, and the remaining $30,000 went towards solving the problems.

Each flow and transport simulation required approximately 10 minutes on a Pentium III, 500 MHZ computer. Running the FORTRAN code required less than one minute. Creating the SURFER grid files, contour maps, and subsequent animations required approximately 1 hour per simulation. The remaining time was spent reviewing the results, deciding what modifications to make to pumping/recharge, and modifying the well package for the subsequent run.

GeoTrans ultimately made 88 simulations, as follows:

formulation 1: 39 simulations
formulation 2: 25 simulations
formulation 3: 24 simulations

Based on a cost of approximately $30,000 allocated towards solving the problems, this represents a cost of approximately $340 per simulation. That represents approximately 3.5 hours for project level staff (Yan Zhang) and approximately 1 hour for senior level staff (Rob Greenwald) for each simulation, associated with setting up, running, and postprocessing the simulation, and determining what to implement for the subsequent simulation.

As noted in Section 2, solutions nearly as good as the optimal solutions were generally found within just a few simulations. For example, for Formulation 1 the optimal simulation (Simulation 28) was only about 10% better than Simulations 2-4, and for Formulation 2 the optimal simulation (Simulation 25) was only about 10% better than Simulations 3. The major difference between these early simulations, versus the optimal simulation, was achieving a cleanup time one year lower. This represents a somewhat artificial “step function” that in real world terms is probably not significant (i.e., cleanup in 5.9999 years results in costs incurred for six years in the objective function, whereas cleanup in 6.0001 years results in costs incurred for 7 years in the objective function).

GeoTrans would not have performed as many trial-and-error simulations if work was not being performed within the context of this project. GeoTrans would have also recommended revising Formulation #3 prior to performing the simulations, if not performed in the context of this project.

4.0 SITE SPECIFIC INFORMATION

The following observations pertain to aspects of this particular site and/or problem statement that GeoTrans feels may not be true of all sites where transport optimization may be attempted.

One Model Layer

The objective function and constraints only applied to one model layer (layer 1). This simplified the problem significantly, and made the trial-and-error process much more simple to perform. Firstly, the graphics and animation procedures employed as part of the trial-and-error approach were easier to generate and evaluate because they were limited to one model layer. Secondly, there were no multi-aquifer wells, which simplified the logistics of specifying well rates. Thirdly, the number of possible alternatives to consider was limited because all extraction and recharge was specified in only one model layer.

Limited Management Periods Required For Formulations 1 and 2

Although the formulation allowed up to four 5-year management period, the solutions for Formulations 1 and 2 quickly indicated cleanup within the first two management periods. This limited the potential number of trial-and-error alternatives to consider.

No continuing Source in the Model

The sources of contamination were assumed to no longer exist in the model. This allowed solution of problems based on achieving cleanup levels (Formulations 1 and 2). Formulations based on cleanup time may not be feasible when continuing sources above cleanup levels are assumed in the model.

Formulations Fixed at the Beginning of the Simulation Period

For this project, the three formulations had to be "locked in" prior to the simulation period. This is not typical for optimization projects. In most cases it would be beneficial to start with one formulation, and based on those results develop different formulations. For instance, after determining in Formulations 1 and 2 that cleanup could be obtained in less than 10 years, the objective function for Formulation 3 (minimize mass remaining after 20 years) seems inappropriate, since pumping for a 20-year time horizon seems unnecessary.

5.0 SENSITIVITY ANALYSIS (IF PERFORMED)

Sensitivity analysis, as it relates to optimization, refers to the extent to which the optimal solution changes with respect to specific changes in the optimization formulation. GeoTrans did not attempt to solve any problems other than the three that were specified. Therefore, sensitivity analysis was not performed. The "trial-and-error" methodology is poorly suited for performing that type of sensitivity analysis, because the solution method is not automated.

6.0 SUMMARY AND LESSONS LEARNED

The trial-and-error approach yielded improved solutions relative to the current system. All three optimal solutions represent reductions in cleanup time (4-7 years) relative to the simulation of the current system (17 years). However, comparison to the current system is somewhat unfair, since the current system was not designed based on any of these three formulations, nor was it based on the specific flow/transport model used for this project (i.e., the model had been updated subsequent to system installation).

More significantly, the trial-and-error approach was rigorously applied, and therefore represents a good baseline for evaluating the benefits of mathematical optimization performed by the other two modeling groups.

The trial-and-error simulations were performed at a cost of approximately $340 per simulation (associated with setting up, running, postprocessing the simulation, and determining what to implement for the subsequent simulation). The trial-and-error approach was limited to only dozens of simulations per formulation, and therefore could only explore a small portion of the potential number of pumping/recharge alternatives. This limitation of trial-and-error may have been even more severe if more than one model layer was involved in the objective function and constraints, and/or solutions to Formulations 1 and 2 were not limited to only one or two of the four potential management periods.

Solutions nearly as good as the optimal solutions were generally found within just a few simulations. For example, for Formulation 1 the optimal simulation (Simulation 28) was only about 10% better than Simulations 2-4, and for Formulation 2 the optimal simulation (Simulation 25) was only about 10% better than Simulations 3. The major difference between these early simulations, versus the optimal simulation, was achieving a cleanup time one year lower. This represents a somewhat artificial “step function” that in real world terms is probably not significant. Also, GeoTrans would not have performed as many trial-and-error simulations if work was not being performed within the context of this project (i.e., total simulations cost of $30,000 would have been lower).

GeoTrans does not believe Formulation 3 is useful to the installation. Pumping for 20 years is unlikely, based on results of the other formulations (which showed cleanup in 6 years or less). Also, most of the mass in model layer 1 is gone after 20 years in all simulations (most simulations had mass of 0.3 to 0.5 kg remaining after 20 years), and it is unclear that there is any tangible difference between any of these results from a management perspective. It would have been more useful to revise Formulation 3 to something like “minimize timeframe to reach a specified amount of remaining mass”, rather than fixing the time horizon to 20 years.

Figure 2-1 System Configuration with Pre-Pumping RDX and TNT Plumes

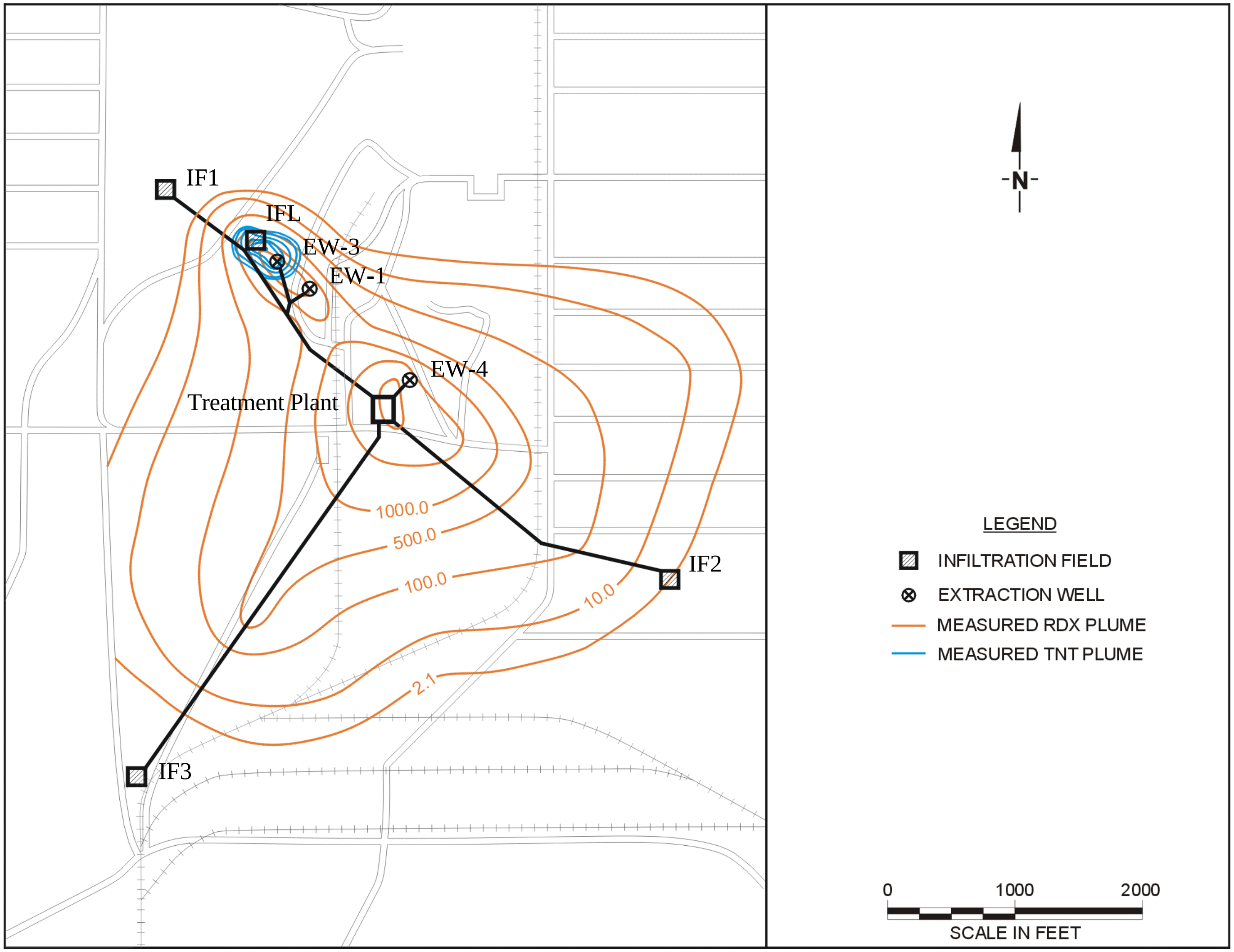

Figure 2-2 Plume Mass versus Time, Current System

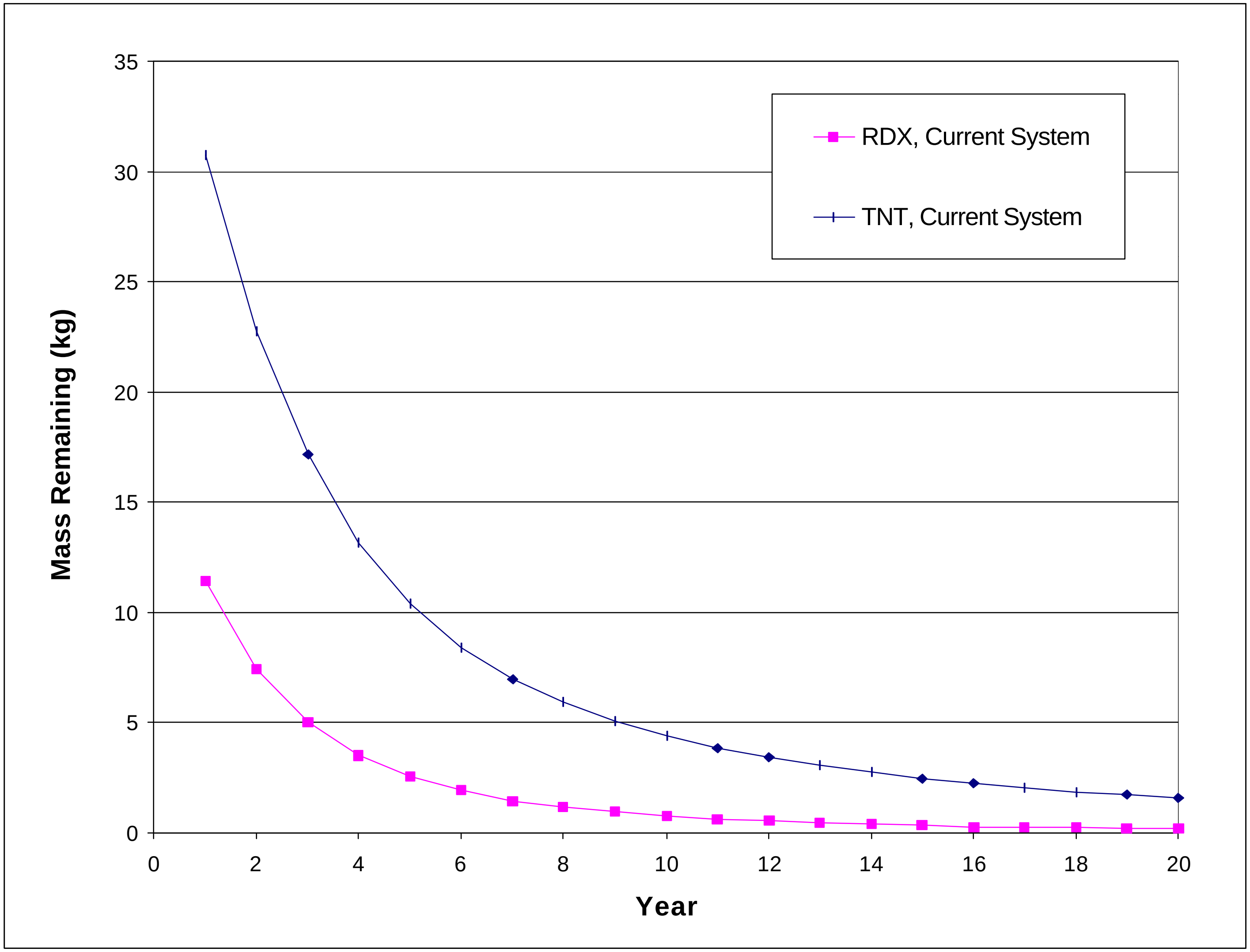

Figure 2-3 Locations of Wells and Recharge Basins, Formulation #1

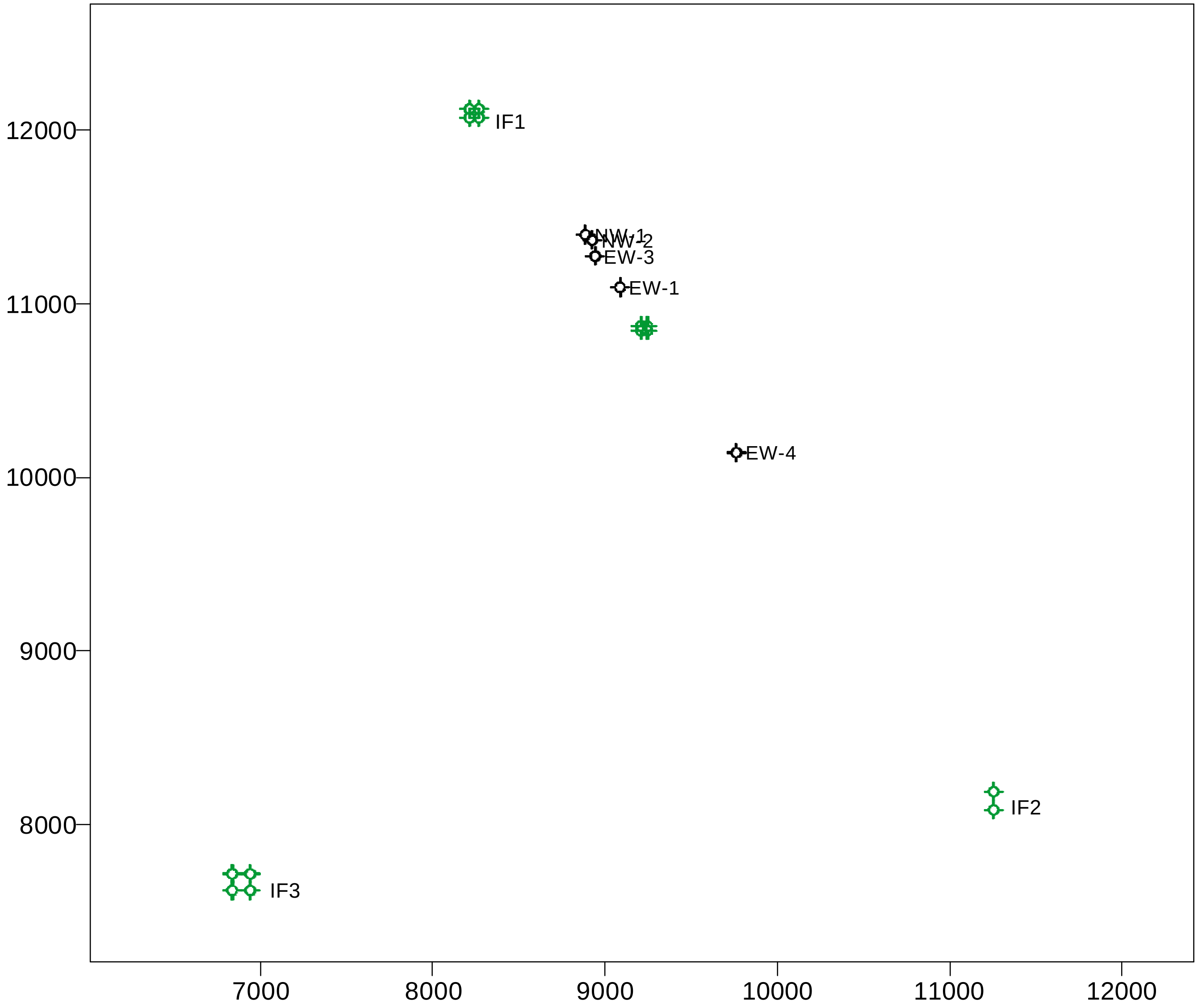

Figure 2-4 Objective Function Value, Formulation #1

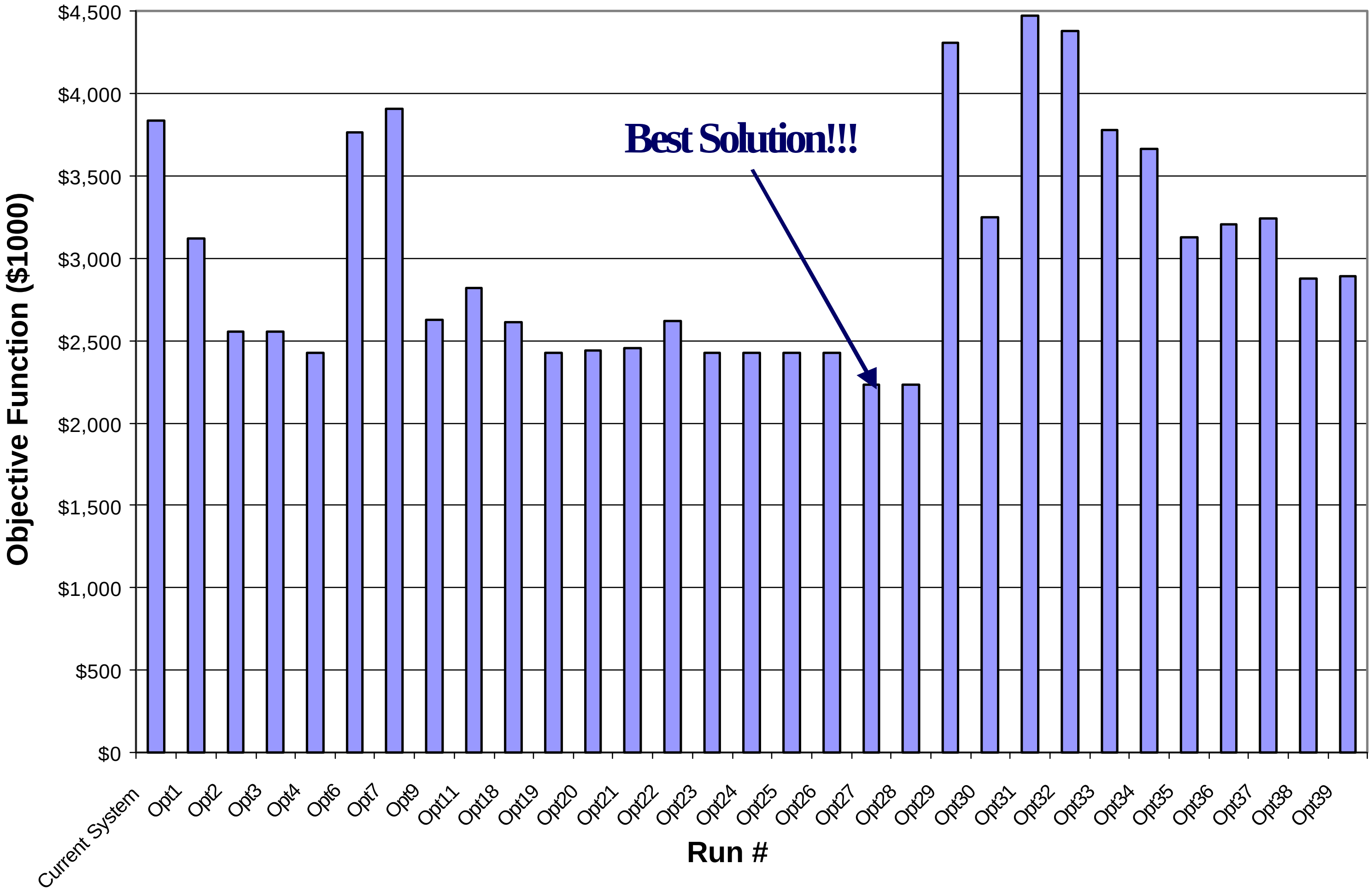

Figure 2-5   Mass Remaining in Layer 1, Current System vs. Formulation #1

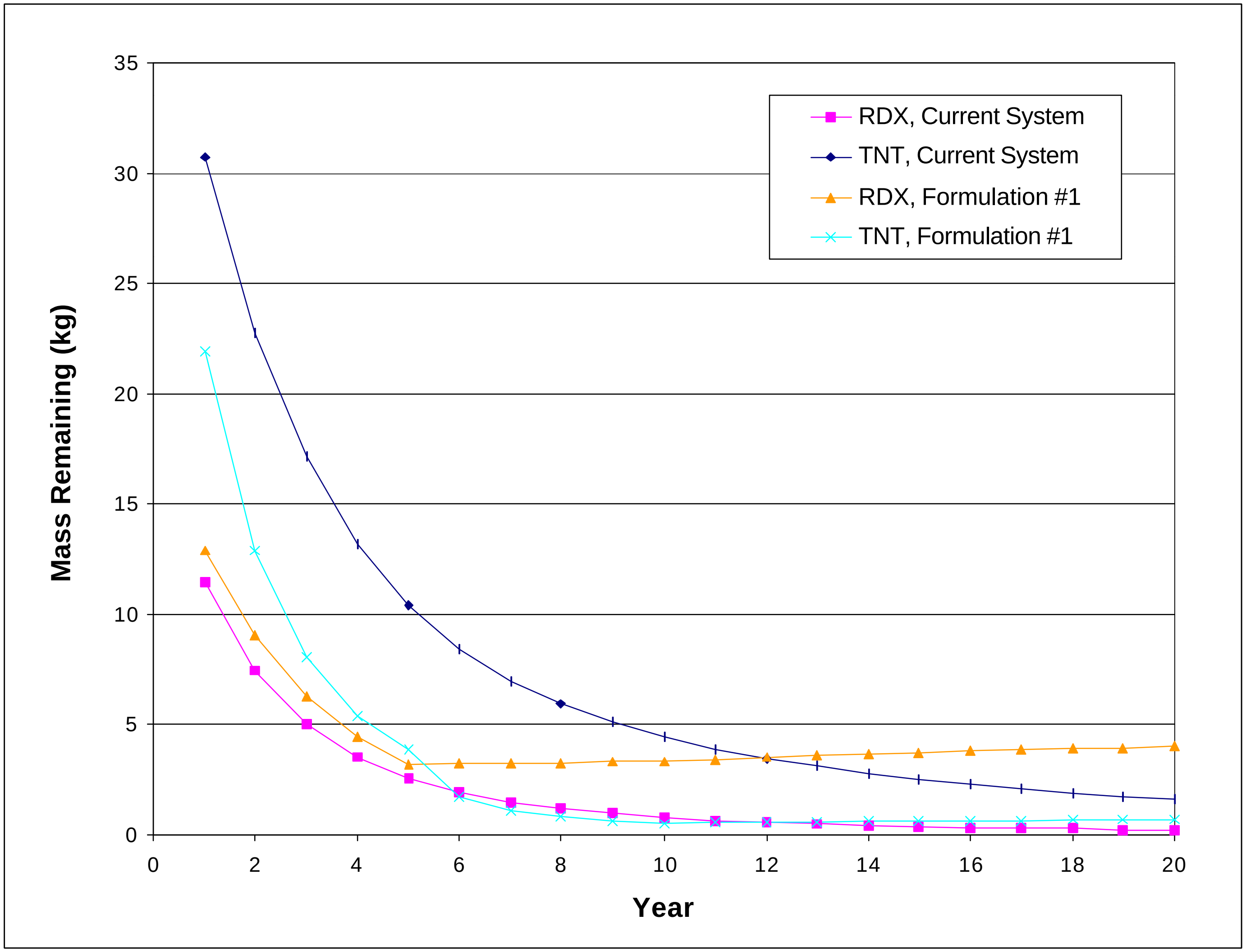

Figure 2-6 Location of Wells and Recharge Basins, Formulation #2

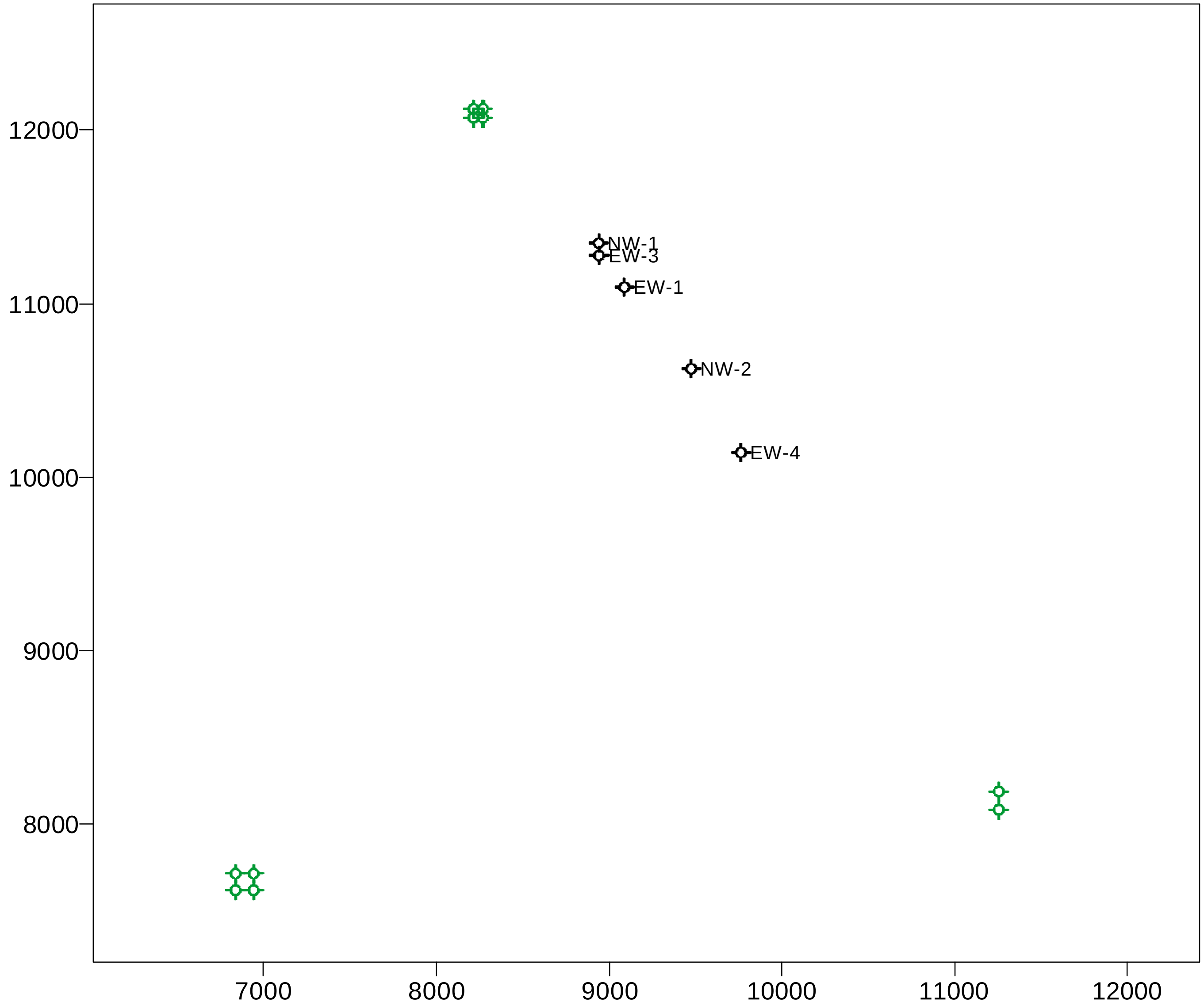

Figure 2-7 Objective Function Value, Formulation #2

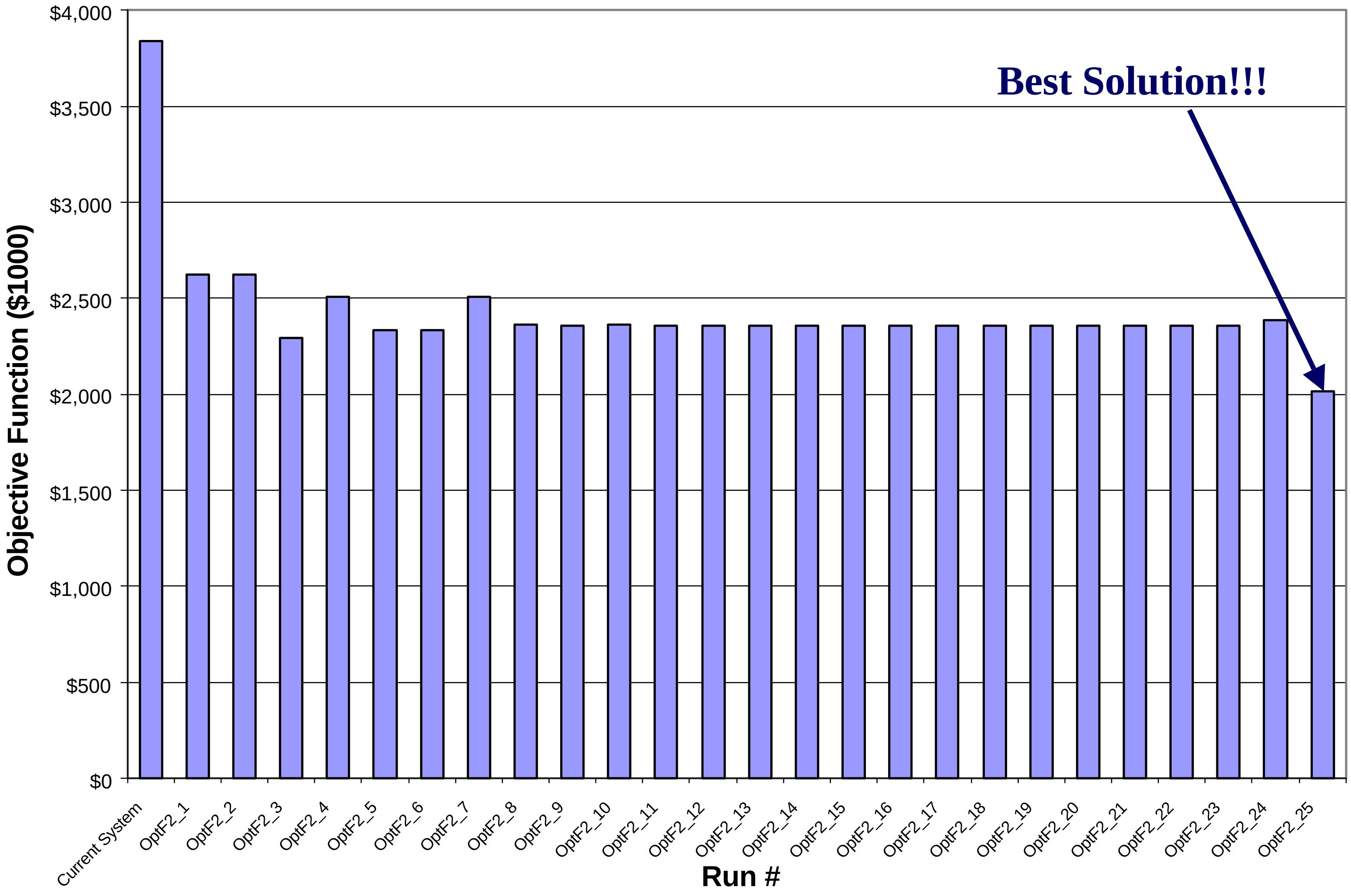

Figure 2-8 Mass Remaining in Layer 1, Current System vs. Formulation #2

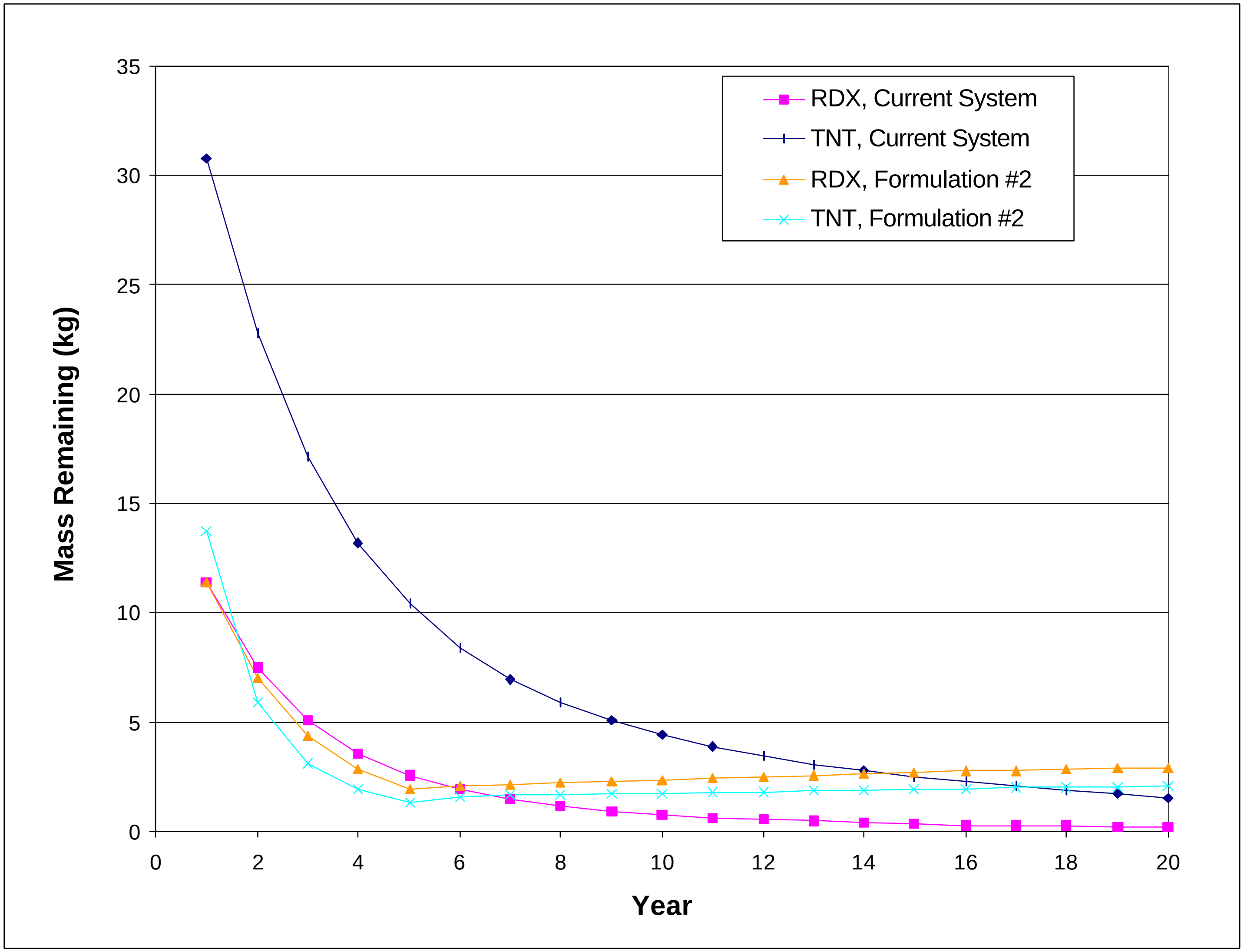

Figure 2-9   Locations of Wells and Recharge Basins, Formulation #3

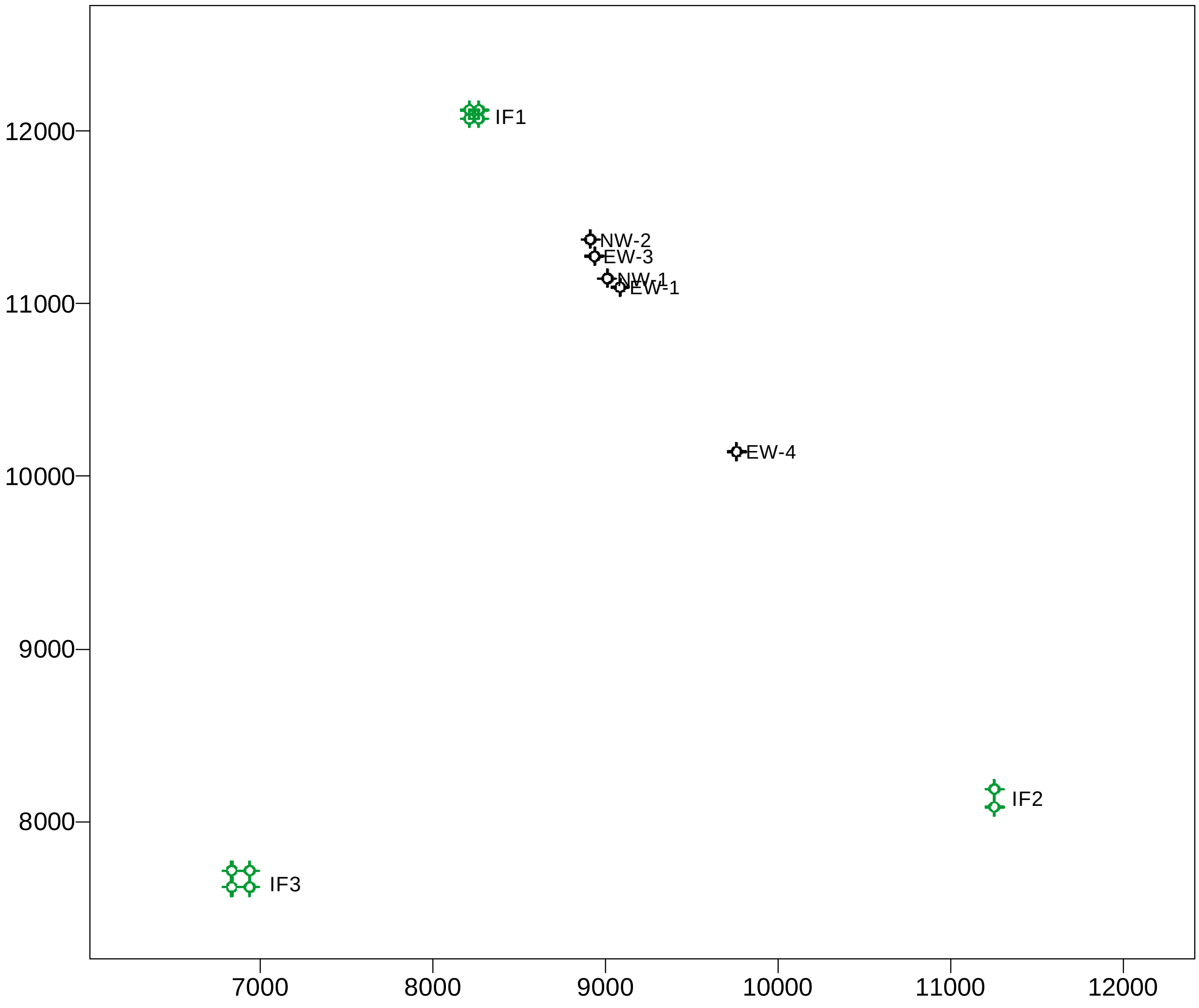

Figure 2-10   Objective Function Value, Formulation #3

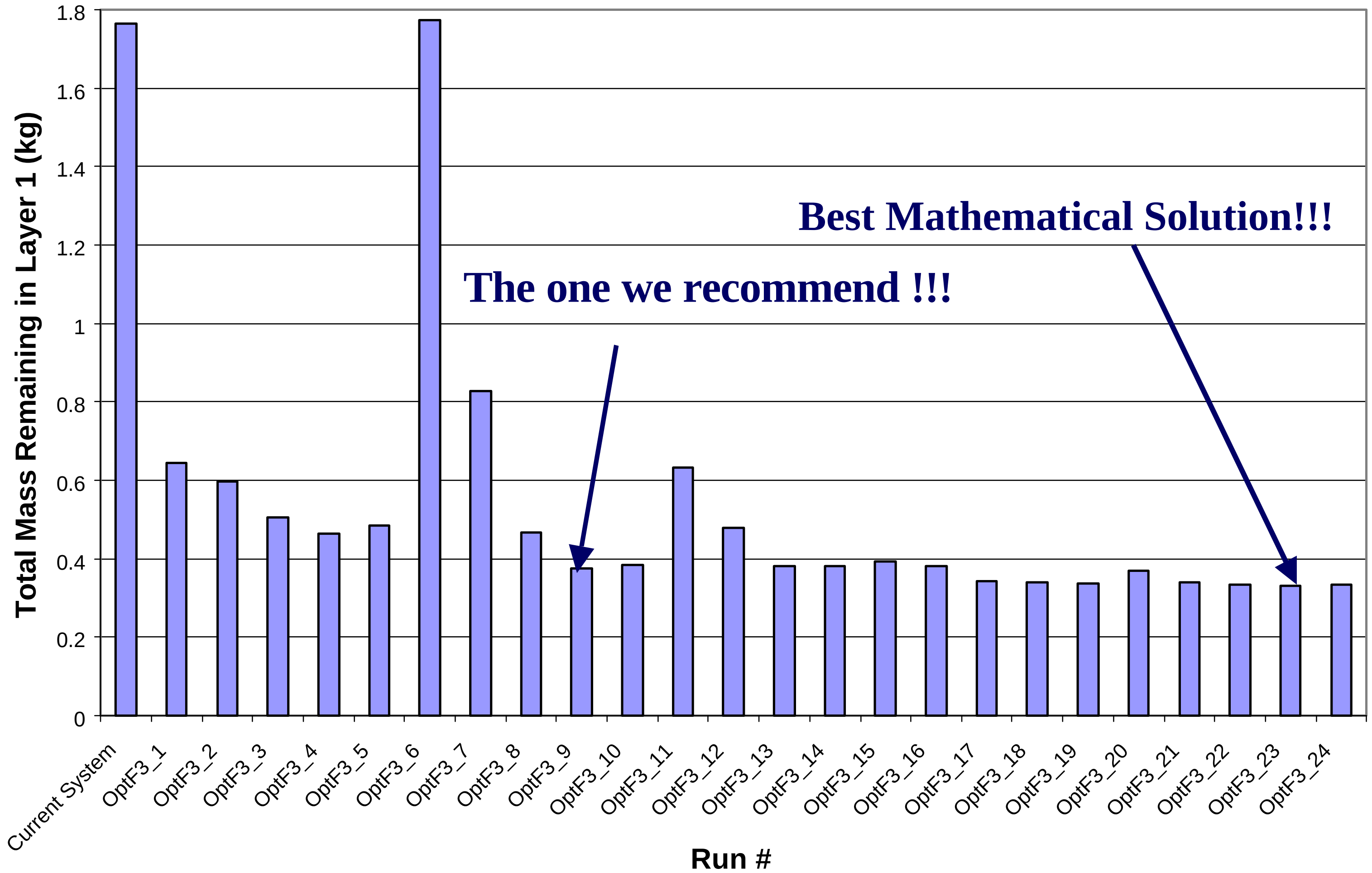

Figure 2-11 Mass Remaining in Layer 1, Current System vs. Formulation #3