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Modeling the Contamination of an Aquifer from a Highway Salt Storage Facility

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ABSTRACT

Groundwater contamination by salt is not exclusively a coastal environmental issue related to seawater intrusion. Salt, either applied directly, or in a mixture with sand, has long been used to de-ice roadways in northern portions of the United States during winter months. Operations involving salt storage, mixing, and loading are done at facilities throughout these states. Commonly, portions of these facilities remain uncovered and such exposure to the environment can result in the transport of salt into surface water and groundwater.

Operation of a salt handling facility in Indiana resulted in the contamination of the aquifer below the facility with high levels of sodium and chloride. Many facility operations occurred without shelter from rain and snow. The main receptor near this facility is a municipal water supply wellfield. The wellfield is located approximately 1,700 feet north of the site (refer to Fig. 1). Groundwater monitoring has confirmed the movement of salt at the base of the aquifer (approximately 120 feet below ground surface) toward the wellfield. Groundwater modeling was done at this site to aid in the design of remedial alternatives.

Initial model calibration involved the use of a single-phase flow model. The flow model was calibrated to steady-state and transient conditions. A 2-phase, sharp-interface model was then used to simulate the historical migration over a 30 year period of a dense salt plume at the base of the aquifer beneath the facility. Concurrently, a solute transport model was linked to the transient simulation. The solute transport model was used to simulate the dispersive movement of salt from the dense phase plume into the surrounding aquifer.

Model results compared favorably with field-measured salt concentrations at monitoring wells in the vicinity of the facility and wellfield. The models were then used to screen remedial alternatives involving groundwater pumping and surface flushing. The screening process involved estimation of remedial well concentrations and clean-up times.

INTRODUCTION

Salt storage, mixing, and loading operations at the highway maintenance facility have occurred over a 30 year time frame. Many of these operations occurred without shelter. Exposure to precipitation resulted in the transport of salt into the groundwater. The risk of contaminating a nearby municipal wellfield (1,700 feet north) resulted in the completion of this study.

The remedial goal of the project was to prevent sodium (Na) levels at the wellfield from exceeding a concentration of 20 mg/L above background levels. Background levels of Na at this site, based on readings in non-impacted municipal wells, was estimated to be between 4.0 and 5.5 mg/L. Assuming a 1:1 equivalent ratio of Na to chloride (Cl), the 20 mg/L Na above background translates to 51 mg/L NaCl. This value was adopted for modeling purposes as a reasonable approximation of the 20 mg/L Na target.

ROLE OF NUMERICAL MODELS

Numerical groundwater models were developed and applied to evaluate the effectiveness of alternative remedial pumping scenarios. Three types of groundwater models were used. All three models were fully 3-dimensional and linked by a shared model database. The three model types are:

- Groundwater flow model (single phase) - incorporates the physical characteristics of the aquifer and computes the distribution of groundwater flow and head in response to pumping, recharge and other boundary conditions.
- 2-Phase flow model - an extension of the single phase flow model which incorporates two interacting fluids of different density, i.e., saltwater and (relatively) fresh water.
- Solute transport model - computes the advection and dispersion of dissolved solutes in groundwater using flow fields computed by the flow models; does not include any fluid density effects.

APPROACH

The models were used first to simulate the development of a salt water plume originating beneath the facility. The basic steps used for this study were as follows:

- The single phase flow model was calibrated in steady-state mode to measured fresh water levels near the site, and in transient mode to pumping tests conducted at the municipal wellfield. Combinations of recharge and hydraulic conductivity were determined which provided good calibration.
- The 2-phase model was run to simulate the growth and migration of a lens of dense (relative to fresh water) salt water at the bottom of the aquifer beneath the site. The simulation began at the start of salt storage on the site (1968) continuing to the end of 1997.
- The solute transport model was run to simulate the dispersion of dissolved salt from the deep salt water lens into the surrounding fresh groundwater, as well as advection and further dispersion of the dissolved salt with the flowing groundwater. As such, the primary source of dissolved salt was specified at the surface of the dense salt water lens computed by the 2-phase model. The lens (or salt source) configuration was updated at regular intervals during the solute transport simulation based on the 2-

phase flow model results. The fresh water flow field input to the transport model was also updated at regular intervals from the 2-phase flow model simulation.

- The distribution of salt concentrations in the groundwater computed with the solute transport model was combined with the simulated dense salt water lens, assuming a uniform concentration of 11,000 mg/L within the lens, to create a composite representation of the salt plume emanating from the INDOT site.
- The single phase flow and solute transport models were used for screening different remedial alternatives. The use of these two models was computationally more efficient than incorporating the 2-phse flow model in the simulation of each screening alternative. For the selected remedial alternative, the 2-phase model was used to confirm the results of the screening level simulations.

MODEL CODES

The modeling software utilized in this study included DYNFLOW (single phase groundwater flow), DYNSWIM (2-phase groundwater flow), and DYNTRACK (solute transport). The results were developed and displayed using the associated DYNPLOT code. The DYN codes run on Windows NT and UNIX platforms.

DYNFLOW

The groundwater flow computer code used in this study is the fully three-dimensional, finite element groundwater flow model, DYNFLOW. This model has been developed over the past 20 years by CDM engineering staff, and is in general use for large scale basin modeling projects and site specific remedial design investigations. It has been applied to over 150 modeling studies in the United States and internationally.

DYNFLOW uses a grid built with a large number of tetrahedral elements. These elements are triangular in plan view, and give a wide flexibility in grid variation over the area of study. An identical grid is used for each level of the model, but the thickness of each model layer (the vertical distance between levels in the model) can vary at each point in the grid. In addition, 2-dimensional elements can be inserted into the basic 3-dimensional grid to simulate thin features such as faults. One-dimensional elements can be used to simulate the performance of wells which are perforated in several model layers.

DYNFLOW accepts various types of boundary conditions on the groundwater flow system including:

- Specified head boundaries (where the piezometric head is known, such as at rivers, lakes, or other points of known head)
- Specified flux boundaries (such as rainfall infiltration, well pumpage, and no-flow "streamline" boundaries)
- Rising water boundaries; these are hybrid boundaries (specified head or specified flux boundary) depending on the system status at any given time.

- Head-dependent flux (3rd type) boundaries including "River" and "General Head" boundary conditions.

The DYNFLOW code has been reviewed and tested by the International Groundwater Modeling Center (IGWMC) [van der Heijde, 1985]. The code has been extensively tested and documented by CDM.

DYNSWIM

DYNSWIM is a three dimensional saltwater intrusion code. Developed from DYNFLOW, it uses the same finite element solution techniques, has all the user interaction features of that code. DYNSWIM is designed to simulate the movement of the interface between fluids of differing densities in a ground water system. It computes the locations of the interface between the two fluids, as well as the pressures and fluxes within each fluid system. The code can simulate the intrusion of multiple seawater lenses into a multi-layer aquifer system. DYNSWIM has been used in coastal modeling studies for Hawaii and the Atlantic and Gulf coasts of the U.S.

DYNTRACK

The solute transport code used in this study is DYNTRACK. DYNTRACK uses the random-walk technique to solve the advection-dispersion equation. DYNTRACK has been developed over the past 18 years by CDM engineering staff.

DYNTRACK uses a Langrangian approach to approximate the solution of the partial differential equation of transport. This process uses a random walk method to track a statistically significant number of particles, wherein each particle is advected with the mean velocity within a grid element and then randomly dispersed according to specified dispersion parameters.

In DYNTRACK, a solute source can be represented as an instantaneous input of solute mass (represented by a fixed number of particles), as a continuous source on which particles are input at a constant rate, or as a specified concentration at a node. The concentration within a particular zone of interest is represented by the total number of particles that are present within the zone multiplied by their associated solute mass, divided by the volume of water within the zone.

DYNTRACK has also been reviewed and tested by the IGWMC [van der Heijde, 1985].

MODEL CALIBRATION

A number of trial simulations were made using the single phase groundwater flow model (DYNFLOW) to determine combinations of hydraulic conductivity and recharge which result in reasonable agreement between simulated and measured water levels. This included steady-state simulations of a typical operating condition and transient simulations of pumping tests conducted at the municipal wellfield.

Steady-State Calibration

The steady-state calibration target was October 1995. A comprehensive set of water levels was available for this time period. For monitoring wells with measured salt concentrations greater than approximately 400 mg/L, equivalent fresh water heads were used for the steady-state calibration.

The steady-state calibration process indicated that the model did not require a unique solution with respect to combinations of horizontal hydraulic conductivity and recharge. Table 1 shows the combinations of horizontal hydraulic conductivity and recharge that yielded acceptable calibration results. The combination of 80 feet/day and 11.4 inches/year was used as the base case property set.

Horizontal Hydraulic Conductivity (feet/day)	**Recharge (inches/year)**
60	9.9
80	11.4
100	12.8

Table 1: Combination of Horizontal Hydraulic Conductivity and Recharge Determined from Steady-State Calibration

Transient Calibration

The flow model was also calibrated in transient mode. Transient calibration involved the simulation of pumping tests conducted at two of the municipal wells. The two pumping tests were conducted in November 1992 and involved pumping the subject well at between 550 and 600 gallons per minute (gpm) for 72 hours. Simulated drawdown was compared to measured drawdown at nearby wells.

The simulated pumping test results were found to be sensitive to the specified vertical hydraulic conductivity of the primary aquifer materials. This sensitivity is caused because the pumping wells are screened over the bottom 30 feet (approximately) of the aquifer. Therefore, because these wells are not fully penetrating, the downward component of groundwater flow towards the well screen is significant.

The transient simulation results were less sensitive to the horizontal hydraulic conductivity values specified. Similar computed drawdowns result using horizontal hydraulic conductivity values ranging from 60 to 100 feet/day (Table 1). The simulation results were also not very sensitive to the specific yield value assigned because the pumping wells are screened at the bottom of the aquifer, at some distance from the water table. Changing the specific yield value from 0.25 to 0.15 resulted in changes in simulated drawdown of less than 0.1 foot.

HISTORICAL PLUME DEVELOPMENT

The 2-phase flow model (DYNSWIM) and the solute transport model (DYNTRACK) were used in a coupled mode to simulate the development and migration of the salt plume. First, the 2-phase flow model was used to simulate the growth and migration of a dense salt water lens at the bottom of the aquifer (approximately 120 feet below ground surface). The solute transport model was then run to simulate the dispersion and advection of dissolved salt in the groundwater with the dense lens acting as a source of dissolved salt.

The DYNSWIM model was run in transient mode for the period from 1968 through 1997. The base case hydraulic properties and recharge rate, as described previously, were assigned. The specific yield value of 0.25 specified for the outwash functions as an effective porosity for salt water lens migration. The effective porosity value of 0.25 was selected based on the results of the solute transport part of the simulation.

The salt water density in this simulation was assigned to be 1.008 times (or 0.8 percent greater than) the fresh water density. This was selected to be representative of water with a salt concentration in the range of approximately 8,000 mg/L to 14,000 mg/L, with an average of about 11,000 mg/L. This value is typical of salt concentrations measured near the bottom of the aquifer beneath the facility and downgradient for a distance of approximately 700 feet. The migration of salt in the groundwater at lower concentrations beyond the limits of the core plume was simulated with the solute transport model as described subsequently.

The entire area of the site together with a surface water outfall along a highway ditch were simulated as potential sources of salt to the aquifer. During the simulation, the municipal well pumping rates were varied as estimated from pumping records.

Fig. 2 shows the extent of the simulated dense salt water lens at the end of 1997. Also shown are measured salt concentrations at deep monitoring wells taken March, 1998. The extent of the simulated dense salt water lens (concentration greater than approximately 8,000 mg/L) is reasonably consistent with the measured data. The contours in Fig. 2 represent the simulated thickness of the lens. The simulated lens is typically 30 to 38 feet thick with an average of just under 34 feet. This is reasonably consistent with the vertical distribution of measured salt concentrations at the TW-2/MW-94 monitoring well cluster, where the concentration exceeds 8,000 mg/L over approximately the bottom 25 feet of the aquifer. It is also consistent with the depth at which the measured conductance is greater than approximately 50% the maximum value in available salinity profiles

The solute transport model (DYNTRACK) was run for the same time period as the DYNSWIM historical simulation, 1968 through 1997. Simulated flow fields from the DYNSWIM simulation were read into the DYNTRACK model for corresponding times during the simulation. Only the fresh water portion of the DYNSWIM model was transferred to DYNTRACK; the solute transport model did not simulate transport within the dense salt water lens. Thus, the bottom of the DYNTRACK model was set at the simulated interface between the dense salt water lens and (relatively) fresh groundwater, and was adjusted during the course of the simulation as the lens expanded.

The primary source of salt in the DYNTRACK simulation was dispersion at the salt water lens interface. This was represented by assigning a specified, fixed concentration value of 11,000 mg/L at the simulated salt water interface. Salt mass which was advected or dispersed away from the interface into the surrounding groundwater was automatically replenished to maintain the specified concentration at the interface. In this way a continuous source of salt to the groundwater surrounding the simulated dense saltwater lens was created. Shallow groundwater under the facility and the surface water outfall were simulated as secondary sources of salt in the dispersed transport model.

Fig. 3 shows the simulated development of the deep salt plume for the years 1976, 1988, and 1997. It can be seen that by 1976 there was little simulated salt migration to the north. This period pre-dates the operation of municipal wells on the eastern edge of the wellfield. By 1988, the simulation indicates salt migration to the north from the facility, towards the wellfield. This migration is due to the fact that by 1988, all of existing pumping locations were in operation.

At the end of 1997, the maximum simulated concentration (above background) in water pumped from the municipals wells was 60 mg/L. For comparison, the maximum average 1997 observed concentration at the wellfield was 52 mg/L. Based on these data, the actual impact of the salt plume at the municipal wells does not exceed the simulated impacts.

Fig. 4 shows the simulated salt concentration distribution near the bottom of the aquifer at the end of 1997. Measured March 1998 concentrations at deep monitoring wells are also shown in Fig. 4. The simulated concentration distribution is reasonably consistent with the field measured data. The simulated salt concentration distribution is shown in a north-south cross section through the site, with measured concentrations at nearby wells, in Fig. 5.

EVALUATION OF REMEDIAL ALTERNATIVES

Using the model simulation as a guide, various remedial alternatives were established. Each of these alternatives was simulated in the model to assess its effectiveness. Simulations of 14 remedial alternatives involving pumping between two and four remedial wells at individual well pumping rates between 50 and 400 gpm were conducted. Based on simulation results, the selected alternative involved pumping four remedial wells at 100 gpm each. Two of the new wells were located on-site and two were located between the site and the municipal wellfield.

The groundwater flow simulation was run with DYNFLOW in a transient mode for a five year period. In addition to the proposed remedial pumping, municipal pumping was included in the simulation and increased at a rate of 1.63 percent per year. Simulated municipal pumping also included a seasonal weighting factor as determined from historical pumping records. To simulate the enhanced soil flushing, a total of 30 feet of recharge was applied over the assumed soil flushing area during the first 1.5 years of the remedial simulation. Enhanced recharge was not simulated during the winter months.

For each computed remedial flow field, the solute transport model (DYNTRACK) was run for the same 5 year period to simulate the migration and transport of dissolved salt. Continuing sources of salt to the groundwater table from the unsaturated soil onsite were included. The simulated rate of salt removal from the aquifer and concentration at municipal wellfield wells was recorded at monthly intervals for each remedial simulation. These were the primary basis for comparing remedial alternatives.

A set of 10 sensitivity simulations was made to test the effectiveness of the remedial scheme for a range of model parameters and conditions. These included hydraulic conductivity, recharge, effective porosity, and continuing salt source assumptions. One of the sensitivity simulations involved running the 2-phase model (DYNSWIM) and the solute transport model (DYNTRACK) together. The simulation involved linking the two models to run the transient simulation through the 5 year remedial simulation.

The groundwater flow field simulated for the selected alternative is shown in Fig. 6 with vectors indicating the simulated flow direction and velocity near the base of the aquifer. These vectors indicate that the salt contaminated groundwater south of the northern-most remedial wells will predominantly flow to the proposed remedial wells, rather than to the municipal wells.

The graphs in Fig. 7 show the simulated rate of aquifer cleanup over time, indicated by the percent of the total simulated salt input removed at the extraction wells. This salt mass includes the starting salt mass plus the mass added at the continuing sources during the simulation. After 5 years, the simulation indicated removal of 95% of the salt mass input.

Also shown in Fig. 7 are simulated salt concentrations over time of water pumped at the extraction wells. Salt concentrations in the extracted water are expected to drop rapidly as the thickness of the highly concentrated salt water lens at the base of the aquifer is reduced and an increasing proportion of relatively fresh water is entrained into the extraction wells. The simulated concentrations in RW-1 and RW-3 decrease sharply over the first year or so. Then the decrease in concentrations at RW-1 and RW-3 is more gradual during the next 2.5 years as the salt flushed from the soil at the site is extracted. At the end of 5 years, the simulated concentrations at all recovery wells is below 160 mg/L.

Simulated concentrations of salt from the facility at two of the municipal wells (the wells closest to the site) are also shown in Fig. 7. These curves indicate a rapid reduction in salt concentration at both municipal wells, i.e. concentrations are nearly halved within 1 year. These results illustrate the degree to which the recovery wells will limit the entrainment of salt from the facility into the municipal wells.

To verify the screening analysis results, a remedial simulation incorporating the 2-phase flow model was made for the selected extraction pumping scenario. This model simulation verified the simulation results from the screening analysis.

SUMMARY

As we have found in most real-world modeling studies, the successful completion of this project required the application of several, inter-related, groundwater modeling codes. No single code typically has all the capabilities required to address the issues arising during a project.

In this case, the model application was facilitated by the fact that the codes were developed with a common model approach and shared a common site data base and basic model structure. Therefore, the results from one code (e.g. the transient flow field from the 3-D flow model) were directly available to each of the other codes. In addition, the results from the simulation runs of any of the codes could be graphically overlaid on the results from other the codes and compared with observations from field data. The ability to analyze model results graphically, in both plan and cross-section, was essential in this project. The model codes' ability to link to widely available GIS and CAD tools further assists in generating input files and assessing model results.

REFERENCES

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van der Heijde, Paul K.M., 1985. "Review of DYNFLOW and DYNTRACK Ground Water Simulation Codes." International Ground Water Modeling Center Report 85-15.

Keywords : sharp interface models, groundwater remediation, salt storage, road salt

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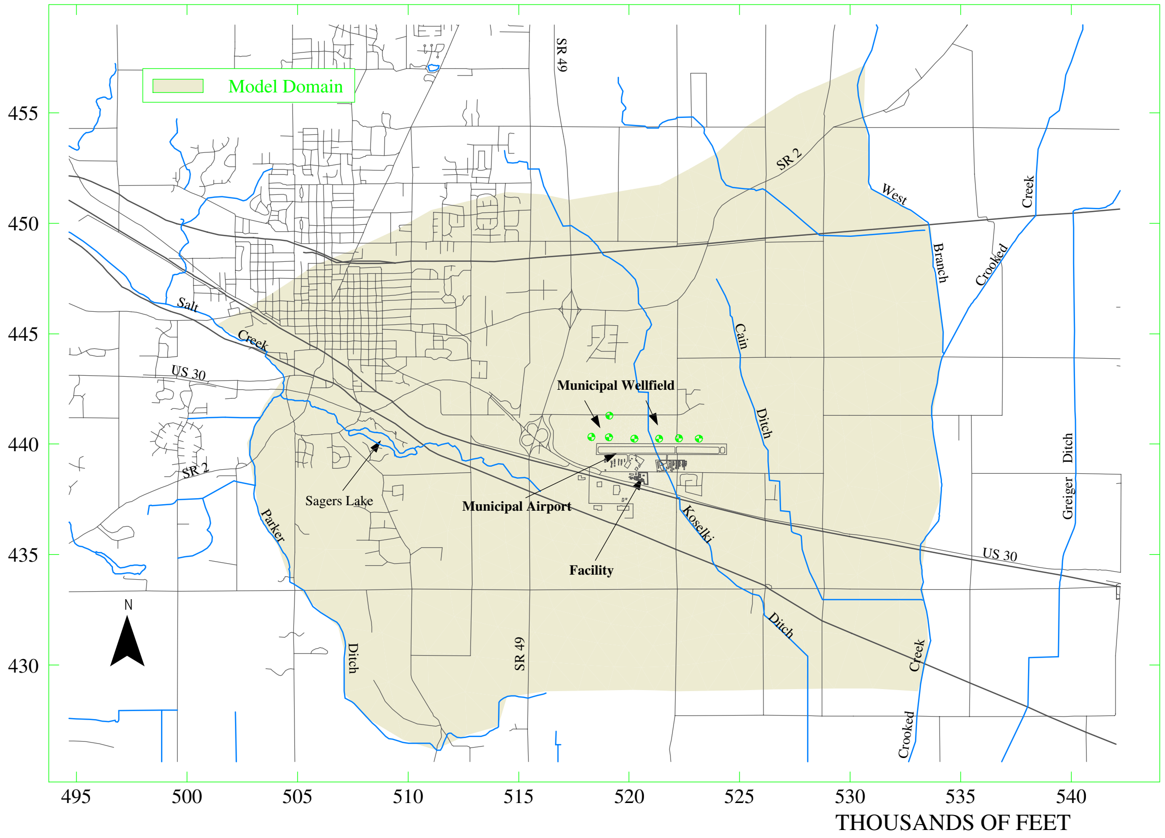


Figure 1: Regional Location Map and Model Domain

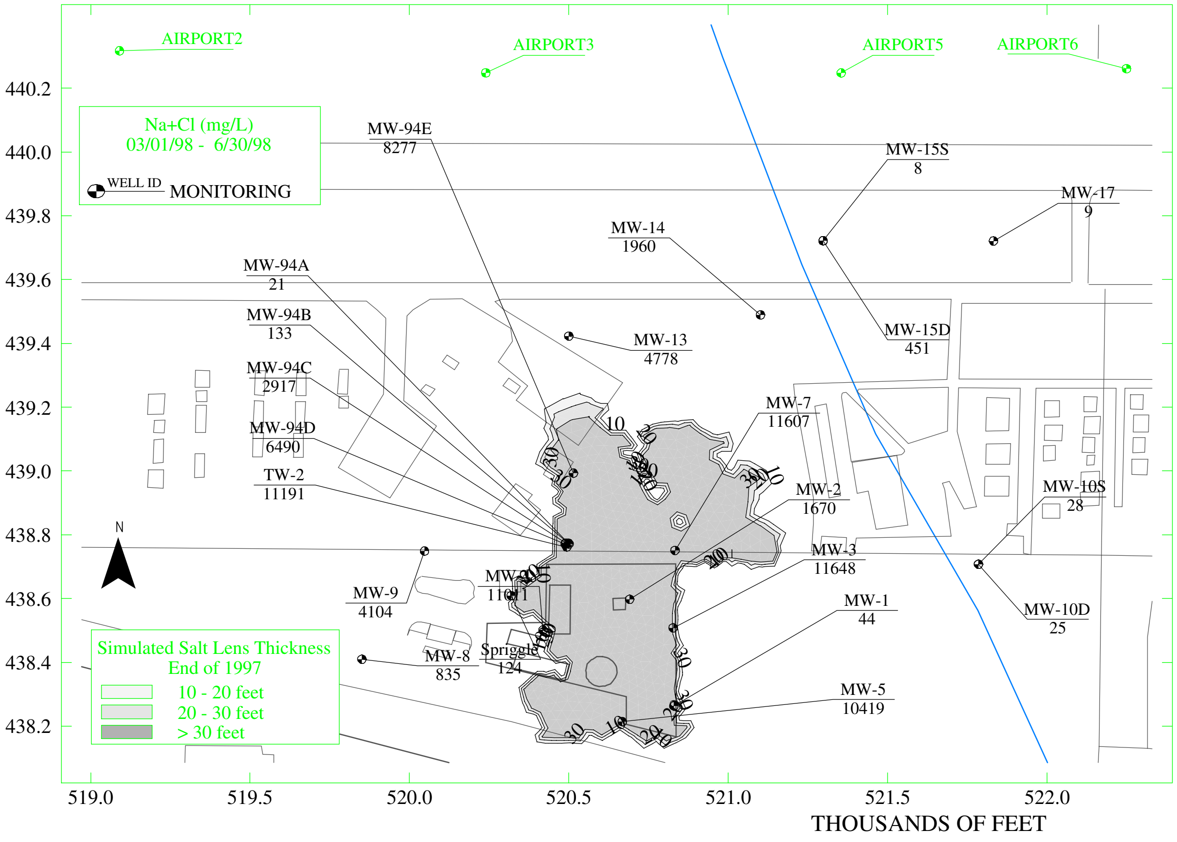


Figure 2: Simulated Salt Lens Thickness, End of 1997

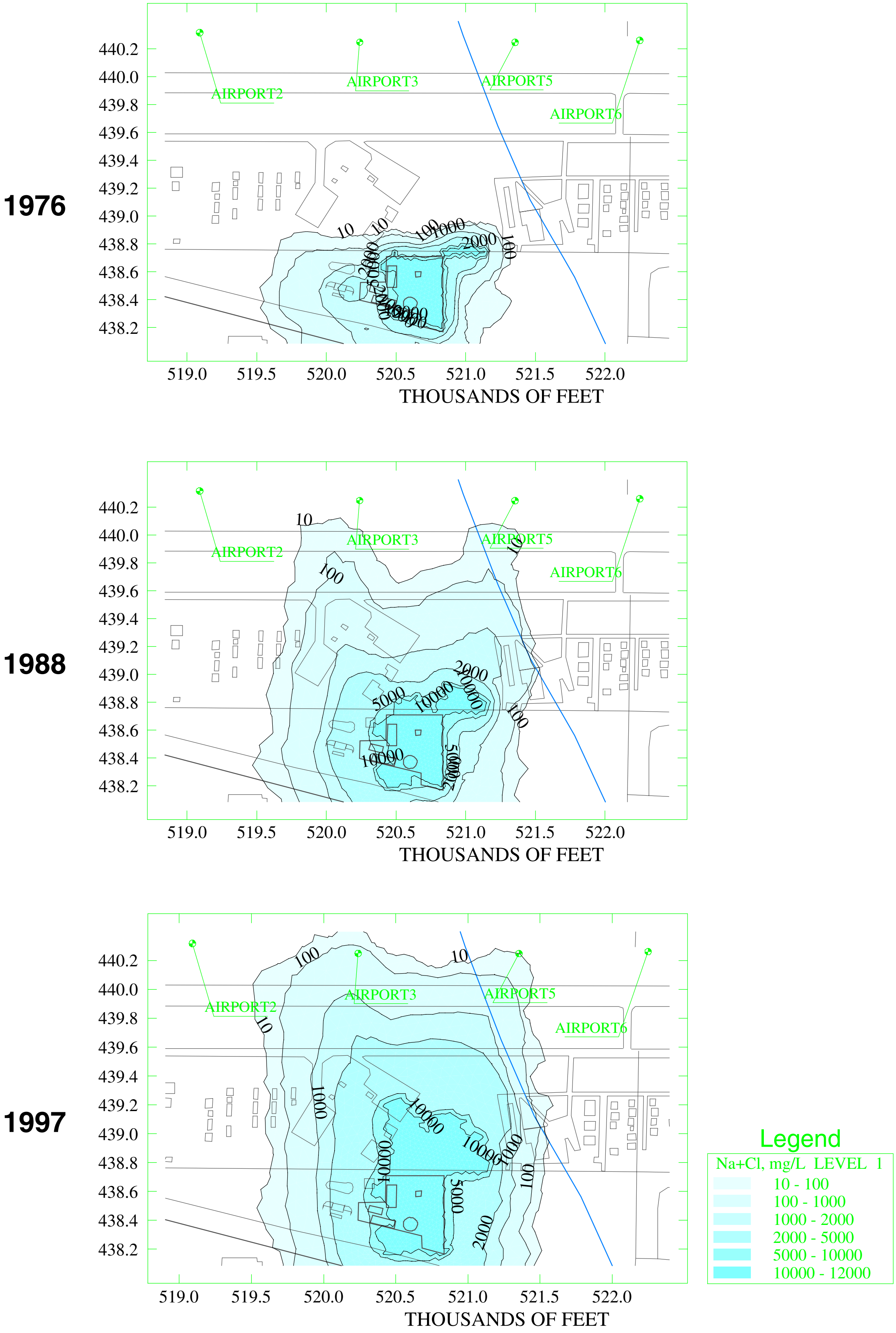


Figure 3: Simulated Salt Plume in 1976, 1988, and 1997 at Base of Aquifer

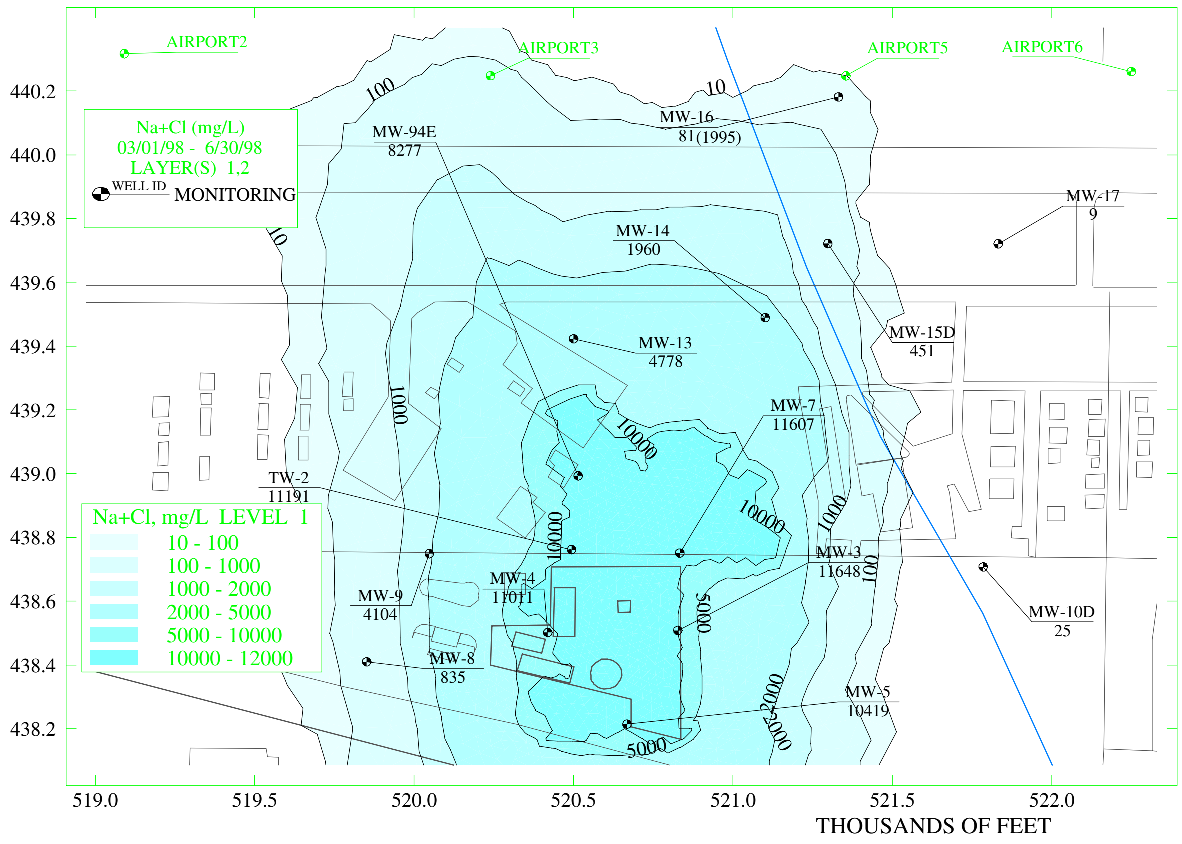


Figure 4: Simulated Deep Concentrations of Na+Cl (mg/L), End of 1997; March 1998 Measured Concentrations at Deep Wells Posted.

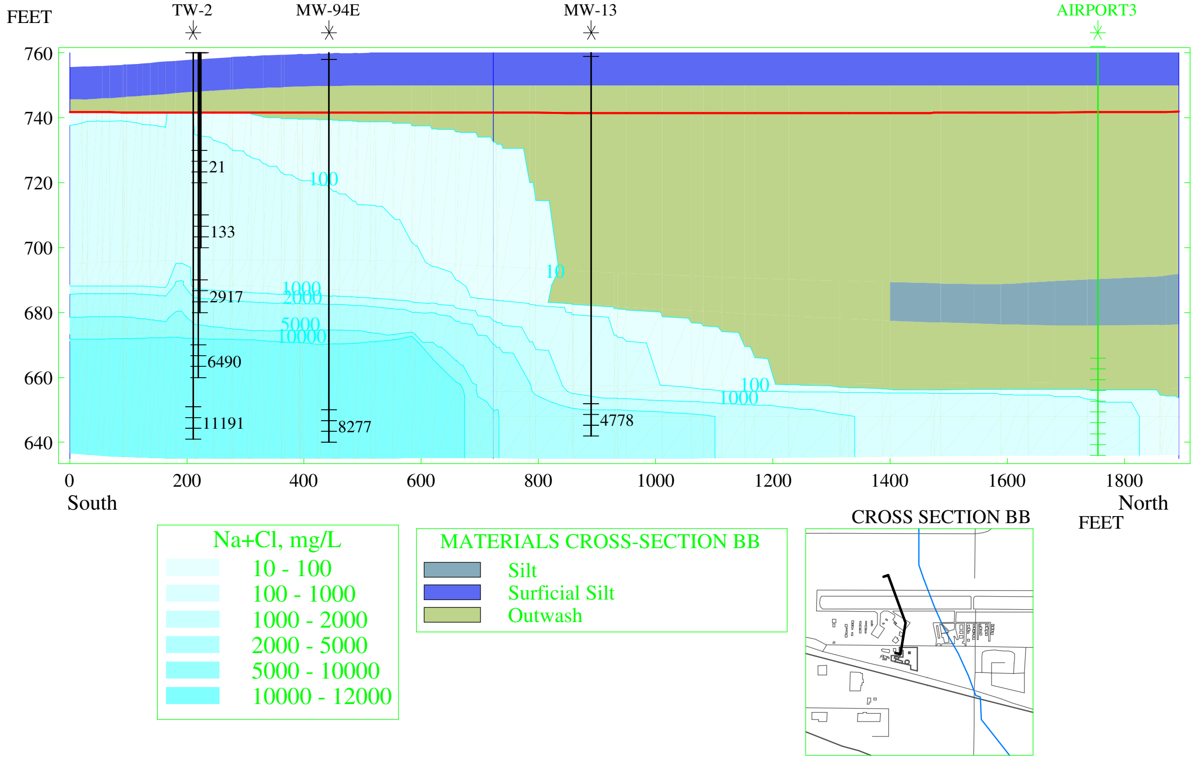
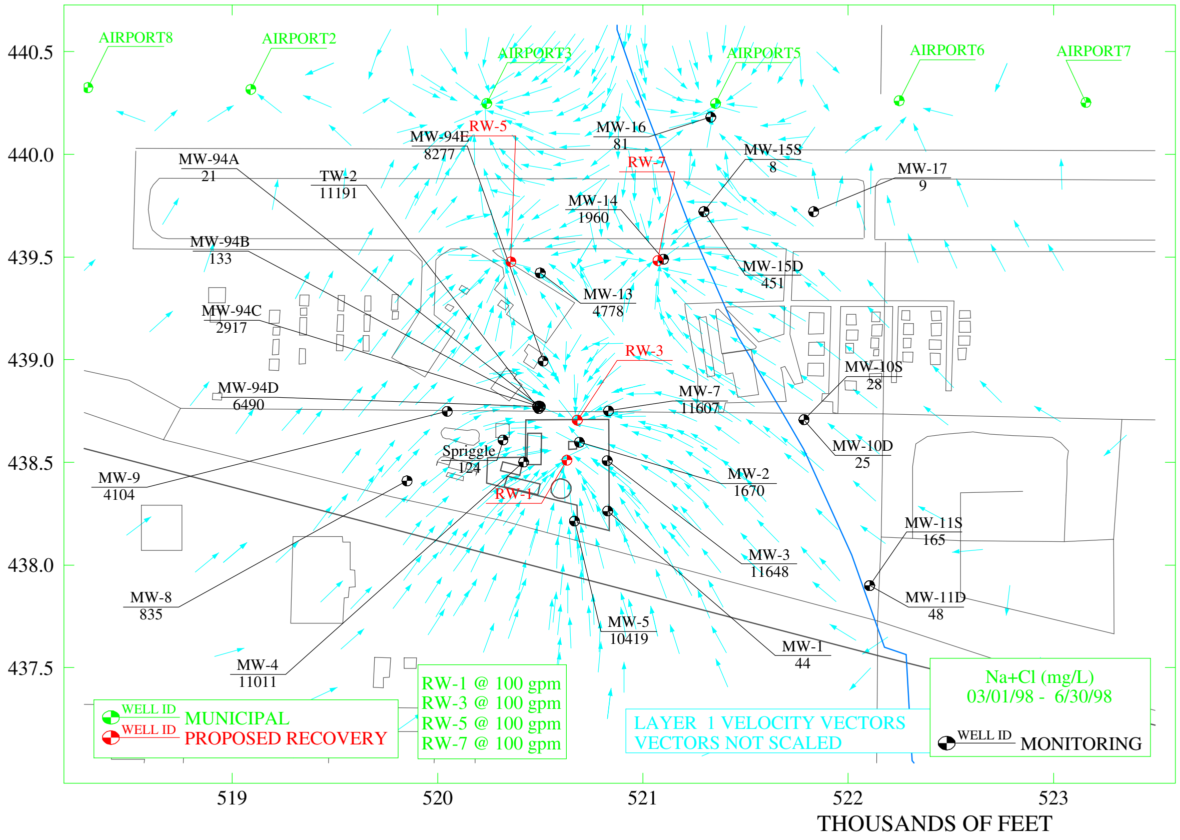


Figure 5: Simulated Deep Concentrations of Na+Cl (mg/L), End of 1997; March 1998 Measured Concentrations at Deep Wells Posted. North-South Cross Section Through Site and Plume

Unscaled Vectors



Scaled Vectors

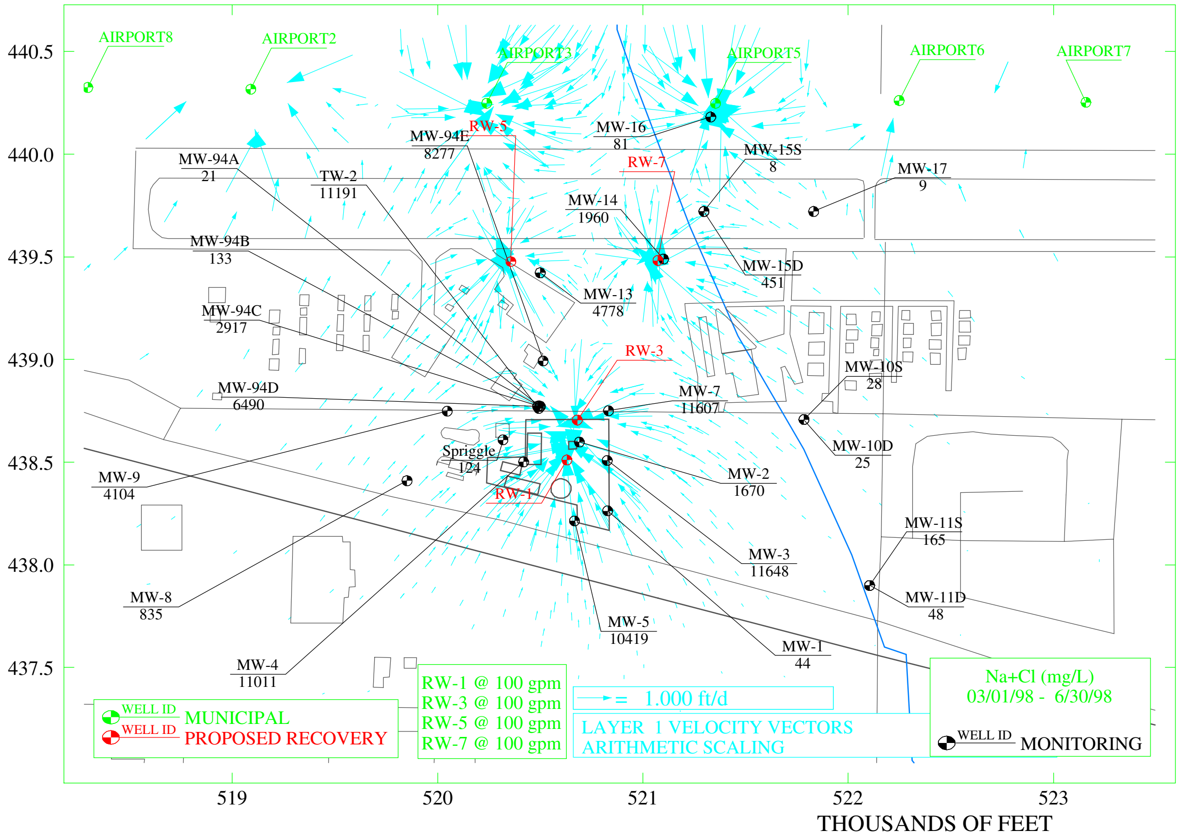


Figure 6: Simulated Deep Velocity Vectors for Selected Remedial Alternative; Observed Average 1998 Na+Cl Concentrations

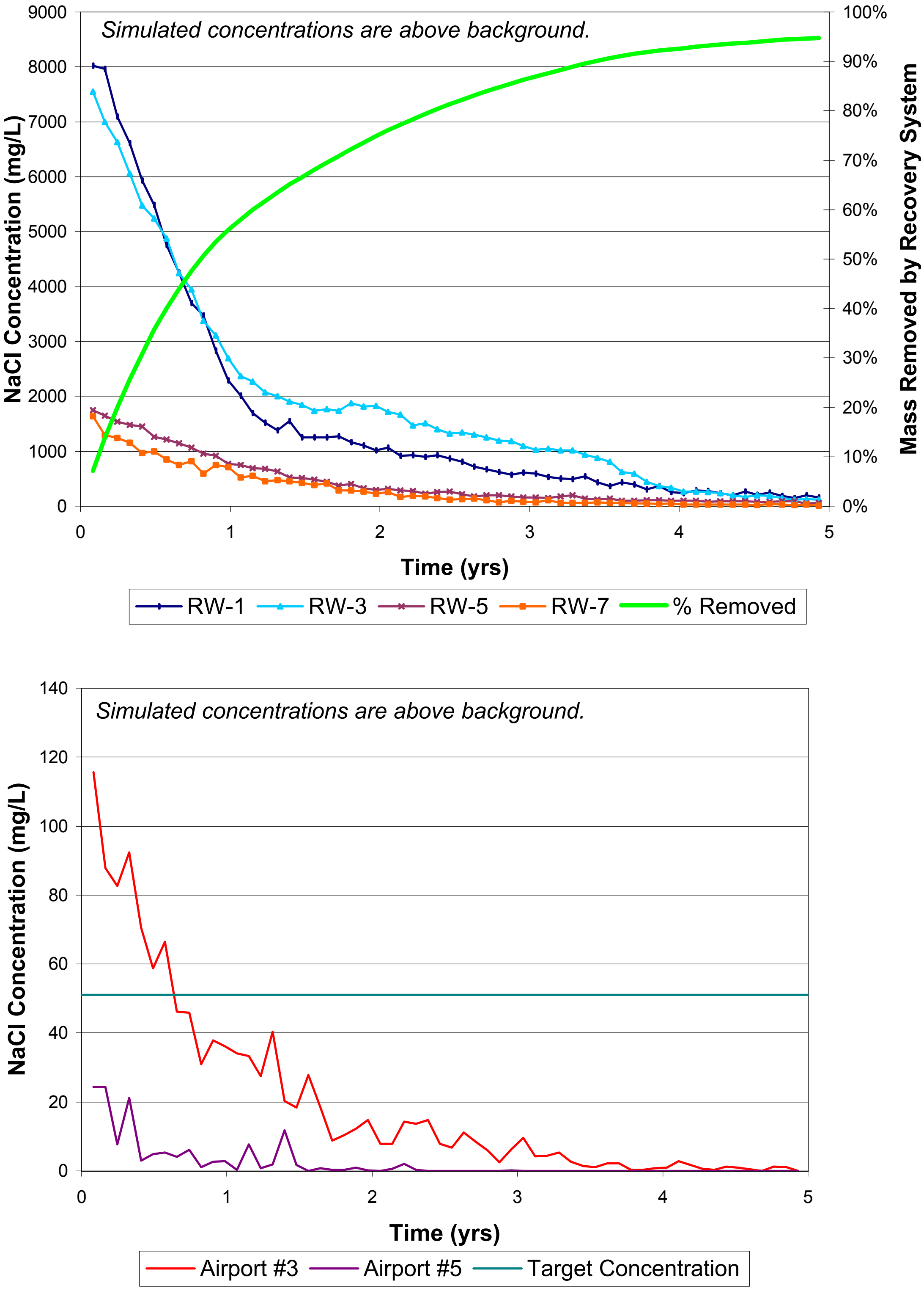


Figure 7: Simulated Mass Removed by Redial Wells; Simulated Concentrations at 4 Remedial and 2 Municipal Wells