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Evaluation and Simulation of Wellfield Restoration at the RAMC Smith Ranch Facility

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EXECUTIVE SUMMARY

This report presents the technical basis and justification necessary to support commercial wellfield restoration cost estimates at the RAMC Smith Ranch ISL facility. This work was initiated in response to a proposed increase in wellfield bonding requirements by the WDEQ/LQD.

RAMC retained Lewis Water Consultants (LWC) to provide a technical evaluation of wellfield restoration costs and associated bonding requirements. To accomplish this objective, site-specific wellfield restoration simulations were conducted. Pore volume requirements were determined for the Q-Sand pilot operation and for the commercial wellfield using the concept of the mixed linear reservoir (MLR) model. The MLR model was supplemented and validated using the equilibrium geochemical mixing model PHREEQC.

Results of the wellfield simulations indicate that pore volume restoration requirements are significantly smaller than originally estimated. It is estimated that RAMC's commercial wellfields can be restored to baseline conditions in less than 4.4 pore volumes. The injection of reducing agents and RO permeate during the latter stages of wellfield restoration is predicted to have a significant effect on reducing the number of pore volumes required to reach restoration objectives.

The affected pore volume for the commercial wellfield was estimated with the aid of a three-dimensional groundwater flow model and advective particle tracking techniques. Results of this modeling suggest that the best estimate of wellfield flare factor is 1.7. This flare factor is higher than RAMC's previous estimate of 1.32, but substantially smaller than estimates presented by WDEQ/LQD. The affected pore volume for Wellfield 1using a flare factor of 1.7 is 68,920,890 gallons (211.48 acre-ft).

A detailed sensitivity analysis of the wellfield flare factor was conducted as part of this work. Results of the sensitivity analyses indicate that the wellfield flare factor is a linear function of the wellfield scale, net production rate, and the ratio of horizontal to vertical hydraulic conductivity of the aquifer. These results can be used to estimate appropriate flare factors for other commercial wellfields at the Smith Ranch facility.

The time required to restore the commercial wellfield to baseline conditions was calculated using the revised pore volume estimates according to the existing restoration plan. Results of this work indicate that the commercial wellfield can be restored to baseline conditions in 210 days. Ground water restoration is driven by conservative constituents (e.g. chloride) that do not respond to the effects of chemical additives and possess low baseline concentrations. This conclusion has broader ramifications for ISL restoration in general, since pore volume requirements could be determined for any existing wellfield using the MLR model.

A review of the basic methodology used by WDEQ/LQD to estimate affected pore volumes and wellfield restoration costs was evaluated as part of this work. In the opinion of LWC,

flare factors developed by WDEQ/LQD have been overestimated due to 1) the small-scale nature of the flow modeling, 2) the methodology employed to estimate the flare factor (plotting of velocity vectors), and 3) inappropriate assumptions used to calculate the vertical flare. In addition, the WDEQ/LQD methodology does not consider all factors necessary to estimate restoration with reasonable accuracy, including the number of pore volumes required to achieve restoration standards, and the affect of reducing agents and RO permeate on restoration timing.

Results of this work can bc used to establish reliable estimates of restoration timing and cost for all of RAMCs commercial wellfields. Given these results, wellfield restoration at the Smith Ranch facility can be accomplished well within original time and cost estimates. Based on these findings, there is no technical basis to support an increase in bonding requirements as proposed by WDEQ/LQD.

1.0 INTRODUCTION

This report presents the technical basis and justification necessary to support commercial wellfield restoration cost estimates at the Smith Ranch ISL facility. This work was initiated at the request of RAMC for use in developing a response to a proposed increase in bonding requirements by the WDEQ/LQD. The proposed increase in bond amount was based upon a WDEQ/LQD estimate of the affected aquifer volume derived from limited groundwater flow modeling. RAMC objected to the proposed bond increase based on technical, operational, and historical grounds, and therefore initiated a third party study to model and evaluate the restoration process at the Smith Ranch Facility.

In April of this year, RAMC retained Lewis Water Consultants (LWC) to provide a technically defensible basis for developing wellfield restoration cost estimates and associated bonding requirements. The following tasks were completed as part of this work:

- the Q-Sand pilot operation was evaluated and simulated. Pore volume requirements for the pilot operation and the commercial wellfields were developed as part of this task.
- the affected pore volume size was determined for the pilot operation and for the commercial wellfield. A detailed sensitivity analysis of the wellfield "flare factor" was completed as part of this task.
- the restoration of the commercial wellfield to baseline conditions was simulated using RAMC's current restoration plan, field data, and data from the Q-sand pilot. The impact of reducing agents and RO permeate injection on aquifer restoration timing was simulated as part of this task.
- the technical approach adopted by the WDEQ/LQD to estimate affected aquifer pore volumes was reviewed and potential problems were identified.
- recommendations were developed that may allow RAMC to accelerate wellfield restoration.
- recommendations on pore volumes and flare factors to be used in restoration cost estimates were developed using detailed modeling.

This report is organized in five sections. Section 2 describes the Q-Sand pilot simulation and the basic methodology used to develop pore volume requirements for the pilot and the commercial wellfields. Section 3 describes the commercial wellfield simulation, including the methodology used to calculate the affected pore volume and the time required to restore the wellfield to baseline conditions. Section 4 provides an evaluation of the methodology used by WDEQ/LQD to estimate wellfield restoration timing. Section 5 provides a summary of findings and conclusions.

2.0 Q-SAND PILOT SIMULATION

In order to predict the time required to restore a commercial wellfield using a pore volume approach, three basic pieces of information are required:

- the number of pore volumes that must be flushed to restore the wellfield to permissible water quality (baseline and/or class-of-use)
- the size of the affected pore volume
- the time required to flush a pore volume (wellfield extraction rate)

The restoration of the Q-sand pilot wellfield in 1985 provided critical information necessary to accurately predict pore volume flushing requirements and the time required to restore a commercial wellfield. The simulation of the Q-sand pilot wellfield restoration is described in the following sections.

2.1 Pore Volume Requirements

Previous estimates of wellfield restoration timing have relied greatly upon estimating the size of the affected pore volume, with little attention devoted to developing accurate pore volume flushing requirements for the commercial wellfields. Water quality data collected during the Q-sand pilot wellfield restoration provides the basis for accurately estimating pore volume flushing requirements for the pilot and for the groundwater sweep phase of commercial wellfield restoration.

2.1.1 Mixed Linear Reservoir (MLR) Model

Pore volume flushing requirements for the groundwater sweep phase of wellfield restoration were calculated by applying the general approach of Zheng et al. (1991,1992) using the concept of the mixed linear reservoir (MLR) or batch mixing model of Gelhar and Wilson (1974). The MLR model is based on the simple principle that an affected aquifer can be represented as a fully mixed solution at some average concentration. The concentration of this solute then changes instantaneously in response to changes in inflow, outflow, and solute mass. The average solute concentration within an ISL wellfield is well known due to the composite nature of water quality sampling. In addition, the relatively close proximity of injection and production wells makes the assumption of complete mixing appropriate.

The number of pore volumes (Npv) required to reduce the initial concentration (Ci) to some regulatory standard or final concentration (Cs) based on the MLR model is given by:

$$Npv = -R \ln (Cs/Ci) \qquad (1)$$

where R is the classical retardation factor, a measure of chemical attenuation within the aquifer.

Water quality data collected during the Q-pilot wellfield restoration provides a unique opportunity to directly compute pore volume flushing requirements and the size of the affected pore volume using the MLR model. To accomplish this, pore volume requirements were first computed for chloride, a conservative constituent (R=1). Because the initial concentration (Ci), final concentration (Cs), and retardation factor (R) of chloride are known at the time the pilot restoration was complete, the number of pore volumes flushed during the pilot (Npv) can be calculated directly. Given an initial chloride concentration of 269 mg/l, a final chloride concentration of 11 mg/l, and a retardation factor of 1.0, the number of pore volumes flushed during the pilot restoration was 3.20. This represents a substantial decrease in pore volume requirements from previous estimates. Figure 2-1 compares observed and modeled chloride flushing curves for the Q-sand pilot restoration. In general, modeled and observed chloride concentrations are in excellent agreement, particularly near the end of the wellfield restoration.

Given the number of pore volumes flushed during the pilot test, retardation factors for other chemical constituents can be back-calculated directly from the MLR model. A knowledge of the site-specific retardation factors allows the concentration of any chemical constituent to be predicted for any set of initial and final conditions using the MLR model. Table 2-1 provides the pore volume requirements and associated retardation factors for key constituents. For some constituents, the initial concentration at the start of the pilot was not known; initial concentrations were estimated for these constituents from observed concentrations in Wellfield 1.

Figure 2-2 compares the relative flushing curves for key constituents. The relative mobility of various chemical constituents can be seen from this graph. Figures 2-3, 2-4, and 2-5 compare modeled and observed pilot flushing curves for uranium, sulfate, and bicarbonate, respectively. In general, modeled and observed concentrations are in excellent agreement, particularly near the end of the pilot restoration. Minor deviations from ideal model behavior are likely due to non-linear, irreversible chemical attenuation within the aquifer not accounted for by the classical retardation factor (linear reversible adsorption).

It is important to note that the pore volume requirements developed from the Q-sand pilot are generally applicable not only for the pilot test area, but for the groundwater sweep portion of RAMC's commercial wellfield restorations. The number of pore volumes required to meet restoration standards is independent of the size of the affected pore volume. Retardation factors should not vary significantly since the commercial wellfields are part of the same aquifer system. Variability in pore volume requirements would exist only if initial wellfield concentrations and baseline target concentrations deviated greatly from those of the Q-sand pilot restoration. Pore volume requirements for chloride developed from the MLR model are

Table 2-1. Retardation Factors at End of Q-sand Pilot Test

Ci = initial concentration (at beginning of restoration)
Cs = concentration at end of pilot test restoration
Npv = number of pore volumes (based on revised affected pore volume)
R = retardation factor from mixed linear reservoir model: R = -Npv/ln(Cs/Ci)

	Ci	Cs	Cs/Ci	ln (Cs/Ci)	Npv	R
mg/L						
Cl	269	11	0.040892	-3.196816	3.20	1.0[a]
U (U_3O_8)	14.4	1.9	0.131944	-2.025374	3.20	1.58
SO_4	450	115	0.255556	-1.364315	3.20	2.34
Ca	273	68	0.249084	-1.389964	3.20	2.30
HCO_3	915	226	0.246995	-1.398389	3.20	2.29
Constituents with estimated Ci values (estimated from Wellfield 1 data)						
Na	80	38	0.475	-0.744	3.20	4.3
K	18	8	0.444	-0.811	3.20	3.9
Mg	90	19	0.211	-1.555	3.20	2.1
B	0.15	0.14[b]	0.933	-0.069	3.20	46.3[b]
Fe	0.05	0.24	4.800	1.569	3.20	na[c]
Mn	0.35	0.06	0.171	-1.764	3.20	1.8
As	0.008	0.008	1.000	0.000	3.20	na[c]
Se	0.08	0.003	0.038	-3.283	3.20	1.0
Ra226 (pCi/L)	4000	477	0.119	-2.127	3.20	1.5

Notes:
a Chloride is assumed to behave conservatively, R = 1
b Final concentration is suspect and results in unreasonably high R
c not applicable - R cannot be calculated from steady or increasing concentrations

more universal in nature (e.g. applicable to all ISL sites), since chloride acts conservatively in essentially all environments.

2.2 Affected Pore Volume Calculation

Another benefit of the MLR model is the ability to calculate the affected pore volume size for the Q-sand pilot directly, without the need for groundwater flow model simulations. Because the number of pore volumes flushed during the pilot restoration is known, and because the total volume of groundwater flushed (extracted) during the test is also known, the affected pore volume (APV) can be computed simply from:

$$APV = TV/Npv \tag{2}$$

where TV is the total volume of groundwater extracted during the pilot restoration. Given a total extracted volume of 2.044 x 10^7 gallons and 3.20 pore volumes flushed, the affected pore volume size of the Q-sand pilot is 6.387 x 10^6 gallons. This affected pore volume is appropriate only for the Q-sand pilot restoration, not the commercial wellfields. This is due to significant differences in net production rate, bleed rate (5 % vs. 0.5%), well construction (full vs. partial penetration), and irregular pattern geometry of the Q-sand pilot relative to the commercial wellfields.

2.3 Verification of MLR Model Using PHREEQC

Results of the Q-sand pilot simulation demonstrate that the MLR model can be used to predict concentration declines during the groundwater sweep phase of wellfield restoration (Phase I). However, the MLR model is not capable of predicting concentration declines due to strongly non-linear chemical reactions including changes in aquifer redox conditions. Significant changes in redox conditions will occur during Phase II and III of RAMC's restoration plan, when reducing agents (H_2S) and RO permeate are injected into the aquifer. A more sophisticated modeling approach is necessary to adequately address these conditions.

The USGS aqueous geochemical model PHREEQC (Parkhurst, 1995) was selected for the purpose of simulating Phase II and III of wellfield restoration, as discussed in section 3. PHREEQC is an equilibrium geochemical model capable of simulating a wide range of complex aqueous geochemical reactions. Because PHREEQC uses a batch or unit-volume approach, it is ideally suited to the pore volume methodology. Details concerning PHREEQC model development and application are provided in Attachment A.

In theory, the MLR model and PHREEQC should provide essentially identical results when simulating mixing of conservative constituents. To test this hypothesis, PHREEQC was used to simulate chloride flushing during wellfield restoration. This simulation could be considered a validation of the MLR model and PHREEQC for commercial wellfield application.

Results of the PHREEQC chloride flushing simulation is provided on Figure 2-6. Results of this simulation illustrate that PHREEQC and the MLR model provide essentially identical results, and that both models simulate measured concentration declines with a high degree of accuracy.

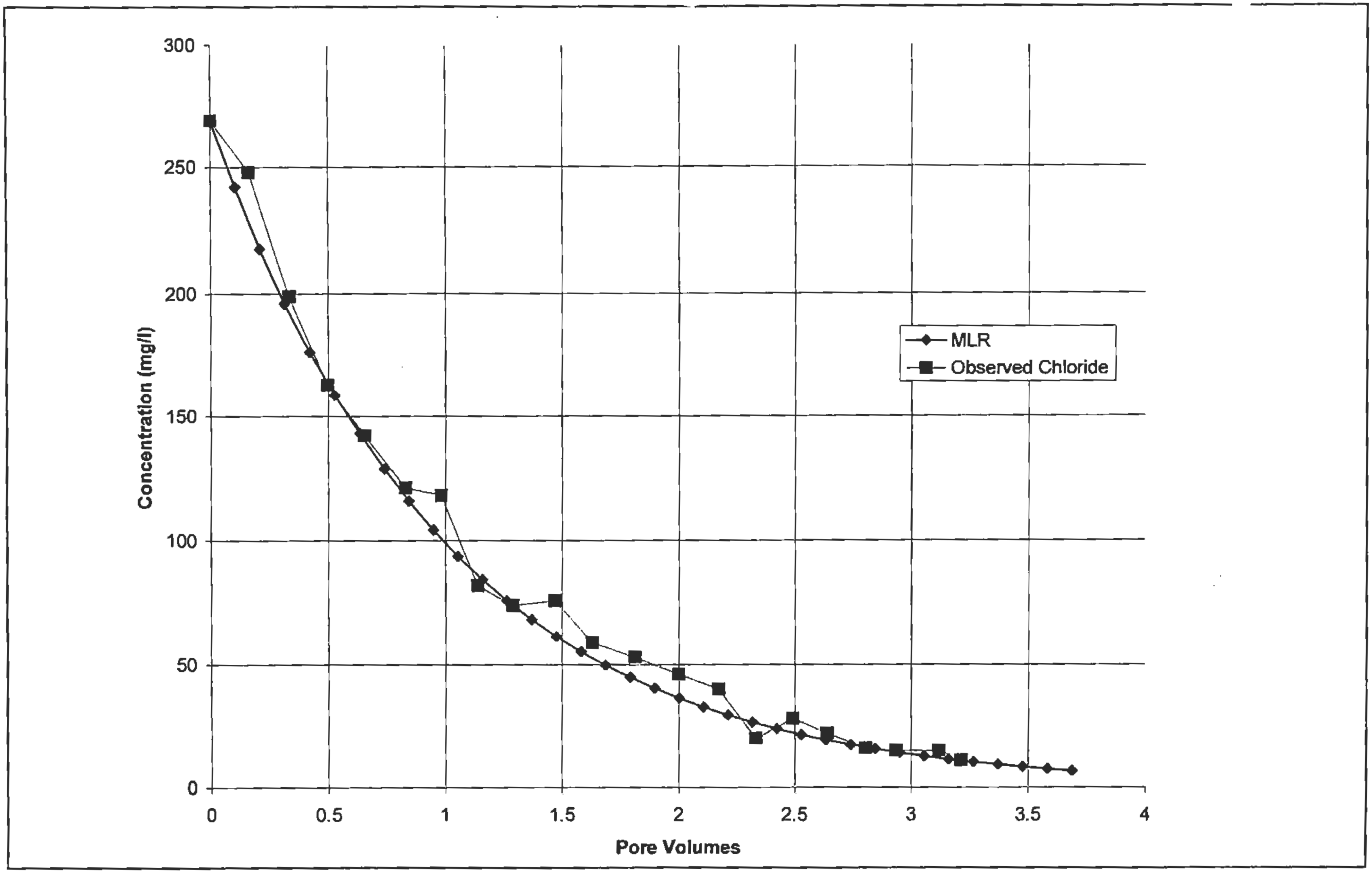

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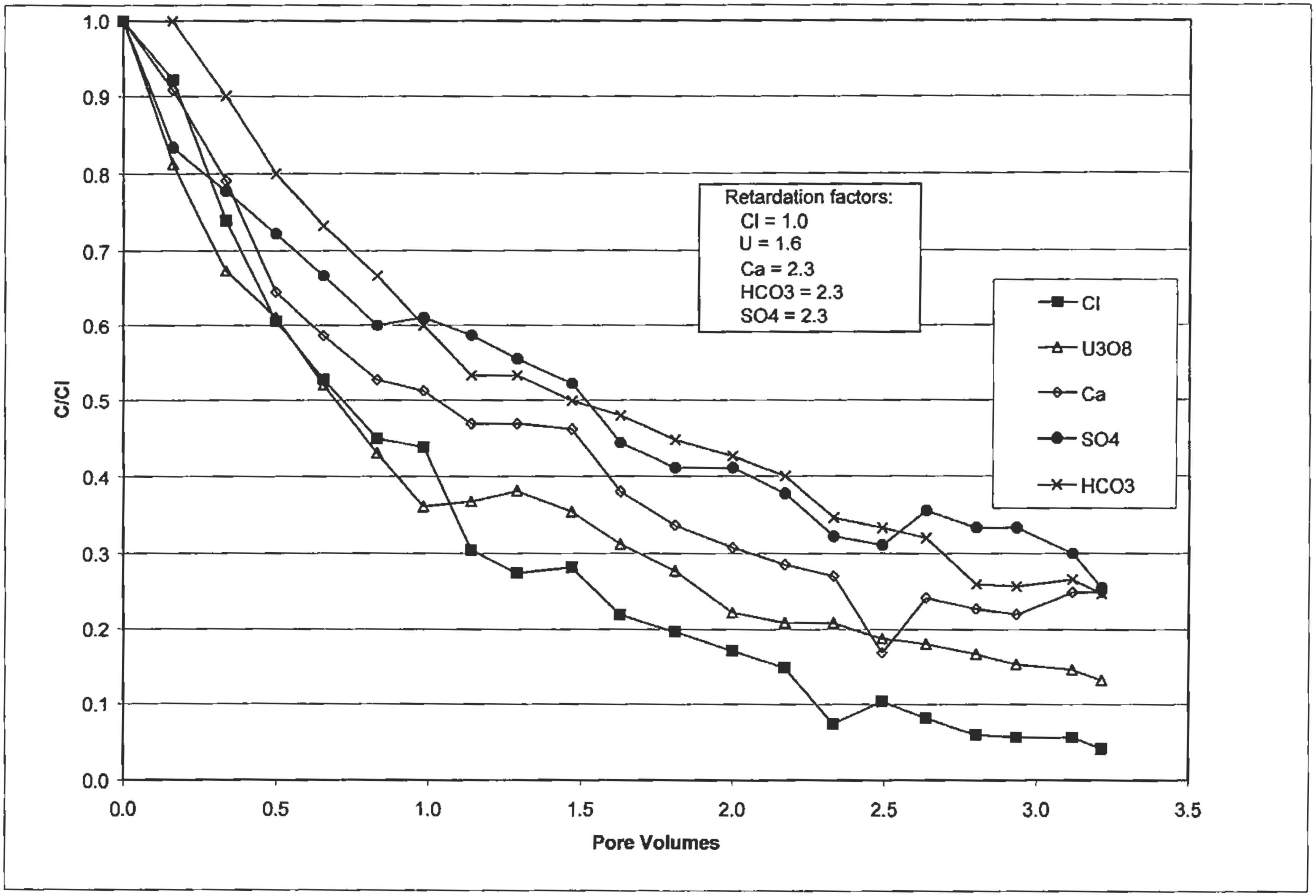
Figure 2-1. Observed vs. simulated chloride flushing curves, Q-Sand Pilot Restoration

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt



Lewis Water Consultants Environmental Science/Engineering/Modeling	**RAMC Smith Ranch Facility** Figure 2-2. Observed Q-Sand pilot flushing curves	Date: 9/14/99 Project: RAMC Wellfield Evaluation File: land.ppt

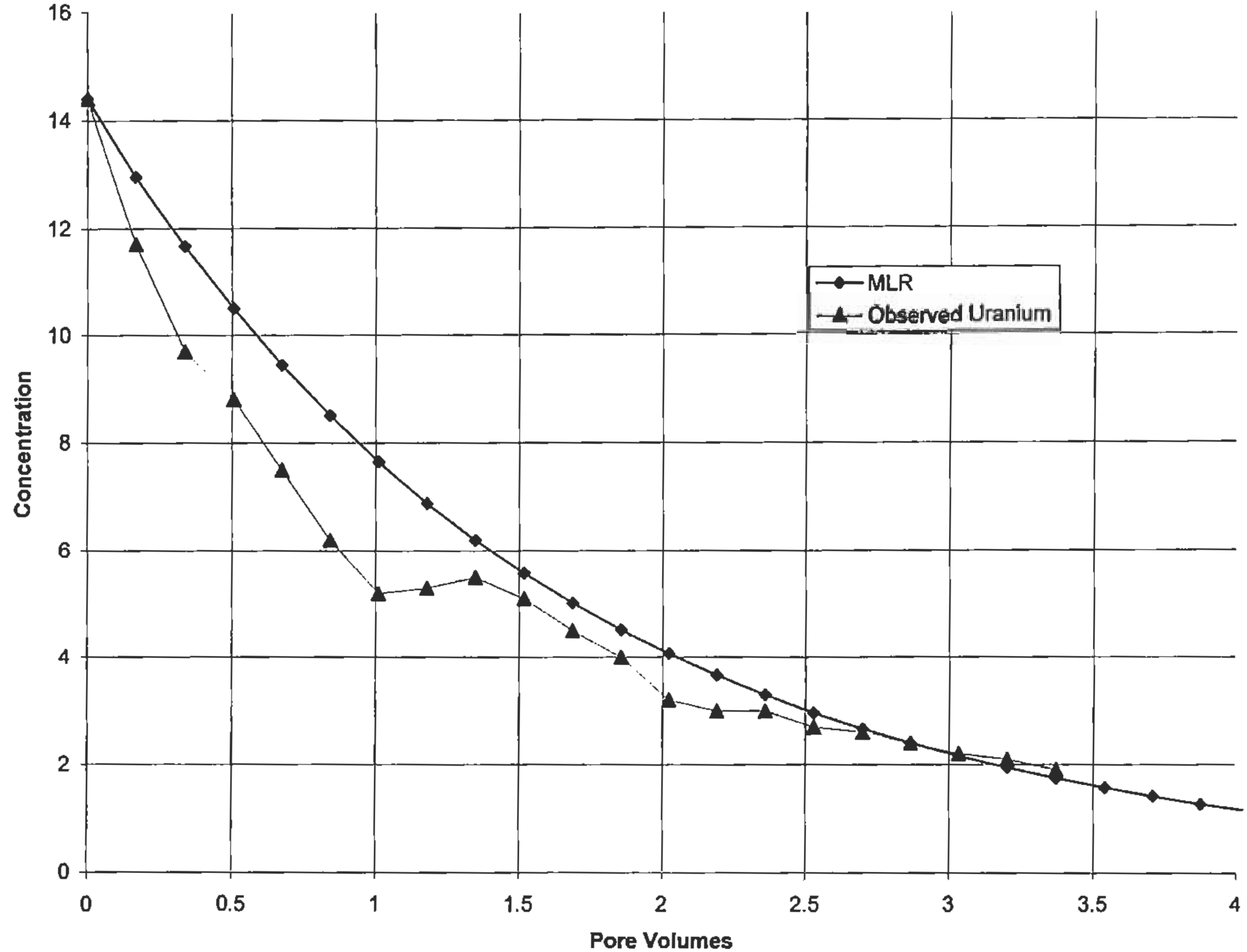


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Figure 2-3. Observed vs. simulated uranium flushing curves, Q-Sand Pilot Restoration

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt

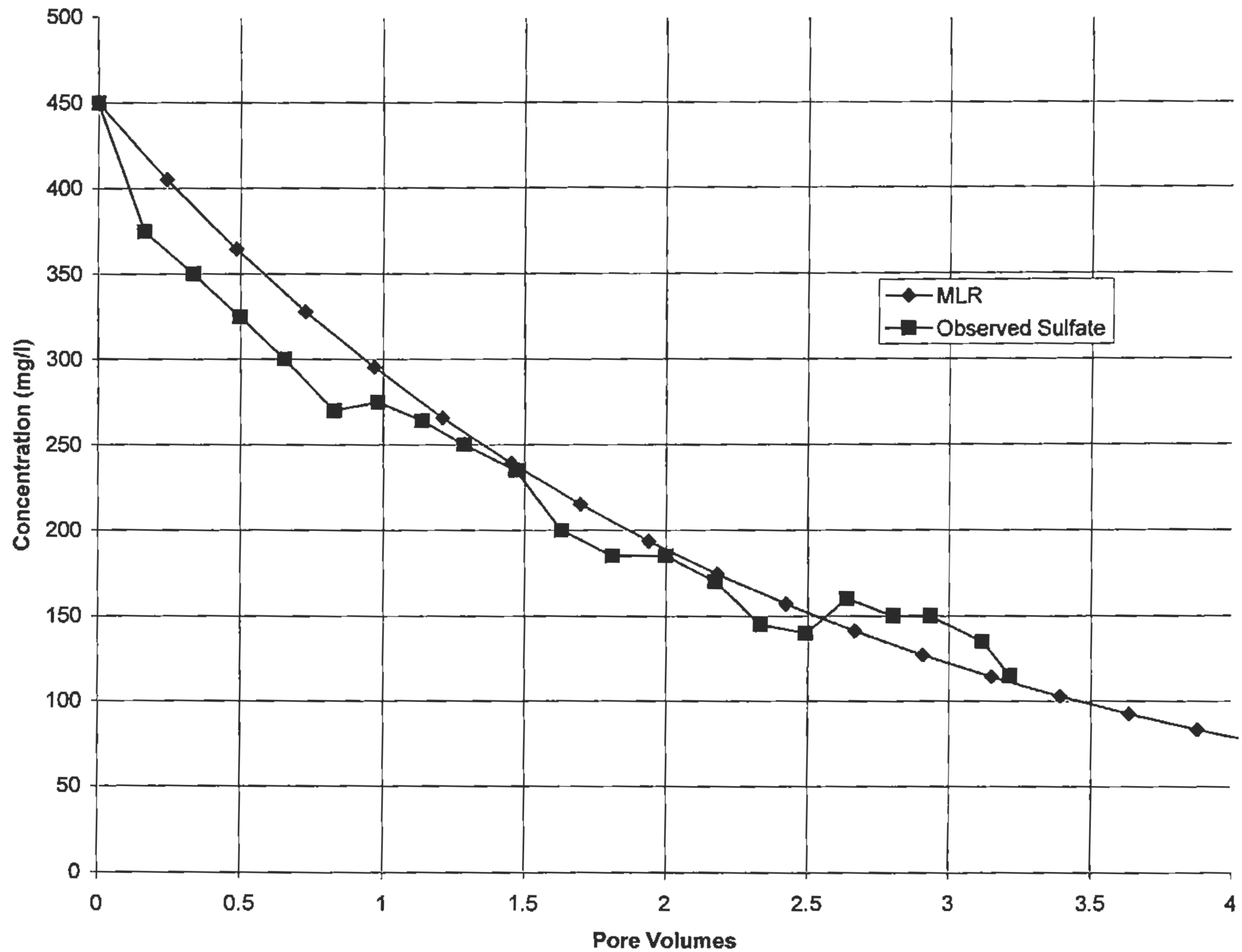

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Figure 2-4. Observed vs. simulated sulfate flushing curves, Q-Sand Pilot Restoration

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt

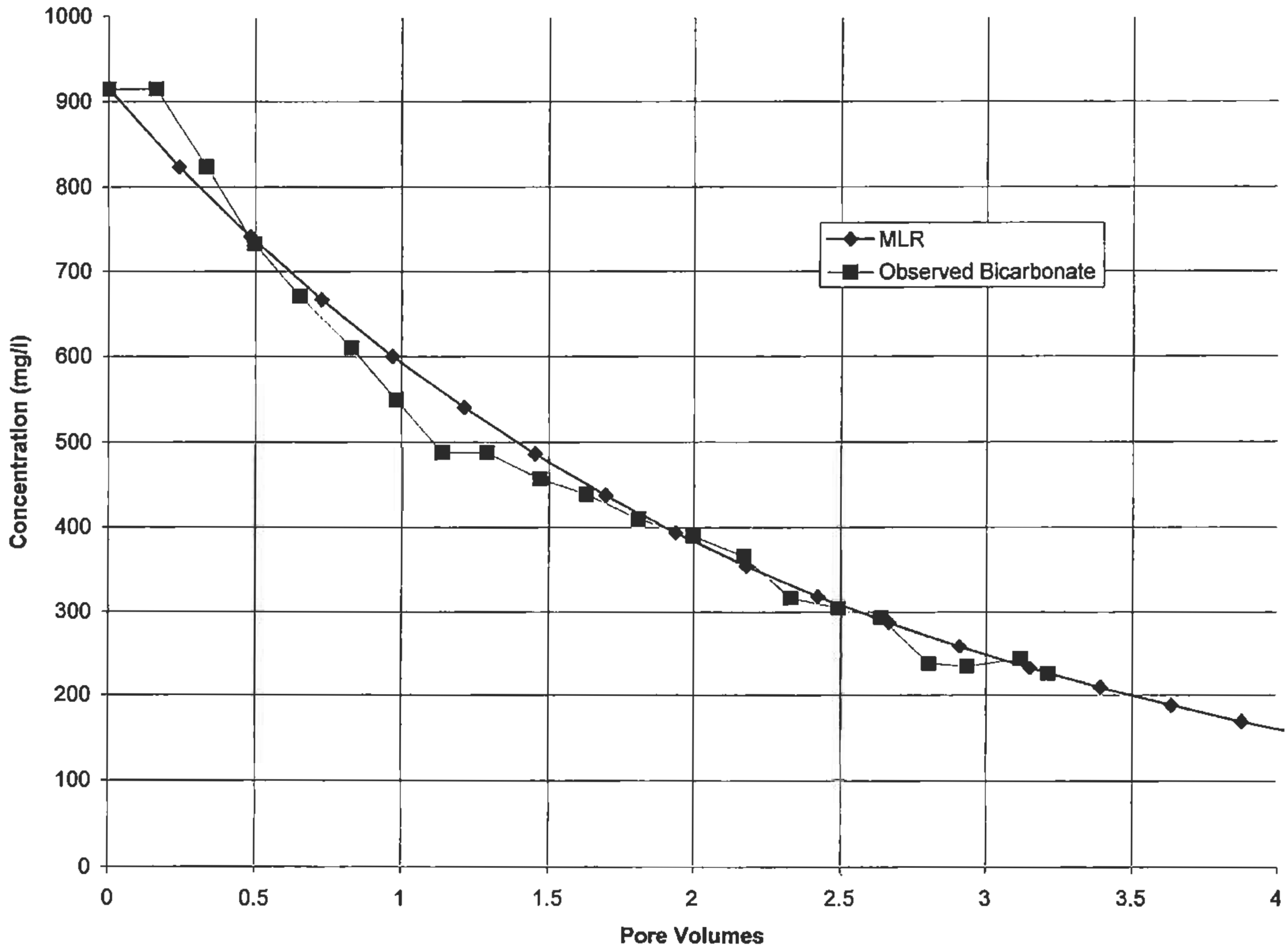

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Figure 2-5. Observed vs. simulated bicarbonate flushing curves, Q-Sand Pilot Restoration

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt

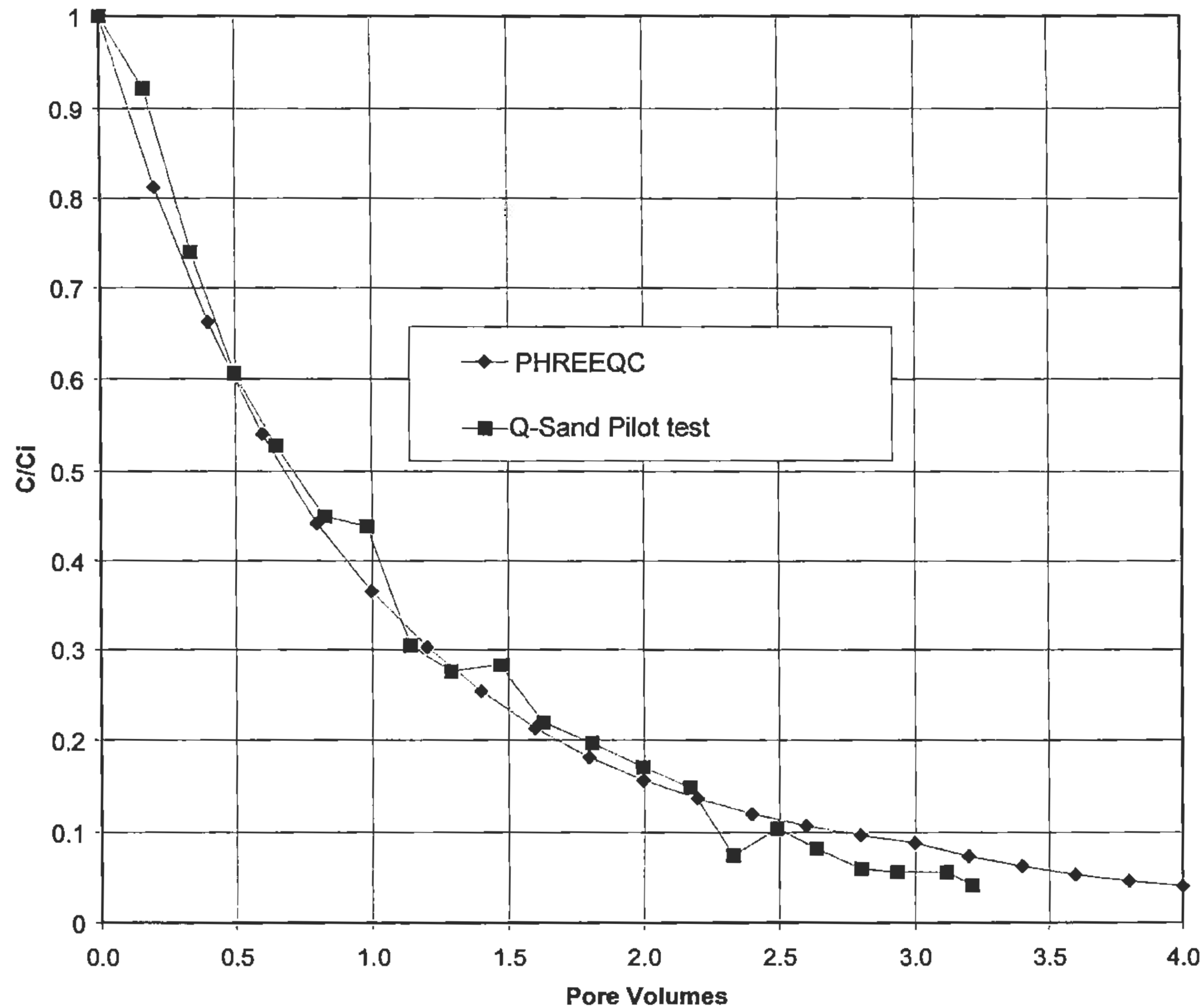

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Figure 2-6. Comparison of PHREEQC and observed chloride flushing curves

Date:	**9/14/99**
Project:	**RAMC Wellfield Evaluation**
File:	**land.ppt**

3.0 COMMERCIAL WELLFIELD SIMULATION

The restoration of RAMC's commercial Wellfield 1 was simulated using the basic methodology applied to the Q-sand pilot restoration. Pore volume requirements for the wellfield were developed using the MLR and PHREEQC models. The size of the affected pore volume was then determined using a three-dimensional groundwater flow model (MODFLOW) in conjunction with particle tracking techniques (MODPATH). Sensitivity analyses of the wellfield "flare factor" was performed as part of this work. Finally, the time required to restore the wellfield was computed by incorporating the pore volume requirements, affected pore volume size, and planned wellfield pumping rates.

Commercial wellfield restoration was simulated according to RAMC's current restoration plan. Wellfield restoration is to proceed as follows:

- 3 Pore Volumes native groundwater sweep at 1015 gpm (Phase I)
- 1 Pore Volume treated by Reverse Osmosis (RO) with chemical reductant (H_2S) added at 250 mg/l sulfide, injected with 5% bleed at 1015 gpm (Phase II)
- 2 Pore Volumes treated by RO, permeate injected with 25 % bleed at 1000 gpm (Phase III)

3.1 Pore Volume Requirements

As stated in Section 2.1.1, pore volume requirements developed from the Q-sand pilot simulation are generally applicable to RAMC's commercial wellfields for the groundwater sweep phase of wellfield restoration. However, small differences may exist due to differences between the initial concentration at the start of restoration and baseline or target concentrations at the end of restoration. Because these conditions are slightly different in Wellfield 1 than observed in the Q-sand pilot, pore volume requirements were recomputed for the commercial wellfield using the most current wellfield concentration data.

Pore volume requirements for Phase I of the wellfield restoration (groundwater sweep) were computed using the MLR model. Pore volume requirements for Phase II and III of the restoration were computed using PHREEQC to account for non-linear chemical reactions due to injection of reducing agents and RO permeate. Details concerning the development and application of PHREEQC are provided in Attachment A.

Restoration of Wellfield 1 is expected to proceed in the third quarter of 2000. Initial concentrations in Wellfield 1 at the beginning of restoration were extrapolated from current conditions using recent historical concentration trends. The pH used in the geochemical modeling was the average of the values measured at each production wellhead in May 1999. Starting concentrations of constituents not routinely measured by RAMC were assumed to be equal to the concentrations measured in header house composite samples collected in May 1999. Table 3-1 provides initial concentrations assumed in the restoration simulation.

Figures 3-1 through 3-6 depict the predicted pore volume flushing curves for select key constituents. Table 3-1 provides a summary of concentrations observed at the end of each restoration phase. In addition to these key constituents, concentrations of all constituents monitored by permit requirements were simulated by PHREEQC (Attachment A). Only those constituents having the greatest bearing on restoration timing are presented in the summary figures and tables.

Based on these results, RAMC's commercial wellfields will be restored to class-of-use within 3.4 pore volumes, and should meet baseline conditions for all constituents within 4.4 pore volumes. Figures 3-1 and 3-2 demonstrate the positive affect of reducing agent and RO permeate on redox sensitive elements (e.g. U and Se).

An important result of this analysis is the observation that ground water restoration is driven by conservative constituents (e.g. chloride) that do not respond to the effects of chemical additives and possess low baseline concentrations. This conclusion has broader ramifications for ISL restoration in general, since pore volume requirements can be simply determined for any existing wellfield using the MLR model.

3.2 Affected Pore Volume Calculation

In order to predict wellfield restoration timing, the size of the affected pore volume must be determined. To accomplish this objective, the affected pore volume size of the commercial wellfield was computed using a three-dimensional groundwater flow model in conjunction with particle tracking techniques. A sensitivity analysis of wellfield "flare factor" was also conducted to identify those parameters that most greatly affect pore volume size.

Prior to conducting flow model simulations, the pattern pore volume size of Wellfield 1 was computed. The pattern pore volume size of Wellfield 1 was determined using AutoCAD for area calculations, and SURFER for volumetric cut-and-fill computations. An isopach (thickness) map of the Q-sand aquifer was digitized to compute the total pattern volume of the Q-sand aquifer. An average thickness of the production interval (ore zone) of 18 ft. was used to compute the production zone pore volume. The barren zone thickness was computed to be the difference between the total Q-sand thickness and the production zone thickness. A porosity value of 0.27 was used to be consistent with previous estimates by WDEQ/LQD and RAMC. Results of the pattern volume calculations are provided on Figure 3-7.

3.2.1 Flare Factor and Affected Pore Volume Definition

For purposes of this document, the wellfield flare factor is defined as:

Horizontal Flare Factor = Total Affected Area / Pattern Area (generally >1)
Vertical Flare Factor = Fractional barren zone intrusion (0-1)

Table 3-1. Initial and Predicted Concentrations at End of Restoration Phases

Constituent	Initial Concentration at Start of Restoration	Modeled Concentration after Phase I (GW Sweep)	Modeled Concentration after Phase II (RO + Reductant)	Modeled Concentration after Phase III (RO permeate)
U	15	2.3	<0.168	<0.168
Se	0.092	0.0047	<0.001	<0.001
Cl	210	10	4.9	1.1
SO_4	720	194	91	20
HCO_3	590	159	89	20
Ca	430	116	55	12
Na	41	23	11	2.4
As	0.006	0.001	<0.001	<0.001
B	0.15	0.10	0.048	0.011
Fe	0.05	0.055	<0.01	<0.01
Mn	0.31	0.059	0.028	0.006

Given this definition, a horizontal flare of 1.0 means no lateral extension of mining fluids beyond the pattern boundaries. A horizontal flare of 2.0 means an affected area twice the size of the pattern area. Similarly, a vertical flare of 0.5 means that 50% of the total barren zone thickness is impacted by mining fluids. These definitions are believed to be identical to those currently used WDEQ/LQD and RAMC.

The affected pore volume (APV) is then calculated as:

$$APV = (PZPV \times \text{Horizontal Flare Factor}) + (BZPV \times \text{Vertical Flare Factor}) \qquad (3)$$

where PZPV is the production zone pore volume and BZPV is the barren zone pore volume. The PZPV and BZPV for Wellfield 1 are provided on Figure 3-7. It should be noted that RAMC has previously calculated the APV with the following equation:

APV= (PZPV x Horizontal Flare x Vertical Flare).

3.2.2 Flare Factor Sensitivity Analyses

Sensitivity analyses of parameters influencing the horizontal flare factor were investigated using the analytical flow and transport model RANDC, a C+ version of the traditional RANDOMWALK particle tracking code (Prickett et al., 1981). RANDC is a full-featured two-

dimensional mass transport model using a particle tracking methodology. If dispersion is not included in simulations, RANDC becomes an advective particle tracking code similar to MODPATH, but has the added ability to release particles in a continuous mode and thus create "particle clouds" rather than traditional streamlines. Flare factors are easier to visualize and compute using particle clouds rather than streamlines. Sensitivity analyses of the vertical flare factor were also investigated using a three-dimensional flow model (MODFLOW) in conjunction with conventional particle tracking techniques (MODPATH).

The following parameters were included in the flare factor sensitivity analyses: 1) pattern scale and perimeter injection well density, 2) net production rate, 3) aquifer transmissivity, and 4) ratio of horizontal to vertical hydraulic conductivity.

The following assumptions and aquifer parameters were used in the RANDC sensitivity analyses unless otherwise stated:

- hydraulic conductivity = 33.7 gpd/ft^2 (4.5 ft/day), derived from Q-sand pilot pump test data. This value is representative of the upper range of hydraulic conductivity observed in Wellfield 1.
- effective porosity = 0.27.
- transmissivity = 1000 gpd/ft. This value is deemed representative of the Q-sand aquifer in Wellfield 1 and the Q-sand pilot.
- regional gradient of 0.002. This value is deemed representative of pre-development conditions in the Q-sand.
- storage coefficient = 0.000048. This value is representative of values derived from Q-sand multi-well pump tests.
- three year simulation period.

3.2.2.1 Wellfield Scale and Perimeter Injection Well Density

The scale of the wellfield pattern was identified as having a significant impact on the horizontal flare factor. This conclusion is logical since the horizontal flare is driven by perimeter injection wells, and the number of perimeter injection wells per unit area generally decreases as the scale of the wellfield increases. Thin, elongate wellfields have a higher number of perimeter injection wells per unit area than thick, rectangular wellfields. The logical conclusion would be that horizontal flare should decrease as the scale of the wellfield increases.

A sensitivity analysis of wellfield scale was conducted by simulating three test cases: 1) an ideal single 5-spot pattern, 2) a double pattern rectangle, and 3) a quad-pattern square. Results of these analyses are presented on Figure 3-8. Modeled particle distributions are provided in Attachment B.

Results of this analysis clearly demonstrate that the horizontal flare factor decreases significantly as the size of the wellfield increases. This "scale effect" is quantified on Figure 3-8 in terms of the number of perimeter injection wells per unit pattern area. This result suggests that small-

scale modeling of ideal wellfield patterns may not provide a reasonable estimate of commercial wellfield flare factors.

3.2.2.2 Net Production Rate

Another parameter found to have a significant impact on horizontal flare factor is the net pattern production rate. The net production rate is similar to the bleed rate, but is more representative of the magnitude of the difference between the injection and extraction rates in the wellfield. For example, a 100 gpm pattern would have a larger flare factor than an equivalent 10 gpm pattern, although both may have an identical bleed rate.

A sensitivity analysis of the net production rate (on a per well basis) was conducted by simulating two cases: 1) a 0.08 gpm/well net production rate, and 2) a 0.125 gpm/well net production rate. Both cases possess bleed rates of 0.5 %. Results of this analysis are provided on Figure 3-8. Modeled particle distributions are provided in Attachment B.

As expected, results of this analysis demonstrate that the horizontal flare factor decreases significantly as the net production rate decreases. RAMC's commercial wellfields possess relatively low net production rates. Alternatively, the Q-sand pilot wellfield possessed a much larger net production rate (greater than 1.2 gpm/well). This result suggests that care must be taken to ensure that modeled "ideal" test patterns possess equivalent net production rates as the commercial wellfields they are intended to simulate.

3.2.2.3 Aquifer Transmissivity (Thickness Variation)

Transmissivity variations were found to have a modest impact on horizontal flare factor. Transmissivity variations in the Q-sand and Wellfield 1 are not substantial; transmissivity typically varies from 500 to 1500 gpd/ft across the large majority of the wellfield, with an average of approximately 1000 gpd/ft. Variations in transmissivity are due almost entirely to changes in aquifer thickness.

A sensitivity analysis of aquifer transmissivity was conducted by simulating two cases: 1) transmissivity of 1500 gpd/ft (+50%), and 2) transmissivity of 500 gpd/ft (-50%). Transmissivity was assumed to vary due to changes in aquifer thickness (hydraulic conductivity was held constant). Modeled particle distributions are provided in Attachment B.

Results of this analysis indicate that a 50 % increase in transmissivity (thickness) results in a 30 % decrease in horizontal flare. Likewise, a 50 % decrease in transmissivity results in only a 5 % increase in pattern flare. These results suggest that the horizontal flare is not particularly sensitive to aquifer transmissivity variation relative to other parameters tested.

3.2.2.4 Kh/Kv Ratio

The ratio of horizontal to vertical hydraulic conductivity (Kh/Kv) was shown to have a significant impact on both horizontal and vertical flare factors. Although the impact of the Kh/Kv ratio on the vertical flare could be predicted, the impact on the horizontal flare was somewhat surprising.

The sensitivity analysis of the Kh/Kv ratio required that three-dimensional modeling techniques be employed. MODFLOW (McDonald and Harbaugh, 1988) and MODPATH (Pollock, 1989) were utilized for this purpose. This analysis was conducted as part of the Wellfield 1 flow model simulation described in Section 3.2.3 and Attachment C.

A sensitivity analysis of the Kh/Kv ratio was conducted by simulating three cases: 1) Kh/Kv = 1.0, 2) Kh/Kv = 10, and 3) Kh/Kv = 100. Results of this analysis are presented on Figure 3.9. MODPATH particle traces for these simulations are provided in Attachment C.

Results of this analysis indicate that horizontal and vertical flare factors decrease significantly as the Kh/Kv ratio decreases. Using a Kh/Kv ratio of 100:1, there is essentially no vertical flare and a horizontal flare of 1.7. As discussed in Section 3.2.3 of this report, a Kh/Kv ratio of 100:1 is believed to be representative for RAMC's commercial wellfield(s).

It should be noted that the total simulation time assumed in the sensitivity analyses (and wellfield simulations) does not appear to have a substantial impact on wellfield flare factors. After only months of operation, the wellfields appear to have reached a pseudo- steady state condition with respect to mine fluid expansion and the radius of influence of production/injection wells (assuming flow rates remain constant). This observation suggests that steady-state flow model simulations should provide similar results as those using transient assumptions.

3.2.3 Wellfield Flow Model Simulation and APV Calculation

The affected pore volume of RAMC's commercial Wellfield 1 was computed with the aid of a three-dimensional flow model (MODFLOW) and particle tracking techniques (MODPATH).

The MODFLOW model of Wellfield 1 consists of 154 Rows, 200 Columns, and 3 layers. Elevation maps of the top and bottom of the Q-sand were digitized and imported directly into the MODFLOW simulator (GW Vistas). The production zone was simulated as a separate (middle) layer, and was assigned a uniform thickness of 18 feet. Boundary conditions for the model were assigned as general heads (not constant heads) at sufficient distances from the wellfield to preclude negative boundary effects from injection/production. The model grid and boundary conditions are provided in Attachment C.

Wellfield operations were simulated using all 112 production wells and 212 injection wells. Based on the most recent production data, the wellfield is currently operating near its maximum

historical production rate of 1750 gpm with a 0.5 % bleed (1741 gpm injection). This combined production rate was divided evenly among production and injection wells for the simulation.

The MODFLOW model was calibrated to approximate pre-development conditions based on water levels observed in the Q-sand prior to the multi-well pump tests conducted in February of 1997 (RAMC and Hydro-Engineering, 1997). The calibrated pre-development surface is provided in Attachment C.

The following aquifer properties and assumptions were used in the wellfield simulation:

- Kh = 2.74 ft/day. This value represents the geometric mean of hydraulic conductivity developed from the Q-sand multi-well pump tests.
- Kv = 0.0274 ft/day (calculation discussed below).
- Porosity = 0.27 (for MODPATH simulations).
- Steady-state flow field
- Total particle tracking period of 2.5 years (for MODPATH simulations)

The Kh/Kv ratio has been shown to have a significant impact on horizontal and vertical flare factor. However, no direct measurements of Kv are available. Despite this limitation, the Kv of the Q-sand can be estimated to a reasonable degree by estimating the Kv of individual sublayers in an ideal section. The Kv of a stratified sequence of porous media can be computed as the harmonic mean of individual sublayers (Isaaks and Srivastava, 1989; McDonald and Harbaugh, 1988), or:

$$1 / Kv = 1/n \sum_{i=1}^{n} (1 / Kv_i) \qquad (4)$$

where Kv_i is the vertical permeability of the i sublayer. A representative section of the Q-sand typically contains an interbedded sequence of fluvial sediments consisting of approximately 45 feet of clean sand and 5 feet of interbedded claystone/shale/lignite. By dividing the typical Q-sand section into 10 sublayers of 5-foot thickness, the result would be nine layers of sand (45 feet) and one layer of clay (5 feet). By allowing the Kv of the sand layers to be 2.74 ft/day (equal to Kh), and the Kv of the claystone layer to be 0.0027 ft/day (representing the upper range of values for the R- and P-shale from pump test analysis), the average Kv for the Q-sand computed from equation (4) is 0.027 ft/day. This equates to a Kh/Kv ratio of 100:1, and is typical of many fluvial depositional environments containing alternating sand/clay layers.

Results of the MODFLOW wellfield simulation were imported into the USGS MODPATH particle tracking model included with the GW Vistas simulator. Ten particles were placed at each injection well location and tracked forward for a period of 2.5 years. MODPATH particle traces for the wellfield simulations are included in Attachment C.

Results of the MODFLOW/MODPATH simulation indicates a flare factor of 1.7 is appropriate for the commercial wellfield (vertical flare factor ≅ 0). This result is higher than RAMC's

original estimate of 1.32, but significantly lower than WDEQ/LQD of 2.94. The resultant affected pore volume for Wellfield 1 from equation (3) is 68,920,890 gallons.

3.3 Wellfield Restoration Timing

Pore volume requirements presented in section 3.1 can be converted to restoration time requirements given a knowledge of the affected pore volume and planned wellfield production rates. The following time periods apply to each stage of restoration:

- Stage I - 3PVs @ 1015 gpm = 141.5 days
- Stage II - 1 PV @ 1015 gpm = 47.2 days
- Stage III - 2 PVs @ 1000 gpm = 95.7 days
- Total 6 PV restoration period = 284.4 days

Table 3-2 presents restoration time requirements for key constituents to achieve class-of-use and baseline standards. Figures 3-10 through 3-15 show wellfield restoration curves for key constituents, and the time required to reach restoration objectives. Based on these results, the wellfield will be restored to class-of-use within 160 days, and will be restored to baseline conditions for all constituents within 210 days. This represents approximately 4.4 pore volumes of circulation.

3.4 Applicability of Results to Other Wellfields

Pore volume requirements developed for Wellfield 1 are generally applicable to all of RAMC's Smith Ranch commercial wellfields. Small differences may exist due to variations in initial and baseline target concentrations between wellfields.

Results of the flare factor sensitivity analyses indicate that the wellfield flare factor is a linear function of the wellfield scale, net production rate, and the ratio of horizontal to vertical hydraulic conductivity of the aquifer. The Smith Ranch commercial wellfields all possess similar net production and bleed rates (0.08 gpm/well), so this parameter is not a variable. Aquifer test data indicate the hydraulic conductivity of the Ft. Union sands are very similar (e.g. 2 to 5 ft/day average), and the construction of injection and production intervals are also very similar (18 ft. open interval, on the average). This means the production zone transmissivity is very similar for all of the Smith Ranch wellfields. Furthermore, because the wellfields are all located within similar fluvial sequences of the Ft. Union formation, they can be assumed to possess similar Kh/Kv ratios. Given these observations, differences in flare factor between wellfields should be primarily the result of differences in wellfield scale.

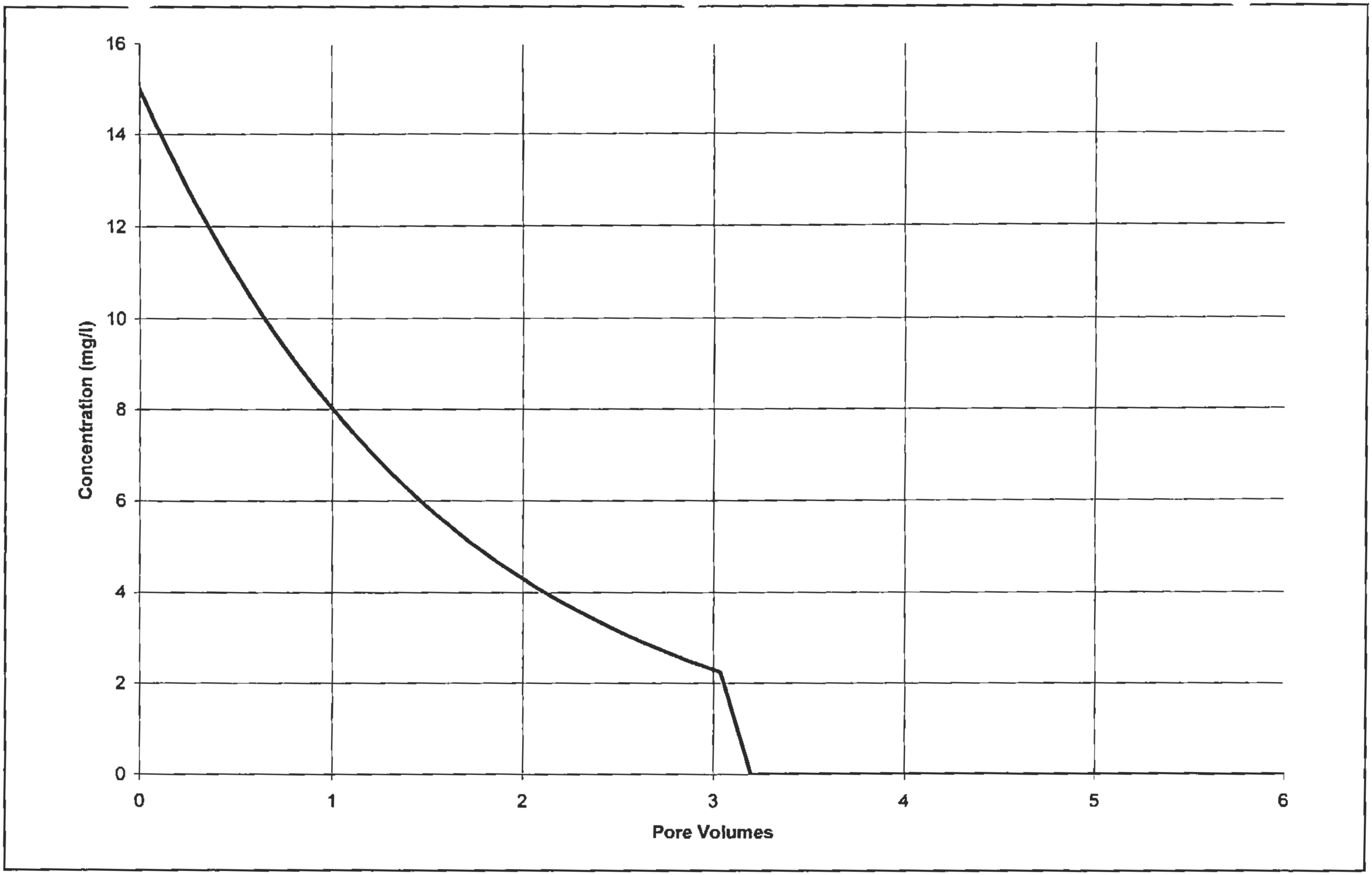
Figure 3-16 provides the predicted flare factor versus wellfield scale (number of perimeter injection wells/ft^2) constructed from results of the sensitivity analyses. Figure 3-16 assumes a net production rate of 0.08 gpm/well and a Kh/Kv ratio of 100:1 (e.g. no vertical flare). These results can be used to estimate appropriate flare factors for remaining commercial wellfields (other than Wellfield 1) at the Smith Ranch facility.

Figure 3-16 assumes that the wellfield flare factor cannot be less than 1.0 (although flare factors less than 1.0 can be shown to exist). Therefore, as a conservative measure, the linear relationship between flare factor and wellfield scale was assumed to be strictly valid only for perimeter injection well densities less than about 1.5e-04 wells/ft^2. It is assumed that the flare factor approaches 1.0 asymptotically at very low injection well densities.

Table 3-2. Predicted Wellfield 1 Restoration Timing

Constituent	Restoration Target (Background)	Number of Pore Volumes to Meet Target	Time Required to Meet Target (Baseline), days	Restoration Target (Class of use[a])	Number of Pore Volumes to Meet Target	Time Required to Meet Target (Class-of-Use),days
U	0.168	3.2	150	5	1.8	86
Se	0.001	3.2	150	0.01	2.3	109
Cl	4.176	4.4	210	250	0	0
SO_4	113.125	3.8	179	250	2.5	117
HCO_3	228.194	2.3	109	na	na	na
Ca	72.617	3.8	179	na	na	na
Na	22.525	3.2	150	na	na	na
As	0.001	3.0	141	0.05	0	0
B	0.100	3.2	150	0.75	0	0
Fe	0.065	0	0	0.3	0	0
Mn	0.022	4.4	210	0.05	3.4	160
Mg	17.364	3.2	150	na	na	na
K	7.269	3.2	150	na	na	na
F	0.322	3.2	150	2.4	na	na
SiO_2	16.975	3.2	150	na	na	na
Zn	0.010	3.2	150	5	0	0

[a] – standards listed are for Wyoming Class I ground water, although baseline wellfield ground water does not meet this standard due to excessive radium.



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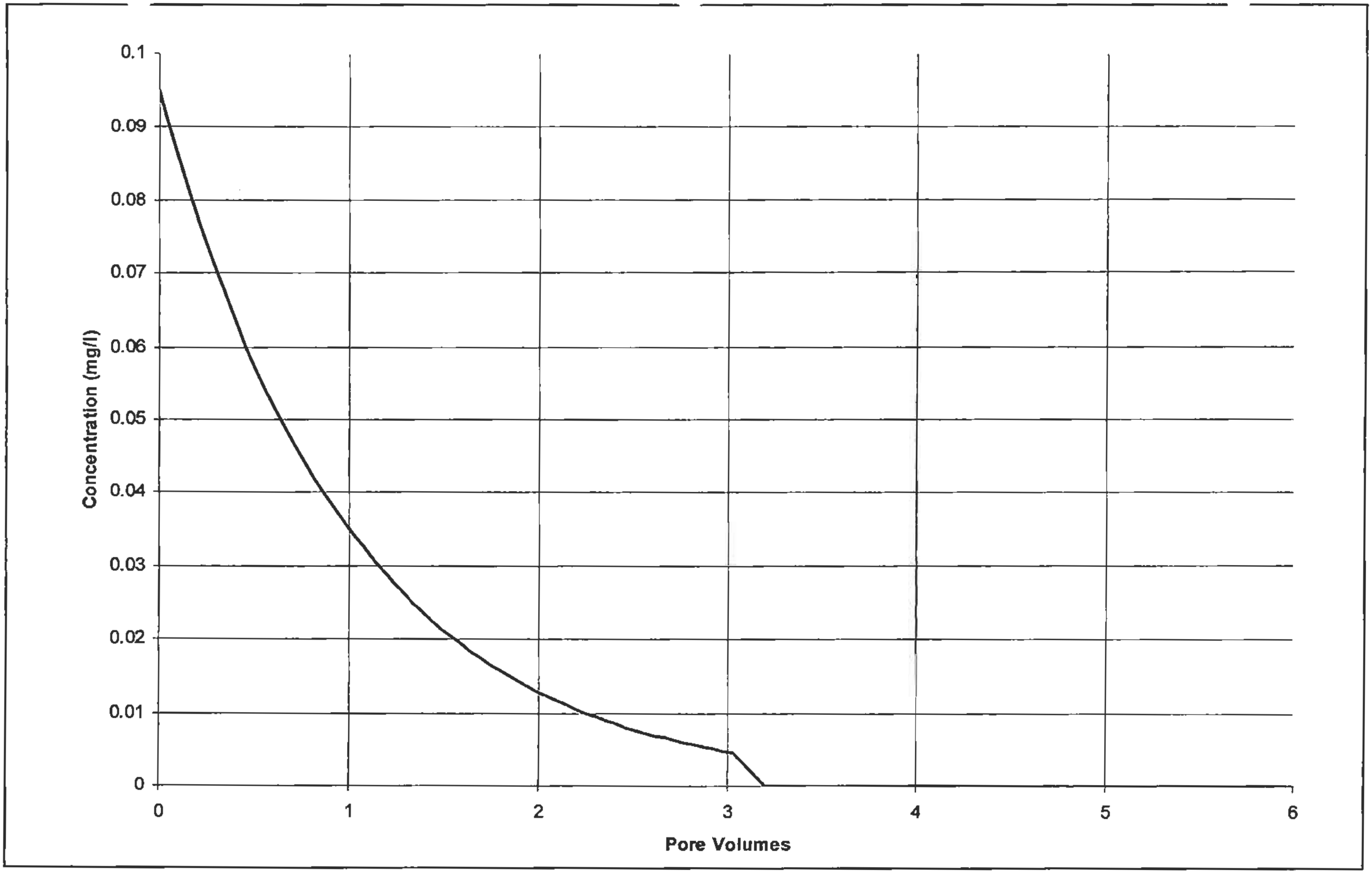
RAMC Smith Ranch Facility

Figure 3-1. Simulated uranium flushing curve, commercial wellfield restoration

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt

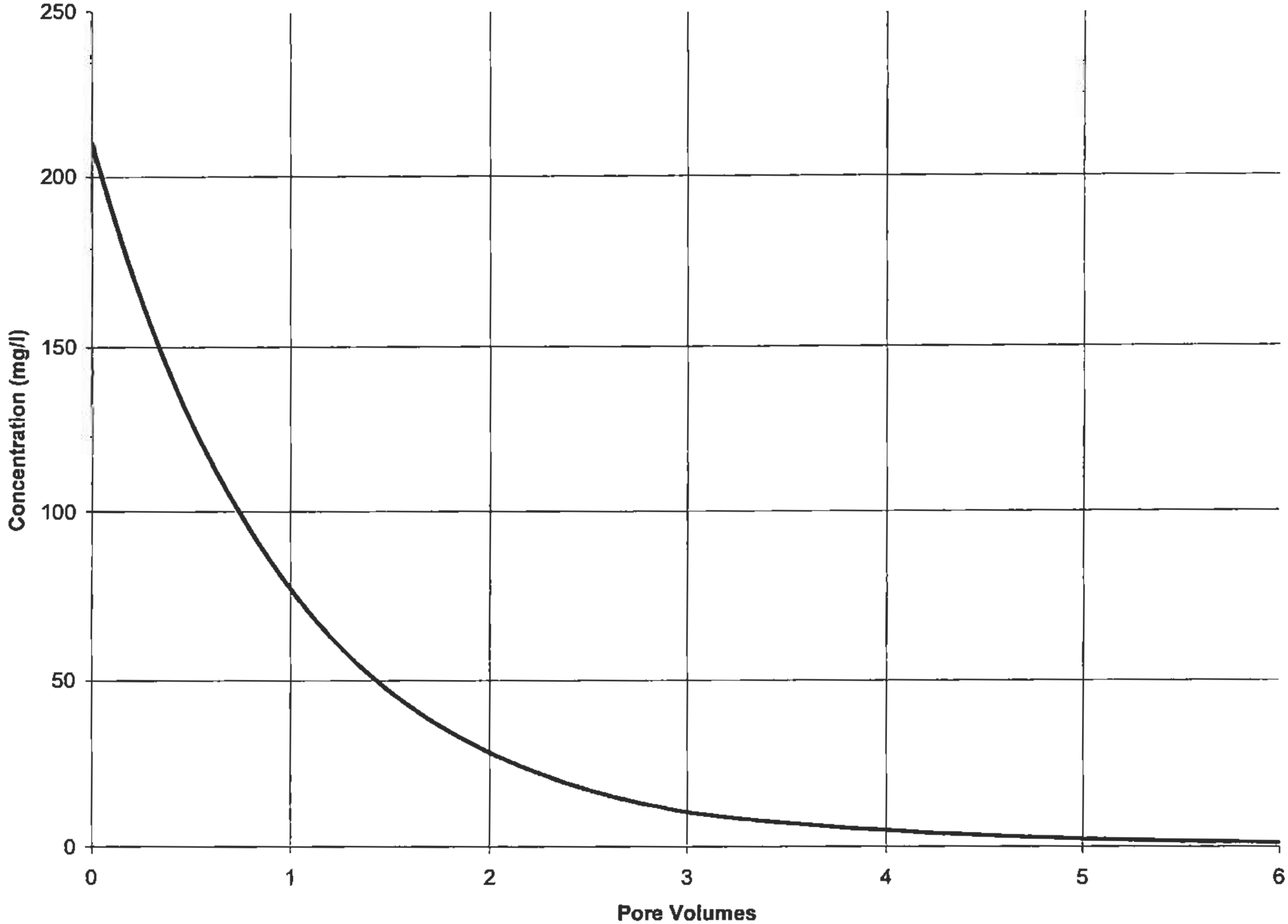


Lewis Water Consultants
Environmental Science/Engineering/Modeling

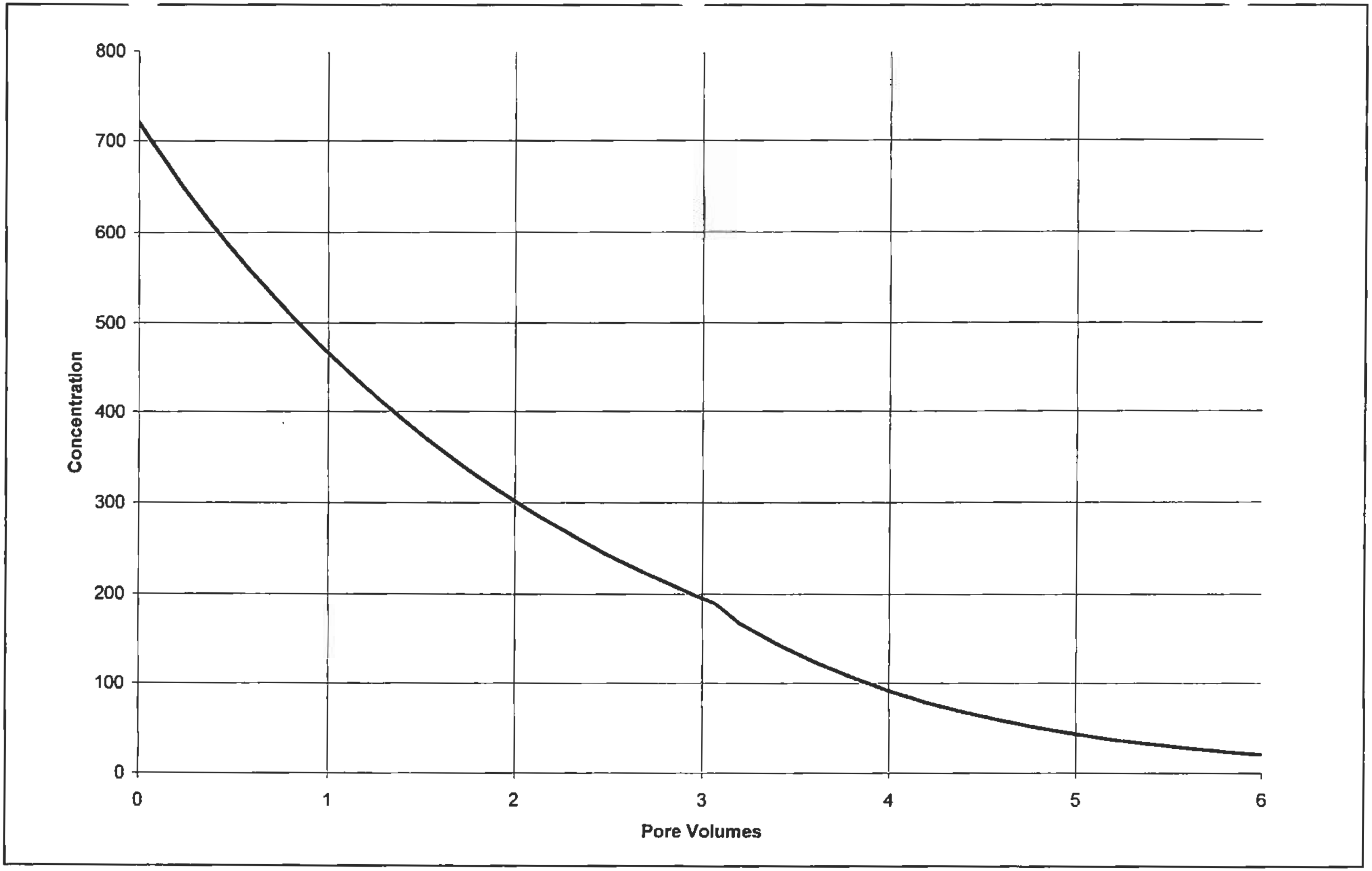
RAMC Smith Ranch Facility

Figure 3-2. Simulated selenium flushing curve, commercial wellfield restoration

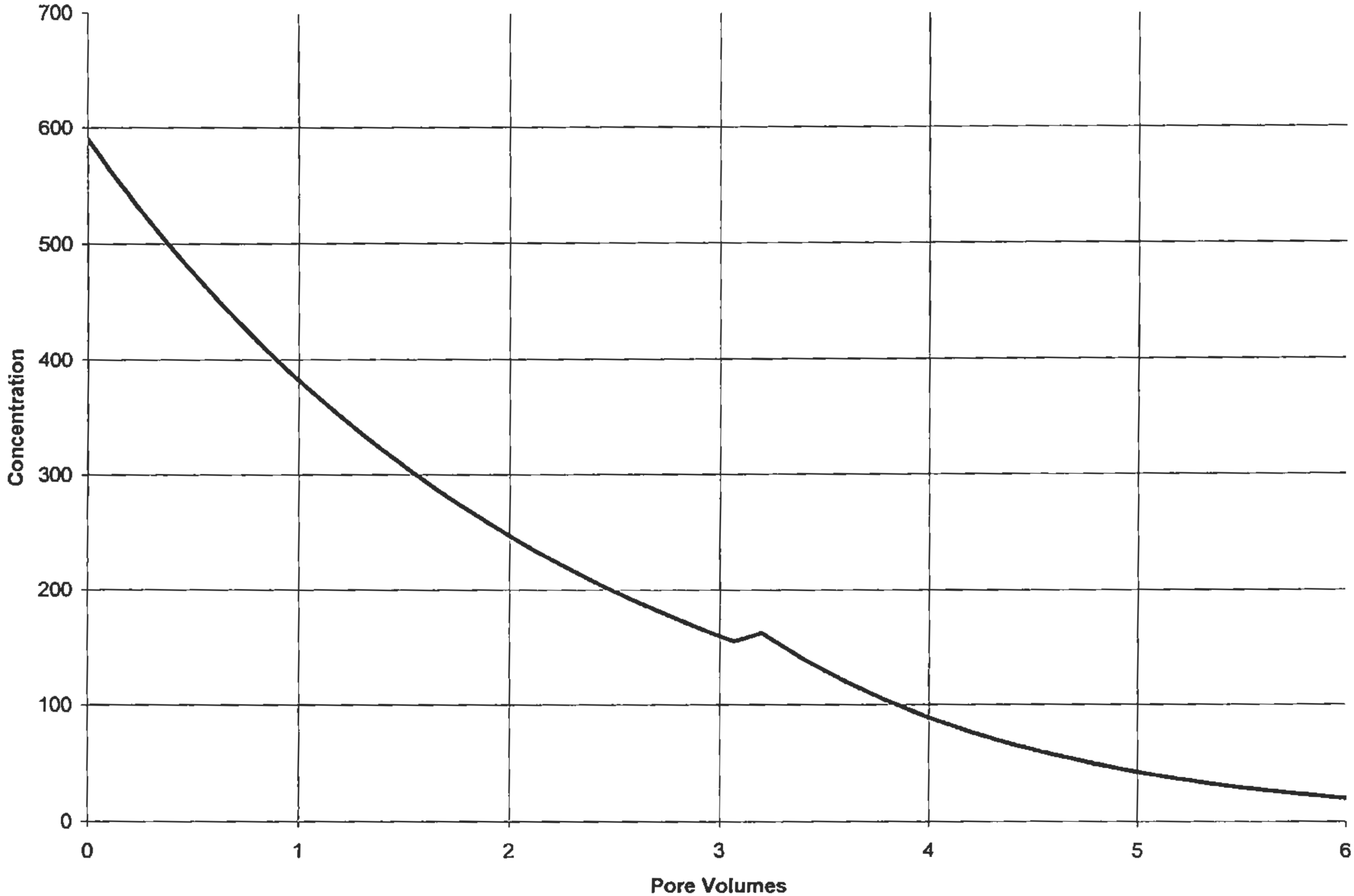
Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt



Lewis Water Consultants *Environmental Science/Engineering/Modeling*	**RAMC Smith Ranch Facility** Figure 3-3. Simulated chloride flushing curve, commercial wellfield restoration	Date: **9/14/99** Project: **RAMC Wellfield Evaluation** File: **land.ppt**



Lewis Water Consultants Environmental Science/Engineering/Modeling	**RAMC Smith Ranch Facility** Figure 3-4. Simulated sulfate flushing curve, commercial wellfield restoration	Date: **9/14/99** Project: **RAMC Wellfield Evaluation** File: **land.ppt**



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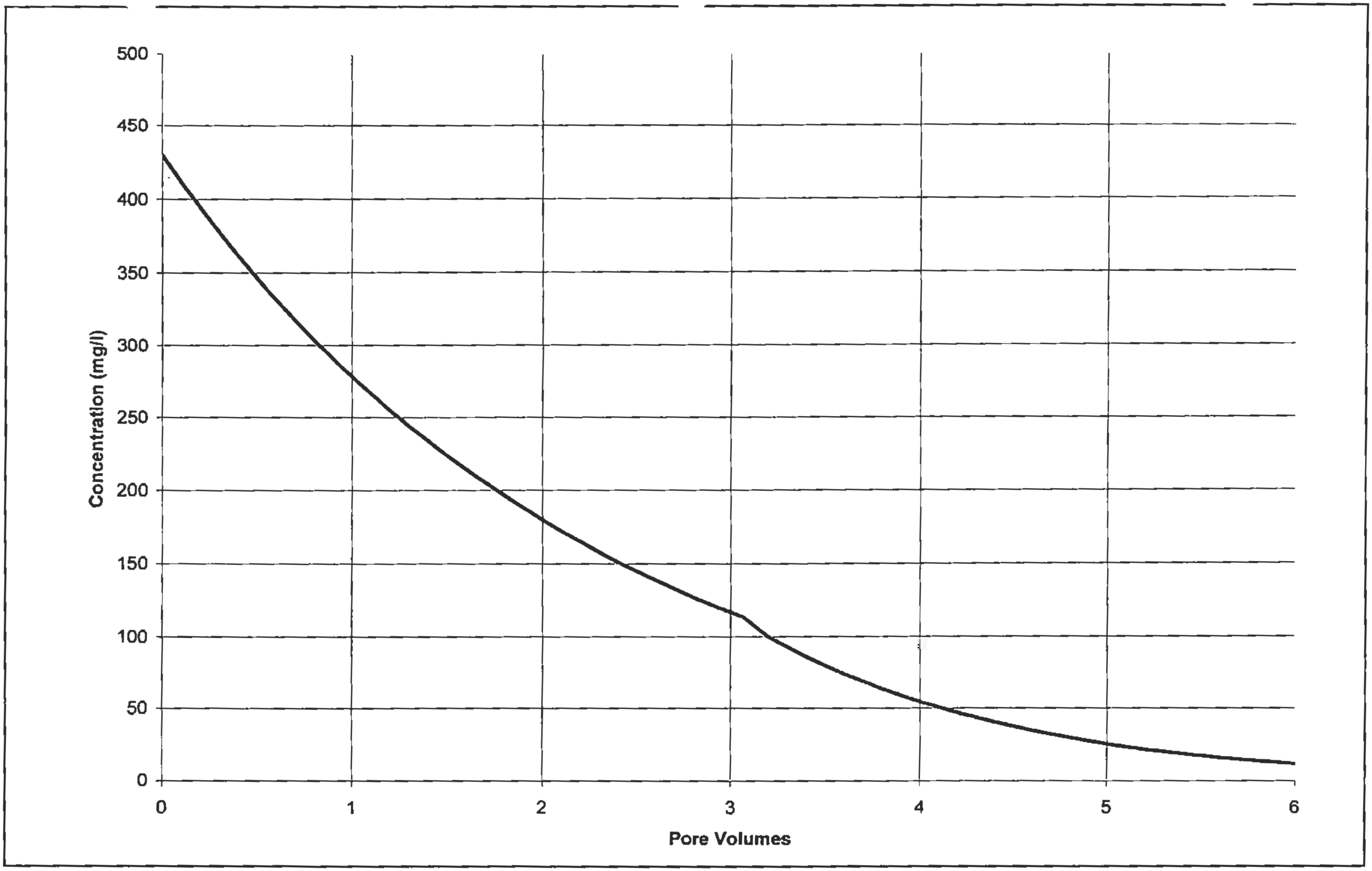
RAMC Smith Ranch Facility

Figure 3-5. Simulated bicarbonate flushing curve, commercial wellfield restoration

Date: 9/14/99
Project: RAMC Wellfield Evaluation
File: land.ppt



Lewis Water Consultants *Environmental Science/Engineering/Modeling*	**RAMC Smith Ranch Facility** Figure 3-6. Simulated calcium flushing curve, commercial wellfield restoration	Date: 9/14/99 Project: **RAMC Wellfield Evaluation** File: **land.ppt**

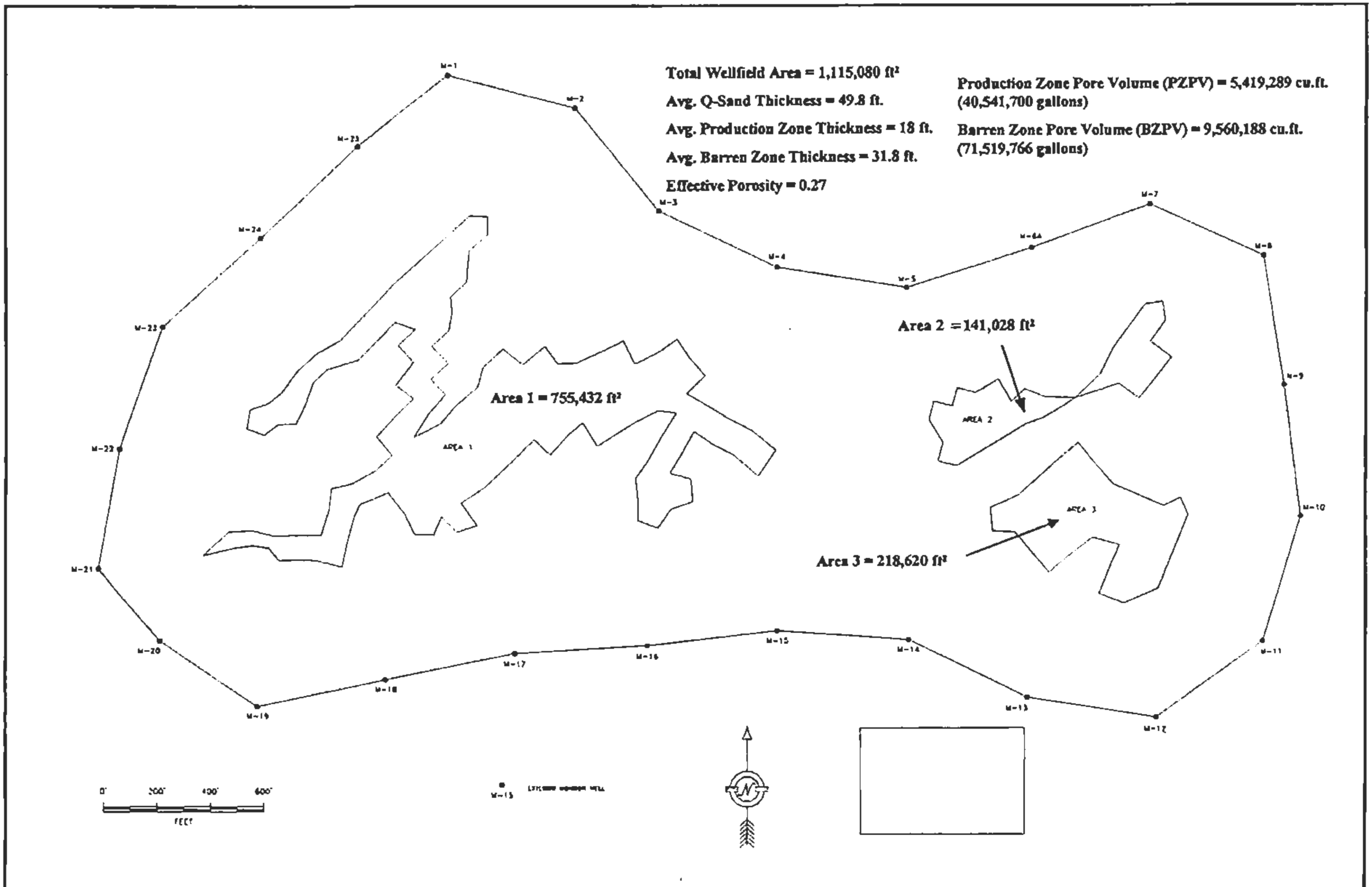


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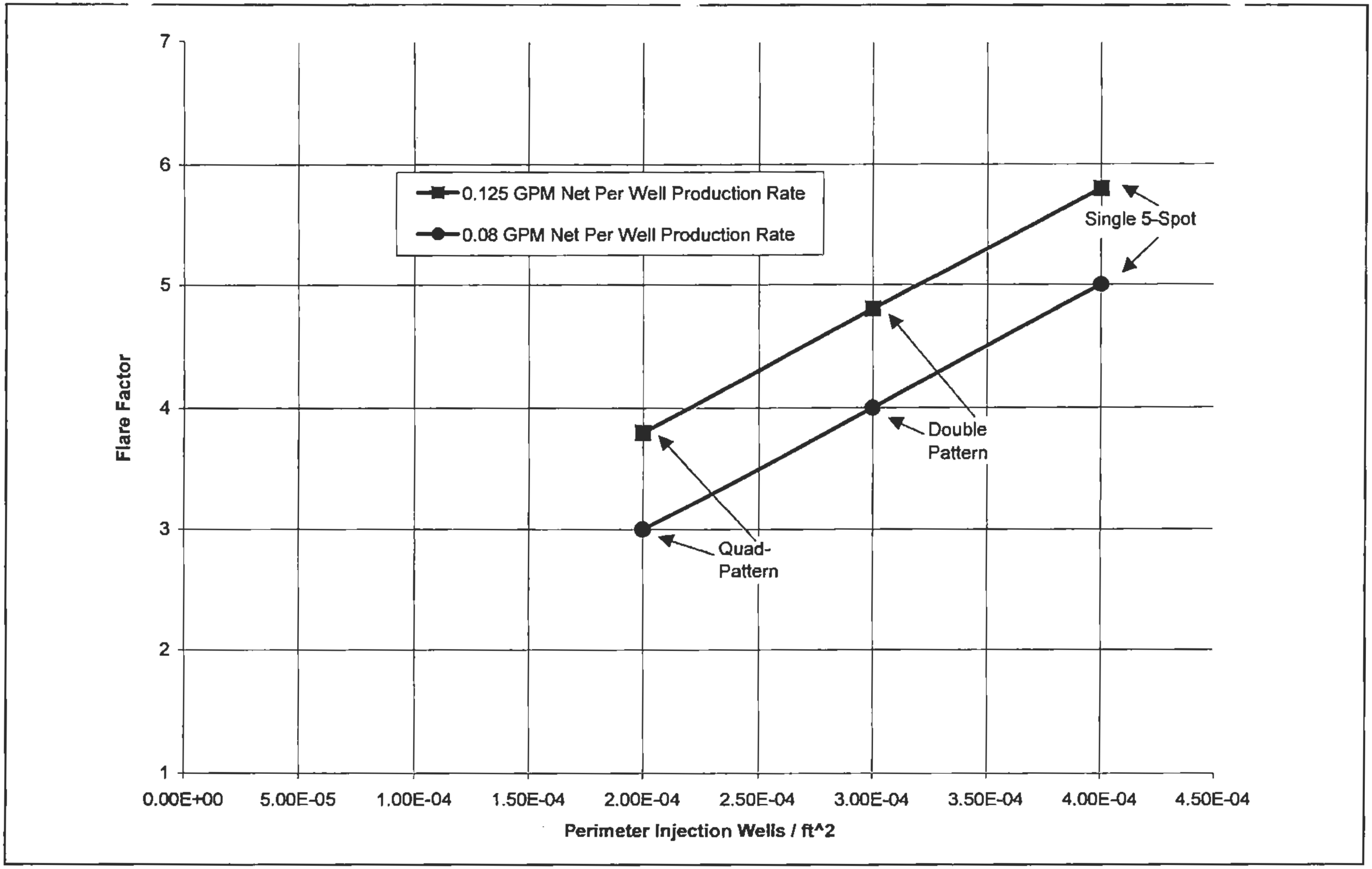
Figure 3-7. Areas and pattern volumes for Wellfield 1

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt



Lewis Water Consultants Environmental Science/Engineering/Modeling	**RAMC Smith Ranch Facility** Figure 3-8. Flare factor sensitivity analyses, pattern scale and net production rate	Date: 9/14/99 Project: RAMC Wellfield Evaluation File: land.ppt

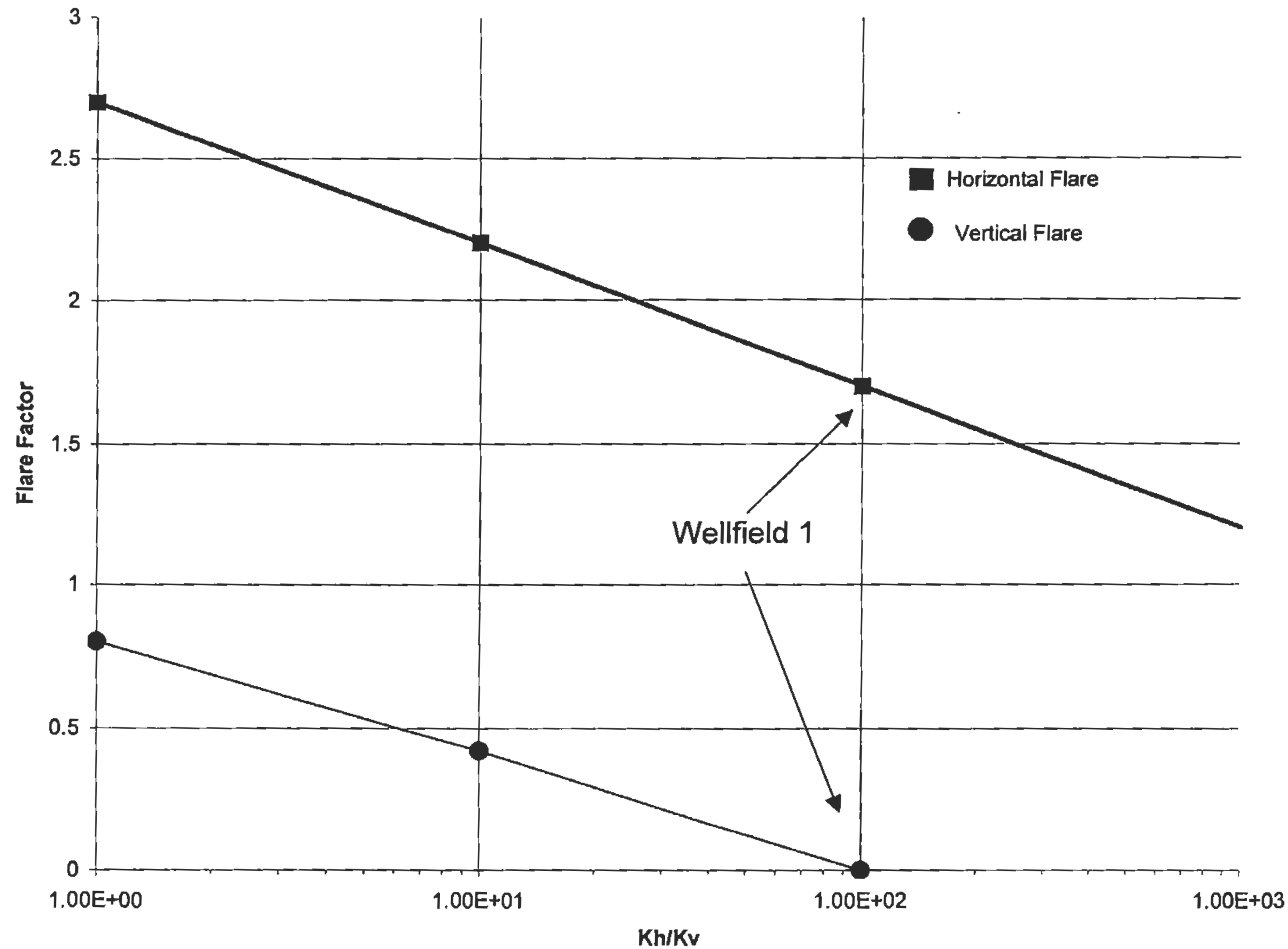


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Figure 3-9. Flare factor sensitivity analyses, Kh/Kv ratio

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt

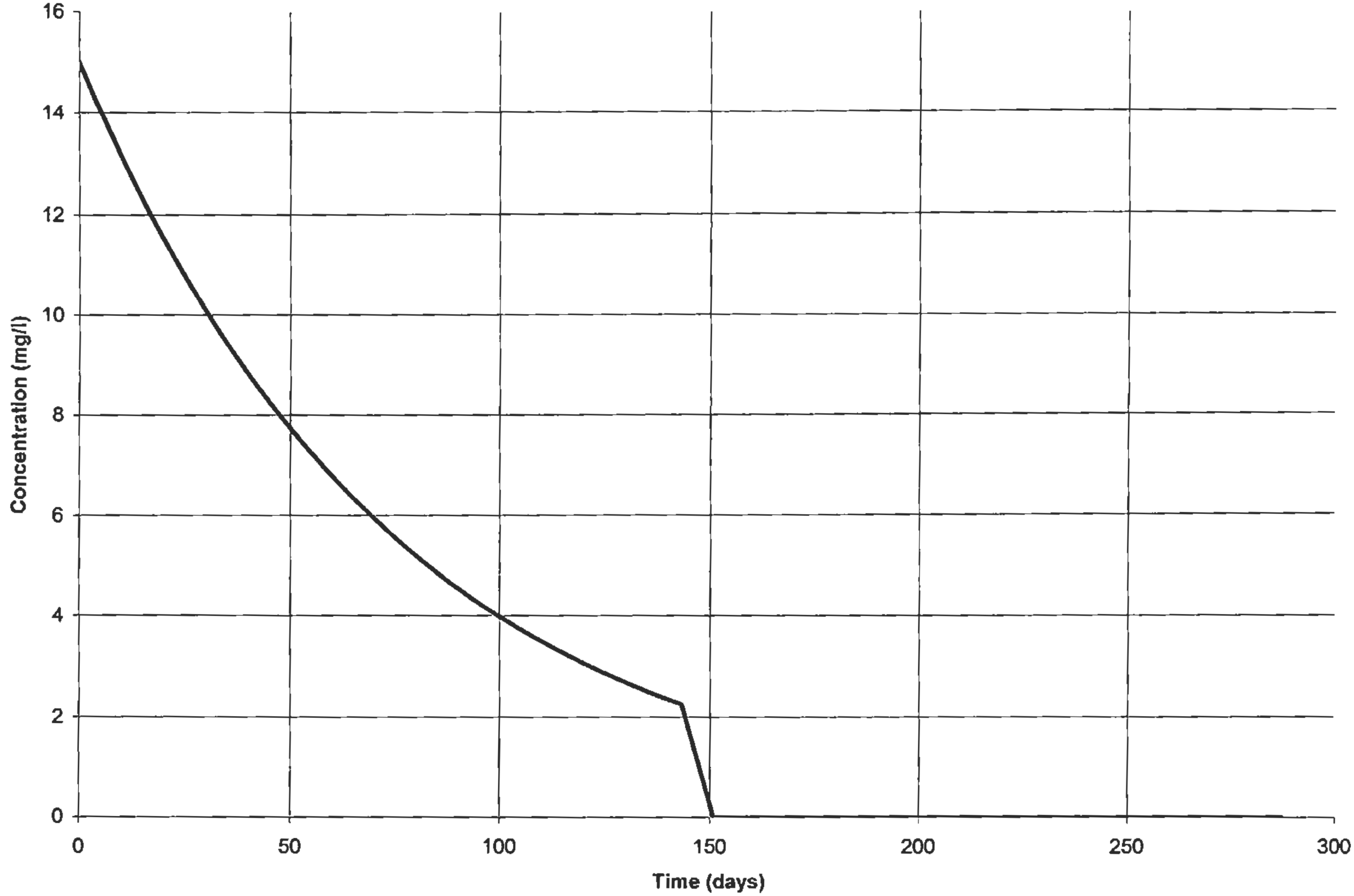

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Figure 3-10. Simulated uranium restoration curve, commercial Wellfield 1

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt

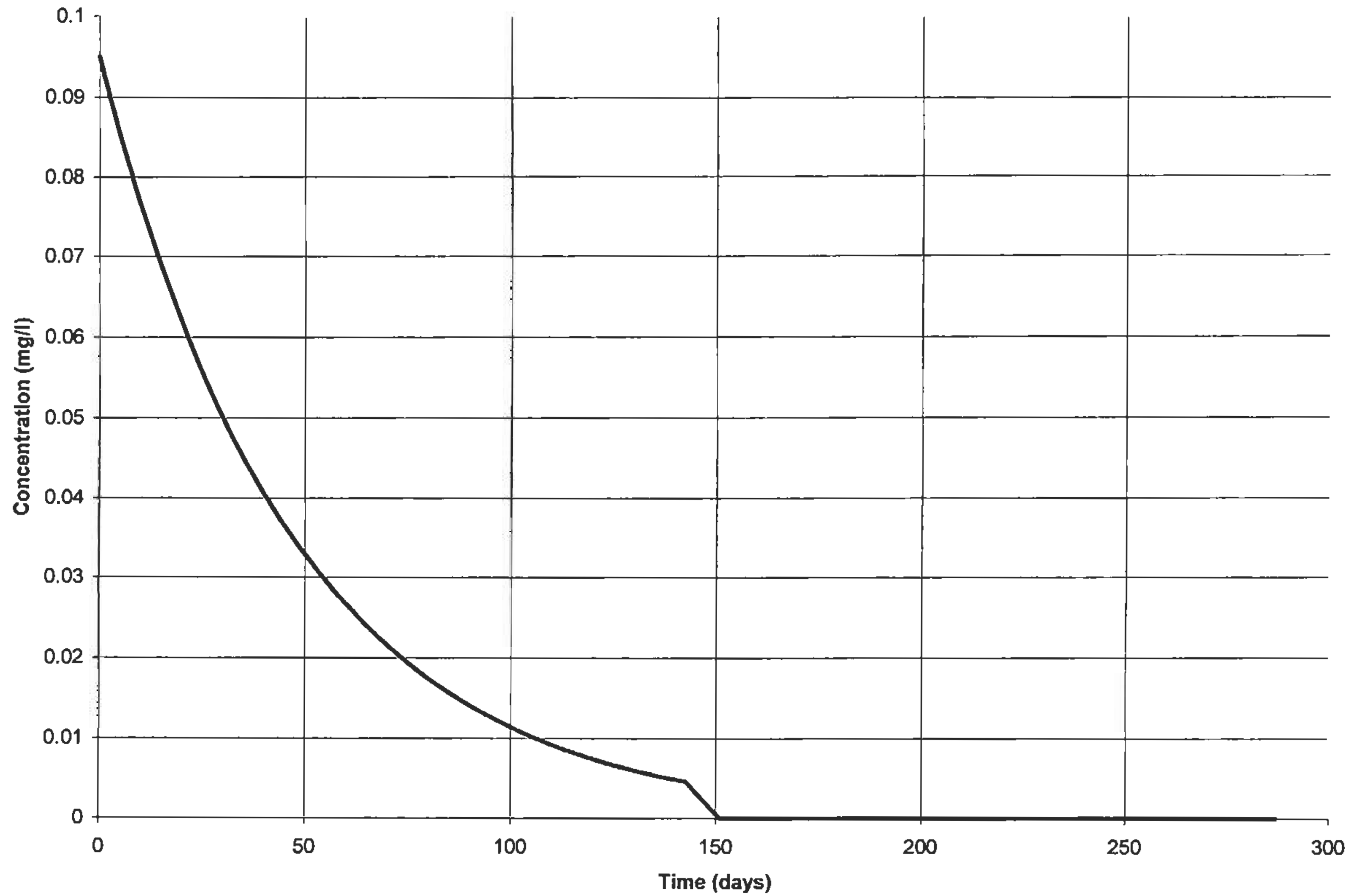

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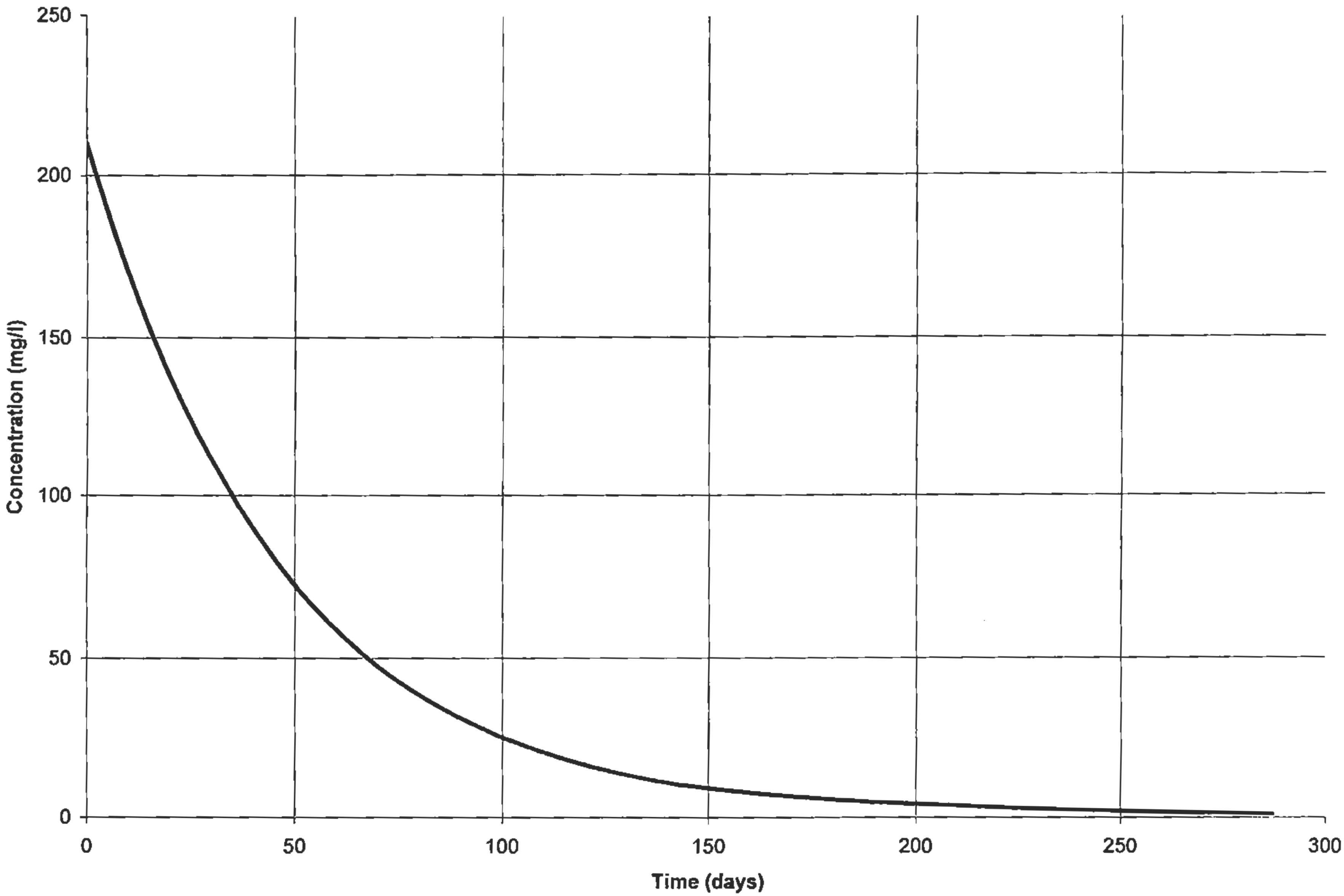
Figure 3-11. Simulated selenium restoration curve, commercial Wellfield 1

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt



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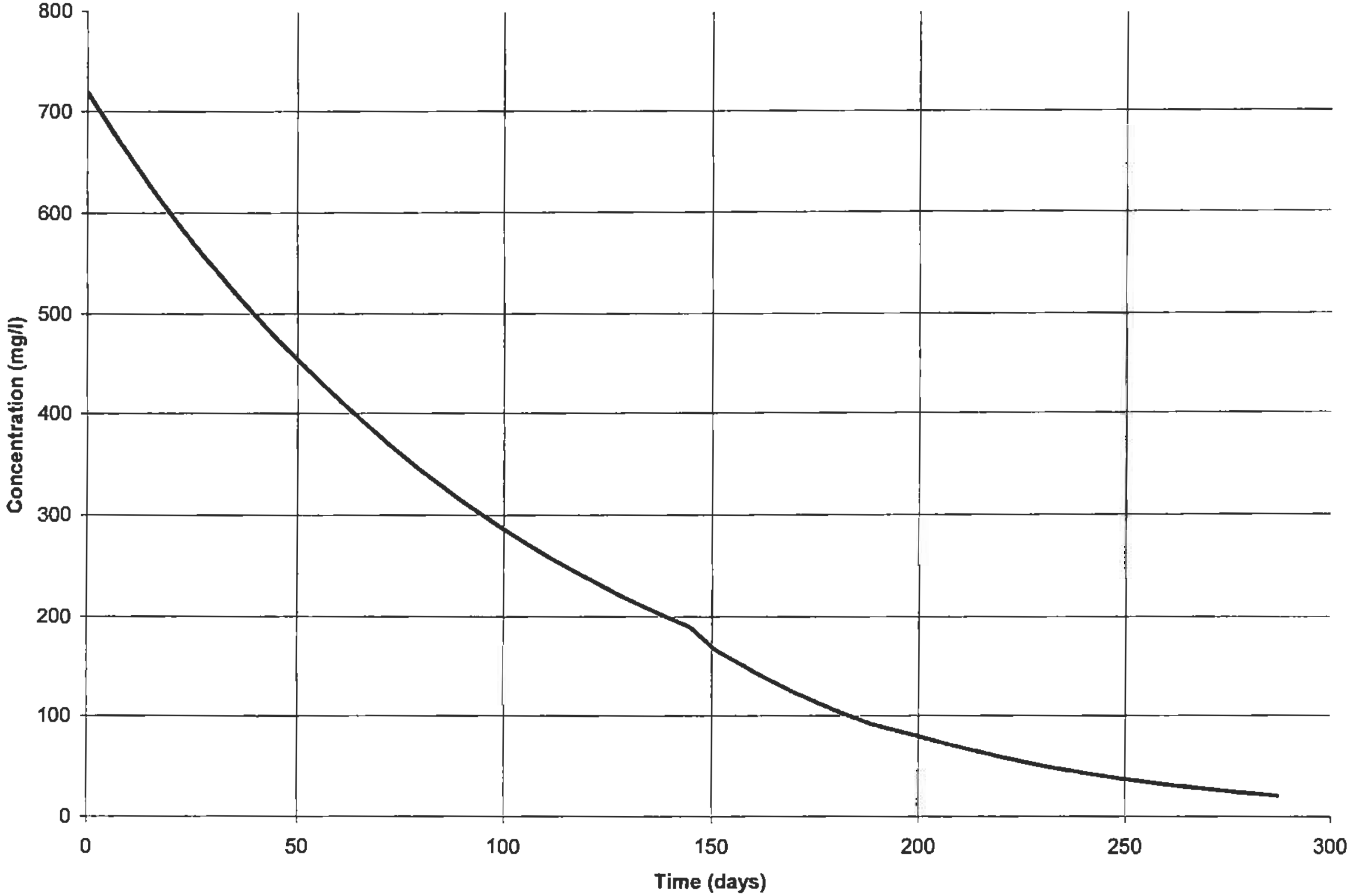
RAMC Smith Ranch Facility

Figure 3-12. Simulated chloride restoration curve, commercial Wellfield 1

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt



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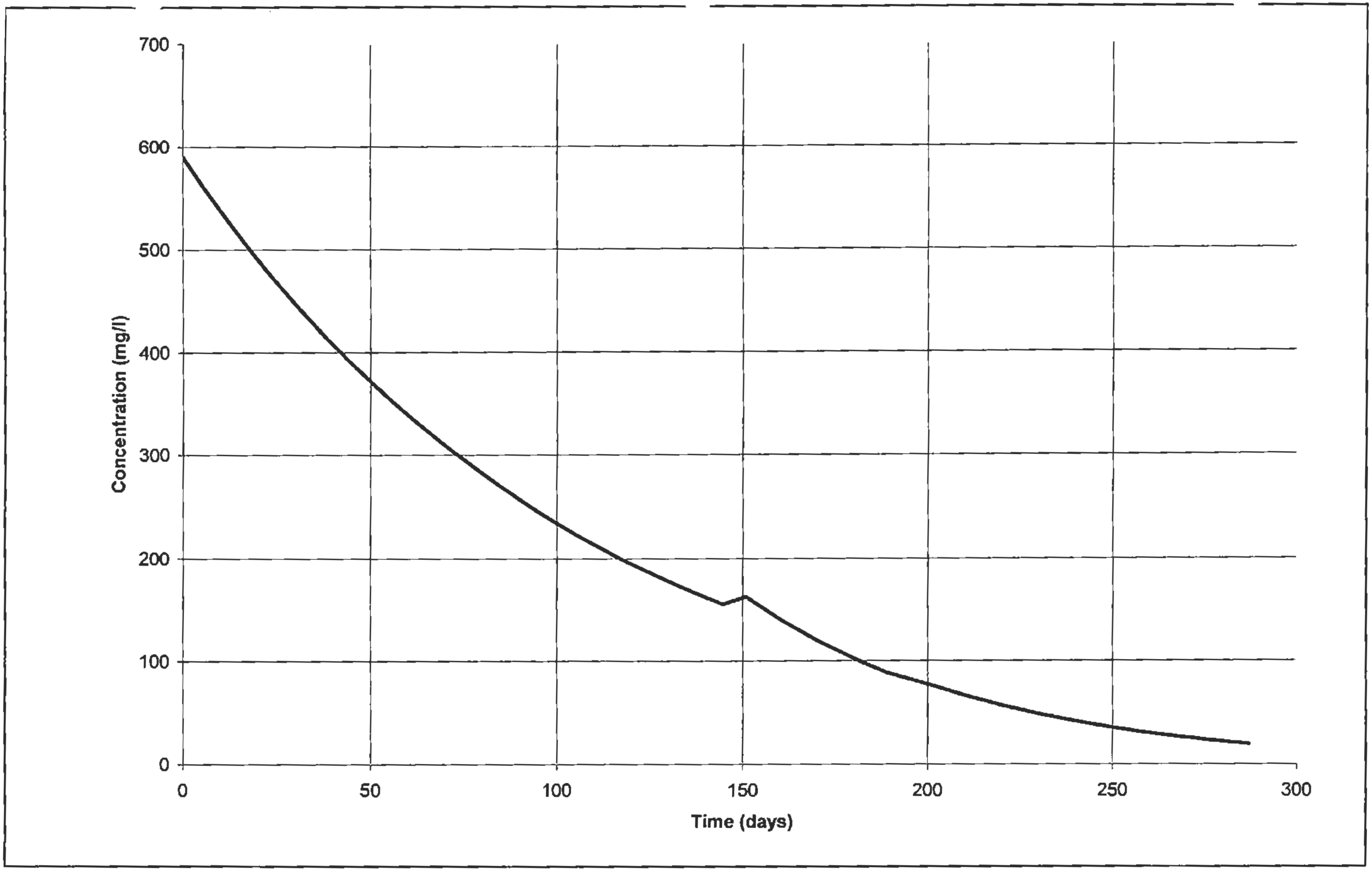
RAMC Smith Ranch Facility

Figure 3-13. Simulated sulfate restoration curve, commercial Wellfield 1

Date:	9/14/99
Project:	RAMC Wellfield Evaluation
File:	land.ppt



Lewis Water Consultants *Environmental Science/Engineering/Modeling*	**RAMC Smith Ranch Facility** Figure 3-14. Simulated bicarbonate restoration curve, commercial Wellfield 1	Date: 9/14/99 Project: RAMC Wellfield Evaluation File: land.ppt

4.0 REVIEW OF WDEQ/LQD METHODOLOGY

LWC has reviewed the basic technical approach used by the WDEQ/LQD to estimate affected aquifer pore volumes. Correspondence between WDEQ/LQD and RAMC was reviewed, as well as a WDEQ/LQD memorandum concerning pore volume estimates at PRI's Highland facility. Correspondence between WDEQ/LQD and RAMC indicates that LQD has conducted limited modeling of the Smith Ranch wellfield(s), and has used this work to estimate affected pore volumes and bonding requirements for RAMC. Unfortunately, this modeling work has not been made available for review to RAMC or its consultants. Despite this limitation, it is RAMC's understanding that the same basic methodology used to evaluate the Highland facility has been applied to evaluate the Smith Ranch wellfields. Therefore, the following review is believed to be applicable to LQD's methodology as applied to the Smith Ranch facility.

The following are technical concerns and limitations identified during the review of the WDEQ/LQD methodology:

- the WDEQ/LQD has based flare factor estimates upon small-scale flow modeling of ideal pattern geometries and sub-areas of large-scale wellfields. Sensitivity analyses presented in this document demonstrate that wellfield flare decreases substantially with increasing scale. In the opinion of LWC, flare factors developed by WDEQ/LQD are overestimated due (in part) to the small-scale nature of the modeling. In addition, large, rectangular, and continuous wellfields (e.g. Wellfield 3) will have lower flare factors than thin, elongate, and discontinuous wellfields (such as those modeled at PRI), all other factors being equal.

- the WDEQ/LQD methodology is based entirely upon the prediction of the affected pore volume; the number of pore volumes required to restore the wellfield has not been critically evaluated. This report documents that pore volume requirements at the RAMC facility (and possibly other facilities) are significantly lower than previously estimated.

- the WDEQ/LQD methodology does not consider the effect of reducing agents and RO permeate in reducing wellfield restoration time (and cost). This report documents the substantial decrease in pore volume requirements observed due to the use of reducing agents and RO injection.

- wellfield flare factors were estimated by LQD by plotting velocity vectors generated from the flow model simulator (Visual MODFLOW). This procedure is subject to significant over-estimation of wellfield flare due to the non-continuous nature of the velocity plots and the judgement required to interpret the results. The more accurate and technically defensible methodology involves transient particle tracking using a program such as MODPATH or PATH3D.

- The statement by WDEQ/LQD that "MODPATH is limited to steady-state conditions" (page 8, LQD's June 1996 Highland facility memorandum) is not entirely correct since more current versions readily incorporate transient pathline analysis. In addition, older versions of MODPATH can be used to conduct transient particle tracing using steady-state results from the groundwater flow model. Constant-discharge, transient flow simulations conducted over extended periods of time (e.g. years) have no technical advantage over steady-state simulations. Psuedo-steady flow is achieved within weeks or months of continuous wellfield operation.

- LQD presented pore volume estimates for RAMC's Wellfield 1 containing large vertical flare factors (e.g. 1.0). Analyses conducted as part of this document suggest that such large vertical flare factors can only be obtained if the ratio of Kh/Kv is assumed to be near 1:1. Given the depositional environment and observed presence of claystone/lignite in typical Q-sand sections, such a high Kh/Kv ratio cannot be supported. Furthermore, geophysical logs obtained from post-coring pilot operations indicate that mining solutions have not migrated vertically beyond the production interval (conductivity profiles show absence of significant TDS in the barren zone relative to the production interval). Calculations presented in this document suggest a more realistic estimate of the Kh/Kv ratio is 100:1.

5.0 SUMMARY AND CONCLUSIONS

RAMC has completed a detailed evaluation and simulation of commercial wellfield restoration at the Smith Ranch facility. Previous estimates of wellfield restoration conducted by WDEQ/LQD have relied solely on estimates of affected pore volume (flare factor) derived from results of limited, small-scale groundwater flow modeling. RAMC believes that flare factors developed by WDEQ/LQD have been over-estimated due to 1) the small-scale nature of the flow modeling, 2) the methodology employed to estimate the flare factor (plotting of velocity vectors), and 3) inappropriate assumptions used to calculate the vertical flare. Further, the WDEQ/LQD methodology does not consider all factors necessary to estimate wellfield restoration with reasonable accuracy. In contrast, RAMC's evaluation includes a detailed examination of all factors affecting wellfield restoration timing (and cost), including:

- pore volume flushing requirements for RAMCs commercial wellfield(s)
- the affect of reducing agents and RO treatment on wellfield restoration
- the affected pore volume size as computed by full-scale simulation of a commercial wellfield, and
- the sensitivity of the flare factor to wellfield scale (and other parameters)

Results of this work can be used to establish reliable estimates of restoration timing and cost for all of RAMCs commercial wellfields. Given these results, wellfield restoration at the Smith Ranch facility can be accomplished well within original time and cost estimates. Based on these findings, there is no technical basis to support the increased affected pore volume sizes proposed by WDEQ/LQD.

6.0 REFERENCES

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Attachment A

PHREEQC Model Description and Application

ATTACHMENT A – PHREEQC MODEL DESCRIPTION AND APPLICATION

The equilibrium geochemical code PHREEQC (Parkhurst 1995) was used to simulate ground water quality in Wellfield 1 during future aquifer restoration. This attachment provides supporting documentation and describes the assumptions used in the modeling.

PHREEQC is a widely used code developed and supported by the U.S. Geological Survey. Version 1.6 of the model, released on 1/16/97, was used. PHREEQC calculates the speciation of constituents in solutions, performs mixing of solutions, identifies solid phases that are oversaturated and thus thermodynamically able to precipitate, and removes constituents from solution as solids in the phases specified by the user, among other capabilities. PHREEQC is an equilibrium model and thus may not adequately simulate reactions with slow rates, but is useful for identifying and quantifying reactions likely to control dissolved concentrations of key constituents.

ASSUMPTIONS USED FOR SMITH RANCH SIMULATIONS

The first three pore volumes of ground water restoration using ground water sweep were simulated using the mixed linear reservoir model for U, Cl, SO4, HCO3, Se, Ca, and Mn as described in the report. PHREEQC was used for the fourth through sixth pore volumes for these constituents, and for the entire restoration period for all other constituents.

Injected water (or baseline water for the first three pore volumes) was mixed with the water from the preceding step of the simulation in a 20:80 ratio to provide smooth interim concentrations for graphing. Other mixing ratios were also investigated, but did not significantly affect the model predictions. The permeate from reverse osmosis (RO) water treatment was mixed with extracted water from the preceding step in 70:30 ratio for pore volumes 4 through 6, as specified in the restoration plan, to prevent excessive leaching of aquifer solids by pure permeate. During the fourth pore volume (steps 3.2 through 4.0) H_2S was added to the injection water at a sulfide concentration of 250 mg/L to cause the reduction of uranium and other redox-sensitive species to their more reduced, less soluble forms.

The PHREEQC simulations were run using the thermodynamic database from the equilibrium speciation model WATEQ4F (Ball and Nordstrom, 1991). The WATEQ4F database includes data for U, As, and Se, which are not in the PHREEQC database, and is fully compatible with PHREEQC.

MINERALS SELECTED AS SOLUBILITY CONTROLS

Because it is known from pilot test core studies that uranium minerals will still be present at the beginning of wellfield restoration, uraninite (the assumed predominant uranium mineral in the ore) was specified as present in the system. Pyrite (FeS_2), native selenium, and orpiment (As_2S_3) were allowed to precipitate if supersaturation was reached, thus

controlling the dissolved concentrations of Fe, S, Se, and As. While orpiment most commonly forms under hydrothermal conditions, it may form in the aquifer after the addition of a reductant.

Desorption from mineral surfaces, which may occur during aquifer restoration, could not be simulated by PREEQC due to the lack of data on aquifer solids chemistry. PHREEQC therefore predicted conservative behavior for those constituents not constrained by mineral solubility and redox controls. Therefore, the behavior of key constituents during the first three pore volumes (groundwater sweep) were more appropriately simulated by the mixed linear reservoir (MLR) model, which accounted for desorption through the use of the constituent retardation factor.

MODEL RESULTS

The input file generated for simulation of restoration in pore volumes 1 through 3 is included as Appendix A-1, and for pore volumes 4 through 6 is included as Appendix A-2. Tabulated concentrations for the modeled constituents are presented in Table A-1 for constituents not simulated by the MLR model, and in Table A-2 for pore volumes 4-6 (all constituents). Graphs of key constituents are presented in the text of the report.

The sensitivity of PHREEQC predictions to variations in baseline water redox conditions and added sulfide concentration were assessed. Varying the input p_e did not significantly affect the predicted speciation and solubilities. Varying the added sulfide concentration indicated that the concentrations of uranium, selenium, and arsenic could potentially be decreased using a lower sulfide concentration. Bench-scale tests would be required to determine the optimal concentration.

REFERENCES

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APPENDIX A-1. INPUT FILE FOR PHREEQC SIMULATIONS, PORE VOLUMES 1 THROUGH 3

```
#
#SIMULATION FOR PV 1 TO 3 RESTORATION OF WELLFIELD 1 AFTER MINING
#
#
SOLUTION 1 #End of mining  Water Chemistry
        units   mg/l
        pH      6.15
        temp    17
        pe      7
        redox   pe
            density     1.0
        Alkalinity    484   mg/l    as CaCO3
        Ca      430    mg/l
        Mg       90    mg/l
        Na       41    mg/l
        K        18    mg/l
        S(6)    720    mg/l
        S(-2)   0.001  mg/l
        Cl      210    mg/l
        Si      27.2   mg/l
        F       0.16   mg/l
        Fe      0.05   mg/l
        Mn      0.31   mg/l
        B       0.12   mg/l
        Zn      0.05   mg/l
        As      0.006  mg/l
        Se      0.092  mg/l
        U       15     mg/l
END
SOLUTION 2 #Baseline Water Chemistry
        units   mg/l
        pH      7.37
        temp    17
        pe      -0.5   # estimated.
        redox  pe
            density     1.0
        Alkalinity      185.9   mg/l    as CaCO3
        Ca      72.6    mg/l
        Mg      17.4    mg/l
        Na      22.5    mg/l
        K       7.3     mg/l
        S(6)    113.1   mg/l
        S(-2)   0.001   mg/l
        Cl      4.176   mg/l
        Si      17.0    mg/l
        F       0.322   mg/l
        Fe      0.065   mg/l
        Se      0.001   mg/l
        Mn      0.021   mg/l
        B       0.100   mg/l
        Zn      0.01    mg/l
        As      0.001   mg/l
        U       0.065   mg/l
END
#
```

```
#Simulation of the three pore volume sweep
#Mix the post mining water in the aquifer
#with 0.2 PV volumes of the baseline sweep water
#until three pore volumes of the sweep water are mixed.
#Save solution after each mixing stage, and use the
#saved solution in the next mixing stage. Each mixing stage
#includes uraninite as an equilibrium phase and allows
#pyrite and orpiment to precipitate if thermodynamically possible.
#Remaining amount of the solids is saved after
#each mixing stage and used in the next stage
#
MIX 1
        1       0.8
        2       0.2
EQUILIBRIUM_PHASES 1
        Uraninite(C)  0.0     0.4
        Pyrite        0.0     0.0
        Orpiment      0.0     0.0
Save solution 3
Save equilibrium_phases 1
END
MIX 2
        3       0.8
        2       0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 4
End
MIX 3
        4       0.8
        2       0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 5
End
MIX 4
        5       0.8
        2       0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 6
End
MIX 5
        6       0.8
        2       0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 7
End
MIX 6
        7       0.8
        2       0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 8
End
MIX 7
```

```
        8       0.8
        2       0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 9
End
MIX 8
        9       0.8
        2       0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 10
End
MIX 9
        10      0.8
         2      0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 11
End
MIX 10
        11      0.8
         2      0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 12
End
MIX 11
        12      0.8
         2      0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 13
End
MIX 12
        13      0.8
         2      0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 14
End
MIX 13
        14      0.8
         2      0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 15
End
MIX 14
        15      0.8
         2      0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 16
End
MIX 15
        16      0.8
```

```
          2        0.2
USE equilibrium_phases 1
Save equilibrium_phases 1
SAVE solution 17
End
```

Table A-1. PHREEQC results for pore volumes 1 through 3, constituents not simulated using MLR

Pore Volume	Mg	Na	K	Si	As	B	F	Fe	Zn
0.0	90.1	41.1	18.0	27.2	0.0060	0.120	0.160	0.050	0.050
0.2	75.6	37.4	15.9	25.2	0.0050	0.116	0.193	0.053	0.042
0.4	64.0	34.4	14.2	23.6	0.0042	0.113	0.219	0.055	0.036
0.6	54.7	32.0	12.8	22.2	0.0036	0.110	0.239	0.057	0.031
0.8	47.2	30.1	11.7	21.2	0.0031	0.108	0.256	0.059	0.026
1.0	41.2	28.6	10.8	20.4	0.0026	0.107	0.269	0.060	0.023
1.2	36.5	27.4	10.1	19.7	0.0023	0.105	0.280	0.061	0.021
1.4	32.7	26.4	9.6	19.2	0.0021	0.104	0.288	0.062	0.018
1.6	29.6	25.6	9.1	18.8	0.0018	0.103	0.295	0.063	0.017
1.8	27.2	25.0	8.7	18.4	0.0017	0.103	0.300	0.063	0.015
2.0	25.2	24.5	8.5	18.1	0.0015	0.102	0.305	0.064	0.014
2.2	23.7	24.1	8.2	17.9	0.0014	0.102	0.308	0.064	0.013
2.4	22.4	23.8	8.0	17.7	0.0013	0.101	0.311	0.064	0.013
2.6	21.4	23.5	7.9	17.6	0.0013	0.101	0.313	0.064	0.012
2.8	20.6	23.3	7.8	17.5	0.0012	0.101	0.315	0.065	0.012
3.0	20.0	23.2	7.7	17.4	0.0012	0.101	0.317	0.065	0.011

APPENDIX A-2. INPUT FILE FOR PHREEQC SIMULATIONS, PORE VOLUMES 4 THROUGH 6

```
#
# SIMULATION FOR RESTORATION OF THE AQUIFER AFTER MINING
# AND AFTER SWEEPING WITH 3 PORE VOLUMES OF NATIVE (BASELINE)
# GROUND WATER
#
SOLUTION 1 #Chemistry of water at end of 3PV ground water sweep
        units   mg/l
        pH      7.04
        temp    17
        pe      1.8
        redox   pe
            density     1.0
        Alkalinity  159  mg/l    as HCO3
        Ca      116      mg/l
        Mg      19.96    mg/l
        Na      23.17    mg/l
        K       7.68     mg/l
        S(6)    194      mg/l   as SO4
        S(-2)   0.001    mg/l
        Cl      10.4     mg/l
        Si      17.4     mg/l
        F       0.32     mg/l
        Fe      0.065    mg/l
        Mn      0.059    mg/l
        B       0.101    mg/l
        Zn      0.011    mg/l
        As      0.001    mg/l
        Se      0.0047   mg/l
        U       2.29     mg/l
END
#
#Making blend of RO permeate and extracted ground water
#at end of 3PV at 70:30 ratio
#
SOLUTION 2 # RO permeate (assume pure water)
        units   mg/l
        temp    20
        pH      7
        pe      4
MIX 1
        2       0.7
        1       0.3
SAVE Solution 3  #Blend of RO permeate and Starting Solution At 3PV
END
#
#Making reductant solution using solution 3
#
USE solution 3
REACTION 1
      H2S  1.0
      0.0078 moles
SAVE Solution 4 #Solution with 250 mg/L sulfide.
END
#
#Introduce reductant to wellfield after 3.0PV
```

```
#
MIX 2           #Mixture at 3.2 PV of restoration process
     1           0.8   #Starting Solution, water after 3PV sweep
     4           0.2
EQUILIBRIUM_PHASES 1
        Uraninite(C)    0.0     0.4
        Pyrite          0.0     0.0
        Se(s)           0.0     0.0
        Orpiment        0.0     0.0
Save equilibrium_phases 1
Save solution 5     #solution after 3.2PV mixing
END
#
#
#
#Making blend of RO and Water @ end of 3.2PV at 70:30 ratio
MIX 3
        2       0.7
        5       0.3
SAVE Solution 6   #Blend of RO permeate and solution after 3.2PV mixing
END
#Making reductant solution Using Solution 6
USE solution 6
REACTION 1
      H2S  1.0
      0.0078 moles
SAVE Solution 7    #Solution with 250 mg/L S-2.
END
#Introduce reductant in Solution 5
MIX 4           # Mixture at 3.4PV
     5           0.8   #Solution After 3.2PV mixing.
     7           0.2
USE equilibrium_phases 1
Save solution 8
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 3.4PV at 70:30 ratio
MIX 5
        2       0.7
        8       0.3
SAVE Solution 9  #Blend of RO permeate and solution after 3.4PV mixing
END
#Making reductant solution using solution 9
USE solution 9
REACTION 1
      H2S  1.0
      0.0078 moles
SAVE Solution 10  #Solution with 250 mg/L S-2.
END
#Introduce reductant in Solution 8
MIX 6           # Mixture at 3.6PV
     8           0.8   #Solution After 3.4PV mixing.
     10          0.2
USE equilibrium_phases 1
Save solution 11
```

```
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 3.4PV at 70:30 ratio
MIX 7
        2       0.7
        11       0.3
SAVE Solution 12  #Blend of RO permeate and solution after 3.6PV mixing
END
#Making reductant solution Using Solution 12
USE solution 12
REACTION 1
      H2S  1.0
      0.0078 moles
SAVE Solution 13   #Solution with 250 mg/L S-2.
END
#Introduce reductant in Solution 11
MIX 8           # Mixture at 3.8PV
     11           0.8   #Solution After 3.6PV mixing.
     13          0.2
USE equilibrium_phases 1
Save solution 14
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 3.8PV at 70:30 ratio
MIX 9
        2       0.7
        14       0.3
SAVE Solution 15  #Blend of RO permeate and solution after 3.8PV mixing
END
#Making reductant solution Using Solution 15
USE solution 15
REACTION 1
      H2S  1.0
      0.0078 moles
SAVE Solution 16   #Solution with 250 mg/L S-2.
END
#Introduce reductant in Solution 14
MIX 10           # Mixture at 4.0PV
     14           0.8   #Solution After 3.8PV mixing.
     16           0.2
USE equilibrium_phases 1
Save solution 17
Save equilibrium_phases 1
END
#
#
#Last 2.0 PV sweep of RO/Restoration Water - blend
#Making blend of RO and Water @ end of 4.0PV at 70:30 ratio
MIX 11
        2       0.7
        17       0.3
SAVE Solution 18  #Blend of RO permeate and solution after 4.0PV mixing
END
```

```
#
#Introduce Blend into Aquifer Solution 17
#
MIX 12            # Mixture at 4.2PV
     17            0.8   #Solution After 4.0PV mixing.
     18           0.2
USE equilibrium_phases 1
Save solution 19
Save equilibrium_phases 1
END
#
#Making blend of RO and Water @ end of 4.2PV at 70:30 ratio
MIX 13
        2       0.7
        19       0.3
SAVE Solution 20  #Blend of RO permeate and solution after 4.2PV mixing
END
#Introduce Blend into Aquifer Solution 19
MIX 14            # Mixture at 4.4PV
     19            0.8   #Solution After 4.2PV mixing.
     20           0.2
USE equilibrium_phases 1
Save solution 21
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 4.4PV at 70:30 ratio
MIX 15
        2       0.7
        21       0.3
SAVE Solution 22  #Blend of RO permeate and solution after 4.4PV mixing
END
#Introduce Blend into Aquifer Solution 21
MIX 16            # Mixture at 4.6PV
     21            0.8   #Solution After 4.4PV mixing.
     22            0.2
USE equilibrium_phases 1
Save solution 23
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 4.6PV at 70:30 ratio
MIX 17
        2       0.7
        23       0.3
SAVE Solution 24  #Blend of RO permeate and solution after 4.6PV mixing
END
#Introduce Blend into Aquifer Solution 23
MIX 18            # Mixture at 4.8PV
     23            0.8   #Solution After 4.6PV mixing.
     24            0.2
USE equilibrium_phases 1
Save solution 25
Save equilibrium_phases 1
END
```

```
#
#
#Making blend of RO and Water @ end of 4.8PV at 70:30 ratio
MIX 19
        2       0.7
        25      0.3
SAVE Solution 26  #Blend of RO permeate and solution after 4.8PV mixing
END
#Introduce Blend into Aquifer Solution 25
MIX 20            # Mixture at 5.0PV
     25            0.8   #Solution After 4.8PV mixing.
     26            0.2
USE equilibrium_phases 1
Save solution 27
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 5.0PV at 70:30 ratio
MIX 21
        2       0.7
        27      0.3
SAVE Solution 28  #Blend of RO permeate and solution after 5.0PV mixing
END
#Introduce Blend into Aquifer Solution 27
MIX 22            # Mixture at 5.2PV
     27            0.8   #Solution After 5.0PV mixing.
     28            0.2
USE equilibrium_phases 1
Save solution 29
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 5.2PV at 70:30 ratio
MIX 23
        2       0.7
        29      0.3
SAVE Solution 30  #Blend of RO permeate and solution after 5.2PV mixing
END
#Introduce Blend into Aquifer Solution 29
MIX 24            # Mixture at 5.4PV
     29            0.8   #Solution After 5.2PV mixing.
     30            0.2
USE equilibrium_phases 1
Save solution 31
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 5.2PV at 70:30 ratio
MIX 25
        2       0.7
        31      0.3
SAVE Solution 32  #Blend of RO permeate and solution after 5.4PV mixing
END
#Introduce Blend into Aquifer Solution 31
```

```
MIX 26           # Mixture at 5.6PV
     31          0.8   #Solution After 5.4PV mixing.
     32          0.2
USE equilibrium_phases 1
Save solution 33
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 5.2PV at 70:30 ratio
MIX 27
        2        0.7
        33       0.3
SAVE Solution 34  #Blend of RO permeate and solution after 5.6PV mixing
END
#Introduce Blend into Aquifer Solution 33
MIX 28           # Mixture at 5.8PV
     33          0.8   #Solution After 5.6PV mixing.
     34          0.2
USE equilibrium_phases 1
Save solution 35
Save equilibrium_phases 1
END
#
#
#Making blend of RO and Water @ end of 5.2PV at 70:30 ratio
MIX 29
        2        0.7
        35       0.3
SAVE Solution 36  #Blend of RO permeate and solution after 5.8PV mixing
END
#Introduce Blend into Aquifer Solution 35
MIX 30           # Mixture at 6.0PV
     35          0.8   #Solution After 5.8PV mixing.
     36          0.2
USE equilibrium_phases 1
Save solution 37
Save equilibrium_phases 1
END
```

Table A-2. PHREEQC results for pore volumes 4 through 6, wellfield 1 restoration

PVs	HCO3	As	B	Ca	Cl	F	Fe	K	Mg	Mn	Na	S(-2)	SO4	Se	Si	U	Zn
3.0	159.1	1.00E-03	0.1011	116.1	10.40	0.320	0.065	7.68	19.97	0.0591	23.17	0.001	194.1	4.70E-03	17.40	2.2913	0.0110
3.2	162.5	4.09E-12	0.0869	99.8	8.95	0.275	7.68E-13	6.61	17.17	0.0508	19.94	50.0	167.2	1.29E-13	15.00	9.20E-09	0.0095
3.4	139.8	1.46E-12	0.0747	85.8	7.70	0.237	8.23E-13	5.68	14.77	0.0437	17.15	93.0	144.1	8.65E-14	12.86	9.35E-09	0.0081
3.6	120.3	8.61E-13	0.0643	73.8	6.62	0.204	8.48E-13	4.89	12.70	0.0376	14.75	129.9	123.9	6.38E-14	11.06	9.50E-09	0.0070
3.8	103.4	6.17E-13	0.0553	63.5	5.69	0.175	8.59E-13	4.20	10.92	0.0323	12.68	161.9	106.6	4.92E-14	9.50	9.64E-09	0.0060
4.0	88.9	4.90E-13	0.0475	54.6	4.90	0.151	8.61E-13	3.61	9.39	0.0278	10.91	189.2	91.5	3.90E-14	8.17	9.77E-09	0.0052
4.2	76.4	6.38E-13	0.0409	47.0	4.21	0.130	8.75E-13	3.11	8.08	0.0239	9.38	162.6	78.6	3.92E-14	7.03	9.64E-09	0.0045
4.4	65.8	8.28E-13	0.0352	40.4	3.62	0.111	8.87E-13	2.67	6.95	0.0205	8.06	139.9	67.6	3.94E-14	6.49	9.90E-09	0.0038
4.6	56.6	1.07E-12	0.0302	34.7	3.11	0.096	8.97E-13	2.30	5.97	0.0177	6.94	120.3	58.1	3.96E-14	5.21	9.95E-09	0.0033
4.8	48.6	1.37E-12	0.0260	29.9	2.68	0.082	9.07E-13	1.98	5.14	0.0152	5.97	103.5	50.0	3.97E-14	4.48	1.00E-08	0.0028
5.0	41.8	1.76E-12	0.0224	25.7	2.30	0.071	9.16E-13	1.70	4.42	0.0131	5.13	89.0	43.0	3.98E-14	3.85	1.00E-08	0.0024
5.2	36.0	2.25E-12	0.0192	22.1	1.98	0.061	9.26E-13	1.46	3.80	0.0112	4.41	76.5	37.0	3.99E-14	3.32	1.01E-08	0.0021
5.4	30.9	2.86E-12	0.0165	19.0	1.70	0.052	9.36E-13	1.26	3.27	0.0097	3.79	65.8	31.8	3.99E-14	2.65	1.01E-08	0.0018
5.6	26.6	3.64E-12	0.0142	16.3	1.46	0.045	9.47E-13	1.08	2.81	0.0083	3.26	56.6	27.4	4.00E-14	2.45	1.01E-08	0.0015
5.6	22.9	4.62E-12	0.0122	14.1	1.26	0.039	9.60E-13	0.93	2.42	0.0071	2.81	48.7	23.5	4.00E-14	2.11	1.01E-08	0.0013
6.0	19.7	5.85E-12	0.0105	12.1	1.08	0.033	9.76E-13	0.80	2.08	0.0061	2.41	41.8	20.3	4.00E-14	1.82	1.02E-08	0.0011

Attachment B

Flare Factor Sensitivity Results

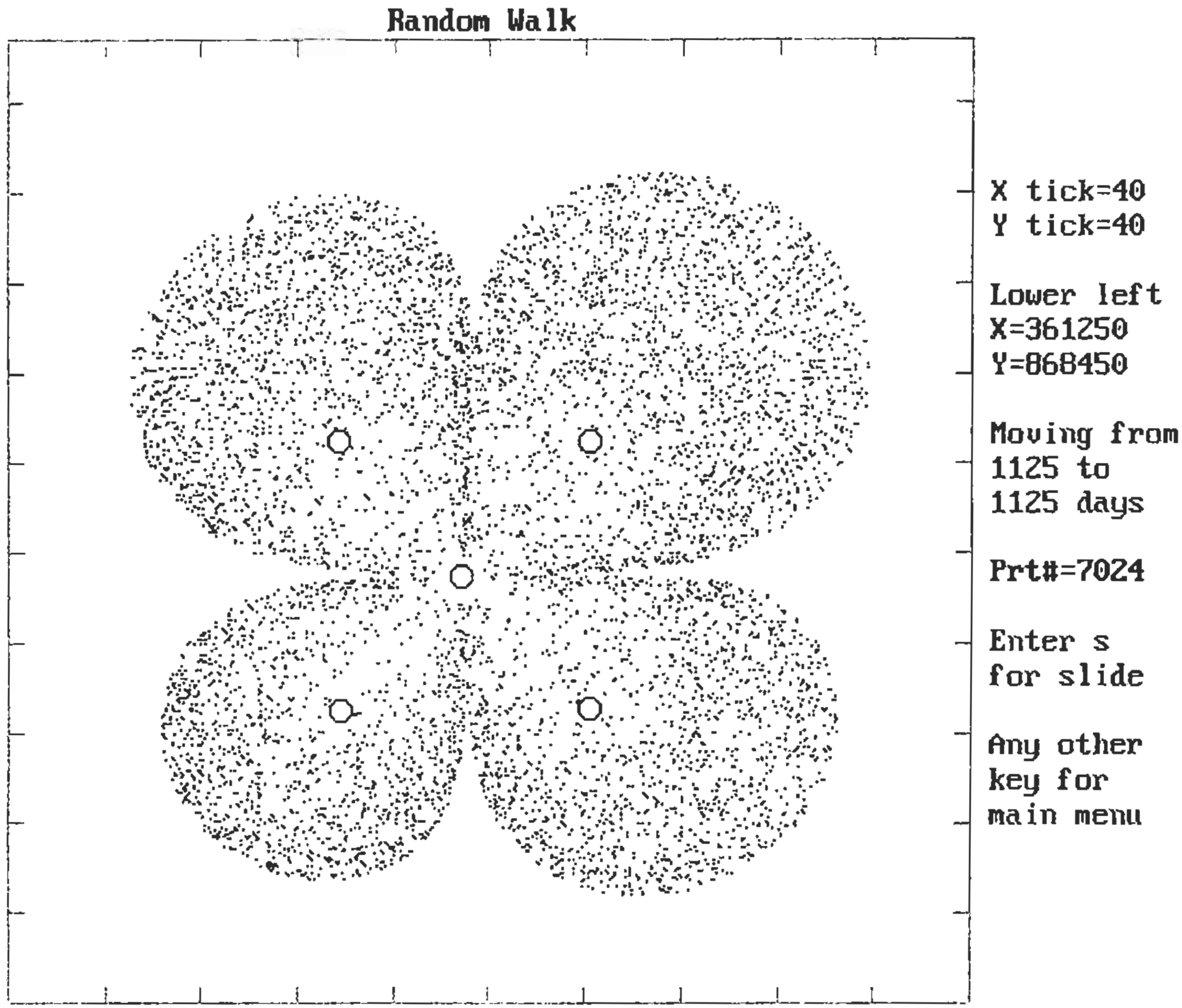

Figure B-1. Single 5-spot pattern advective particle cloud, 0.125 gpm/well net production rate, T=1000 gpd/ft, Flare Factor = 5.8

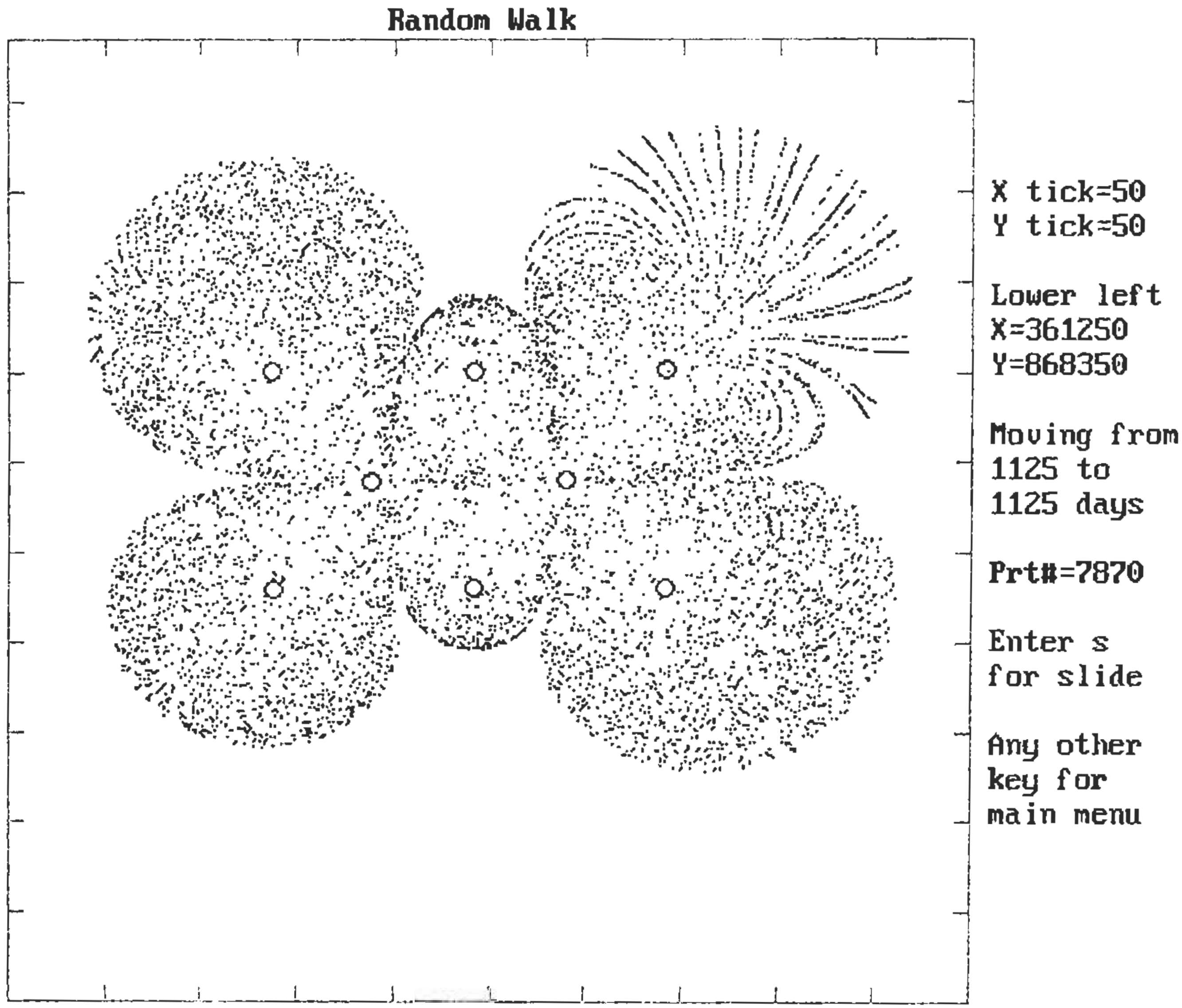

Figure B-2. Double 5-spot pattern advective particle cloud, 0.125 gpm/well net production rate, T=1000 gpd/ft, Flare Factor = 4.8

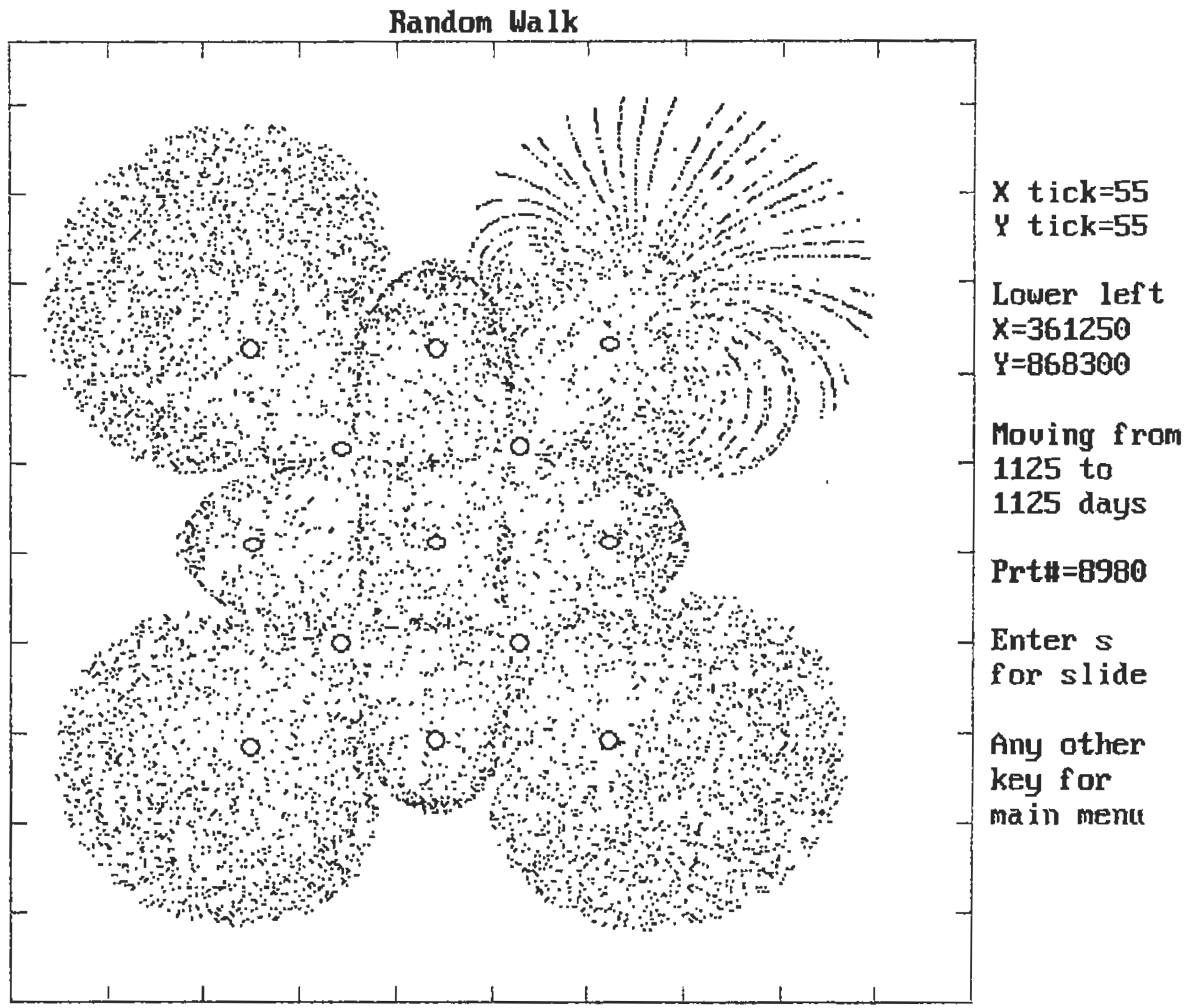

Figure B-3. Quad-square pattern advective particle cloud, 0.125 gpm/well net production rate, T=1000 gpd/ft, Flare Factor = 3.8

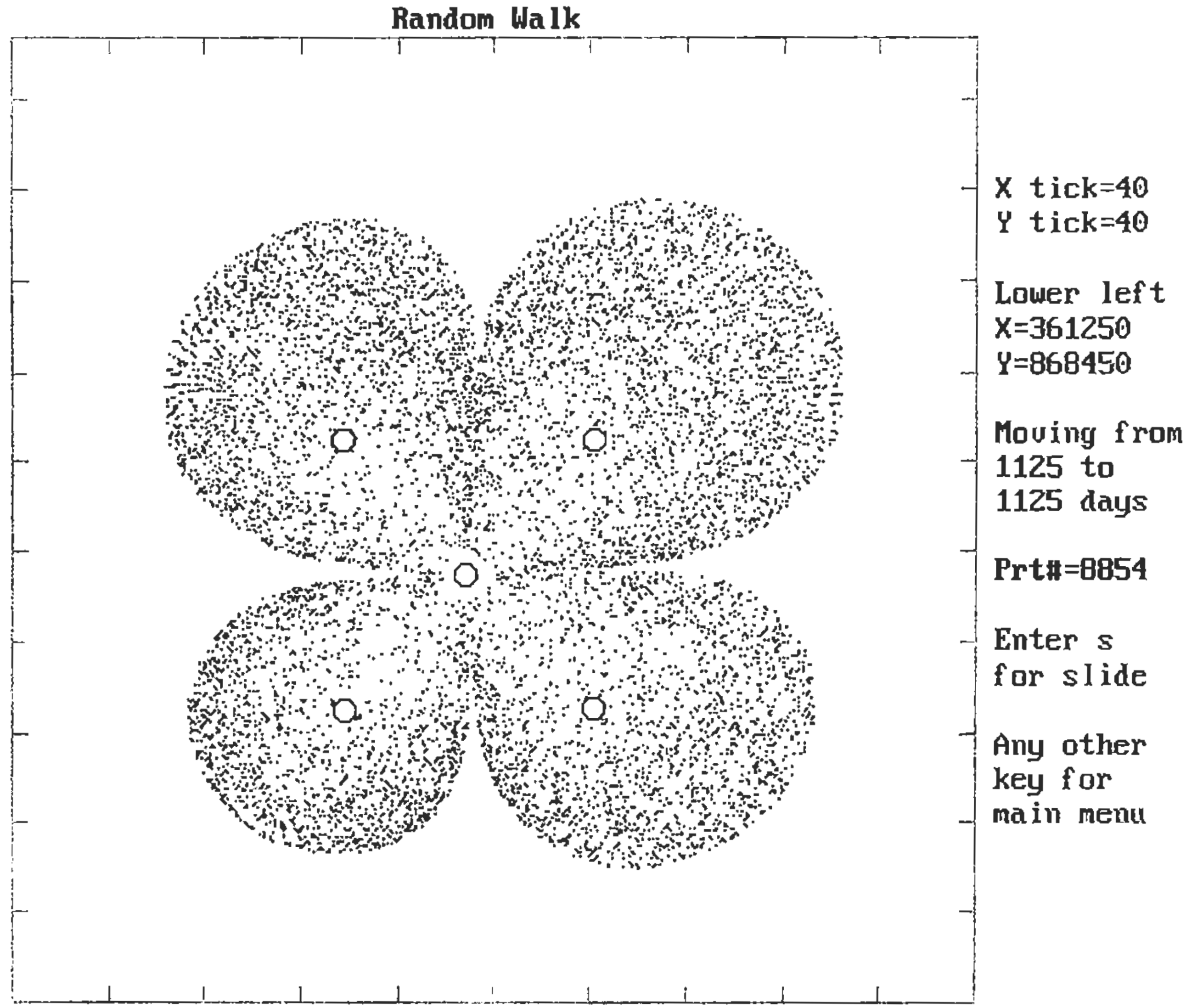

Figure B-4. Single 5-spot pattern advective particle cloud, 0.08 gpm/well net production rate, T=1000 gpd/ft, Flare Factor = 5.0

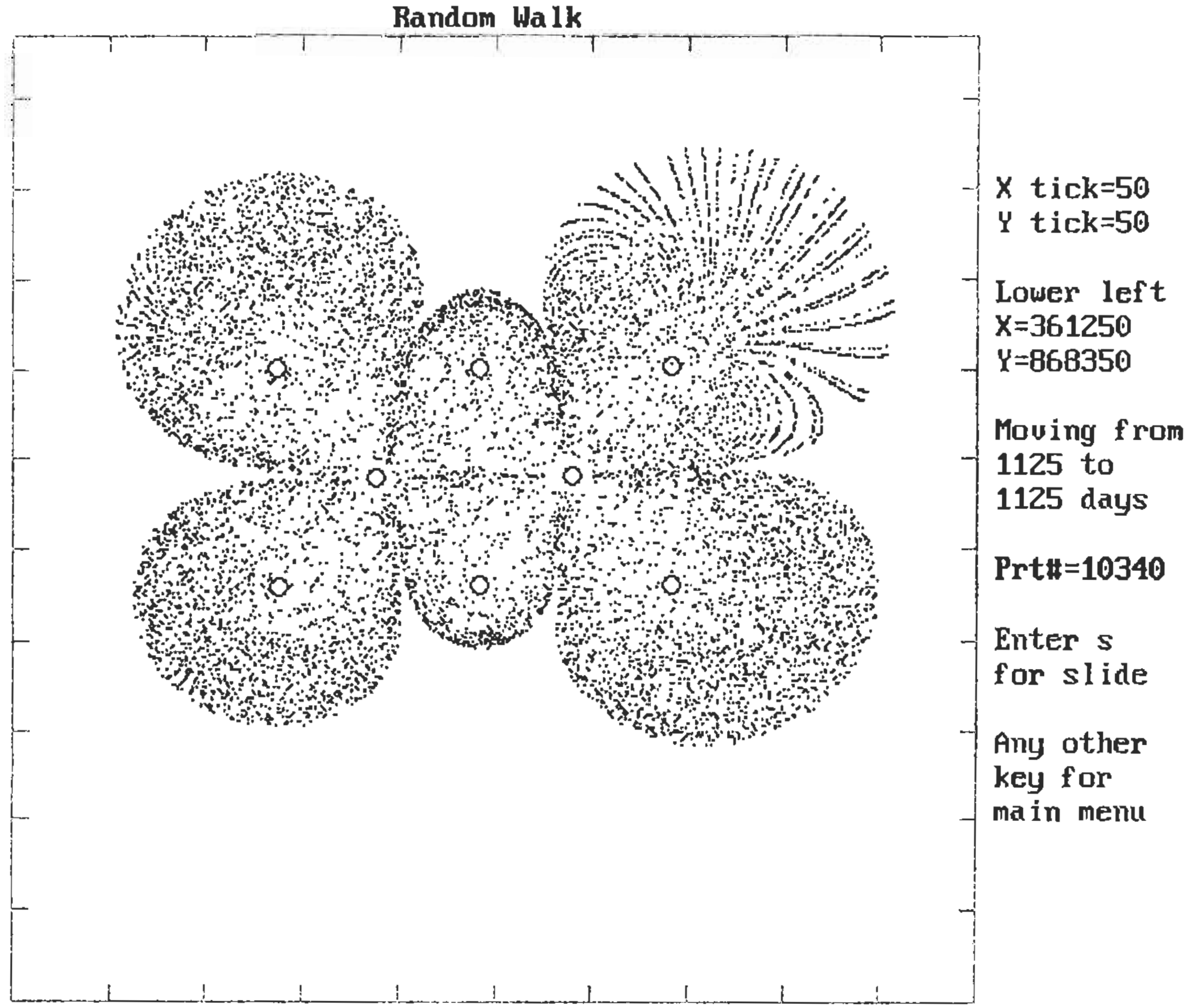

Figure B-5. Double 5-spot pattern advective particle cloud, 0.08 gpm/well net production rate, T=1000 gpd/ft, Flare Factor = 4.0

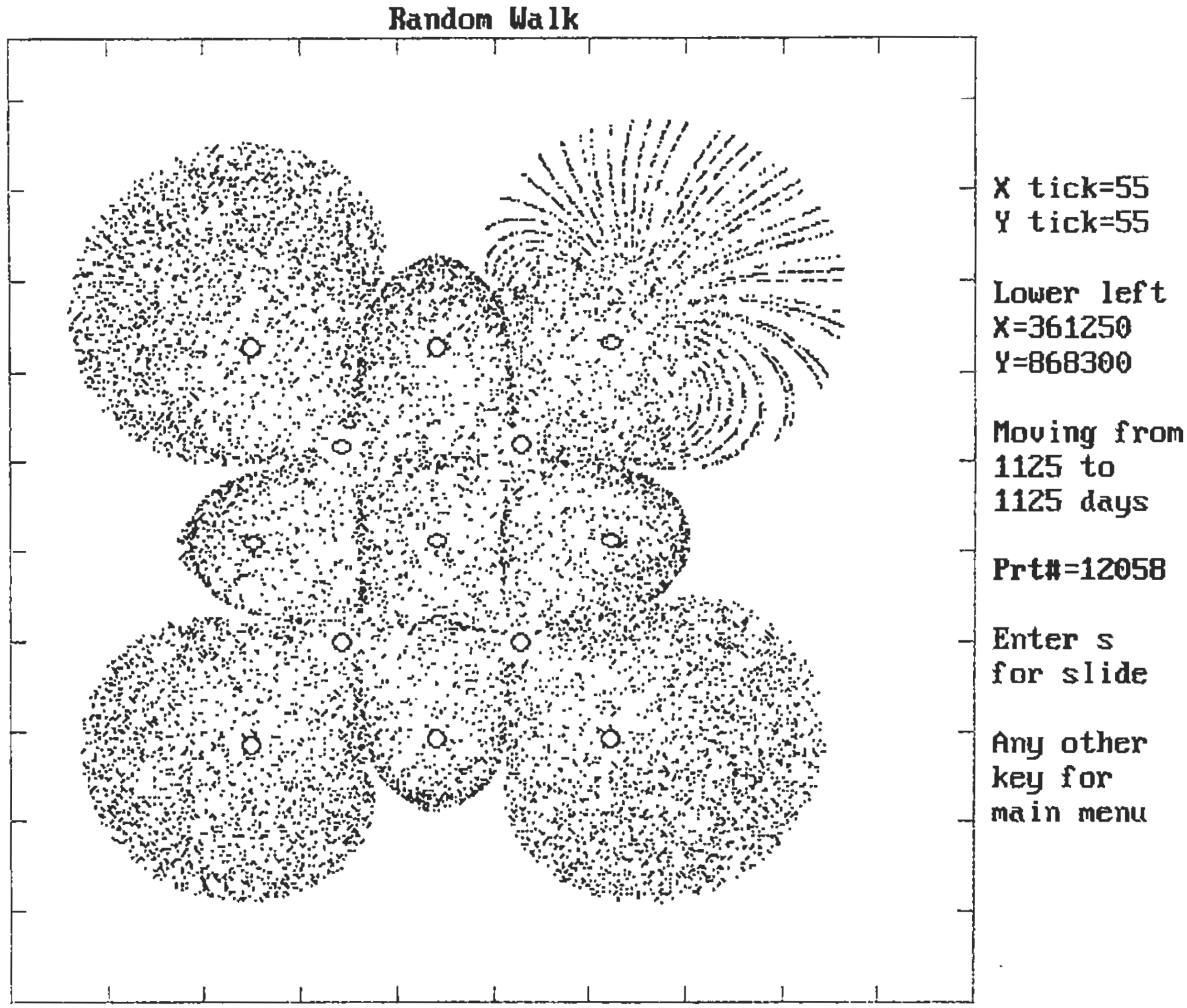

Figure B-6. Quad-square pattern advective particle cloud, 0.08 gpm/well net production rate, T=1000 gpd/ft, Flare Factor = 3.0

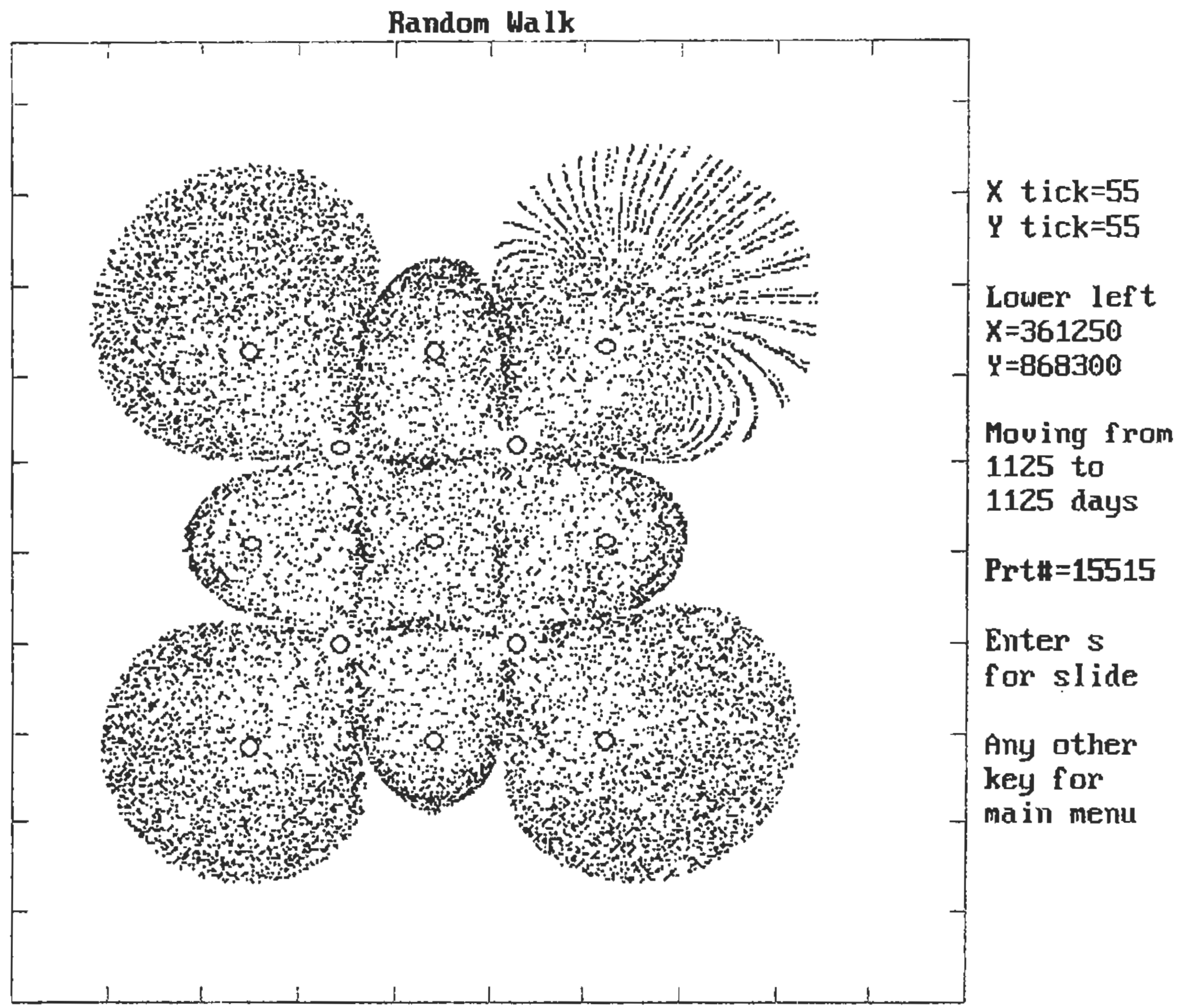

Figure B-7. Quad-square pattern advective particle cloud, 0.08 gpm/well net production rate, T=1500 gpd/ft (+50%), Flare Factor = 2.9

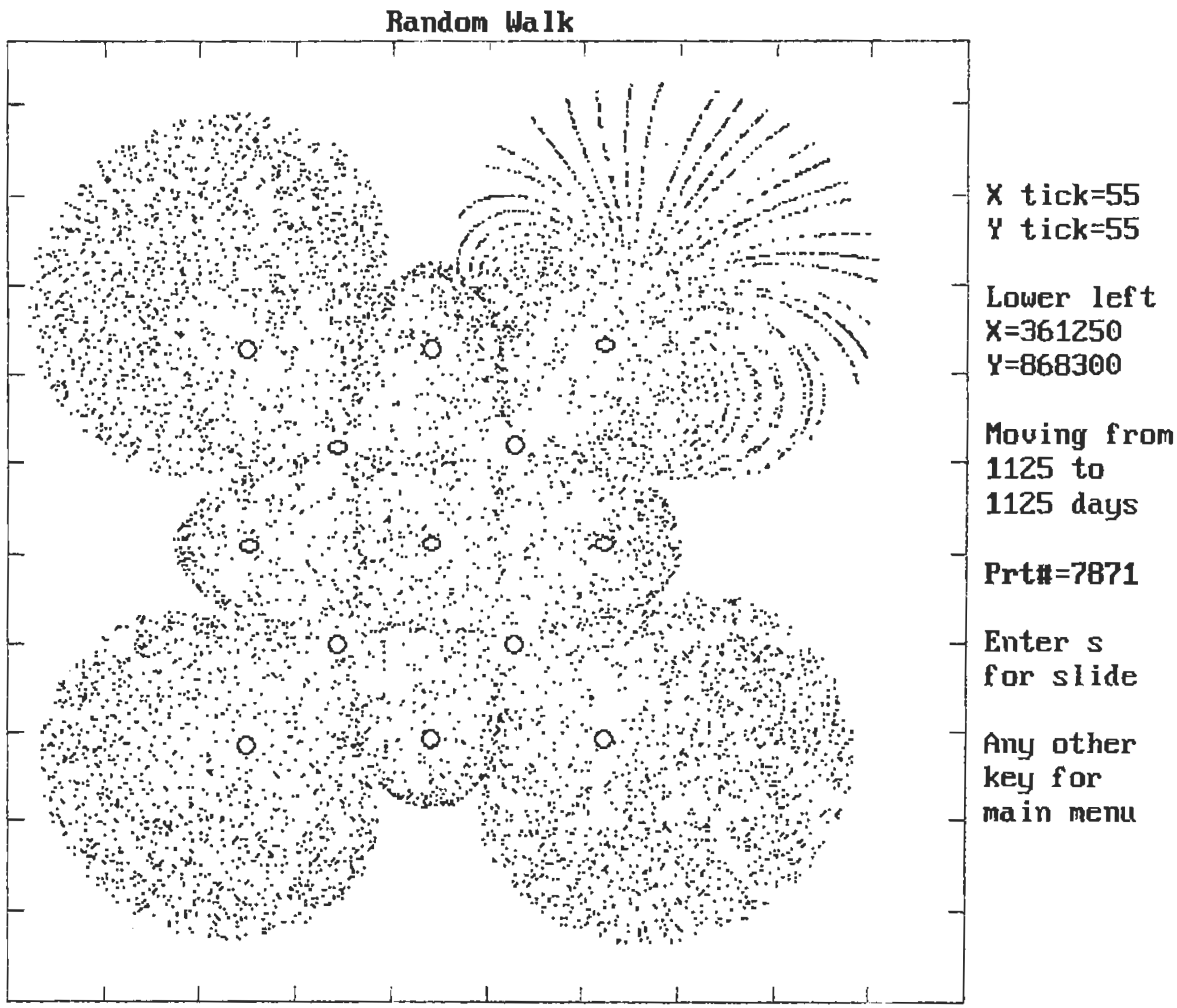

Figure B-8. Quad-square pattern advective particle cloud, 0.08 gpm/well net production rate, T=500 gpd/ft (-50%), Flare Factor = 4.0

Attachment C

Wellfield 1 MODFLOW and MODPATH Information

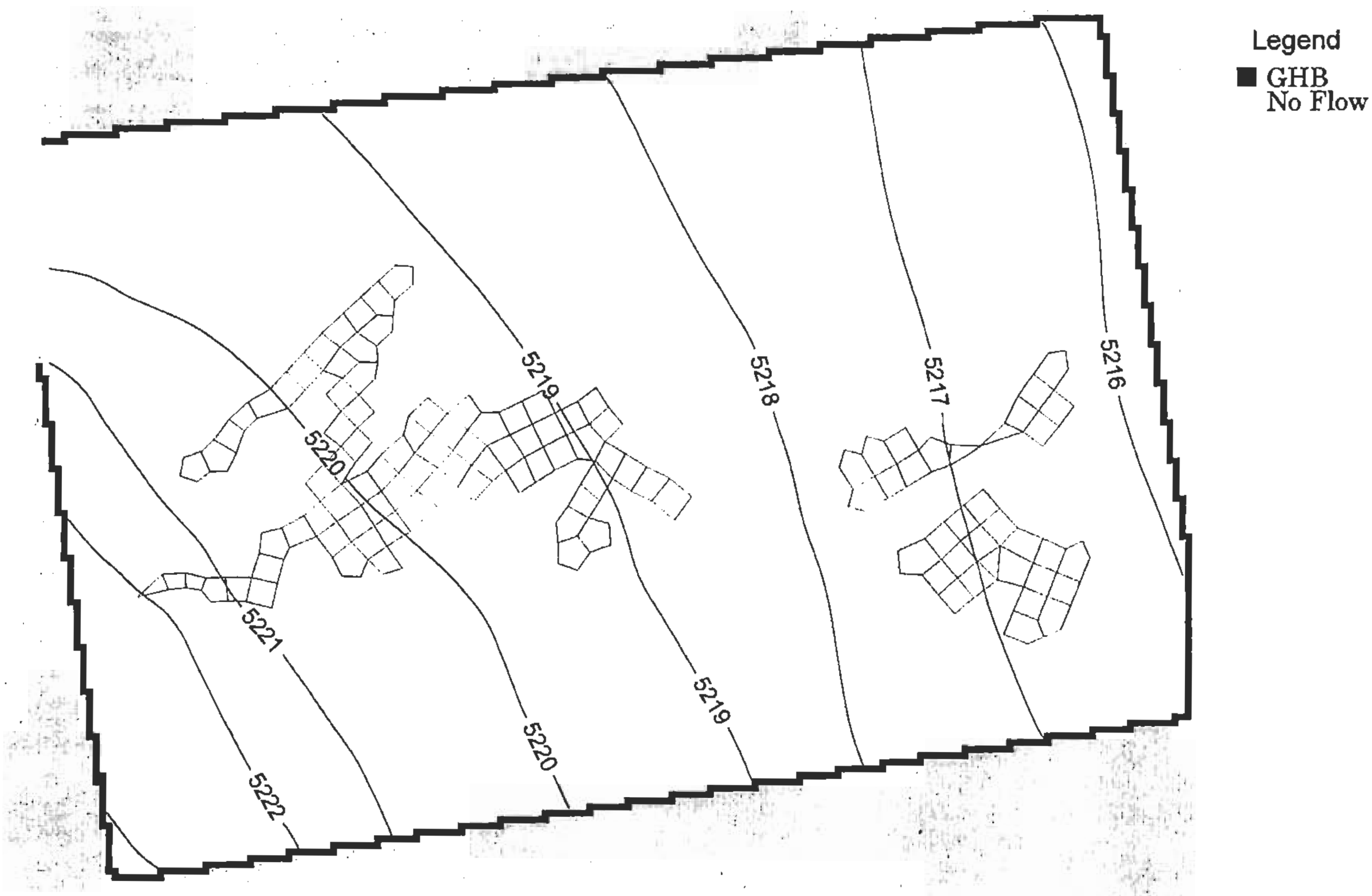

Figure C-1. Wellfield 1 MODFLOW boundary conditions and calibrated potentiometric surface.

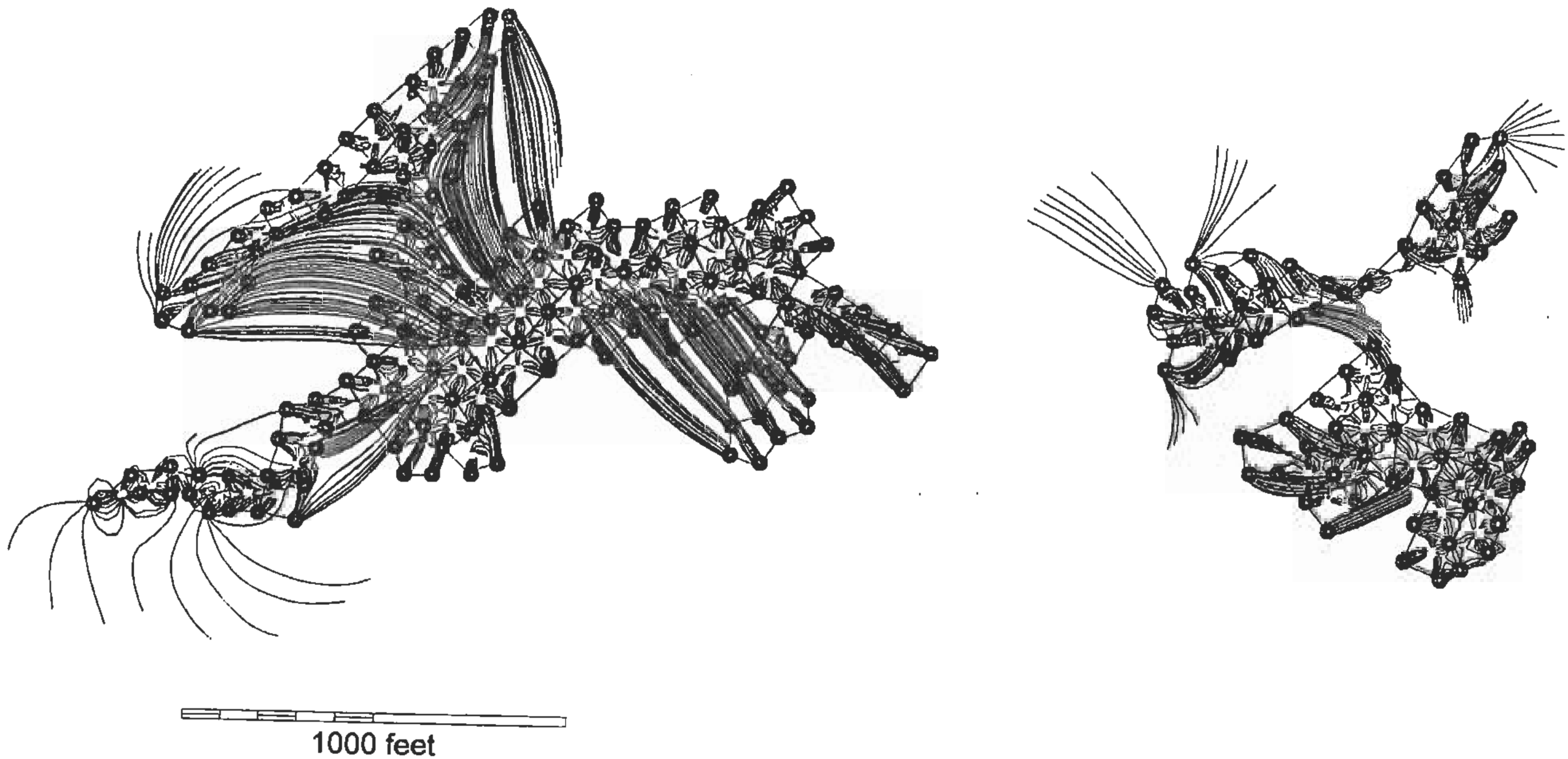

Figure C-2. MODPATH advective particle track after 2.5 year production period, Kh/Kv = 100/1. Flare Factor = 1.7

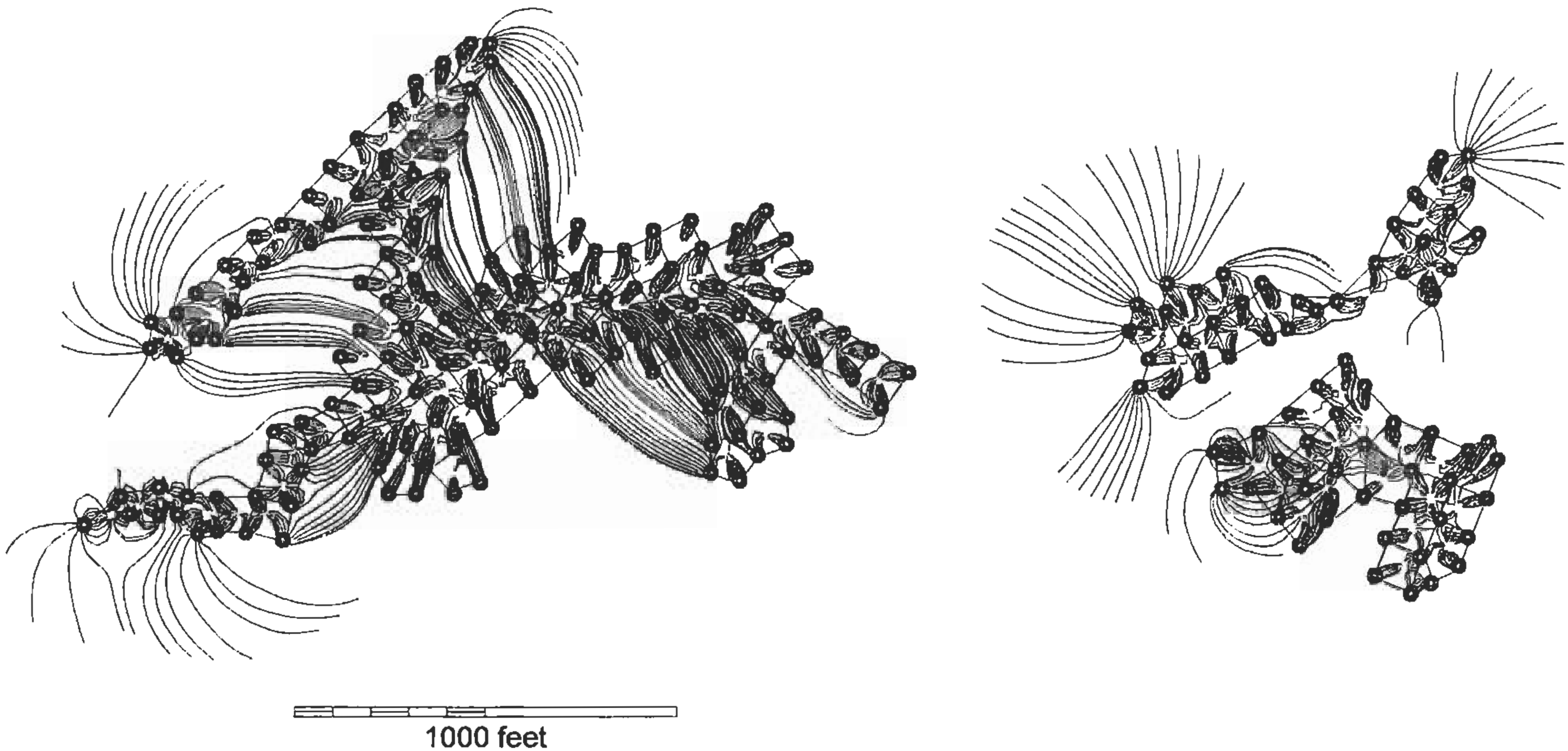

Figure C-3. MODPATH advective particle track after 2.5 year production period, Kh/Kv = 10/1. Flare Factor = 2.2

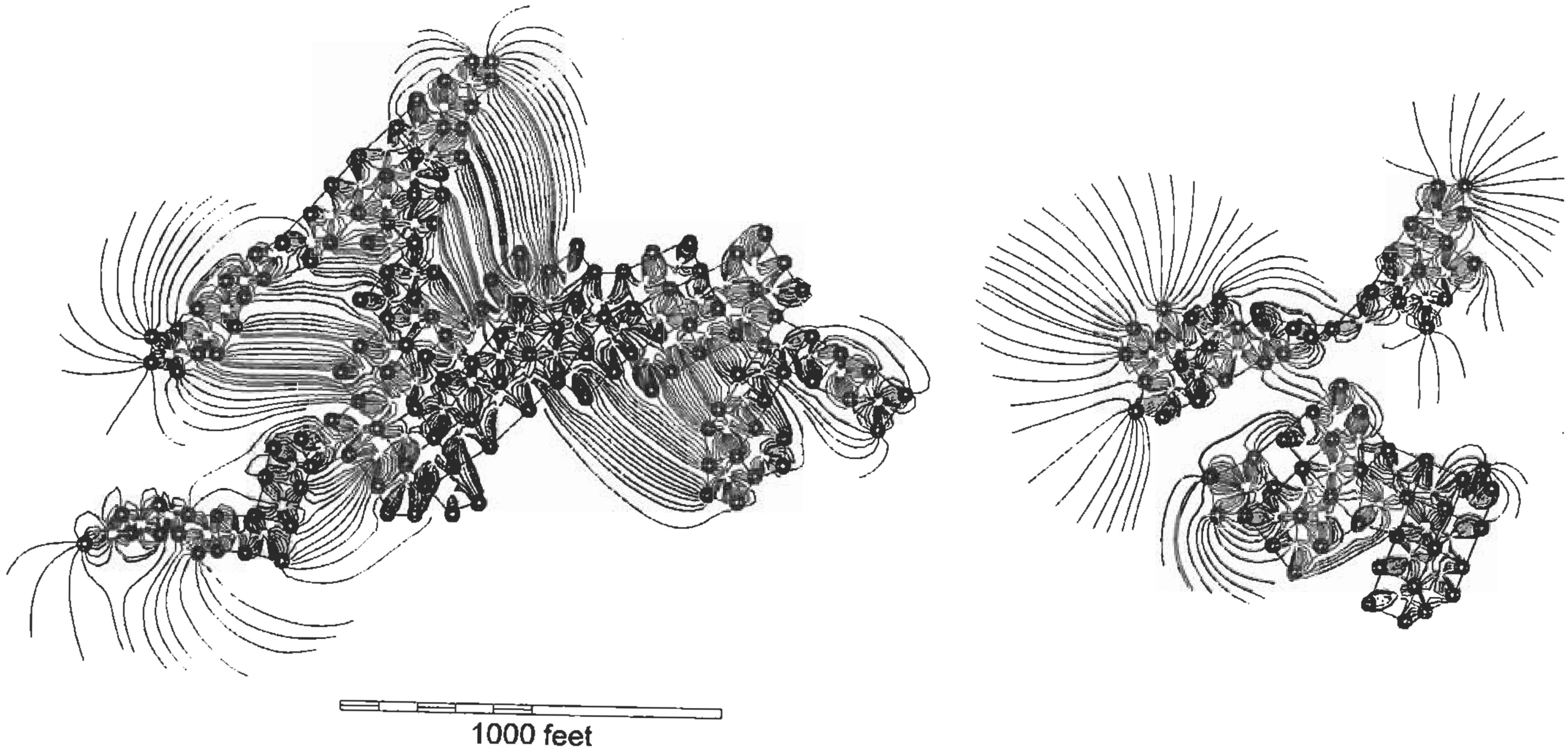

Figure C-4. MODPATH advective particle track after 2.5 year production period, Kh/Kv = 1/1. Flare Factor = 2.7

Cross-Section along Row 64

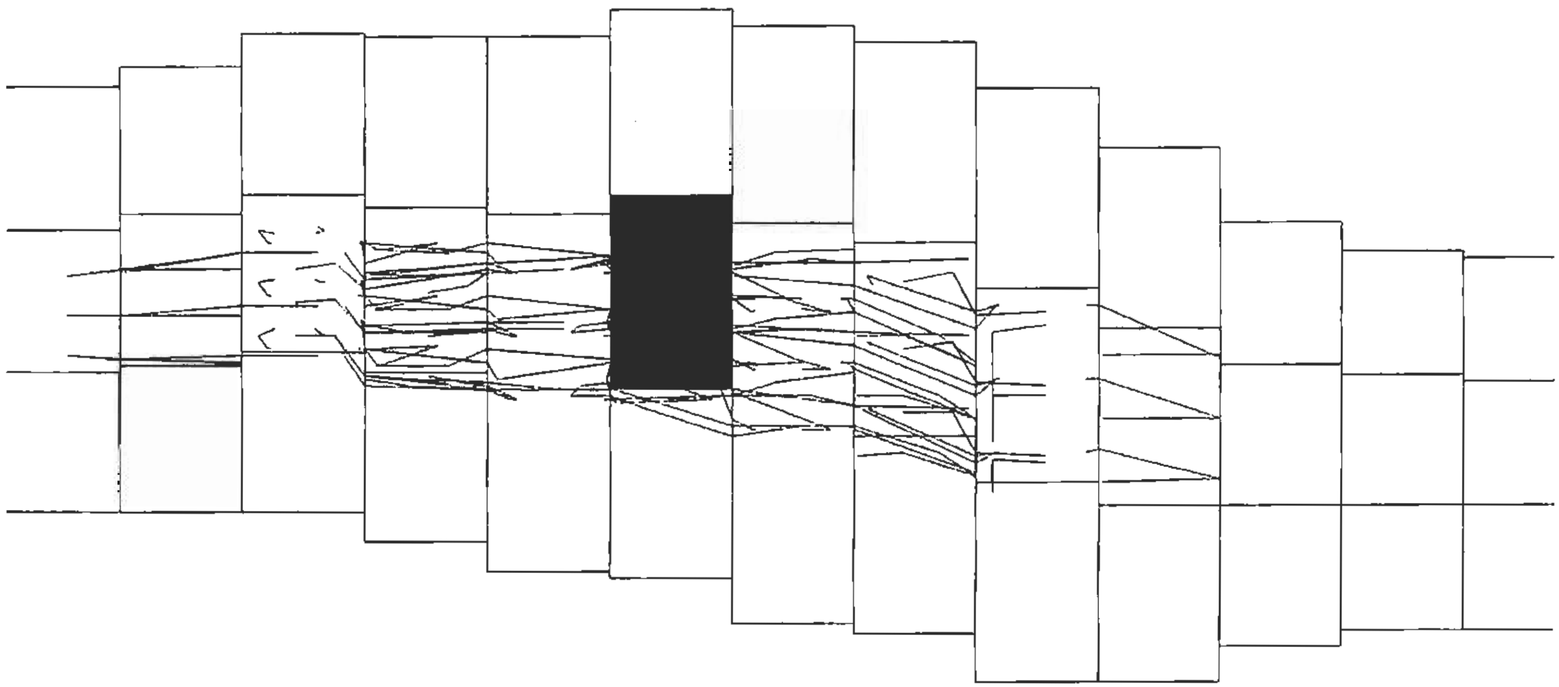

Figure C-5. Typical MODPATH wellfield cross-section showing no vertical flare for Kh/Kv = 100.