7.0 GROUNDWATER AND STABILIZER TRANSPORT MODELING

7.1 Introduction

The concept of passive site remediation is the slow injection of stabilizing materials at the up gradient edge of a site and delivery of the stabilizer to the target location using the natural groundwater flow. The concept is illustrated in Figure 1-1. As the stabilizer moves through the formation, it will replace the groundwater in the pores of the formation. After the stabilizer reaches the end of the treatment zone, it will gel to stabilize the formation. The set time of the stabilizer would be controlled so there would be adequate time for it to reach the desired location beneath the site prior to gelling, setting, or precipitating. If the natural groundwater flow were inadequate to deliver the stabilizer to the right place at the right time, it could be augmented by use of low-head injection wells or downgradient extraction wells. Once the stabilizer reached the desired location beneath the site, it would set, precipitate, or gel to stabilize the formation.

The purpose of groundwater modeling was to conduct a "numerical experiment" to determine the conditions under which the stabilizer could be delivered to a formation using the natural groundwater flow as a delivery system. For scenarios where the natural groundwater flow regime would be inadequate to deliver the stabilizer in an appropriate time frame, augmentation of the flow regime with low-head injection wells was considered. In addition, solute transport modeling was done to estimate the concentration of stabilizer that would need to be injected at the up gradient edge of the treatment area to deliver the required concentration of stabilizer to the down gradient edge of the treatment area.

The steps of the modeling study are listed below:

1. Set up a conceptual model for a typical liquefiable formation.
2. Select modeling codes appropriate for the application (see Sections 3.11 and 4.7).
3. Define a numerical model to accurately represent the conceptual model.
4. Determine the conditions under which the natural groundwater flow could be used as a delivery system.

5. For situations where the natural groundwater flow regime would be inadequate to deliver the stabilizer in the necessary time frame, determine if the system could be augmented with injection or extraction wells. Determine if single or multiple injection wells would be required to achieve adequate coverage.
6. Determine the concentration of stabilizer that must be injected at the up gradient edge of the site to deliver the minimum concentration necessary at the down gradient edge of the treatment area.
7. Consider the effects of heterogeneity in a liquefiable formation on the ability of the flow regime to deliver the stabilizer in the necessary time frame.

7.2 Conceptual Model

Liquefaction typically occurs in saturated loose cohesionless deposits. Liquefiable deposits can be very deep or be underlain by a relatively shallow impermeable base layer, but liquefaction typically occurs at depths of less than 50 feet. Soil deposits formed in depositional environments that produce uniformly graded, loose deposits are most susceptible to liquefaction. Examples include fluvial, aeolian, hydraulic fill, and mine tailings deposits. A potentially liquefiable deposit is most susceptible to liquefaction if the depth to groundwater is shallow. The grain size ranges of most liquefiable soils are shown in Figure 2-1.

For this study, a conceptual model of a generic liquefiable deposit was developed. The deposit was assumed to be a loose, uniform sand deposit with a thickness of 60 feet and an impermeable base. The groundwater was assumed to be at a depth of 10 feet, so the liquefiable thickness was 50 feet. The liquefiable layer was modeled as an unconfined aquifer.

The size of the treatment area will be specific to the project and depend on the size of the facilities that will need remediation. For initial modeling purposes, a treatment area of 200 feet by 200 feet, or approximately one acre, was selected. These dimensions are likely to cover the plan dimensions of many sites needing treatment. If larger sites need to be treated, it is likely that there would be access to install delivery wells at least every 200 feet.

The treatment area was assumed to be present within a local groundwater flow system that had already been characterized. Therefore, the treatment area was situated within the local flow system so flow would occur laterally throughout the treatment area. A sketch of the problem is shown in Figure 7-1. A local flow area of 2000 feet by 1600 feet was assumed, with the 200-foot by 200-foot treatment area situated in the middle of the local flow area. The size of the local flow area was selected so that the boundary conditions of the model would not influence the flow of water or stabilizer in the treatment area. Water was supplied to the system with a specified flow boundary, as shown in Figure 7-1. The effects of recharge were assumed to be negligible. It was also assumed that no rivers, wells, or other water sources were present within the local flow system. The system was modeled as a steady-state problem since the stabilizer will be supplied over a period of about 100 days.

Since this modeling study is a numerical experiment, some of the items that would typically be fixed in the conceptual model or calibrated during the numerical modeling of a specific site become variables to be investigated during the modeling process. The variables that will affect the outcome of the modeling process include the size and shape of the treatment area, the thickness of the liquefiable layer and the depth of treatment, the location of the phreatic surface, the hydraulic conductivity and dispersivity of the formation, the hydraulic gradient of the local groundwater flow regime, and heterogeneity within the formation. A numerical model was developed considering these variables.

7.3 Numerical Model

7.3.1 Mathematical Models

The available codes were discussed in Section 3.11 and evaluated for use in modeling for passive site remediation in Section 4.7. MODFLOW was selected for groundwater modeling. The governing partial differential equation solved in MODFLOW is (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=0 \qquad (7\text{-}1)$$

where

K_{xx}, K_{yy}, and K_{zz} = values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (ft/day)

h = potentiometric head (ft)

W = volumetric flux per unit volume; represents sources/sinks of water (day^{-1})

t = time (days).

The addition of boundary conditions completes the mathematical formulation of the problem. The solution computed by MODFLOW is a time-varying head distribution that accounts for both the energy of flow and the amount of water stored in the aquifer. This solution can be used to calculate the direction and rate of movement of the water.

MODPATH was selected for particle tracking to determine the travel time for purely advective flow and to estimate the stabilizer delivery width for a given simulation. As discussed in Section 3.11, MODPATH (Pollock 1989) tracks advective transport of particles through a flow field computed using MODFLOW. The user designates a set of particles that are tracked through time using MODPATH. The travel time is also computed, so the length of time it takes a particle to travel through the flow field can be determined.

MODPATH computes the average linear groundwater velocity across each face in a cell. The principal flow components for each cell are then computed using linear interpolation, which results in a continuous velocity vector in the cell that satisfies the differential conservation of mass equation (Pollock 1989). The velocity and width of the cell are used to determine the time it takes a particle to cross the cell. The particle's exit point from the cell can be computed using the velocity components and the time.

MT3DMS was selected for solute transport modeling. The governing partial differential equation in MT3DMS describes the mass balance of chemicals entering, leaving, and remaining in the cell at any given time (Zheng and Wang 1998):

$$\frac{\partial(nC^k)}{\partial t} = \frac{\partial}{\partial x_i}\left(nD_{ij}\frac{\partial C^k}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(nv_iC^k) + q_sC_s{}^k + \sum R_n \ . \quad (7\text{-}2)$$

where

C^k = dissolved concentration of species k, (g/l)

n = porosity of the subsurface medium, dimensionless

t = time (days)

x_i = distance along the respective Cartesian coordinate axis (ft)

Dij = hydrodynamic dispersion coefficient tensor (ft^2/day)

v_i = seepage or linear pore water velocity (ft/day)

q_s = volumetric flow rate per unit volume of aquifer representing fluid sources and sinks

ΣR_n = chemical reaction term (g/l-day).

Boundary conditions are added to complete the mathematical formulation of the problem. The flow field computed by MODFLOW is used by MT3DMS to calculate the time-varying concentration field of the solutes.

The Department of Defense Groundwater Modeling System (GMS) was used to develop the model grid for the study using the grid module. The packages used in MODFLOW included the block-centered flow package, the preconditioned conjugate gradient solver and the well package. The output from MODFLOW consisted of an output file and solution files including heads and cell-to-cell flow. The MODFLOW solution was used to run both MODPATH and MT3DMS. The input for MODPATH consisted of the aquifer porosity and designation of a series of particles to be tracked through time. The output included a summary file and endpoint and pathline solution files. The packages used in MT3DMS included advection, dispersion, and source/sink mixing. A third-order, total-variation-diminishing (TVD) solution (ULTIMATE) was used with the generalized conjugate gradient (GCG) solver. MT3DMS output included a summary file and concentration files.

7.3.2 Grid Design and Boundary Conditions

It was assumed that for a project of this nature, the local flow regime would be evaluated prior to design of passive site remediation. Given that the aquifer would be well characterized, the model grid for passive site remediation could be oriented such that the treatment area would be centered in the middle of the local flow system. As noted in Section 7.2, a local flow area of 2000 feet by 1600 feet was assumed, with the 200-foot by 200-foot treatment area situated in the middle of the local flow area. The size of the local flow area was selected so that the boundary conditions of the model would not influence the flow of water or stabilizer in the treatment area.

A 20-foot spacing was used for the model grid, resulting in 100 cells in the x-direction and 80 cells in the y-direction. The up gradient boundary was modeled as a specified flow boundary. The down gradient edge of the site was modeled as a constant head boundary. The base of the model was assumed to be an impermeable layer and was modeled as a no-flow boundary. The lateral boundaries of the local flow area represent streamlines, meaning water flows along these lines rather than crossing them. Therefore, these boundaries were modeled as no-flow boundaries.

7.3.3 Layer Definition

The aquifer was modeled using 5 layers. The top layer was modeled as an unconfined layer. The four remaining layers were modeled as "confined/unconfined with variable transmissivity" layers. This layer definition means that if the layer is fully saturated, it will be treated as a confined aquifer. However, if the water level drops below the top of the layer, it will be treated as an unconfined aquifer and the transmissivity will be calculated based on the hydraulic conductivity and the saturated thickness. The base of layer 5 was assumed to be impermeable and was modeled as no-flow boundary. The elevation of the bottom of the model was assumed to be zero. The thickness of each of the bottom four layers was 10 feet. The thickness of the top layer depended on the thickness required to obtain the desired hydraulic gradient. For example, if a hydraulic gradient of 0.01 was desired, the top layer had to be a minimum of 20 feet thick.

7.3.4 Flow System

If passive site remediation is designed for a specific site, the hydraulic conductivity of the formation will be defined as part of the conceptual model or calibrated during numerical modeling. However, for this feasibility study, a range of hydraulic conductivities was considered to determine the various scenarios where passive site remediation might work. Typical hydraulic conductivity values for fine to coarse sand are shown in Table 7-1. Values selected for modeling ranged from 0.001 to 0.1 cm/s (2.8 to 280 feet/day). Simulations were run for each half-order of magnitude in this range.

Table 7-1 Typical Values of Hydraulic Conductivity for Sands

Reference	Type of Sand	Hydraulic Conductivity	
		(cm/s)	(ft/day)
Freeze and Cherry (1979)	Clean sand	10^{-4} to 1	0.28 to 2800
Domenico and Schwartz (1990)	Coarse sand	9×10^{-5} to 6×10^{-1}	0.26 to 1700
	Medium sand	9×10^{-5} to 5×10^{-2}	0.26 to 140
	Fine sand	2×10^{-5} to 2×10^{-2}	0.056 to 57
NAVFAC P-418 (1983)	Medium to coarse sand	0.15 to 0.20	420 to 570
	Medium sand	0.10 to 0.15	280 to 420
	Fine to medium sand	0.05 to 0.10	140 to 280
	Fine sand	0.02 to 0.05	57 to 140

In an unconfined aquifer, the transmissivity is defined as the saturated thickness of the aquifer times the hydraulic conductivity. MODFLOW has the capacity to calculate the transmissivity based on the values of hydraulic conductivity input and the saturated thickness of the layer. This option was used to calculate the values of transmissivity for this study.

The porosity of the aquifer was necessary for particle tracking and solute transport modeling. Various estimates of porosity for sand deposits are shown in Table 7-2. A value of 35 percent was used for this study.

Table 7-2 Typical Values of Porosity for Sands

Reference	Type of Sand	Porosity (%)
Domenico and Schwartz (1990)	Coarse sand	31 to 46
	Fine sand	26 to 53
Karol (1990)	Loose uniform sand	46
	Dense uniform sand	34
	Loose mixed-grain sand	40
	Dense mixed-grain sand	30

Dispersivity is a parameter that accounts for the mixing that occurs due to groundwater velocities that differ from the average linear groundwater velocity. On a microscopic scale, the variations in groundwater velocities are due to differences in the pore size of the media, differences in the path lengths taken by fluid particles, and differences in resistance between different pore channels (Freeze and Cherry 1979). There will also be heterogeneities on a macroscopic scale. Heterogeneities at both the microscopic and macroscopic levels are due primarily to variations in the hydraulic conductivity.

Dispersivity is a difficult parameter to quantify because it may depend on the scale of the experiment used to measure it. In laboratory experiments, values of longitudinal dispersivity typically range from 0.01 to 1 cm; in field experiments with short transport distances the values may range from 0.1 to 2 m (Domenico and Schwartz 1990). It is thought that microscopic dispersivity is measured in laboratory experiments while macroscopic dispersivity is measured in field experiments.

Based on these considerations, the effects of dispersion were considered using two methods. First, a regional dispersion coefficient was used in conjunction with a uniform hydraulic conductivity. A common estimate for longitudinal dispersivity is about one-tenth of the flow length (Fetter 1993). Horizontal transverse dispersivity can range from about one-sixth to about one-twentieth of the longitudinal dispersivity (Fetter 1993). Vertical transverse dispersivity is often estimated as one-tenth of the horizontal dispersivity. A longitudinal dispersivity of 20 feet was used, which is one-tenth of the flow length. Horizontal transverse and vertical transverse dispersivities of 1 and one-tenth foot, respectively, were used.

The second way of addressing dispersion was to vary the hydraulic conductivity in each layer to account for macroscopic effects and to use a small dispersivity to account for heterogeneity at the pore level. The hydraulic conductivity was varied slightly in different layers of the aquifer for a total variation in all of the layers of about one order of magnitude. An example for a hydraulic conductivity of 0.05 cm/s (140 ft/day) is shown in Table 7-3. The values of longitudinal, transverse, and vertical dispersivity used in these simulations were 2 feet, 0.1 feet and 0.01 feet, respectively.

In a real flow system, the variations in hydraulic conductivity would not be as abrupt or convenient as those assumed in this simplified case. However, this approach gives an approximation of how stabilizer delivery could vary in the field. Future modeling could include variations of hydraulic conductivity within layers rather than simply between layers.

Table 7-3 Example Variation in Hydraulic Conductivity by Layer

Layer	Hydraulic Conductivity (ft/day)
1	28
2	210
3	140
4	280
5	84

7.3.5 Water Budget

The water budget is the amount of water that enters and leaves the system. The conservation of mass equation requires that the inflow to the system plus the change in storage of water in the aquifer must equal the outflow from the model. In this case, there was no change in storage, so all the water supplied to the system was extracted at the down gradient edge through the constant head boundary.

The hydraulic gradient of a regional flow system will vary from region to region. To investigate the effects of different hydraulic gradients, values of 0.001, 0.005, 0.01 and 0.02 were considered. This range should cover the variation expected at sites where passive site remediation might be considered for use. The water budget was based on the flow required to provide the desired gradient for each simulation.

In MODFLOW, a specified flow boundary can be specified using injection wells in every cell at the up gradient edge of the site. A total of 400 wells (80 per layer in each of 5 layers) were used to establish the regional groundwater flow system. The flow in each cell was adjusted to provide the desired hydraulic gradient for each simulation. In cases where the hydraulic conductivity was varied in each layer, the quantity of flow in each layer was adjusted to provide the appropriate global hydraulic gradient.

In cases where the flow regime was augmented using an injection well in the treatment area, an additional well was defined at the up gradient edge of the treatment area (x-coordinate of 900 feet, y-coordinate of 800 feet) in each of the five layers. Although a well had to be defined in each layer, the augmentation well was considered to be one well and the flow values reported below are the sum of the flow in each of the 5 layers, i.e. a flow of 1000 cubic feet per day means that 200 cubic feet per day were injected in each of the 5 layers.

7.3.6 Colloidal Silica

Colloidal silica was the stabilizer selected for use in passive site remediation. As discussed previously, colloidal silica is a colloidal suspension of microscopic silica particles. For solute transport modeling, colloidal silica was assumed to be a non-sorbing, aqueous species. Based on laboratory testing, the viscosity of the stabilizer solution is expected to be about 2 cP for the majority of the travel time. This viscosity would cause the hydraulic conductivity of the formation to decrease by half according to the relation described by Equation 2-3. The hydraulic conductivity of the formation would progressively decrease as the stabilizer replaced the groundwater in the pores of the formation. Once the stabilizer began to gel, the viscosity would increase exponentially, causing a corresponding decrease in the hydraulic conductivity of the formation. Once the viscosity of the stabilizer increases by two orders of magnitude, the hydraulic conductivity of the formation will be so low that the stabilizer will essentially stop moving.

MODFLOW does not have the capacity to account for the introduction of an aqueous phase with a viscosity different than the viscosity of water. However, a different viscosity can be modeled by varying the hydraulic conductivity of the treated formation for the duration of a simulation. The hydraulic conductivity cannot be changed progressively as the stabilizer moves through the formation. However, if the hydraulic conductivity of the entire treatment area were decreased by one-half at the time the stabilizer is introduced, a maximum travel time for the stabilizer could be calculated. The actual travel time would be between the time required for a decreased hydraulic conductivity and the time required for water to travel through the treatment area.

The density of colloidal silica was assumed to be equal to the density of water, which should be fairly accurate for low concentrations of colloidal silica. However, it is not a variable or parameter in MODFLOW.

It is expected that the concentration required will be about 10 percent by weight colloidal silica. For contaminant transport modeling, values of 100 and 150 grams per liter (g/l) were used for the source concentration, which correspond to about 10 and 15 percent by weight.

7.4 Results

7.4.1 Purely Advective Flow

MODPATH was used to compute the travel time for advective transport under steady-state conditions for each combination of hydraulic conductivity and hydraulic gradient for the following cases:

1. Regional hydraulic gradient, with hydraulic conductivity in treatment area equal to the regional hydraulic conductivity ($k_{TA} = k_R$)
2. Regional hydraulic gradient, with hydraulic conductivity in treatment area equal to half the regional hydraulic conductivity ($k_{TA} = ½\ k_R$).
3. Regional flow augmented with injection well adding 1000 cubic feet per day (cfd) with $k_{TA} = k_R$
4. Regional flow augmented with an injection well adding 1000 cfd with $k_{TA} = ½\ k_R$
5. Regional flow augmented with an injection well adding 2500 cfd with $k_{TA} = k_R$ (except for hydraulic gradient of 0.001)
6. Regional flow augmented with an injection well adding 2500 cfd for $k_{TA} = ½\ k_R$ (except for hydraulic gradient of 0.001)

The results from these simulations are presented in Table 7-4. The travel time is shown for each combination of hydraulic gradient and hydraulic conductivity for the cases where $k_{TA} = k_R$ and $k_{TA} = ½\ k_R$. An example is shown in Figure 7-2. This example corresponds to a hydraulic conductivity of 140 ft/day and a hydraulic gradient of 0.005. Flow is augmented with a single well supplying 2500 cfd. The minimum travel time would be about 85 days, while the maximum travel time would be between about 120 and 130 days. These two travel times show the lower and upper limits for travel time, assuming the viscosity of the stabilizer is 2 cP during the travel time. The actual travel time would be somewhere between these values. Travel times of 150 days or less are shown in bold type in Table 7-4.

These plots can also be used to determine the approximate delivery width for a single well. The delivery width is the lateral distance that the stabilizer will travel from a single injection well, as shown in Figure 7-2. The magnitude of the delivery width depends on the volume injected through the well, the flow rate in the aquifer, and the hydraulic conductivity of the formation. The delivery widths reported here were measured at a distance of 100 feet down gradient from the well. The delivery width corresponding to the cases where $k_{TA} = k_R$ and $k_{TA} = ½ k_R$ are about 65 feet and 90 feet, respectively. The actual delivery width would be somewhere between these limits.

Based on a treatment area of 200-feet by 200-feet, the range of gel times available with colloidal silica grout, typical values of hydraulic conductivity for liquefiable sands, and the range of hydraulic gradients expected in regional flow systems, passive site remediation is expected to be feasible for travel times of about 100 days or less. Therefore, for the assumptions made in the conceptual model, the following broad observations can be made:

1. For all of the hydraulic gradients considered, if the hydraulic conductivity is below about 0.01 cm/s, the travel times will be too long for passive site remediation to be feasible, even if the flow regime is augmented with a single line of injection wells.
2. If the hydraulic conductivity is above about 0.05 cm/s, passive site remediation may be feasible for hydraulic gradients of about 0.005 and above.
3. If the hydraulic conductivity is between about 0.01 and 0.05 cm/s, passive site remediation may be feasible, but only if the regional hydraulic gradient is very high.

These broad observations are valid for a 200-foot by 200-foot treatment area only. Based on these observations, the rest of the groundwater modeling study focused on scenarios where the hydraulic conductivity was above 0.05 cm/s (140 ft/day) and the regional hydraulic gradient was at least 0.005. These values of hydraulic conductivity and hydraulic gradient would be expected to be present in many liquefiable formations.

7.4.2 Combined Advection and Dispersion

The travel times for advective flow are based on an average groundwater flow velocity and do not account for the mixing that occurs at the front of the plume. The actual concentration of stabilizer that will reach the down gradient edge of the treatment area will depend on the concentration of stabilizer injected, as well as the mixing that occurs as the plume moves through the formation. The results of the travel time analyses for advective flow were extended to include the combined effects of advection and dispersion and to estimate the concentration of stabilizer that would be required for adequate coverage of the treatment area. MT3DMS was used to simulate delivery of the stabilizer and to calculate the concentration distribution at various times after injection.

As discussed in Section 7.3.4, the effects of dispersion were considered in two ways:

1. Assuming a regional dispersion coefficient for a "typical" liquefiable formation based on published correlations with flow length, and
2. Modeling macroscopic heterogeneity by varying the hydraulic conductivity in each layer and using a small dispersion coefficient to approximate local dispersivity.

A detailed analysis of the combined effects of advection and dispersion was done for the case of a hydraulic gradient of 0.005 and a hydraulic conductivity of 0.05 cm/s (140 ft/day). This case was selected because the combination of hydraulic conductivity and gradient is expected to be fairly common among liquefiable formations. Additionally, travel times due to advection are fairly long, so if passive site remediation could be designed for this case, it could likely be designed for other cases when the hydraulic conductivity or the hydraulic gradient are greater. Models of combined advection and dispersion were developed for three cases:

1. Regional flow used to deliver stabilizer.
2. Regional flow augmented with 7 injection wells, each delivering 1000 cubic feet per day of stabilizer, and
3. Regional flow augmented with 3 injection wells, each delivering 2500 cubic feet per day of stabilizer

Case 1: Regional Flow Used to Deliver Stabilizer

Case 1 was modeled by assuming a constant concentration of colloidal silica at the up gradient edge of the treatment area. The constant concentration was assumed to extend for the entire 200-foot width of the treatment area and the full 50-foot thickness of the liquefiable layer. Actual delivery of the stabilizer in the field for this scenario would likely be through an infiltration trench or low-head injection wells that would have a minimal impact on the regional groundwater flow regime. Constant concentrations of 100 and 150 g/l were considered. These concentrations correspond to about 10 and 15 percent colloidal silica, respectively.

Figure 7-3 (a) is a plot of the stabilizer plume for Layer 3 after 103 days of stabilizer delivery in a formation with a uniform hydraulic conductivity of 140 ft/day, a regional dispersion coefficient of 20 ft, and a constant source concentration of 100 g/l (Case 1-1). Each layer has the same concentration field since the aquifer is assumed to be homogeneous for this case. Flowlines are superimposed on the plot to show the advective travel times of fluid particles moving through the treatment area. Each dot on the flowlines represents a 10-day increment. The concentration at the down gradient edge of the treatment area is about 60 g/l in the center and drops to about 40 g/l at each edge. The maximum extent of the 90 g/l contour is in the center of the treatment area. If stabilizer delivery is continued for 150 days, the 90 g/l contour moves about 140 feet through the treatment area, as shown in Figure 7-3 (b). If the source concentration is increased to 150 g/l, the concentration at the down gradient edge of the treatment area is about 90 g/l in the center and 60 g/l at the edges after 103 days, as shown in Figure 7-3 (c). In this case, the concentration in most of the treatment area is above 100 g/l. Only the outer corners of the down gradient edge of the treatment area show concentrations below 100 g/l. The plume is elliptical and extends well beyond the extents of the treatment area down gradient from the source. This suggests the need for a collector trench or extraction well at the down gradient side of the treatment area.

Figures 7-4 (a) and (b) are plots of the stabilizer plume at times of 103 and 150 days, respectively, for the case where the hydraulic conductivity in the treatment area was decreased by 50 percent (Case 1-2). As expected, the down gradient extent of the stabilizer plume is less at 103 days than shown for Case 1-1. However, by 150 days, the plumes look similar and the concentration distribution across the treatment area is about the same, although the total extent of the plume is somewhat larger when the hydraulic conductivity in the treatment area is decreased. Similar results are observed when concentrations of 150 g/l are used with a reduced hydraulic conductivity in the treatment area, except the concentration is higher (Figures 7-4 (c) and (d)).

If two extraction wells are added at the center of the down gradient edge of the treatment area, the travel times decrease and the extent of dispersion down gradient from the treatment area also decreases, as shown in Figure 7-5 for Case 1-1. The total volume of water extracted is 7500 cfd, which is comparable to the volume of stabilizer that would need to be injected daily to treat the formation in 100 days. After 100 days of treatment, the peak concentration at the down gradient edge of the treatment zone remains about the same, but the lateral extent of treatment decreases slightly (compare Figure 7-5 with Figure 7-3(a)). The maximum extent of dispersion decreases down gradient from about 140 feet to about 100 feet. Similar trends are observed when two extraction wells are added to Case 1-2 (reduced hydraulic conductivity in treatment area), as shown in Figure 7-6. The maximum extent of dispersion down gradient is reduced from about 80 feet to about 60 feet after 100 days and from about 180 feet to about 130 feet after 150 days (compare Figure 7-6 with Figure 7-4(a)). The peak concentration in the treatment area remains about the same, but the lateral extent of treatment is reduced slightly.

When the hydraulic conductivity is varied within the layers and a local dispersion coefficient is used, there is non-uniform movement of the plume through the formation. Profiles through the centerline of the treatment area resulting from a constant concentration of 100 g/l are shown in Figure 7-7 for times of 48, 100, and 150 days (Case 1-3). The hydraulic conductivity was varied slightly in each layer for a total variation across the profile of one order of magnitude distributed as shown. The hydraulic conductivity used in each layer is shown in Table 7-3. The travel times ranged from about 50 to 470 days.

Not surprisingly, the shape of the plume is more rectangular when a local dispersion coefficient is used, as shown in Figure 7-8. Only the concentrations and extents of the plumes vary when different hydraulic conductivity values are used. Layer 3 of this case (local dispersivity) can be compared to Layer 3 of Case 1-1, where a regional dispersion coefficient was used (Figure 7-3 (a)). The stabilizer concentration is much more uniform transversely when a local dispersion coefficient is used. Additionally, the front progresses more rapidly through the treatment area, as shown in Figure 7-7. After 100 days of treatment, the concentration at the down gradient edge ranges from about 20 g/l in the top layer to above 80 g/l in the higher hydraulic conductivity layers. The lower 35 feet of the liquefiable layer have concentrations in excess of 70 g/l. The maximum extent of the stabilizer plume is about 150 feet beyond the down gradient edge of the treatment area. After 150 days, the concentration at the down gradient edge is above 60 g/l for the entire thickness of the liquefiable layer and above 90 g/l for the lower 35 feet. The plume extends about 290 feet beyond the down gradient edge of the treatment area. If source concentrations of 150 g/l are used, the concentrations at the down gradient edge are above 100 g/l for the lower 40 feet of the liquefiable formation at 100 days (Figure 7-9). The plume extends about 170 feet beyond the down gradient edge of the treatment area.

If two extraction wells are placed in the center of the down gradient edge of the treatment area, the advective travel times decrease substantially and the overall profile is more uniform, as shown in Figure 7-10. The extraction wells also help to control the down gradient extent of the stabilizer plume. The maximum down gradient extent of the plume decreases from about 150 feet to about 90 feet after 100 days of treatment. Additionally, the concentration at the end of the treatment area is above 80 g/l for the lower 40 feet of the liquefiable layer at the down gradient edge. However, the extraction wells limit the lateral extent of the delivery, as shown in Figure 7-11. Row 40 is along the centerline of the treatment area; Rows 38 and 36 are 40 and 80 feet, respectively, from the centerline. The concentration profile at the centerline is above 80 g/l for most of the thickness of the liquefiable layer at the down gradient edge. The concentration profile 40 feet from the centerline (Row 38) is between 50 and 70 g/l. At a distance of 80 feet from the centerline (Row 36), the concentration is only about 20 g/l for most of the liquefiable layer.

If the wells are separated, with one placed on either side of the treatment area at a distance of 40 feet from the centerline, the concentration profile in the treatment area changes only slightly. Profiles through Rows 40, 38, and 36 are shown in Figure 7-12. The extraction well is located in Row 38. The concentration profile through Row 36 is very similar to that shown in Figure 7-11.

When the hydraulic conductivity in the treatment area is reduced by 50 percent in each layer (Case 1-4), the trends are the same as for Case 1-3, but the travel times are longer. A profile through the centerline of the treatment area is shown in Figure 7-13. After 150 days of treatment, the concentration is above 70 g/l in the lower 40 feet of the layer. When a source concentration of 150 g/l is used, the concentration in the lower 35 feet of the layer is above 60 g/l after 100 days, as shown in Figure 7-14.

Several conclusions can be made based on the results of this analysis. First, extraction wells decrease the travel time and help control the down gradient stabilizer plume. The profile plots show a small amount of stabilizer moving past the extraction wells. However, this movement is attributed to numerical dispersion in the model. Extraction wells also help to even out the concentration profile for Cases 1-3 and 1-4. Concentrations in excess of 80 g/l were obtained with source concentrations of 100 g/l after 100 days. If extraction wells were not used, a constant concentration of 100 g/l for 150 days or 150 g/l for 100 days would be necessary to adequately treat the formation. The main drawback of extraction wells is that they decrease the lateral extent of stabilizer delivery slightly. If necessary, this could be handled by adding another low-head well.

There is a fairly large difference in the results between a regional dispersion coefficient in a homogeneous aquifer and a local dispersion coefficient in heterogeneous aquifer. It is likely that there will be at least some heterogeneity in the aquifer, although it is not likely to be such a dramatic case as was modeled here. The actual behavior will probably be between these limits. The degree of non-uniformity of the profile will depend on the amount of variation in the hydraulic conductivity between layers. In the scenarios modeled here, the top layer has the lowest hydraulic conductivity and ends up with the lowest concentration of stabilizer of all the layers. This may or may not be acceptable depending on the type of material in the layer. If the layer were dense sand, having a low concentration of stabilizer would likely not be a problem. However, if the layer were loose, silty fine sand, it could be a problem. It is likely that treatment of the adjacent layers would limit the amount of deformation that could occur in the entire formation, but this issue would have to be handled on a case-by-case basis.

Case 2: Stabilizer Delivered Via 7 Injection Wells

Case 2 was modeled by assuming that the stabilizer would be delivered to the formation through 7 injection wells. The volume of stabilizer delivered through each well would be 1000 cubic feet per day, or about 5 gallons per minute. It is expected that these flows could be delivered through wells with less than three feet of head. The stabilizer would contain concentrations of 100 or 150 g/l of colloidal silica.

The number of injection wells necessary to cover a 200-foot-wide treatment area was determined by considering the delivery width of a single well. As noted earlier, the delivery width is the transverse distance that the stabilizer will travel from the injection well. An example is shown in Figure 7-2. Table 7-5 repeats the travel times for cases where passive site remediation might be feasible, as well as the delivery widths for single wells pumping at rates of 1000 cubic feet per day and 2500 cubic feet per day. The delivery width is a function of the volume of stabilizer injected through the well, the hydraulic conductivity of the aquifer and the average linear groundwater velocity. As the hydraulic conductivity and the groundwater velocity increase, the delivery width decreases. As the volume injected increases, the delivery width increases. For passive site remediation, the delivery width would need to be balanced with the volume injected into the well to deliver an adequate amount of stabilizer to the formation.

When the hydraulic conductivity is 140 feet per day and the hydraulic gradient is 0.005, a single well injecting 1000 cfd has a delivery width of about 40 feet. However, when multiple wells are operating, the total delivery width may not be equal to the sum of the individual delivery widths. In this case, 7 delivery wells were necessary to obtain a delivery width of 180 feet. When the hydraulic conductivity in the treatment area was reduced by 50 percent, 7 wells had a delivery width of 210 feet. The actual delivery width would be somewhere between these widths. Each delivery well was paired with an extraction well removing 1000 cfd.

Figures 7-15 (a) and (b) are plots of the stabilizer plume for Layer 3 after 99 and 150 days of stabilizer delivery, respectively. The formation has a uniform hydraulic conductivity, a regional dispersion coefficient, and a constant source concentration of 100 g/l delivered through the injection wells (Case 2-1). Flowlines are superimposed on the plot to show the advective travel times of fluid particles moving through the treatment area. Travel times are about 70 days. Each dot on the flowlines represents a 10-day increments. The concentration at the down gradient edge of the treatment area is about 45 g/l in the center and drops to about 25 g/l at each edge. The maximum concentration in the treatment area is about 60 g/l. This contour extends about 100 feet into the treatment area after 99 days and extends about 115 feet into the treatment area after 150 days. The concentration at the down gradient edge ranges from 50 g/l in the center to about 30 g/l at the edges. Figure 7-16 is a plot of the concentration field if the source concentration is increased to 150 g/l. The maximum concentration in the treatment area is about 90 g/l. This contour extends about 100 feet into the treatment area after 100 days and about 115 feet after 150 days. The concentration at the center of the down gradient edge is about 65 g/l after 100 days and about 75 g/l after 150 days.

The maximum concentrations for Case 2-1 are less than the comparable situation in Case 1. In Case 1, a constant concentration of 100 g/l was assumed for all the fluid leaving the source cells. In Case 2, only the water injected through the wells has a concentration of 100 g/l. Therefore, there will be more mixing and dilution in Case 2, with a resultant decrease in concentrations across the treatment area.

When the hydraulic conductivity is reduced by 50 percent in the treatment area (Case 2-2), the concentration throughout the treatment area is higher and the extent of down gradient dispersion is reduced compared to Case 2-1. Figure 7-17 (a) is a plot of the concentration field in Layer 3 after 98 days of treatment. The concentration at the down gradient edge of the treatment area is similar to Case 2-1, but the maximum concentration in the treatment area has increased to about 80 g/l. This contour extends about 75 feet into the treatment area. By 147 days, the 80 g/l contour extends about 90 feet into the treatment area, as shown in Figure 7-15 (b). Figures 7-17 (c) and (d) are plots of the concentration field if the source concentration is increased to 150 g/l. The maximum concentration in the treatment area is about 120 g/l. This contour extends about 80 feet into the treatment area after 98 days and about 90 feet after 147 days. The concentration at the center of the down gradient edge is about 60 g/l after 98 days and 90 g/l after 147 days.

When the hydraulic conductivity is varied within the layers and a local dispersion coefficient is used, there is non-uniform movement of the plume through the formation. The variation in hydraulic conductivity between layers is shown in Table 7-3. The travel times ranged from about 35 to about 380 days. Profiles through the centerline of the treatment area resulting from a constant concentration of 100 g/l in the injection wells are shown in Figures 7-18 (c) and (d) for times of 98 and 150 days (Case 2-3). The concentration is at least 60 and 70g/l in the lower 40 feet of the layer at 98 days and 150 days, respectively. The concentration in the upper layer is about 50 and 60 g/l at times of 98 and 150 days, respectively. Profiles through Rows 36 and 38 are shown in Figures 7-18 (a) and (b). The concentration is above 40 g/l at the down gradient edge of the treatment zone in Row 38, but drops to about 30 g/l in Row 36. Similar plots are shown in Figure 7-19 for a source concentration of 150 g/l. The shape of the profiles is the same but the concentration increases.

Layer 3 of Case 2-3 (local dispersivity) can be compared to Layer 3 of Case 2-1 (Figure 7-15 (a)). The stabilizer concentration is much more uniform laterally for Case 2-3 since a local dispersion coefficient is used. Additionally, the front progresses through the treatment area faster for Case 2-3, which can be seen if Figures 7-15 (a) and 7-18 (c) are compared.

Profiles through the treatment area when the hydraulic conductivity is decreased by 50 percent (Case 2-4) are shown in Figure 7-20. Figures 7-20 (a) through (c) are profiles through Rows 36, 38, and 40, respectively after 100 days of treatment with a source concentration of 100 g/l. The concentrations at the down gradient edges are about 15, 50, and 70 g/l for Rows 36, 38, and 40, respectively. Figure 7-20 (d) is a profile through Row 40 after 150 days of treatment. The concentration at the down gradient edge is above 80 g/l for most of the liquefiable thickness.

Profiles through the centerline of the treatment area when the source concentration is increased to 150 g/l are shown in Figures 7-21 (a) through (c) for times of 75, 100, and 150 days. The concentration at the down gradient edge is above 70 g/l for the lower 35 feet of the liquefiable formation after 75 days. It is above 100 g/l for the lower 40 feet of the formation after 100 days and above 110 g/l throughout the layer after 150 days.

Case 3: Stabilizer Delivered Via 3 Injection Wells

Case 3 was modeled using 3 injection wells, each delivering 2500 cfd (13 gpm) of stabilizer. It is expected that a head of less than 3 feet would be required to deliver this flow. The stabilizer concentration was modeled as a point source of 100 g/l from the wells. As shown in Figure 7-22, the wells were spaced 40 feet center-to-center so an adequate delivery width could be obtained. The combined delivery widths for the wells are 160 and 200 feet for the cases of $k_{TA} = k_R$ and $k_{TA} = ½ k_R$, respectively. Three extraction wells were used at the down gradient edge of the treatment area. Each extraction well withdrew 2500 cfd.

The stabilizer plumes for Layer 3 after 100 and 150 days of treatment with a concentration of 100 g/l are shown for Case 3-1 in Figures 7-22 (a) and (b), respectively. The formation was modeled with a uniform hydraulic conductivity, a regional dispersion coefficient, and a point source concentration of 100 g/l in the injection wells. After 100 days of treatment, the concentration at the down gradient edge of the treatment area is about 50 g/l in the center and drops to about 25 g/l at each edge. The maximum concentration in the treatment area is about 70 g/l. This contour extends about 60 feet along the centerline of the treatment area after 100 days and about 70 feet after 150 days. Figures 7-22 (c) and (d) are plots of the corresponding cases when the hydraulic conductivity is reduced by 50 percent in the treatment area (Case 3-2). The maximum concentration in the treatment area is about 80 g/l; this contour extends a maximum of about 80 feet along the centerline of the treatment area after 100 days and about 100 feet after 150 days. The concentration at the down gradient edge is about 40 g/l after 100 days and about 60 g/l after 150 days. The maximum concentrations in this case are similar to the comparable situations in Case 2.

When the hydraulic conductivity is varied within the layers and a local dispersion coefficient is used, there is non-uniform movement of the plume through the formation. The variation in hydraulic conductivity across the layers is shown in Table 7-3. Profiles through the centerline of the treatment area resulting from a constant concentration of 100 g/l are shown in Figure 7-23 for times of 51, 102, and 150 days (Case 3-3). The travel times ranged from about 30 to 370 days. The concentrations at the down gradient edge are about 30, 65, and 70 g/l at times of 51, 102, and 150 days, respectively, in the lower 4 layers. In the upper layer, the concentrations are about 10, 50, and 65 g/l at 51, 102 and 150 days, respectively.

A plot for the concentration field for each layer at a time of 102 days is shown in Figure 7-24. Each layer has a slightly different concentration field depending on the hydraulic conductivity in the layer. Profiles for Rows 40, 37, and 35 are shown in Figure 7-25. Coverage is fairly good for Rows 40 and 37, but drops to between 10 and 30 g/l at Row 35.

The concentration profile through the centerline of the treatment area for a reduced hydraulic conductivity in the treatment area is shown in Figure 7-26 for times of 50, 99, and 150 days. The concentrations at 99 and 150 days are about 60 and 80 g/l, respectively, for the lower 40 feet of the layer. A plot of the concentration field for each layer is shown in Figure 7-27. Profiles for Rows 40, 39, 36, and 35 are shown in Figure 7-28.

7.5 Conclusions

The modeling study was a “numerical experiment” to determine if the stabilizer could be delivered to the liquefiable formation using the natural groundwater flow system as a delivery system or by augmenting the flow regime with injection or extraction wells. The treatment area considered was 200 feet by 200 feet and 50 feet thick. Augmentation of the flow regime was done with a single line of injection wells and a single line of extraction wells. The viscosity of the stabilizer is higher than the viscosity of water and was modeled by decreasing the hydraulic conductivity in the treatment area. Based on these assumptions, the results indicate that if the liquefiable formation has a hydraulic conductivity of 0.05 cm/s or above in combination with a hydraulic gradient of 0.005 or above, the natural groundwater flow can be used to deliver the stabilizer, especially if injection or extraction wells are used. These results are applicable only to a treatment area of 200 feet by 200 feet.

The selection of a dispersion coefficient has an extremely large influence in determining if an appropriate amount of stabilizer can be delivered to the formation. The effects of dispersion were considered by two methods, including 1) selecting a regional dispersion coefficient in conjunction with a uniform hydraulic conductivity throughout the formation and 2) varying the hydraulic conductivity slightly throughout the formation and using a local dispersion coefficient to model small scale dispersivity. The actual behavior in the field is expected to be somewhere between these boundaries. For field applications, it will be extremely important to thoroughly characterize the hydraulic conductivity profile throughout the liquefiable layer and across the proposed treatment area.

The results of the numerical modeling analyses are discussed with respect to the feasibility of passive site remediation in Chapter 8.

Table 7-4 Travel Times for Advective Flow (days)

		i = 0.001		i = 0.005		i = 0.01		i = 0.02	
		$k_{TA}=k_R$	$k_{TA}=½k_R$	$k_{TA}=k_R$	$k_{TA}=½k_R$	$k_{TA}=k_R$	$k_{TA}=½k_R$	$k_{TA}=k_R$	$k_{TA}=½k_R$
k (cm/s)	Flow (cfd)	Time (d)	Time (d)	Time (d)	Time (d)	Time (d)	Time (d)	Time (d)	Time (d)
0.001	0	48000	70000	4800	7000	2500	3550	1275	1875
	1000	1700	2500	1500	1900	1250	1600	775	1125
0.005	0	4875	7000	975	1400	500	700	255	370
	1000	1250	1690	610	850	380	530	225	310
	2500	625	850	415	575	300	410	195	270
0.01	0	2450	3500	500	700	250	350	130	185
	1000	825	1125	370	510	220	300	120	165
	2500	460	620	280	385	180	250	**110**	**150**
0.05	0	480	720	**100**	**145**	**50**	**75**	**25**	**35**
	1000	355	500	**90**	**130**	**48**	**70**	**25**	**37**
	2500	265	360	**85**	**118**	**46**	**65**	**24**	**35**
0.1	0	245	350	**50**	**75**	**25**	**35**	**13**	**20**
	1000	205	290	**50**	**67**	**24**	**35**	**13**	**18**
	2500	**70**	235	**45**	**63**	**23**	**34**	**12**	**17**

Table 7-5 Travel Times and Delivery Widths for Advective Flow

		Hydraulic Gradient											
		0.005				0.01				0.02			
		$k_{TA} = k_R$		$k_{TA} = ½ k_R$		$k_{TA} = k_R$		$k_{TA} = ½ k_R$		$k_{TA} = k_R$		$k_{TA} = ½ k_R$	
k (cm/s)	Flow (cfd)	Time (d)	Width (ft)	Time (d)	Width (ft)	Time (d)	Width (ft)	Time (d)	Width (ft)	Time (d)	Width (ft)	Time (d)	Width (ft)
0.05	0	**100**		**145**		**50**		**75**		**25**		**35**	
	1000	**90**	*40*	**130**	*50*	**48**	*30*	**70**	*35*	**25**	*25*	**37**	*30*
	2500	**85**	*65*	**118**	*90*	**46**	*40*	**65**	*55*	**24**	*30*	**35**	*40*
0.1	0	**50**		**75**		**25**		**35**		**13**		**20**	
	1000	**50**	*25*	**67**	*35*	**24**	*25*	**35**	*27*	**13**	*25*	**18**	*25*
	2500	**45**	*40*	**63**	*55*	**23**	*30*	**34**	*37*	**12**	*25*	**17**	*30*

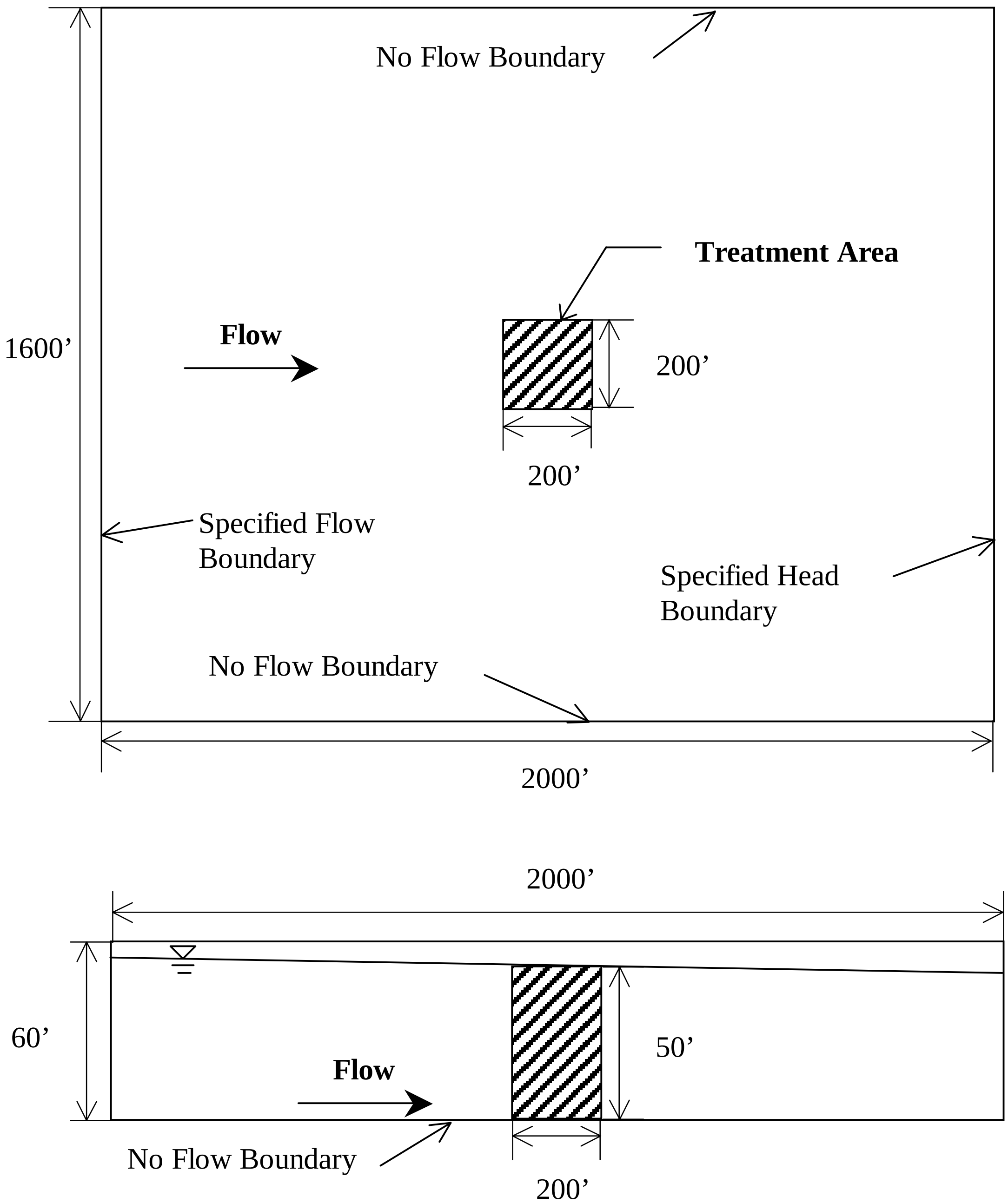
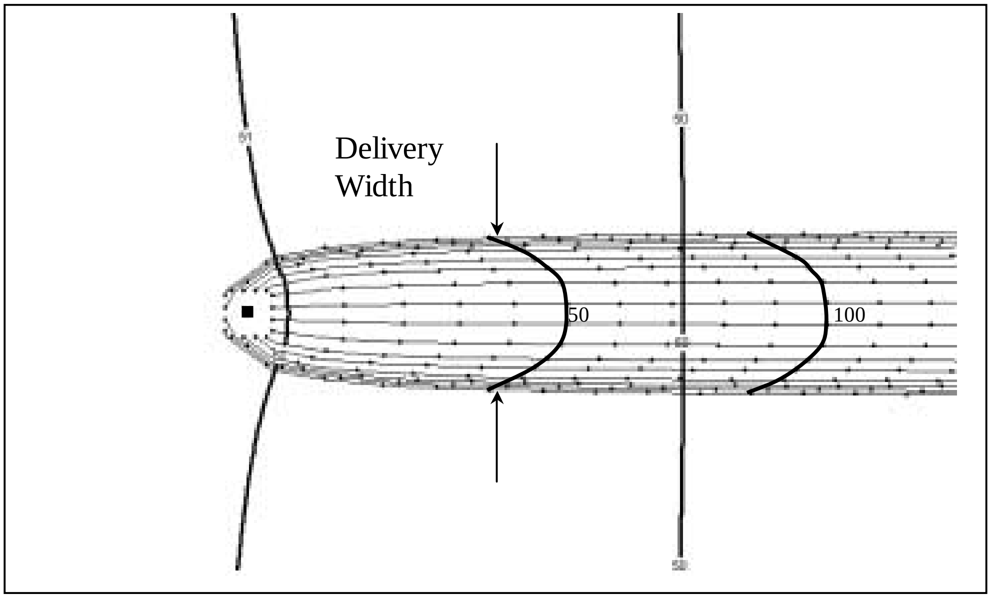
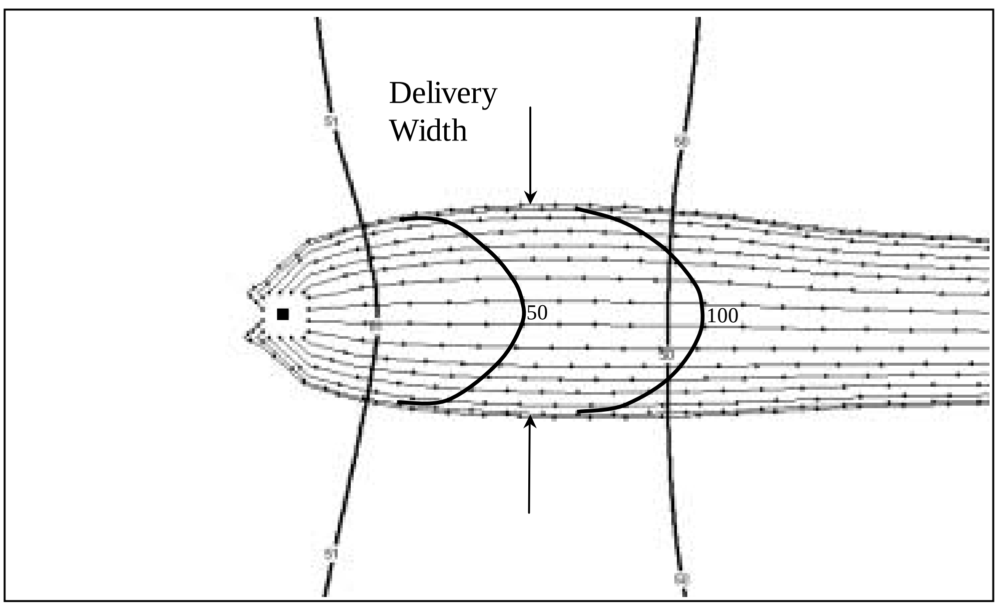


Figure 7-1 Model Domain and Boundary Conditions

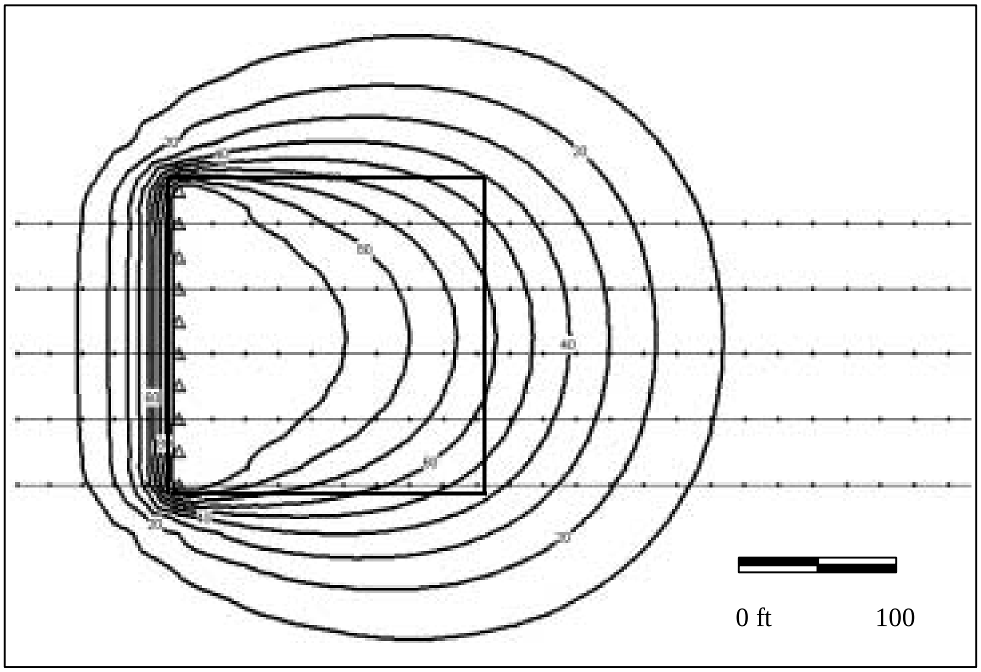


a) Lower limit, $k_{TA}=k_R$, delivery width = 65 feet, 1 dot = 10 days

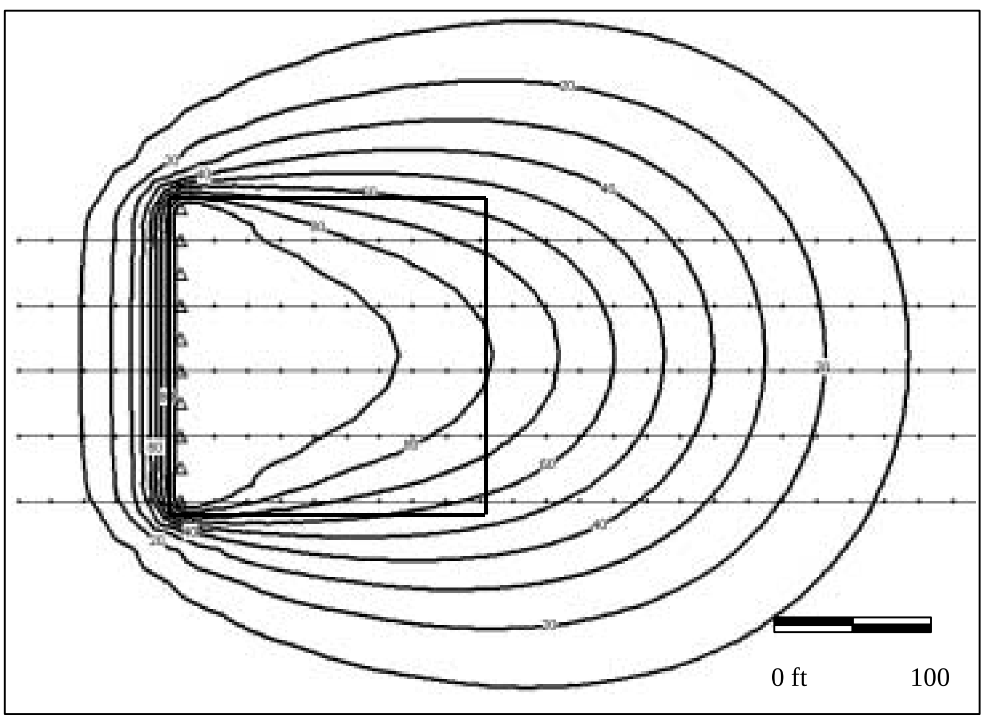


b) Upper limit, $k_{TA}= ½ k_R$, delivery width = 90 feet, 1 dot = 10 days

Figure 7-2 Lower and upper limits for travel time. Contours shown for travel times of 50 and 100 days. Delivery width shown for a single well injecting 2500 cfd.

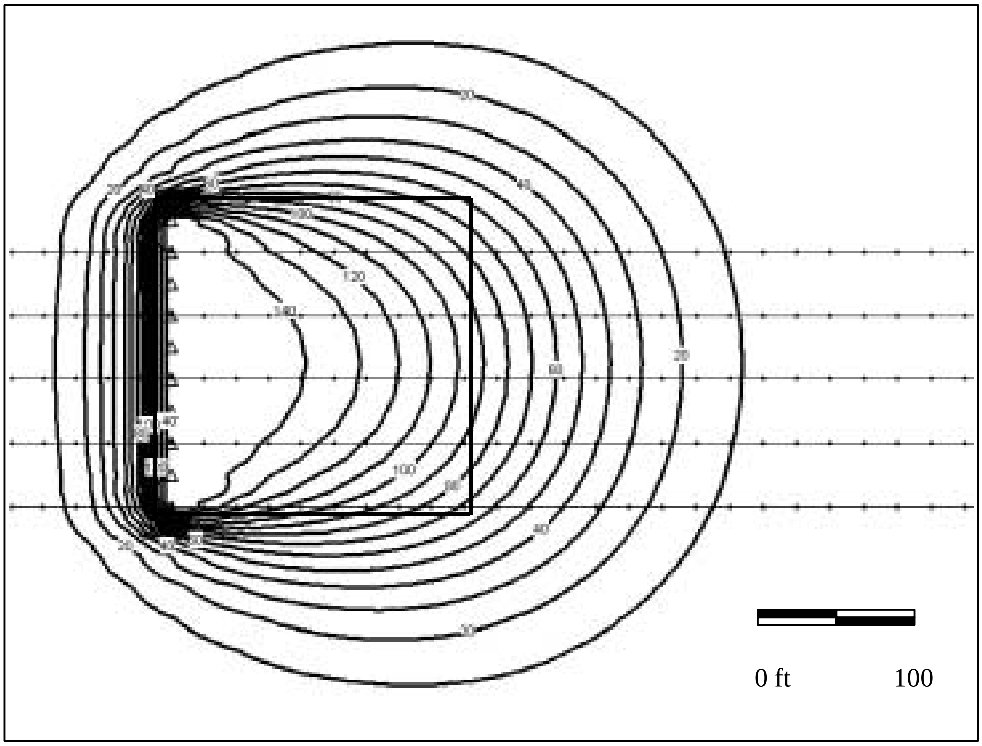


a) Constant concentration = 100 g/l, 103 days



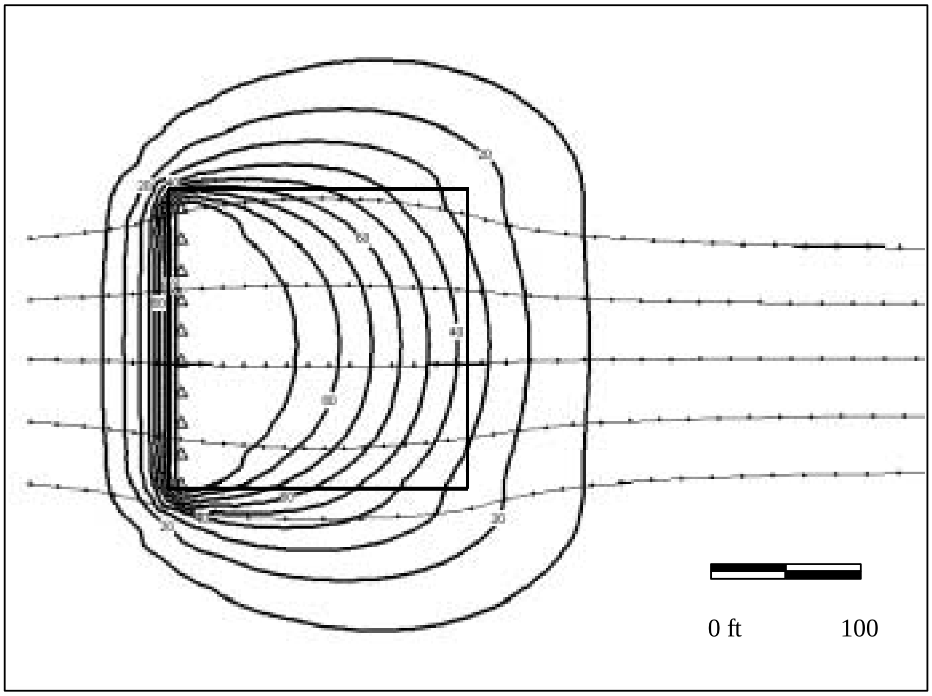
b) Constant concentration = 100 g/l, 150 days

Figure 7-3 Case 1-1: Regional flow used to deliver stabilizer.
Constant concentration delivered through infiltration trench.
$k_{TA}=k_R$, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days

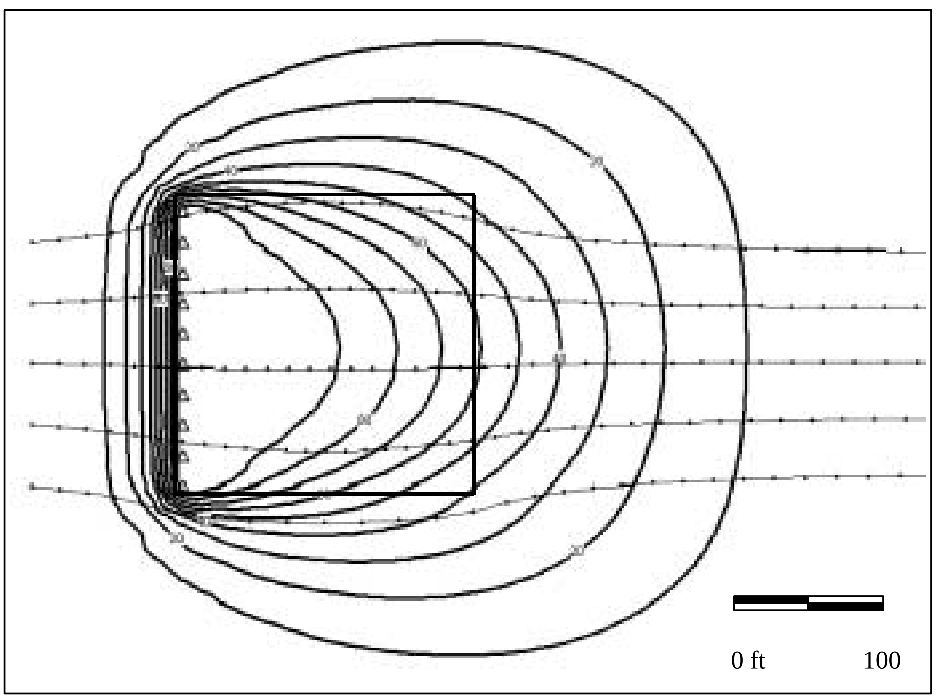


c) Constant concentration = 150 g/l, 103 days

Figure 7-3 (cont'd) Case 1-1: Regional flow used to deliver stabilizer.
Constant concentration delivered through infiltration trench.
$k_{TA}=k_R$, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days

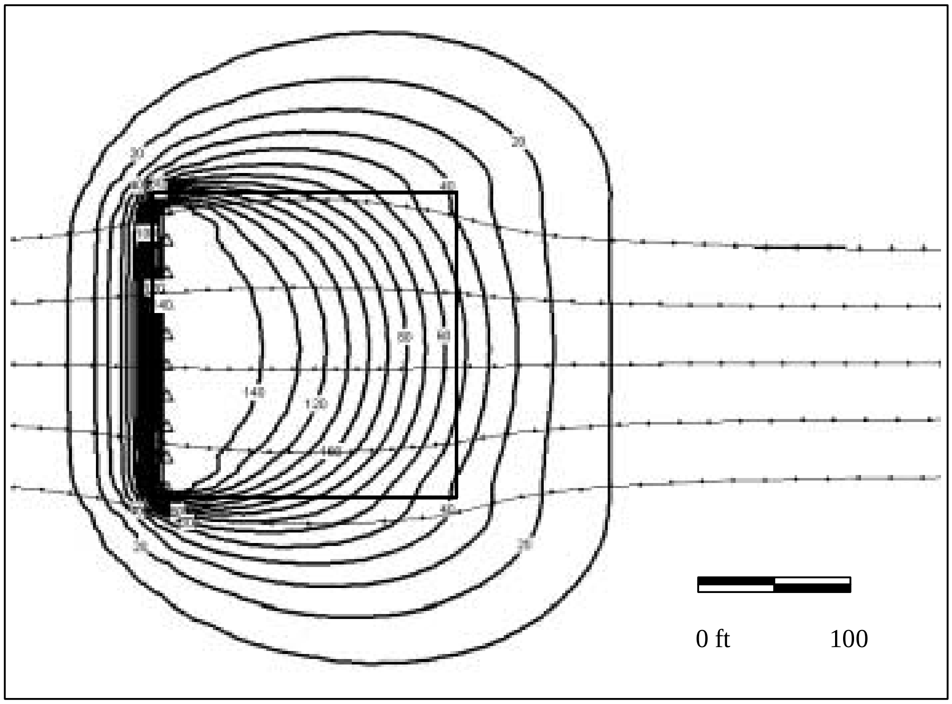


a) Constant concentration = 100 g/l, 105 days

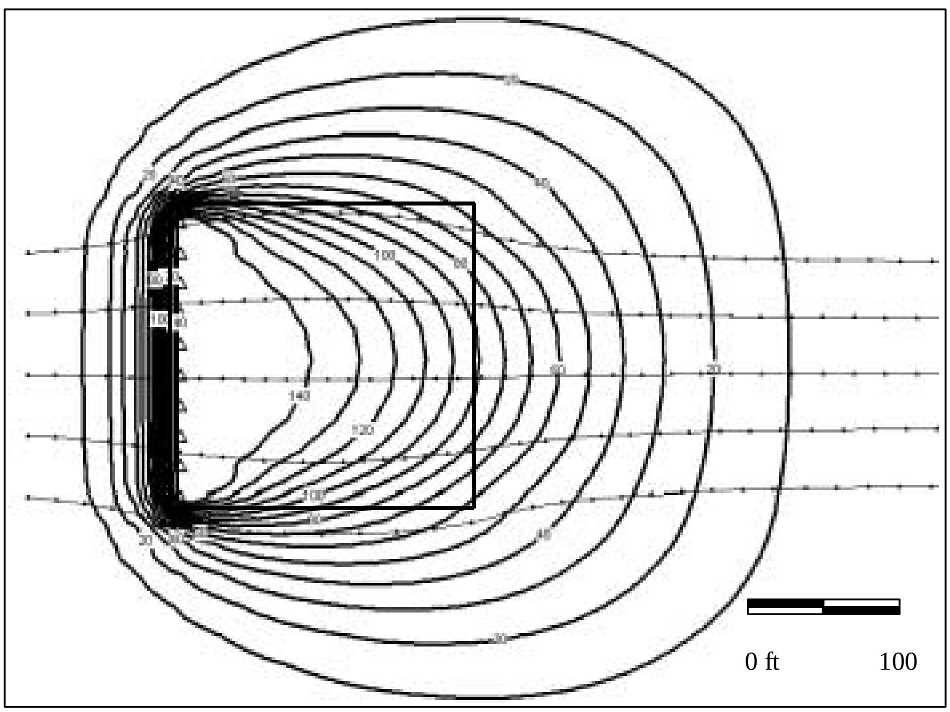


b) Constant concentration = 100 g/l, 150 days

Figure 7-4 Case 1-2: Regional flow used to deliver stabilizer.
Constant concentration delivered through infiltration trench.
$k_{TA} = ½ k_R$,, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days



c) Constant concentration = 150 g/l, 103 days



d) Constant concentration = 150 g/l, 150 days

Figure 7-4 (cont'd.) Case 1-2: Regional flow used to deliver stabilizer. Constant concentration delivered through infiltration trench. $k_{TA} = ½\ k_R$, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days

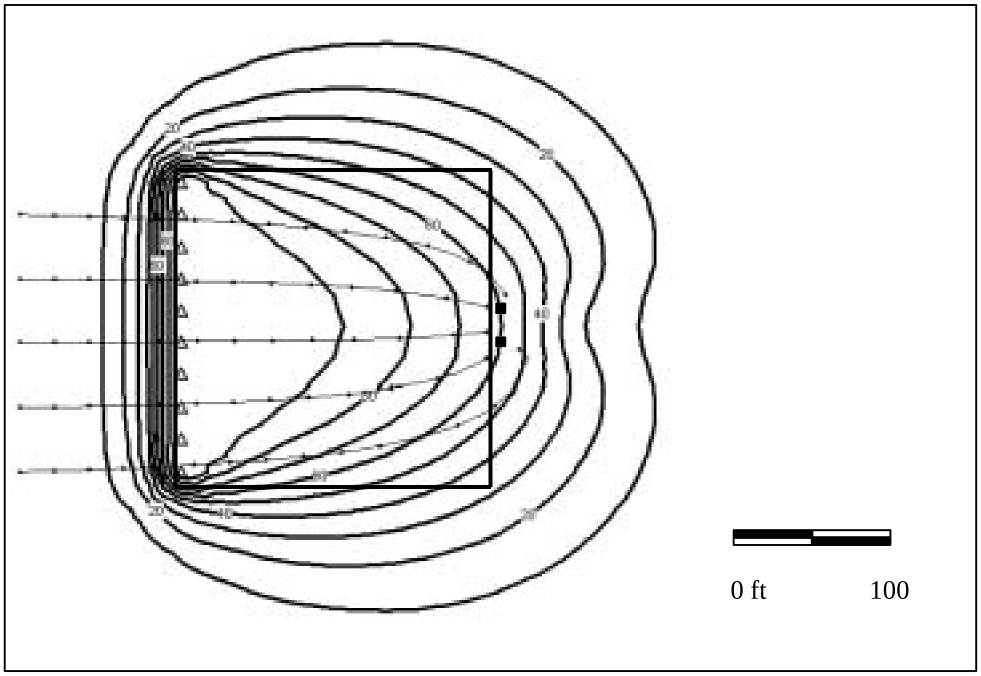


Figure 7-5 Case 1-1: With extraction wells. Regional flow used to deliver stabilizer. Constant concentration = 100 g/l, delivered through infiltration trench. Wells extract 7500 cfd total, $k_{TA}=k_R$, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days

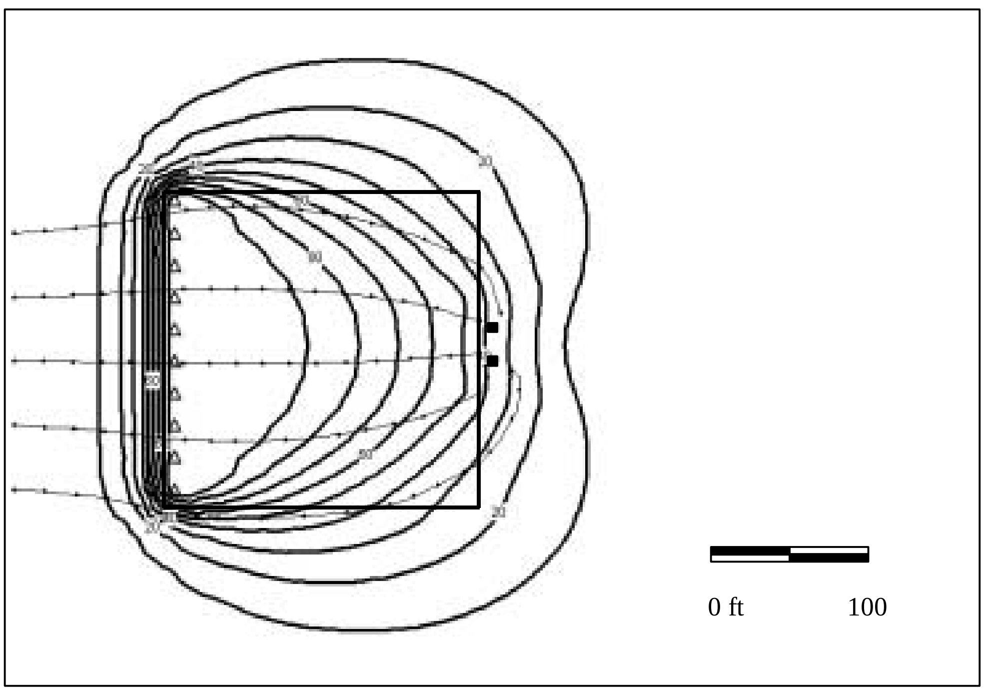
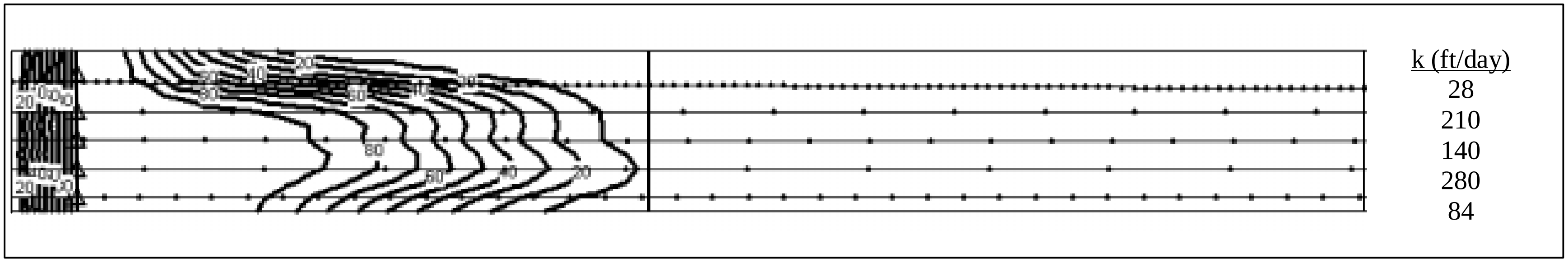
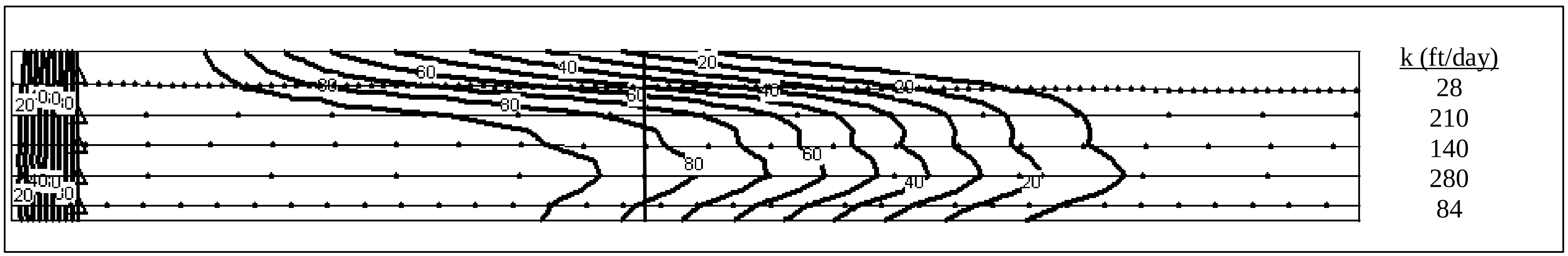


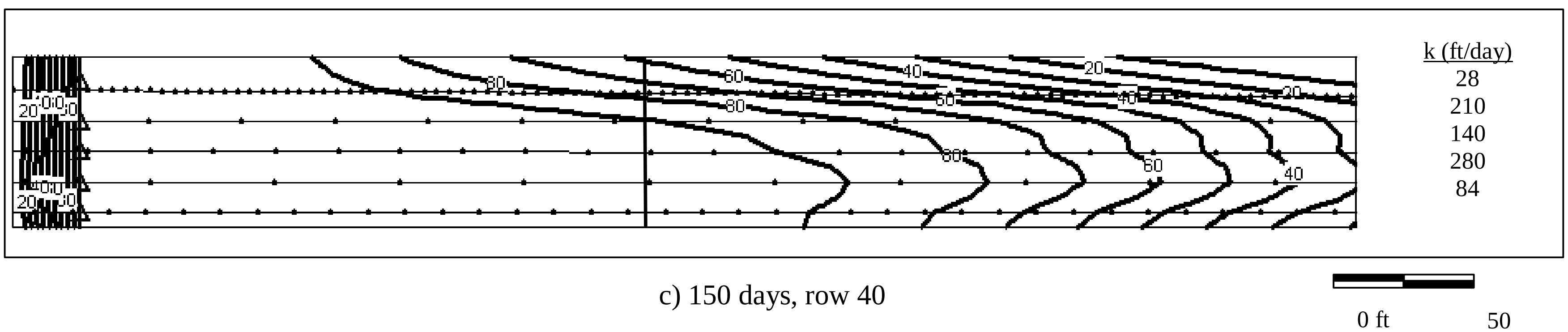
Figure 7-6 Case 1-2: With extraction wells. Regional flow used to deliver stabilizer. Constant concentration = 100 g/l, delivered through infiltration trench. Wells extract 7500 cfd total, $k_{TA} = \frac{1}{2} k_R$, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days



a) 48 days, row 40

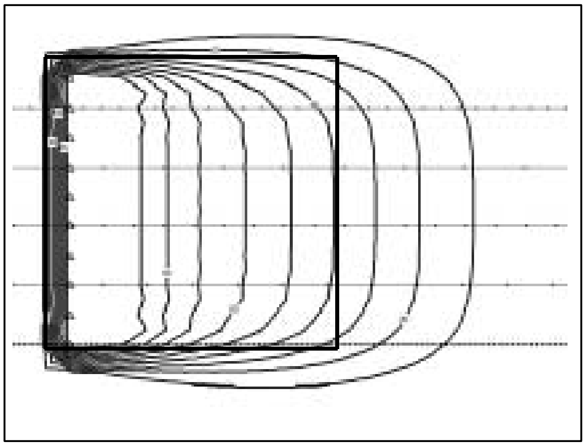


b) 100 days, row 40

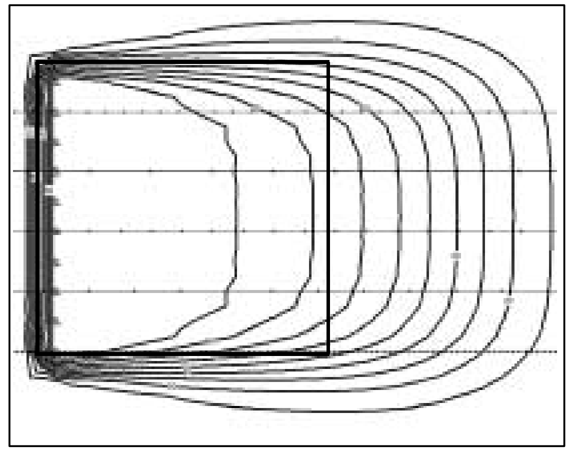


c) 150 days, row 40

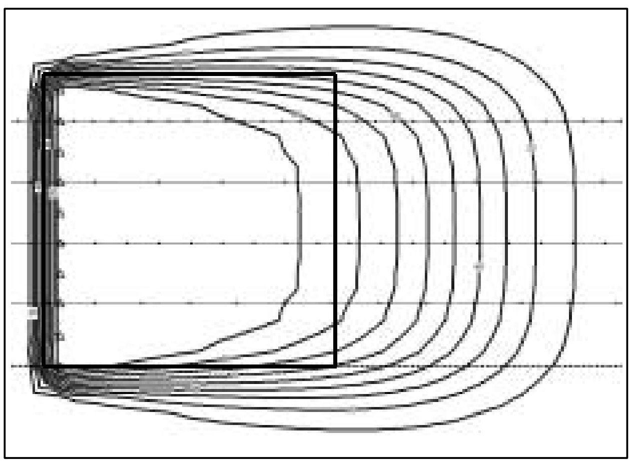
Figure 7-7: Case 1-3, Regional flow used to deliver stabilizer. Profiles through centerline.
Constant concentration = 100 g/l, delivered through infiltration trench, k_{TA}=k_R, variable k, α_L = 2 ft, 1 dot = 10 days



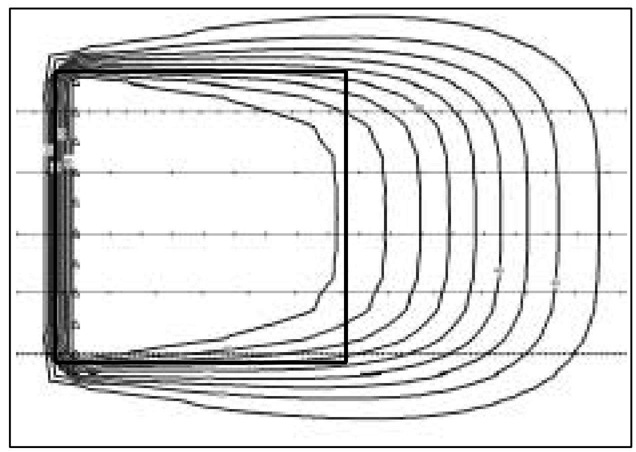
Layer 1, k=28 ft/d



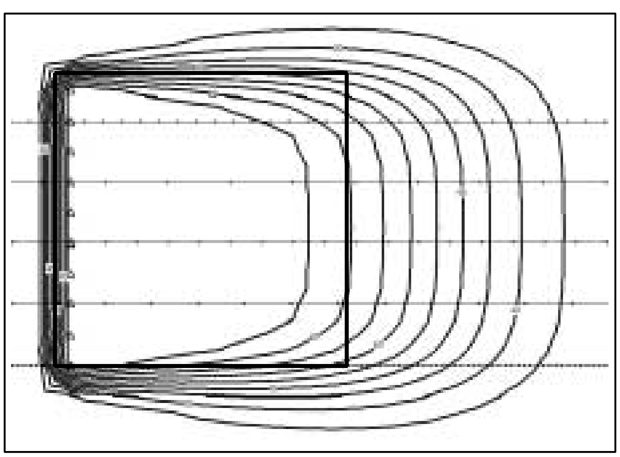
Layer 2, k=210 ft/d



Layer 3, k=140 ft/d



Layer 4, k=280 ft/d



Layer 5, k=84 ft/d

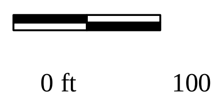
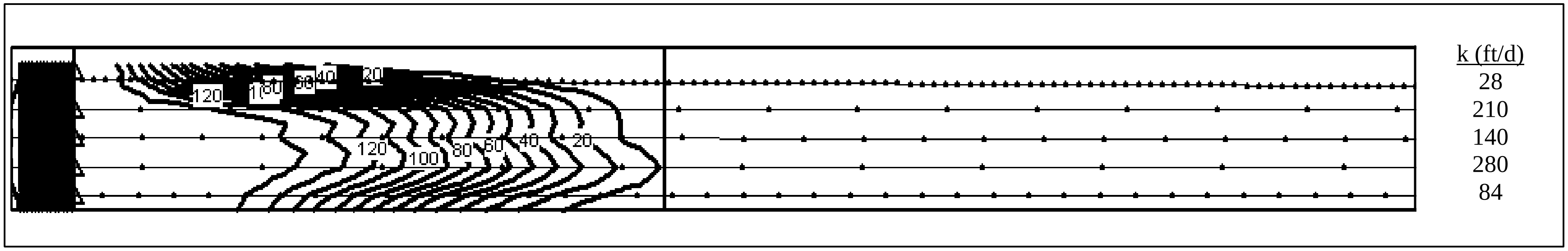
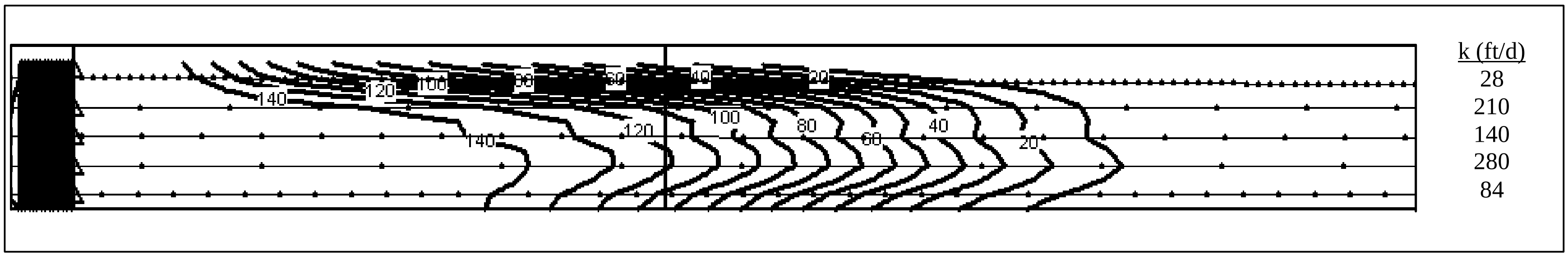


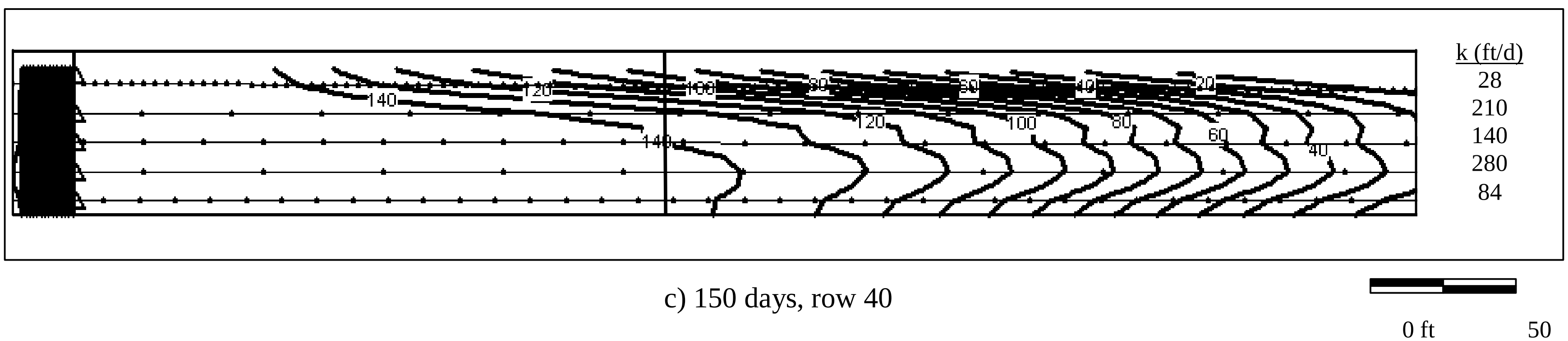
Figure 7-8 Case 1-3: Regional flow used to deliver stabilizer.
Constant concentration = 100 g/l, delivered through infiltration trench, k_{TA}=k_R, variable k, α_L = 2 ft,
1 dot = 10 days
Layers 1 through 5 after 100 days



a) 48 days, row 40

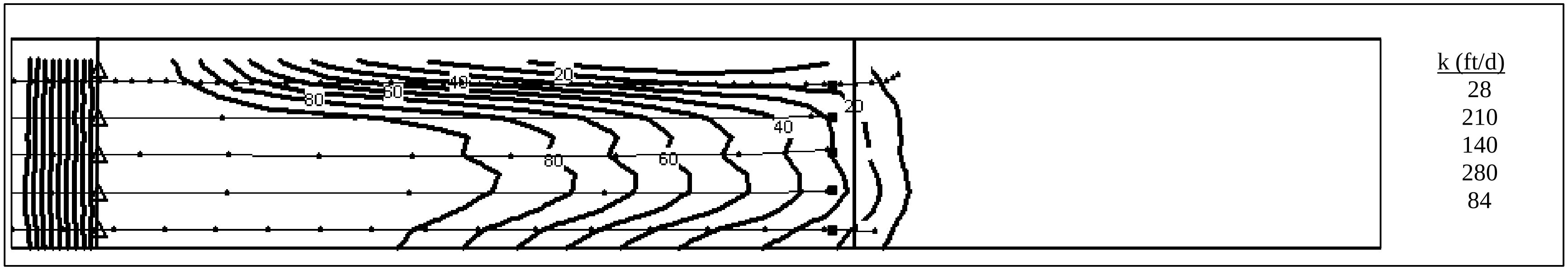


b) 100 days, row 40

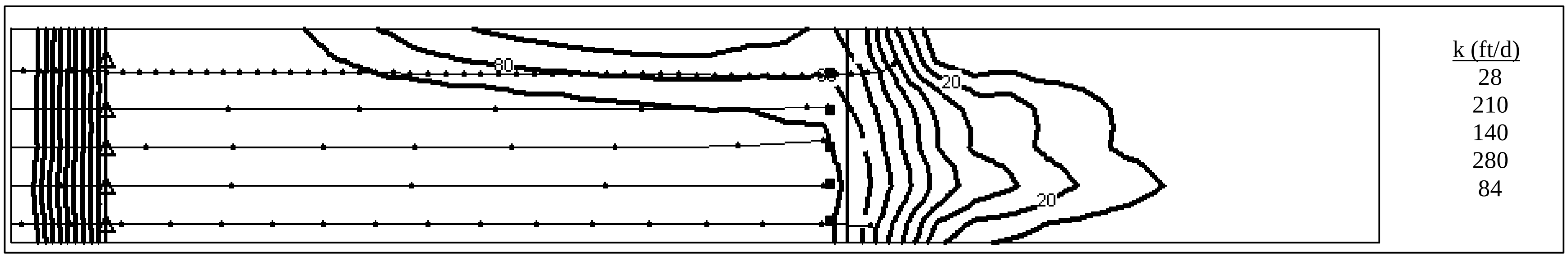


c) 150 days, row 40

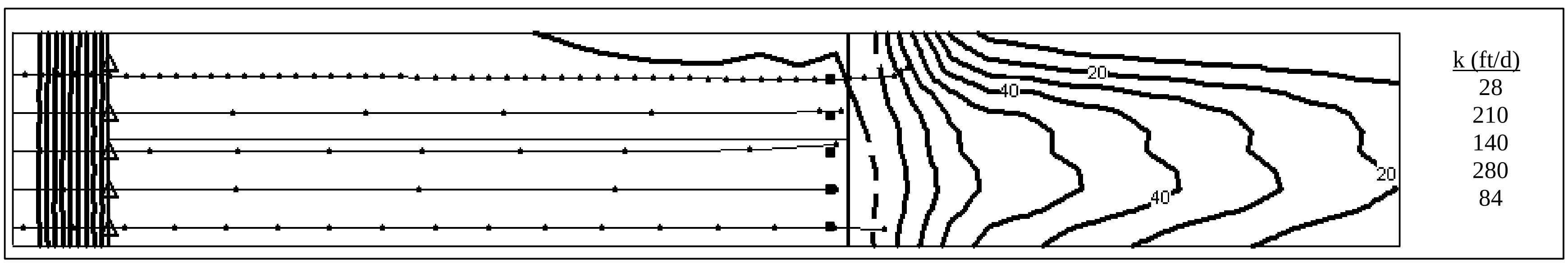
Figure 7-9 Case 1-3: Regional flow used to deliver stabilizer. Profiles through centerline.
Constant concentration = 150 g/l, delivered through infiltration trench, $k_{TA}=k_R$, variable k, α_L = 2 ft, 1 dot = 10 days



a) 49 days, row 40



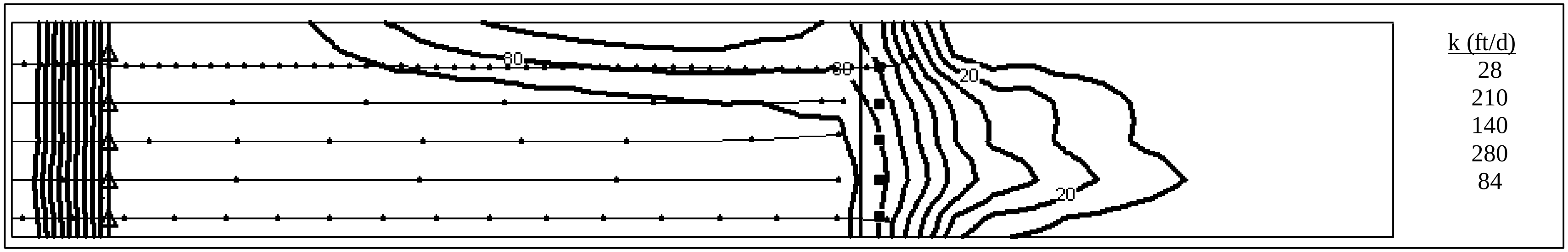
b) 100 days, row 40



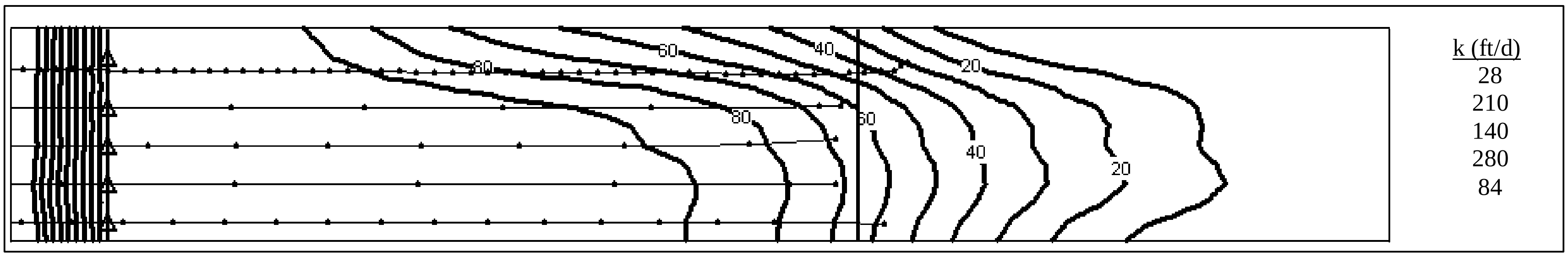
c) 150 days, row 40

0 ft 50

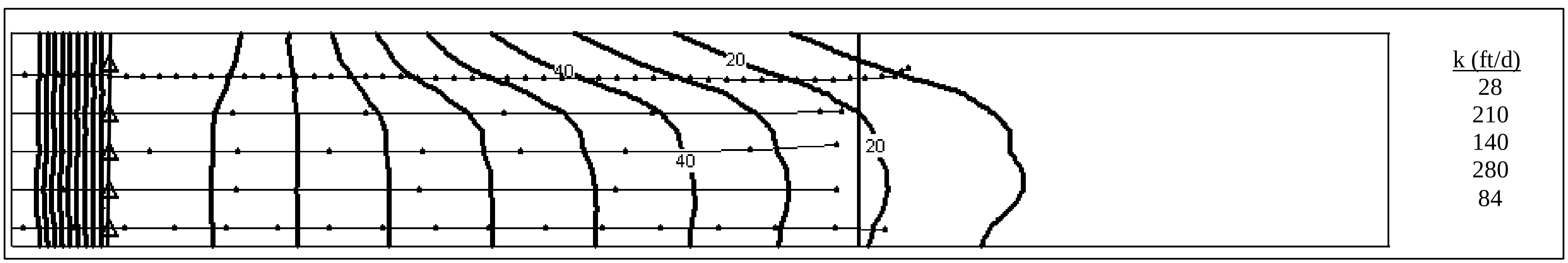
Figure 7-10: Case 1-3, with extraction wells. Regional flow used to deliver stabilizer. Profiles through centerline. Constant concentration = 100 g/l, delivered through infiltration trench, $k_{TA}=k_R$, variable k, α_L = 2 ft, 1 dot = 10 days. Extraction wells withdraw 7500 cfd



a) 100 days, row 40 (centerline)

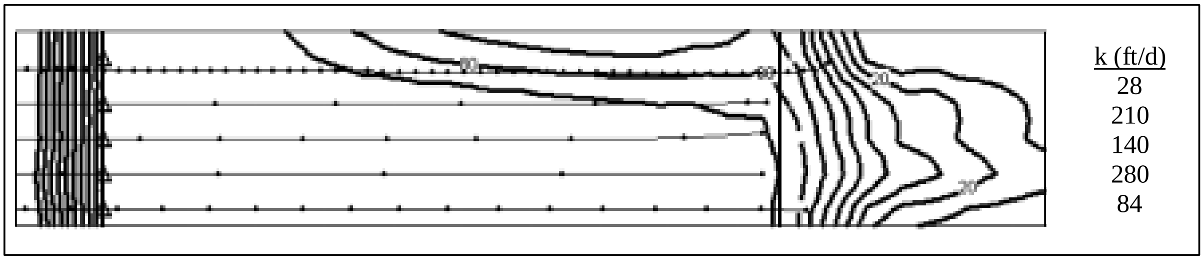


b) 100 days, row 38 (40 feet laterally from centerline)

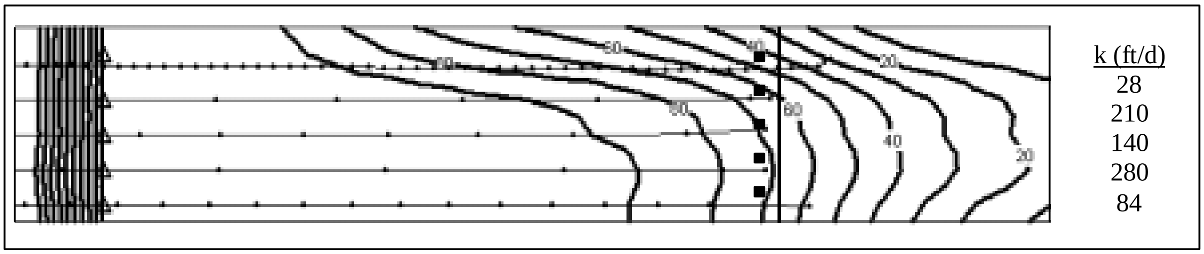


c) 100 days, row 36 (80 feet laterally from centerline)

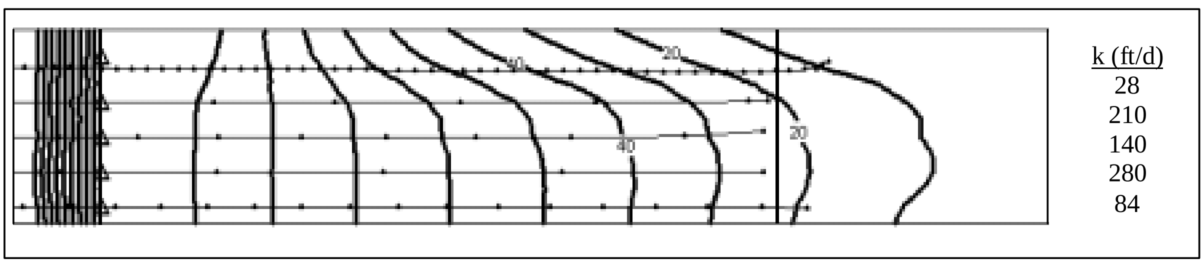
Figure 7-11: Case 1-3, with extraction wells. Regional flow used to deliver stabilizer. Profiles through treatment area. Constant concentration = 100 g/l, delivered through infiltration trench, $k_{TA}=k_R$, variable k, α_L = 2 ft, 1 dot = 10 days. Extraction wells withdraw 7500 cfd.



a) 100 days, row 40 (centerline)



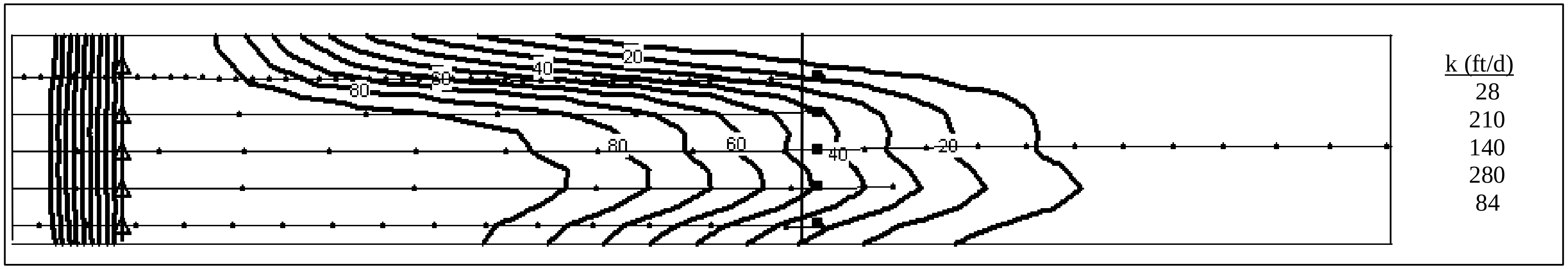
b) 100 days, row 38 (40 feet laterally from centerline)



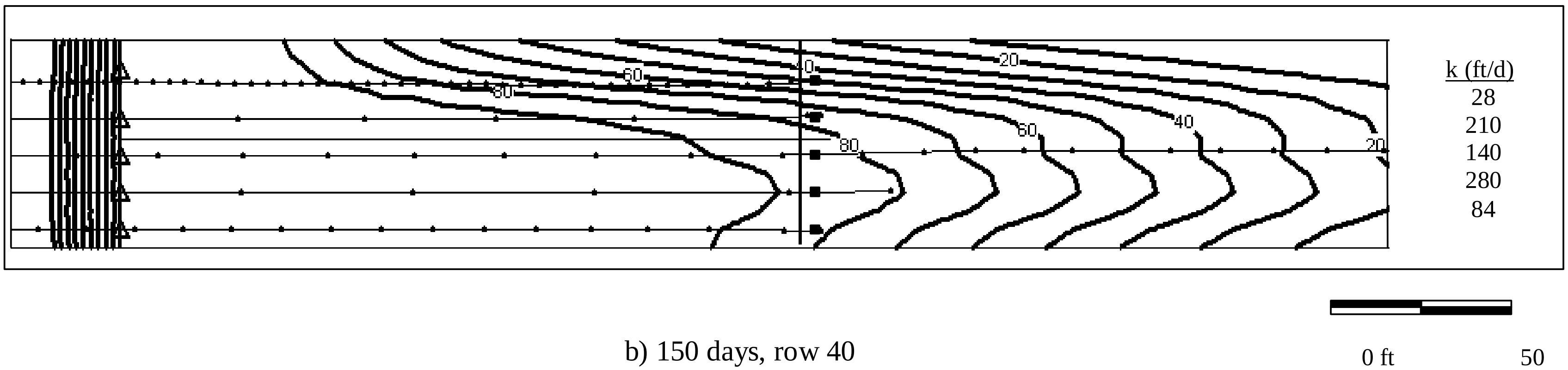
c) 100 days, row 36 (80 feet laterally from centerline)

0 ft 50

Figure 7-12: Case 1-3, Case 1-3, with extraction wells separated by 80 feet. Regional flow used to deliver stabilizer. Profiles through treatment area. Constant concentration = 100 g/l, delivered through infiltration trench, $k_{TA}=k_R$, variable k, α_L = 2 ft, 1 dot = 10 days. Extraction wells withdraw 7500 cfd.

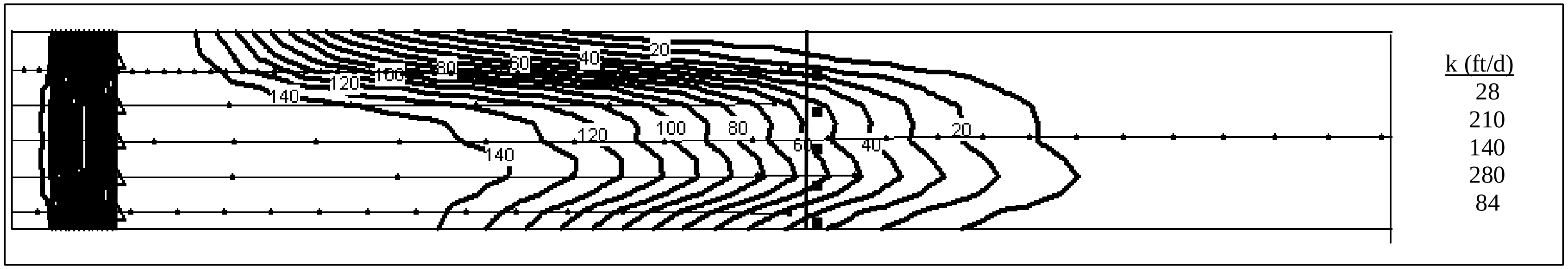


a) 100 days, row 40

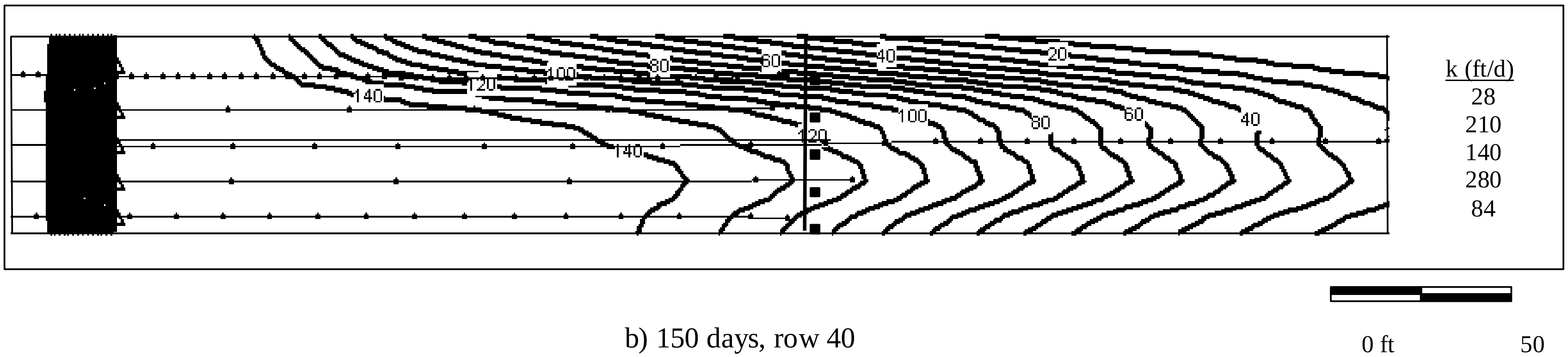


b) 150 days, row 40

Figure 7-13: Case 1-4, with extraction wells. Regional flow used to deliver stabilizer. Profiles through treatment area. Constant concentration = 100 g/l, delivered through infiltration trench, k_{TA}= ½ k_R, variable k, α_L = 2 ft, 1 dot = 10 days. Extraction wells withdraw 7500 cfd.

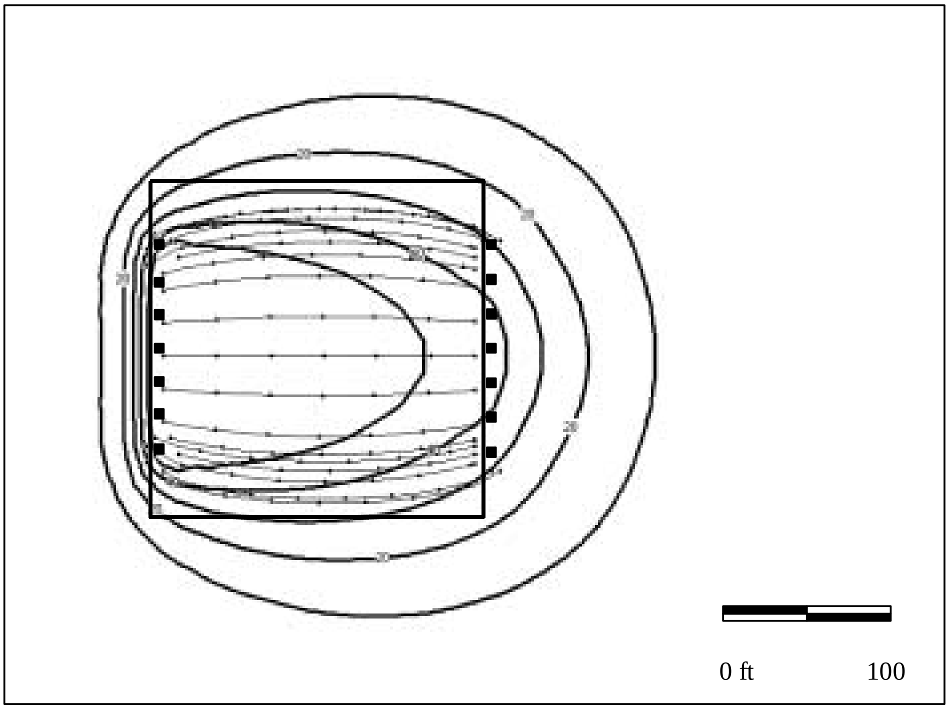


a) 100 days, row 40

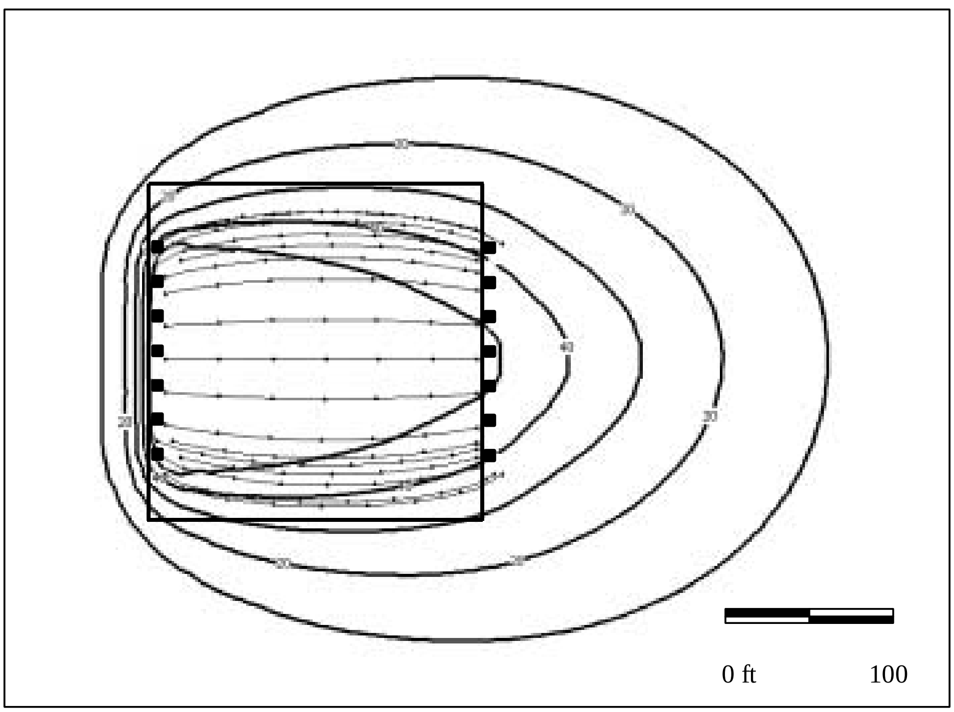


b) 150 days, row 40

Figure 7-14: Case 1-4, with extraction wells. Regional flow used to deliver stabilizer. Profiles through treatment area. Constant concentration = 150 g/l, delivered through infiltration trench, $k_{TA}= ½\ k_R$, variable k, α_L = 2 ft, 1 dot = 10 days. Extraction wells withdraw 7500 cfd.

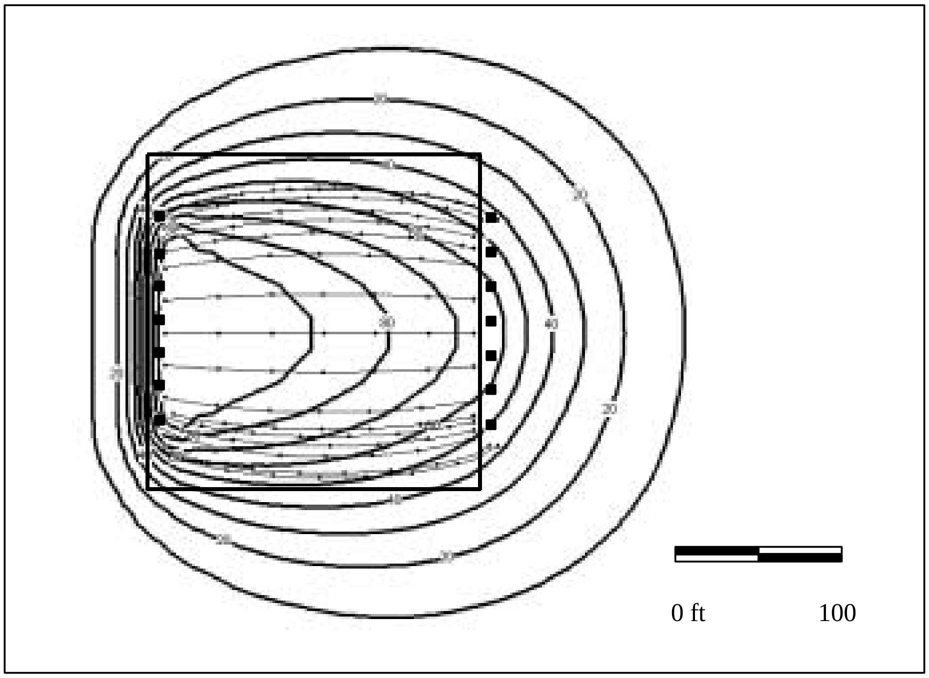


a) Constant concentration = 100 g/l, 99 days

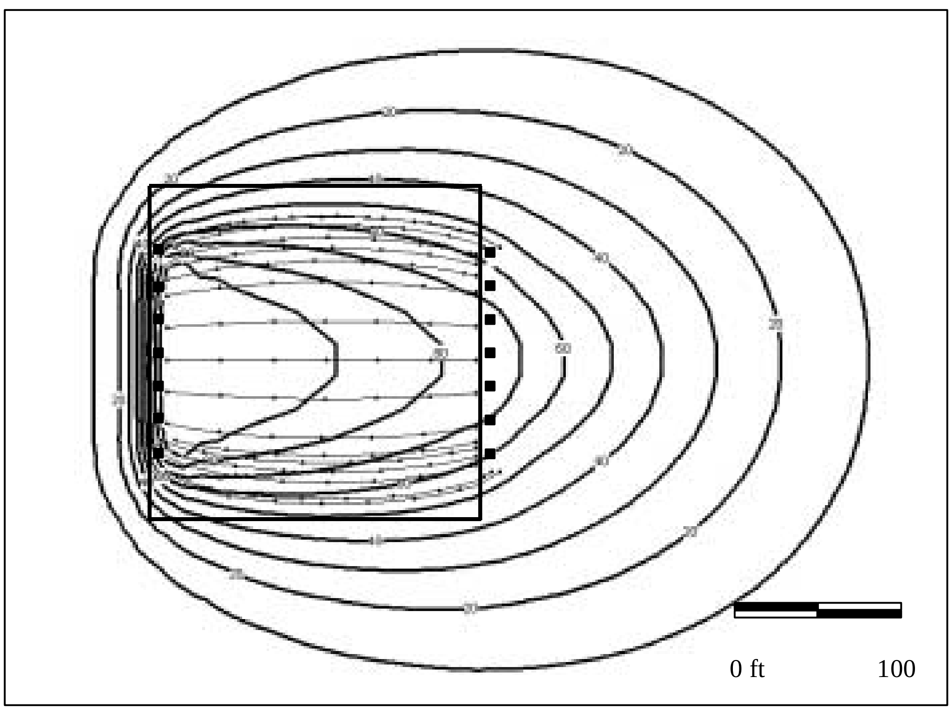


b) Constant concentration = 100 g/l, 150 days

Figure 7-15 Case 2-1: Stabilizer delivered via 7 injection wells delivering 7000 cfd total. Extraction wells extract 7000 cfd total. Constant concentration, $k_{TA} = k_R$, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days

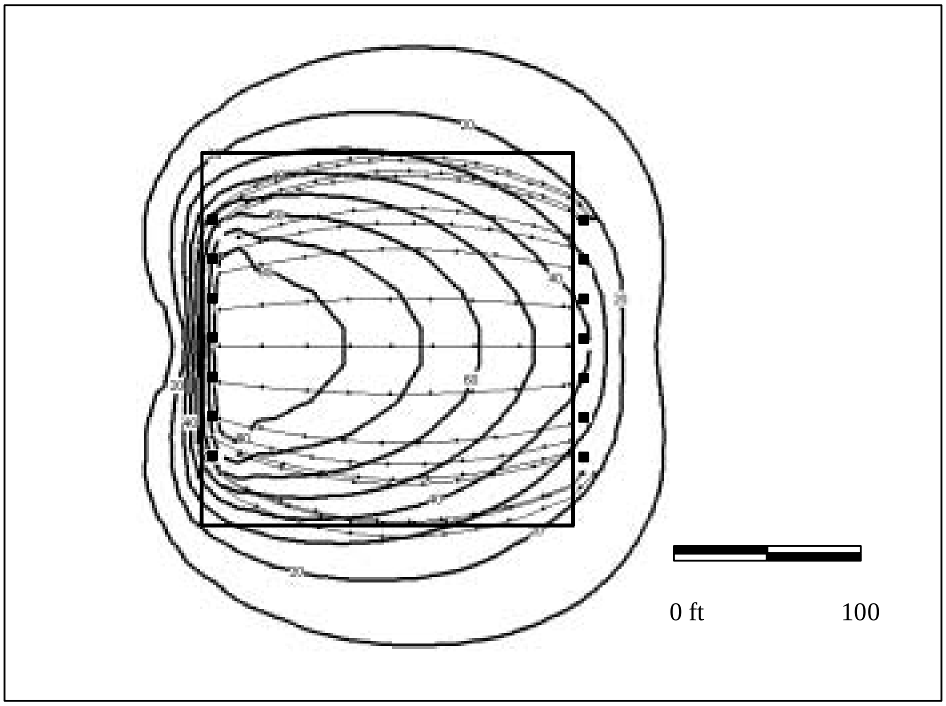


a) Constant concentration = 150 g/l, 99 days

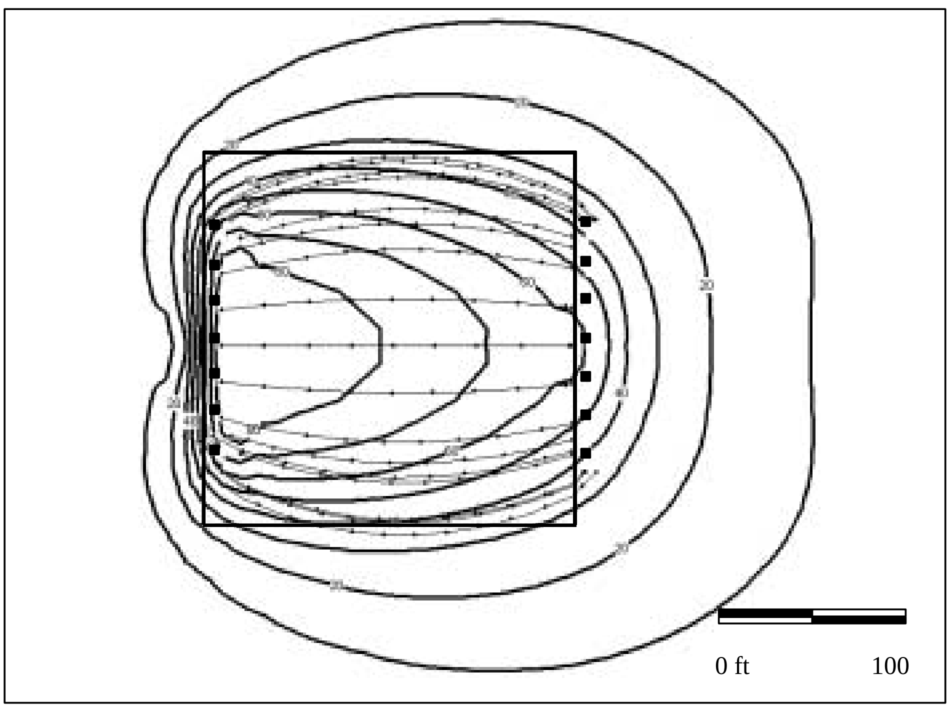


b) Constant concentration = 150 g/l, 150 days

Figure 7-16 Case 2-1: Stabilizer delivered via 7 injection wells delivering 7000 cfd total. Extraction wells extract 7000 cfd total. Constant concentration, $k_{TA} = k_R$, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days

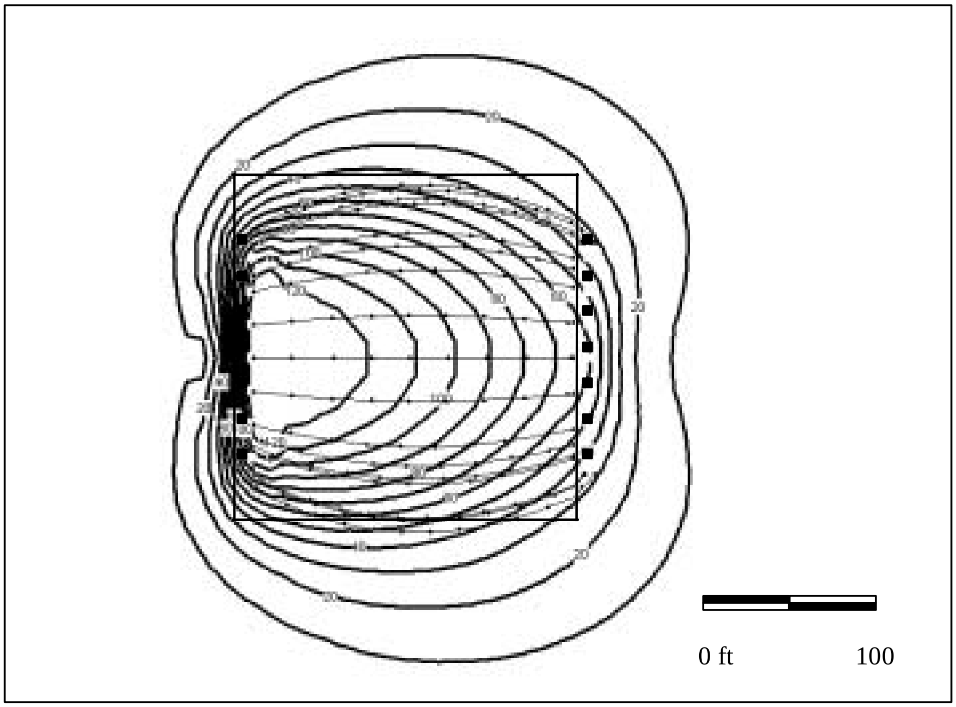


a) Constant concentration = 100 g/l, 98 days

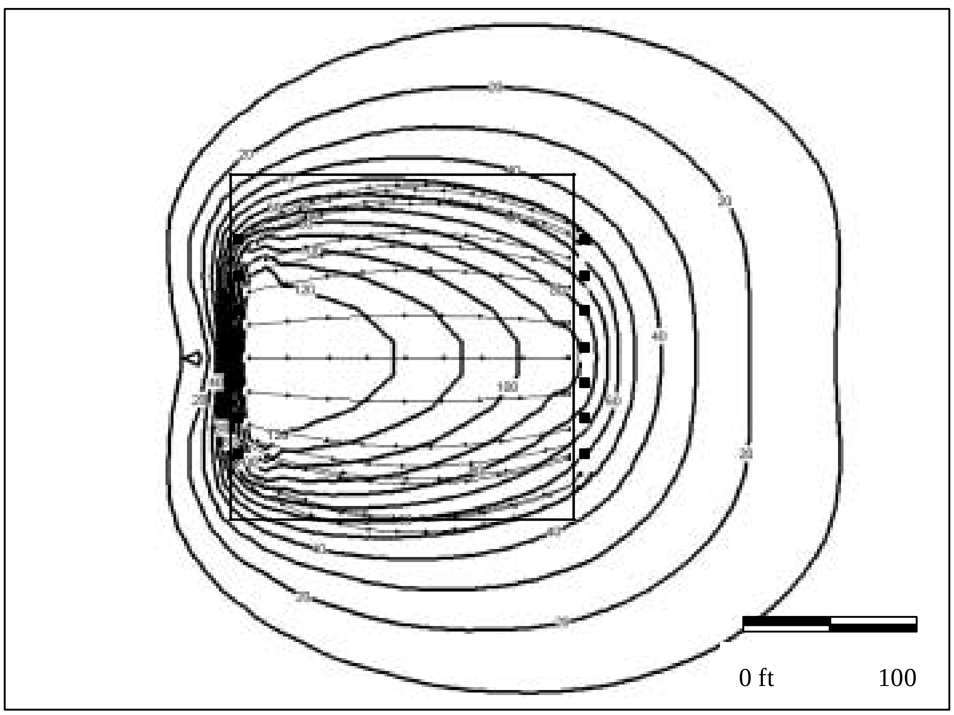


b) Constant concentration = 100 g/l, 147 days

Figure 7-17 Case 2-2: Stabilizer delivered via 7 injection wells delivering 7000 cfd total. Extraction wells extract 7000 cfd total. Constant concentration, $k_{TA} = ½\ k_R$, uniform k = 140 ft/day, α_L = 20 ft, 1 dot = 10 days

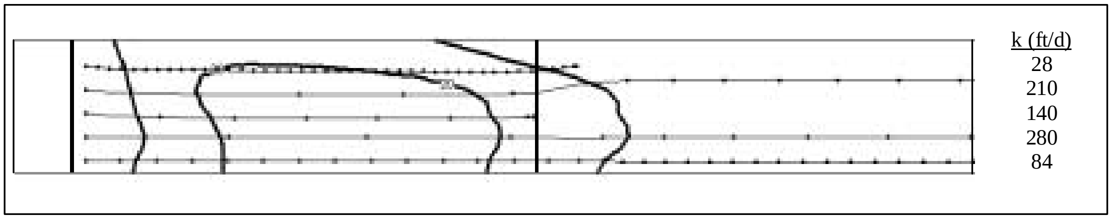


c) Constant concentration = 150 g/l, 98 days



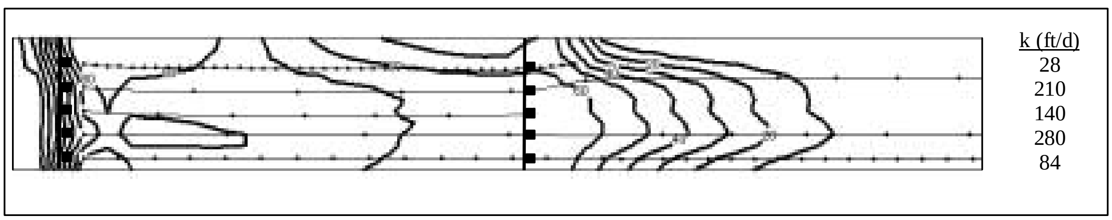
d) Constant concentration = 150 g/l, 147 days

Figure 7-17 (cont'd.) Case 2-2: Stabilizer delivered via 7 injection wells delivering 7000 cfd total. Extraction wells extract 7000 cfd total. Constant concentration, $k_{TA} = ½ k_R$, uniform k = 140 ft/day, α_L = 20 ft, 1 dot = 10 days

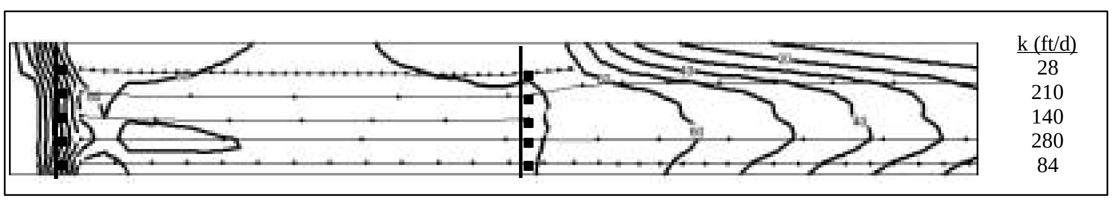


a) 98 days, row 36 (80 feet laterally from centerline)

b) 98 days, row 38 (40 feet laterally from centerline)



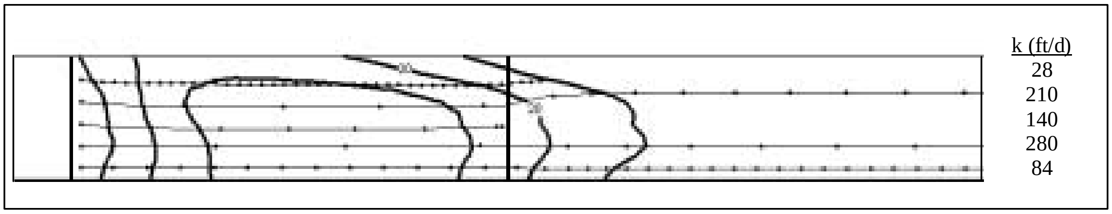
c) 98 days, row 40 (centerline)



d) 150 days, row 40 (centerline)

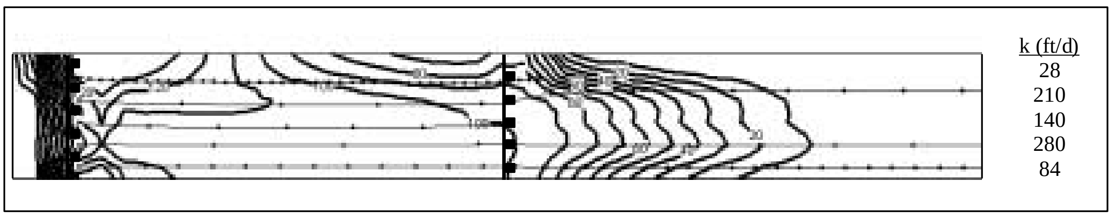
0 ft 50

Figure 7-18 Case 2-3: Stabilizer delivered via 7 injection wells delivering 7000 cfd total. Extraction wells extract 7000 cfd total. Constant concentration = 100 g/l, $k_{TA} = k_R$, variable k, α_L = 2 ft, 1 dot = 10 days. Profiles through treatment area.

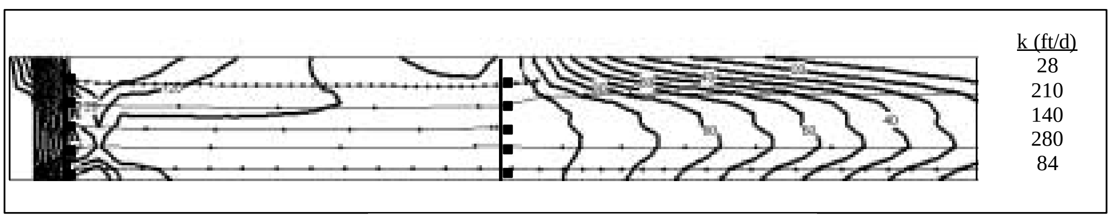


a) 98 days, row 36 (80 feet laterally from centerline)

b) 98 days, row 38 (40 feet laterally from centerline)



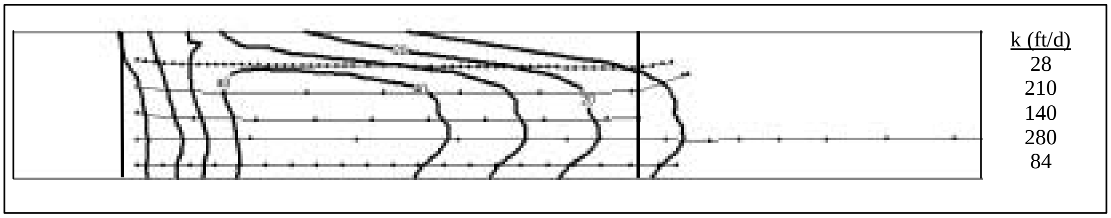
c) 98 days, row 40 (centerline)



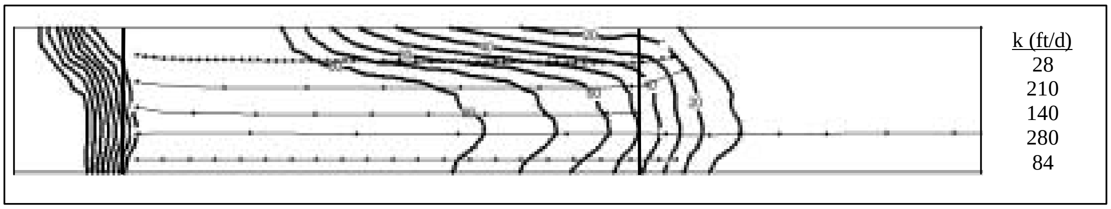
d) 150 days, row 40 (centerline)

0 ft 50

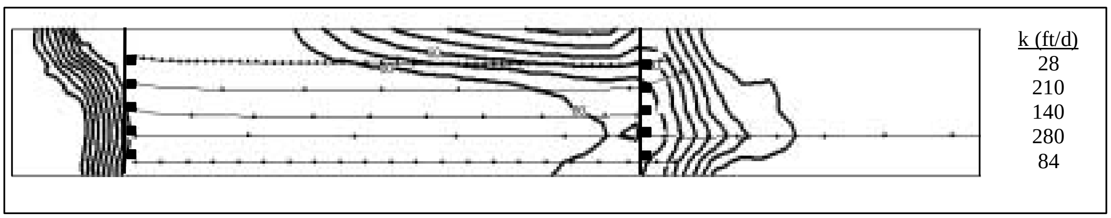
Figure 7-19 Case 2-3: Stabilizer delivered via 7 injection wells delivering 7000 cfd total. Extraction wells extract 7000 cfd total. Constant concentration = 150 g/l, $k_{TA} = k_R$, variable k, α_L = 2 ft, 1 dot = 10 days. Profiles through treatment area.



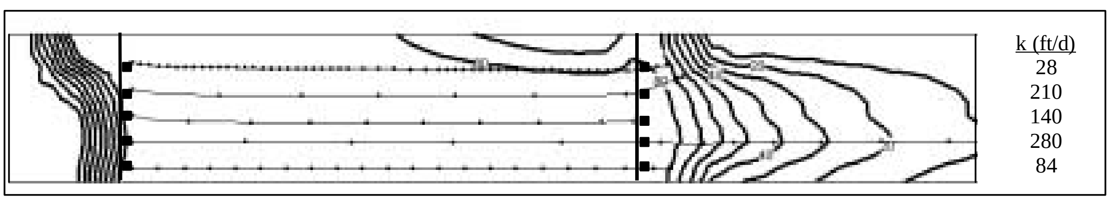
a) 98 days, row 36 (80 feet laterally from centerline)



b) 98 days, row 38 (40 feet laterally from centerline)



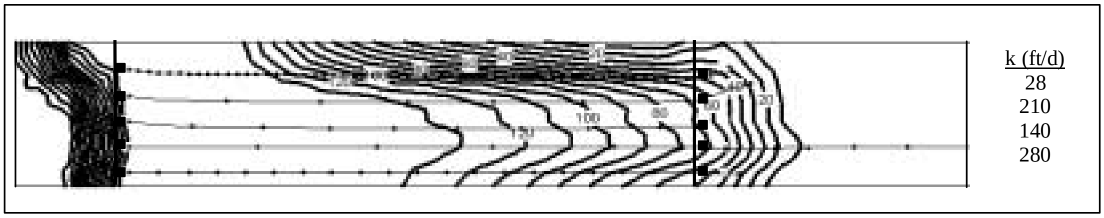
c) 98 days, row 40 (centerline)



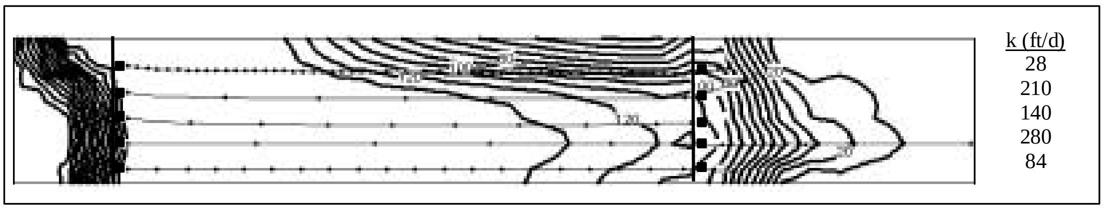
d) 150 days, row 40 (centerline)

0 ft 50

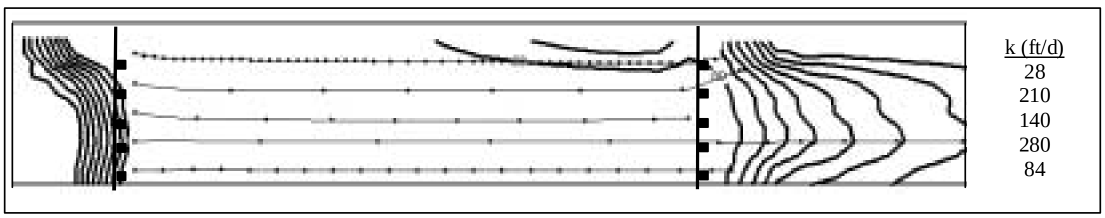
Figure 7-20 Case 2-4: Stabilizer delivered via 7 injection wells delivering 7000 cfd total. Extraction wells extract 7000 cfd total. Constant concentration = 100 g/l, k_{TA} = ½, variable k, α_L = 2 ft, 1 dot = 10 days. Profiles through treatment area.



a) 75 days, row 40



b) 100 days, row 40



c) 150 days, row 40

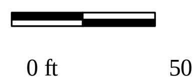
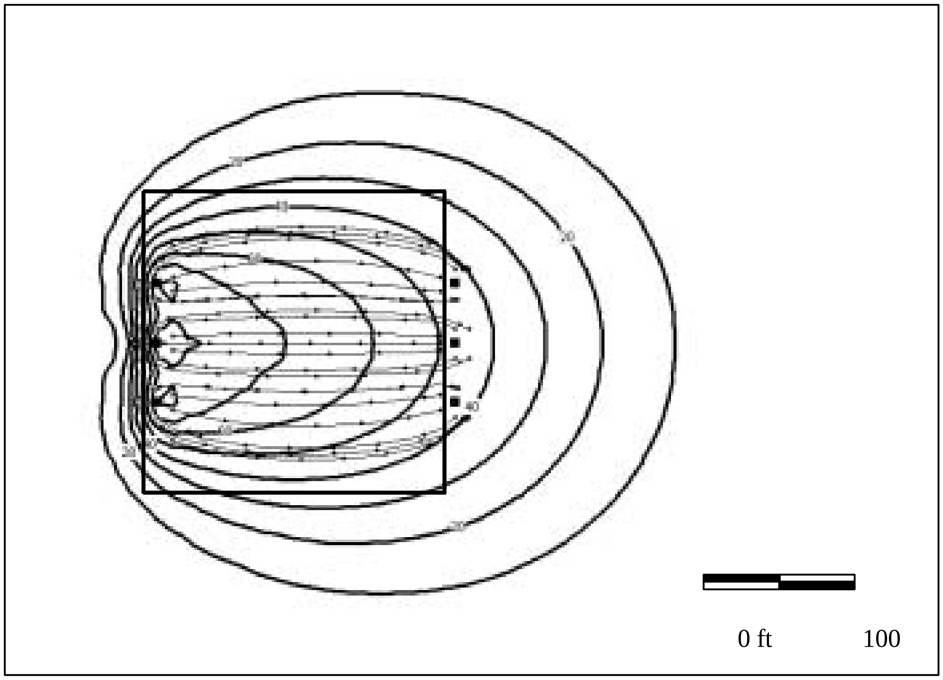
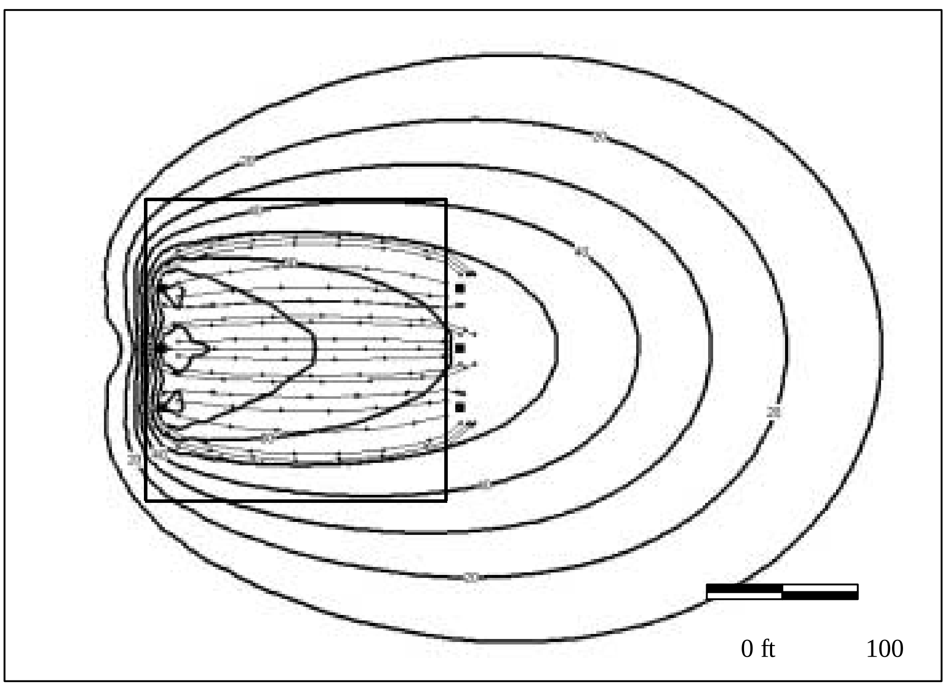


Figure 7-21 Case 2-4: Stabilizer delivered via 7 injection wells delivering 7000 cfd total. Extraction wells extract 7000 cfd total. Constant concentration = 150 g/l, k_{TA} = ½, variable k, α_L = 2 ft, 1 dot = 10 days. Profiles through centerline.

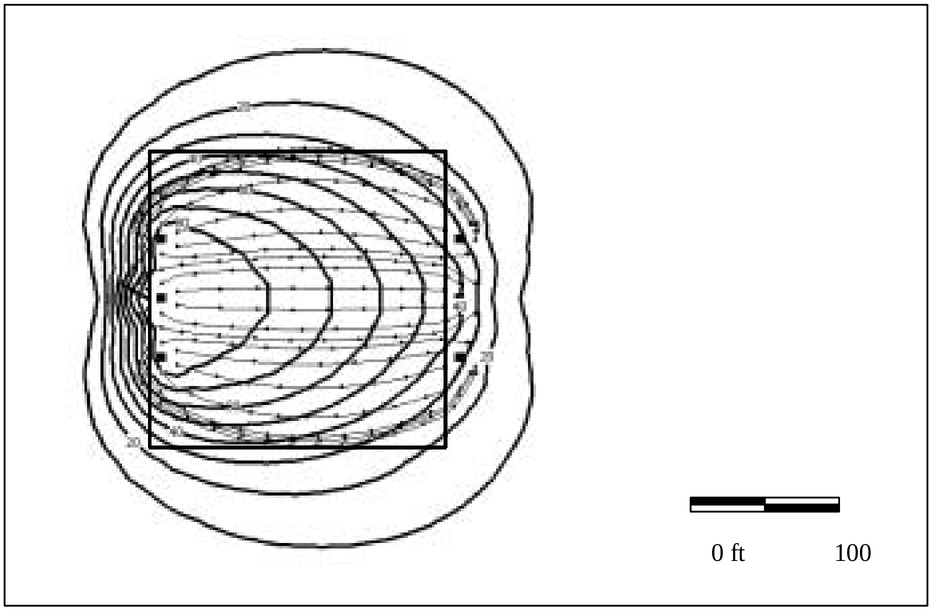


a) Case 3-1, 100 days, $k_{TA} = k_R$

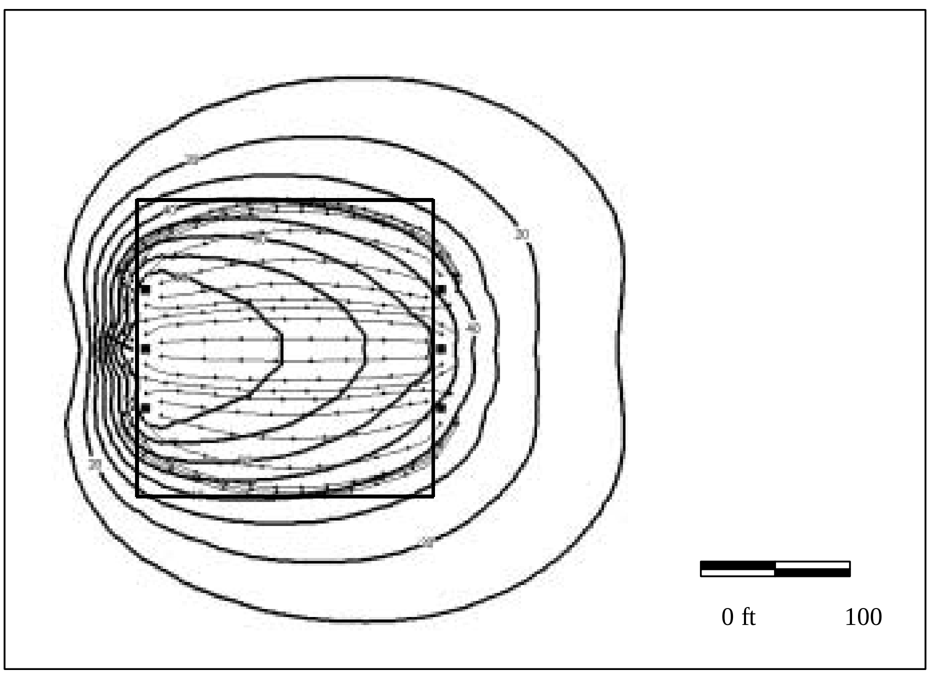


b) Case 3-1, 150 days, $k_{TA} = k_R$

Figure 7-22 Cases 3-1 and 3-2: Stabilizer delivered via 3 injection wells delivering 7500 cfd total. Extraction wells extract 7500 cfd total. Constant concentration = 100 g/l, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days

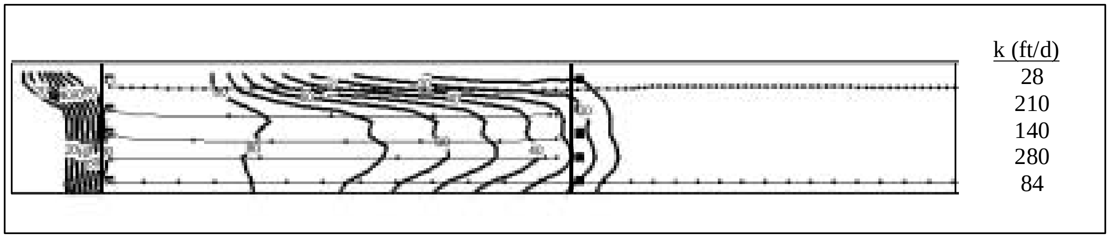


c) Case 3-2, 100 days, $k_{TA} = \frac{1}{2} k_R$

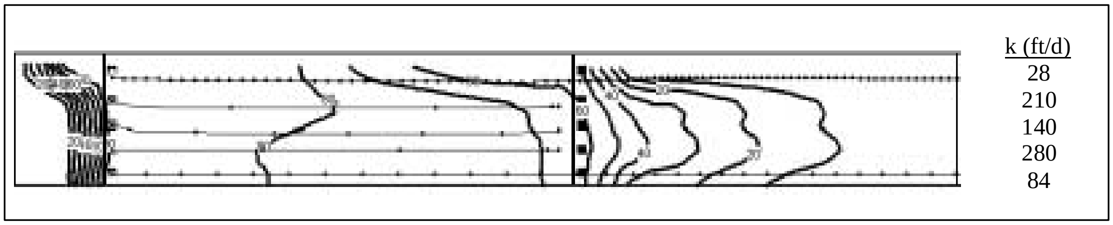


d) Case 3-2: 150 days, $k_{TA} = \frac{1}{2} k_R$

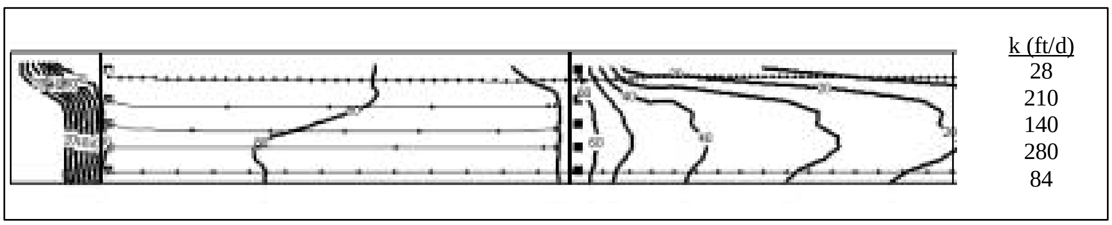
Figure 7-22 (cont'd.) Cases 3-1 and 3-2: Stabilizer delivered via 3 injection wells delivering 7500 cfd total. Extraction wells extract 7500 cfd total. Constant concentration = 100 g/l, uniform k = 140 ft/day, regional α_L = 20 ft, 1 dot = 10 days



a) 51 days, row 40



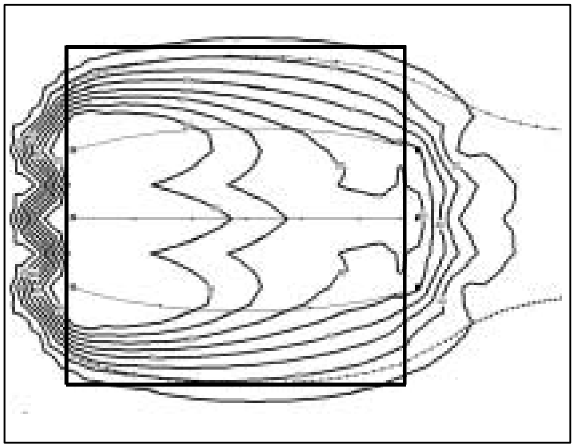
b) 102 days, row 40



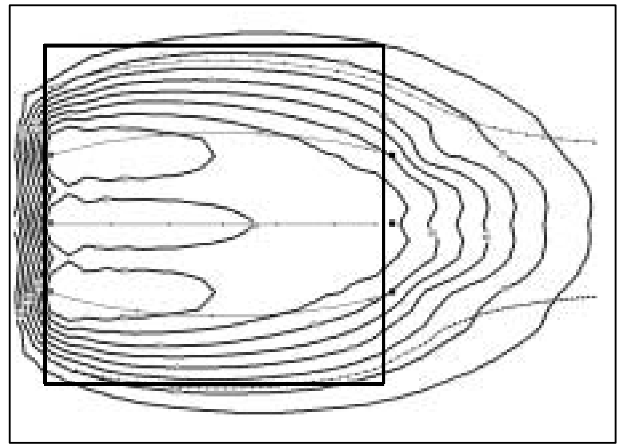
c) 150 days, row 40

0 ft 50

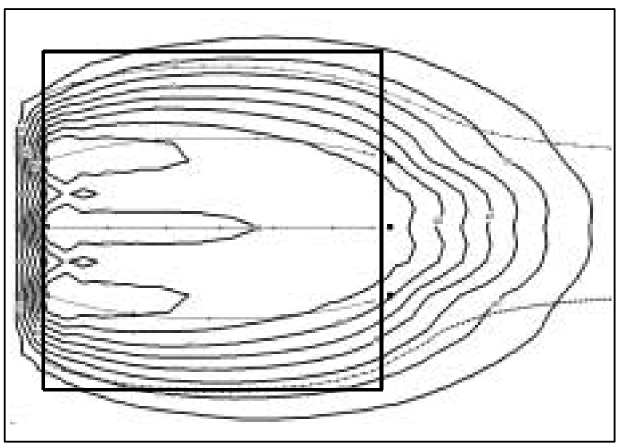
Figure 7-23 Case 3-3: Stabilizer delivered via 3 injection wells delivering 7500 cfd total. Extraction wells extract 7500 cfd total. Constant concentration = 100 g/l, $k_{TA} = k_R$, variable k, α_L = 2 ft, 1 dot = 10 days. Profiles through centerline



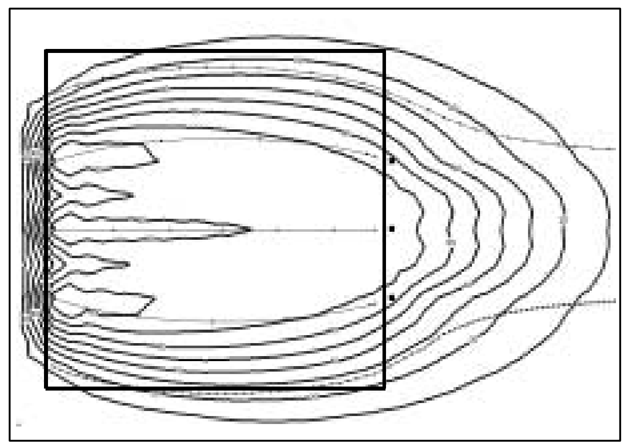
Layer 1, k=28 ft/d



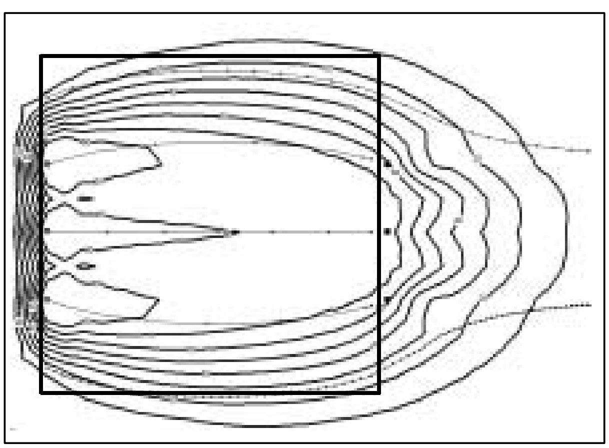
Layer 2, k=210 ft/d



Layer 3, k=140 ft/d

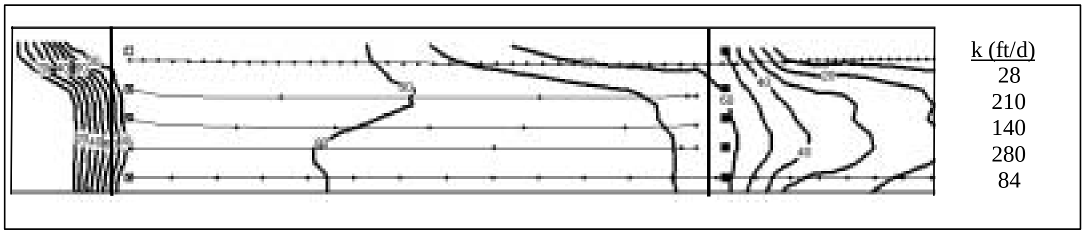


Layer 4, k=280 ft/d

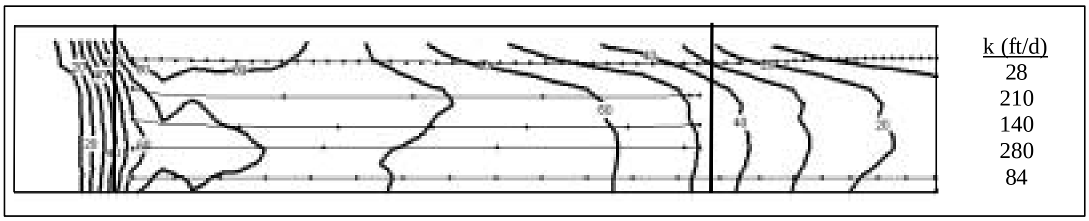


Layer 5, k=84 ft/d

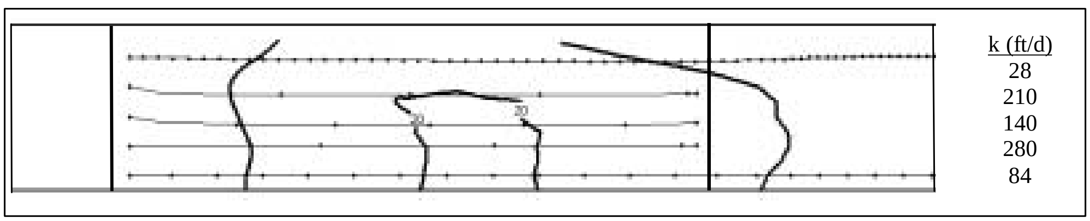
Figure 7-24 Case 3-3: Stabilizer delivered via 3 injection wells delivering 7500 cfd total. Extraction wells extract 7500 cfd total. Constant concentration = 100 g/l, $k_{TA} = k_R$, variable k, α_L = 20 ft, 1 dot = 10 days Layers 1 through 5 after 102 days.



a) 102 days, row 40 (centerline)



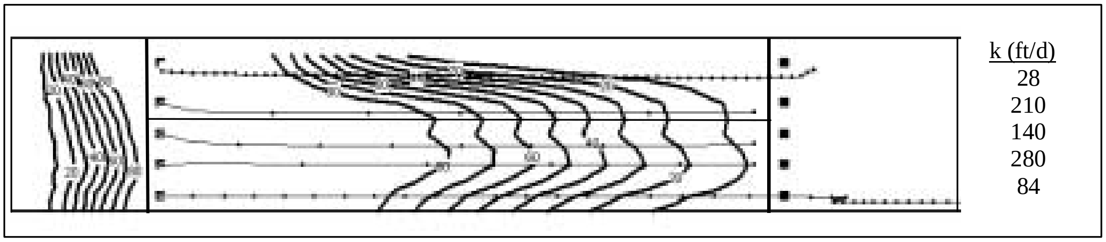
b) 102 days, row 39 (20 feet laterally from centerline)



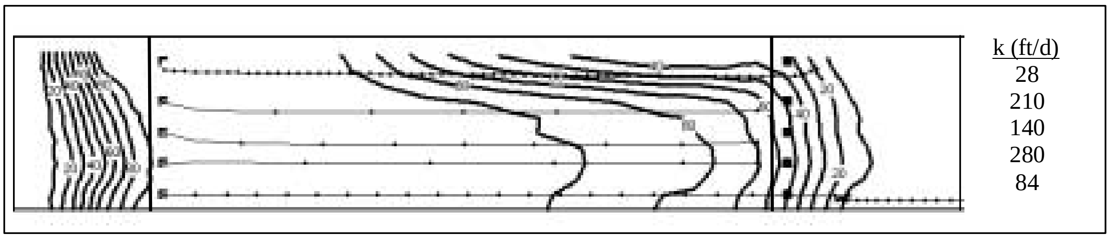
c) 102 days, row 37 (60 feet laterally from centerline)

0 ft 50

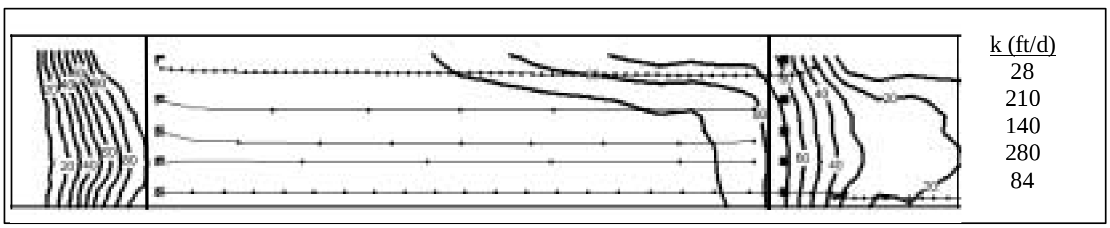
Figure 7-25 Case 3-3: Stabilizer delivered via 3 injection wells delivering 7500 cfd total. Extraction wells extract 7500 cfd total. Constant concentration = 100 g/l, $k_{TA} = k_R$, variable k, α_L = 2 ft, 1 dot = 10 days. Profiles through treatment area.



a) 50 days, row 40

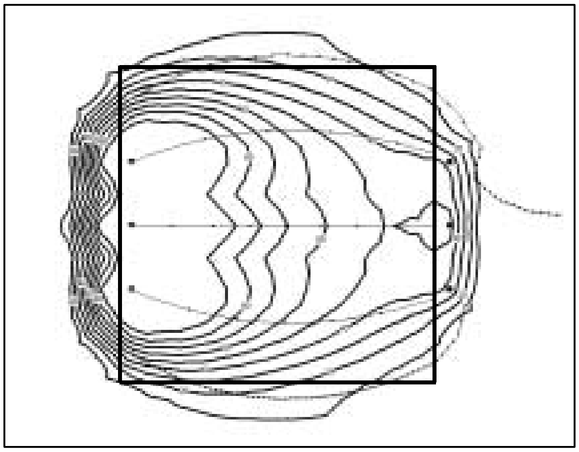


b) 99 days, row 40

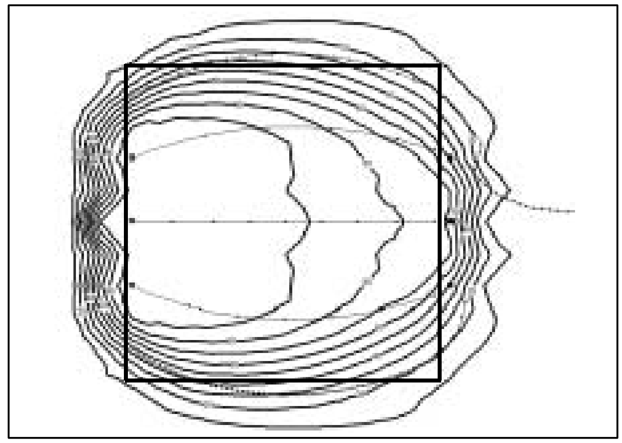


c) 150 days, row 40

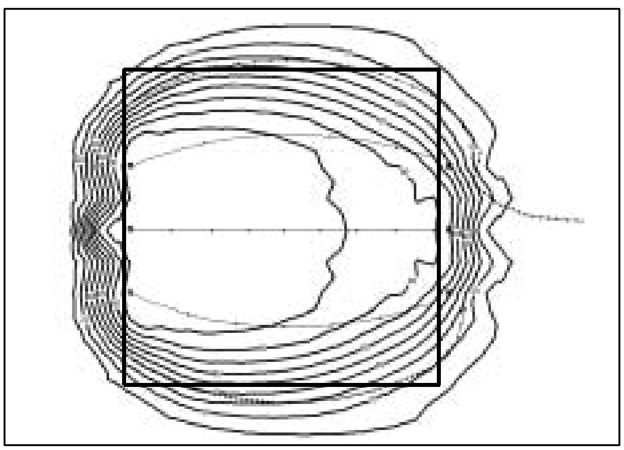
Figure 7-26 Case 3-4: Stabilizer delivered via 3 injection wells delivering 7500 cfd total. Extraction wells extract 7500 cfd total. Constant concentration = 100 g/l, k_{TA} = ½ k_R, variable k, α_L = 2 ft, 1 dot = 10 days. Profiles through centerline.



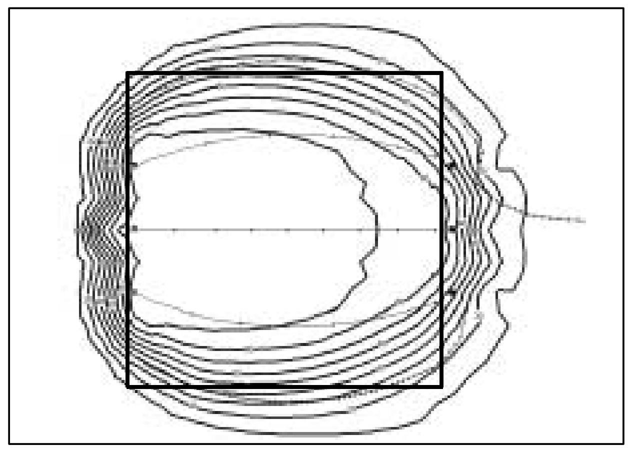
Layer 1, k=28 ft/d



Layer 2, k=210 ft/d

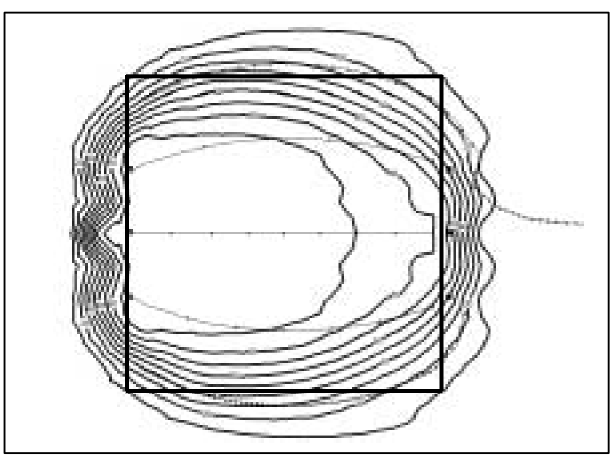


Layer 3, k=140 ft/d



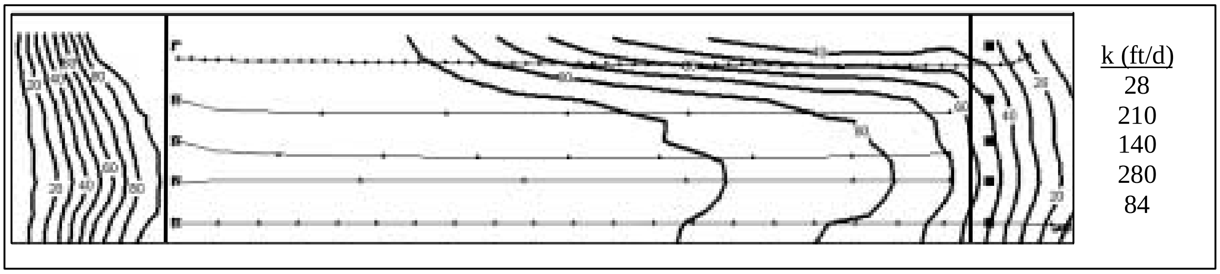
Layer 4, k=280 ft/d

0 ft 100

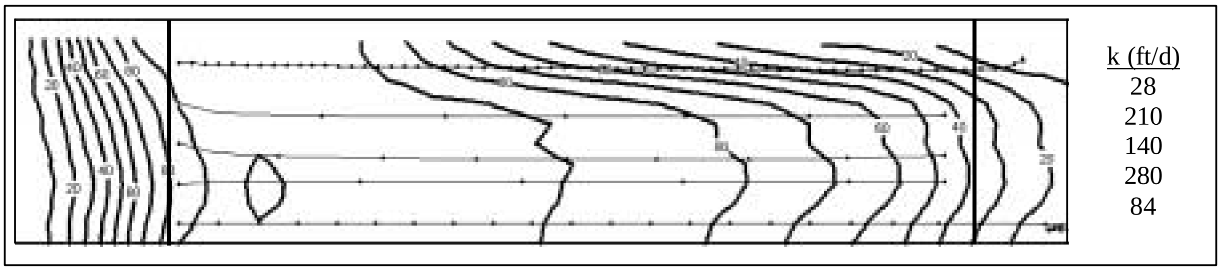


Layer 5, k=84 ft/d

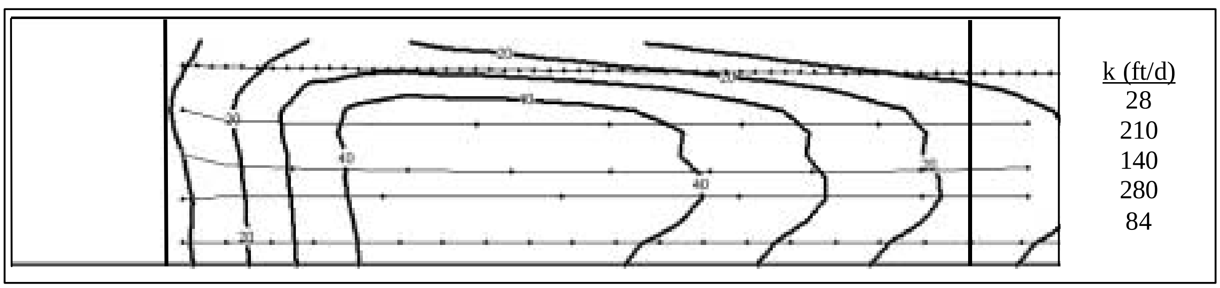
Figure 7-27 Case 3-4: Stabilizer delivered via 3 injection wells delivering 7500 cfd total. Extraction wells extract 7500 cfd total. Constant concentration = 100 g/l, k_{TA}= ½ k_R, variable k, α_L = 20 ft, 1 dot = 10 days Layers 1 through 5 after 102 days.



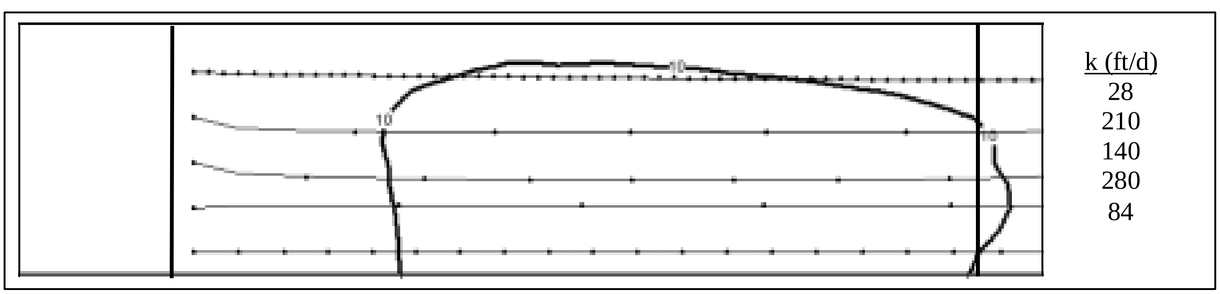
a) 99 days, row 40 (centerline)



b) 99 days, row 39 (20 feet laterally from centerline)



c) 99 days, row 37 (60 feet laterally from centerline)



d) 99 days, row 36 (80 feet laterally from centerline)

Figure 7-28 Case 3-4: profiles through treatment area, constant concentration = 100 g/l, variable k, $k_{TA} = ½ k_R$