# HYDROLOGIC CONTROLS ON THE SUBSURFACE TRANSPORT OF OIL-FIELD BRINE AT THE OSAGE-SKIATOOK PETROLEUM ENVIRONMENTAL RESEARCH "B" SITE, OKLAHOMA

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# ABSTRACT

As a part of a multidisciplinary study of the impact of oil wells and oil production on the environment, we are investigating the hydrology and the fate and transport of contaminants at the Osage-Skiatook Petroleum Environmental Research (OSPER) "B" Site, which is located at Skiatook Lake in Osage County, Oklahoma. Salt and crude oil from oil well waste pits and accidental releases from oil tank batteries have contaminated soil, ground water, and surface water at this site. Based on soil cores, water table measurements, chemical analyses of water samples, and field observations, we developed conceptual models of the hydrology and solute transport mechanisms near a waste pit at the south end of the site. We propose two main mechanisms for solute transport from the waste pit to the lake. One mechanism is the relatively slow and steady flow of saline ground water from the waste pit to the lake in a near-surface aquifer. The other mechanism is relatively fast overland flow of salt-laden runoff during rainfall. Using the USGS model SUTRA, we simulated steady-state ground-water flow and solute transport from the pit to the lake. Preliminary modeling results indicated that the solute travel time from the pit to the lake in saline ground water is 2-4 years.

# INTRODUCTION

A large quantity of water containing high concentrations of dissolved salts is produced as a byproduct of oil production. In the early days of the oil business in the United States, brine was commonly "disposed of" by dumping into streams or infiltration into the soil (1). Present law requires that the brine be injected into deep formations. However, even today oil-field brine and oil are often spilled on the soil surface and into shallow holding pits. The brine often flows out the bottom of unlined holding pits and into the ground-water system. Movement of the brine and the oil into the subsurface poses a threat to ground water quality. Nearby streams and lakes may also be threatened. It is important to understand the processes that influence subsurface transport of oil-field brine and associated oil and to document the effects on the environment in order to help regulators and other responsible parties make informed decisions regarding oil well siting and site remediation.

In 2001 the U.S. Geological Survey, in cooperation with the U.S. EPA, began a multidisciplinary study of the impact of oil production on the near-field environment. Two oil-field sites, designated "Osage-Skiatook Petroleum Environmental Research" (OSPER) Sites "A" and "B", located near Skiatook Lake in Northeastern Oklahoma, were selected for intensive study. Oil and brine from producing oil wells has entered the subsurface at these sites, resulting in extensive killing of vegetation and degradation of local ground water and surface water quality. A research team of geologists, geophysicists, geochemists, hydrologists, microbiologists, and biologists is evaluating data obtained in the first field season at the OSPER sites.

In this paper only results from OSPER Site "B" are presented. The purpose of the paper is to describe conceptual models of the hydrology and solute transport processes at Site "B", and to present preliminary computer modeling simulations of ground-water flow and associated transport of dissolved salt from a waste pit at the southern end of Site "B" to Skiatook Lake. The general concepts developed in this paper are applicable to nearby areas where oil-field brines have been spilled.

# FIELD SITE DESCRIPTION

As shown in the site map (figure 1), at Site "B" there is an oil tank battery and a waste pit located about 20 meters from Skiatook Lake. There also is a brine injection well and an associated smaller pit at the north end of the site. The land surface slopes upward west of the lake at approximately a 5% grade. Three areas where salt has killed the vegetation are denoted "salt scars" in figure 1. There are salt scars east of the oil tank battery, east of the injection well, and east of a location in the center of the site where a tank battery and pit have been removed. As a part of a remediation effort, in 2000 about 6 inches of topsoil was brought in and hay was planted in the salt-scarred areas. However, as of 2002, there were no plants growing the salt-scarred areas.

Soil and rock cores (2) obtained at the site showed that beneath 0.5-2 meters of surficial deposits (fill, soil, colluvium, and alluvium), a layer of shale that is at least 6 meters thick underlies the site. The near-surface material near the waste pit is mapped as "fill" or "colluvium." The colluvium consists of weathered shale with some weathered sandstone blocks. There is generally weathered shale beneath the colluvium. Surface soil is thin or has been removed. Pits and roads were made by cutting and filling local materials with a bulldozer. Much of the near-surface material near the waste pit is "fill."

A Geoprobe rig was used to obtain shallow (<6 meters deep), 2-inch diameter cores at 19 locations at the site. Sampling wells were installed at each of these locations. The wells were made by placing 1-inch diameter PVC pipe with a 1 to 6 foot well screen at bottom into the Geoprobe boreholes. Clean sand was packed into the annulus between the PVC pipe and the borehole. These wells are labeled "BE#" in figure 1.

Six-inch diameter boreholes that were up to 16 meters deep were also cored at three locations using an auger rig. Two 2-inch diameter PVC wells with 5 to 10 foot long well screens at the bottom were installed in each borehole. There was a "deep" and a "shallow" well in each borehole. Sand was packed around the PVC pipe in the screened intervals. Bentonite was used to isolate the screened intervals from one another. These wells are labeled "BA#" in figure 1.

# HYDROLOGY AND SOLUTE TRANSPORT IN THE WASTE PIT AREA

Based on analysis of the soil cores, water table measurements in the wells, chemical analysis of water samples obtained from the wells and the waste pit, and other field observations, we developed preliminary conceptual models of the hydrology and solute transport mechanisms in the waste pit area.

## The Brine Source in the Waste Pit

Equipment failures at the active oil production facility at the site lead to aperiodic spillage of brine and associated oil into the waste pit at the south end of the site (figure 1). Brine from the oil wells has a concentration of about 150,000 mg/L total dissolved solids (3). The brine fills the waste pit to a variable extent depending on the volume of the spill. Once in the pit, the brine is diluted by precipitation. The pit collects some of the runoff from an area of about 600 $m^2$.

Water and brine leave the pit by several mechanisms. The oil-field operator periodically pumps water out of the pit and into water tanks that are pumped into the injection well. Also, we observed that when the pit contains water, brine often flows out through seeps on the east side of the pit berm. The water flowed out of the seep, on top of the soil for a few feet, and then infiltrated into the soil down slope from the pit. In the past, the pit has overflowed the east side of the berm. We hypothesize that brine also flows out through the bottom of the unlined pit. When the weather is hot, water may evaporate from the pit, which increases the brine concentration. However, there is generally a layer of oil on top of the water in the pit, which may inhibit evaporation of water.

It is likely that quantitative understanding of the fate and transport of contaminants from the waste pit will be limited by how accurately the source is characterized. The measured salinity of the brine that enters the ground near the pit varies greatly as a function of time (3). The flow rate out of the pit also varies as a function of liquid depth in the pit. Accurate characterization of the source will require frequent monitoring of the solute concentration and the water level in the pit.

## Ground-Water Flow from the Waste Pit to the Lake

Figure 2 shows a simplified cross section of the subsurface beneath the B-B' transect (figure 1). We hypothesize that the primary subsurface pathway for water flow from the pit to the lake is in the surface “fill” or “colluvium” layer (F/C). We hypothesize that the underlying undisturbed “weathered shale” layer is much less permeable than the F/C layer.

The water table elevations measured in wells in June 2002 line up well with the measured water levels in the pit and the lake (figure 2). The water-level measurements suggest that whenever there is water in the pit, there is ground-water flow from the pit to the lake in response to a hydraulic head gradient of about 0.05 m/m.

We carried out slug tests in the wells in order to estimate the hydraulic conductivity of the F/C layer. A slug test was initiated by inserting a solid volume of stainless steel into a well in order to displace water and rapidly raise the water level in the well. The subsequent transient decline in water level in the well was monitored with a pressure transducer. The slug tests were analyzed using the Bouwer and Rice (4) method, as described by Butler (5). Hydraulic conductivity values estimated from the slug test data ranged from about 1 cm/day to about 10 cm/day.

One can use the Darcy flow equation to estimate the flow rate from the waste pit to the lake. For example, assuming the F/C layer in figure 2 is a uniform, homogeneous, one-dimensional aquifer, the flow rate per unit cross section is $q = k\ (dp/dx)$, where $k$ is the hydraulic conductivity, and $dp/dx$ is the hydraulic gradient. Assuming the hydraulic conductivity is 10 cm/day, and the gradient is 0.05, $q \sim 1.8$ m/year.

## Water Flow in the Unsaturated Zone

Inspection of soil cores and observation of rainfall events at the site suggest that there is relatively little infiltration and recharge of fresh rainwater into the saturated zone. In the bare, salt-scarred areas of the site, because the soil is clay-rich, the drainable porosity of the soil is low. Drying of bare soil by evaporation is limited to a thin layer at the soil surface. Even after a long dry period, the subsoil remains nearly saturated. When it rains, the available porosity is quickly filled, the water table rises rapidly to the surface, and runoff begins. Soil surface sealing by mobile clays and air entrapment in the soil also enhance runoff. Most of the water that falls on bare soil flows toward the lake as runoff. Infiltration and recharge of fresh rainwater into the saturated zone is limited. After the rain, the water table falls rapidly back to the level that is supported by outflow from the waste pit.

In vegetated areas, soil drying is more extensive because of plant root uptake. As a result, there is more infiltration and less runoff from vegetated areas. However, evapotranspiration is generally so high at the site that the plants rapidly remove water that has infiltrated into the root zone, and there is little ground-water recharge.

## Solute Transport

We propose two main mechanisms for transport of solutes from the waste pit to the lake. One mechanism is the flow of saline ground water in the F/C aquifer. Brine from the pit flows down through the bottom of the pit and travels laterally in the aquifer to the lake. The weathered shale beneath the F/C layer is relatively impermeable, and not much brine penetrates into this layer. The saline ground-water flow is relatively slow and steady, and not much influenced by the weather, except that the level of water in the pit changes in response to rainfall and evaporation. We hypothesize that there is relatively little dilution of the saline ground water by rainwater once the brine has entered the aquifer.

The second mechanism for solute transport is the overland flow of salt-laden surface runoff. Rainfall at the site generally comes in short bursts followed by dry periods lasting many days. During dry periods, as the bare soil surface dries by evaporation, ground water containing dissolved salts is pulled upward from the aquifer toward the surface by capillary action. The salt concentration in the water near the surface is increased by evaporation of water. Salt crystals may precipitate near the soil surface. We hypothesize that during rainfall rainwater rapidly mixes with the highly saline water in the surface soil, dissolves salt crystals, and carries dissolved salt down slope in runoff. It is likely that solute transport via the runoff mechanism is much faster than via the saline ground water flow mechanism.

The fact that the brine is denser than water may influence mixing and solute transport. Fingers of brine tend to move downward into a porous material that is initially saturated with fresh water. This effect tends to increase mixing when salt water lies above fresh water. However, fresh rainwater infiltrating on top of a brine-filled aquifer tends to remain stratified and not mix with the brine.

# PRELIMINARY MODELING RESULTS

We used the U.S. Geological Survey model SUTRA (6) to simulate steady-state flow of ground water and subsurface transport of solutes from the waste pit to the lake. SUTRA is a two-dimensional, finite element model that solves the Darcy flow equation and the convection dispersion equation. The model is convenient to use because a graphical-user interface (7) is available to set up a problem and display results. Another advantage of SUTRA is that the program enables simulation of subsurface transport when the density of the flowing water solution varies as a function of solute concentration. Although this feature will be important in future work, in the simulations reported in this paper water density was assumed to be that of pure water.

As a first approximation, we assumed that the area near the waste pit is underlain by a homogeneous aquifer that is one meter thick. The idealized aquifer roughly corresponds to the F/C layer in figure 2. We assumed the following values for aquifer parameters: hydraulic conductivity = 10.0 cm/day; porosity = 0.3; longitudinal dispersivity = 10.0 m, transverse dispersivity = 1.0 m. Hydraulic conductivity was assumed to be isotropic.

The layout of the homogeneous aquifer problem and the boundary conditions are illustrated in figure 3. We used SUTRA to solve the areal flow problem. For the purposes of this simulation the waste pit was assumed to be a rectangle 7.6 meters wide and 15.2 meters long. The hydraulic head at the pit boundary was assumed to be constant, three meters above the constant head boundary at the lake. The domain boundaries to the west and north were assumed to be no-flow boundaries.

Flow and transport were simulated for two years. Water flow was assumed to be steady state. We assumed the initial salt concentration in the aquifer was zero. At t=0, brine with a solute concentration of 100,000 mg/L was assumed to enter the aquifer at the pit boundary. Solute concentration in the lake was assumed to be zero.

Results of the homogeneous simulation are illustrated in figures 4 and 5. Figure 4 shows the simulated distributions of hydraulic head and flow velocity. In figure 4, the flow velocity at a point is proportional to the length of the flow vector. As shown in figure 4, in the homogeneous simulation there was flow outward from the pit in all directions. The maximum flow velocity was toward the southeast, where the distance from the pit to the lake is minimum. Simulated concentration profiles after 600 days are shown in figure 5. Concentrations are expressed as a percentage of the initial source concentration, which was 100,000 mg/L. As shown in figure 5, in this simulation the brine plume spread out in all directions from the pit, but the concentration profiles were slightly advanced toward the southeast. Travel time of the solute from the pit to the lake, indicated by the arrival time of the 50% concentration profile at the lake, was about two years.

In contrast to the results of the homogeneous simulation, field evidence suggests that most of the flow is to the east, and there is reduced flow of brine south and west of the pit (3). One explanation of the discrepancy between the homogeneous simulation and the field results is that the hydraulic conductivity of the near-surface materials south and west of the pit is reduced. We simulated the effect of a permeability barrier using SUTRA. As shown in figure 6, for this simulation the hydraulic conductivity west and south of the pit was assumed to be 1.0 cm/day, or 1/10 the assumed hydraulic conductivity of the rest of the aquifer. Flow and transport were simulated for five years. All other model parameters were unchanged.

Results of the simulation with the permeability barrier are illustrated in figures 7 and 8. As shown by the velocity vectors in figure 7, in this simulation most of the flow was directed to the northwest. The concentration profiles shown in figure 8 are also lengthened toward the northwest. In this simulation, travel time of the solute front from the pit to the lake, indicated by the arrival time of the 50% concentration profile at the lake, was about four years.

# DISCUSSION

The ground-water flow and transport problems we solved were highly simplified, designed only to provide first-order hypotheses as an aid in organizing future experiments and data collection at the site. The model has many shortcomings. For example, a major problem is lack of knowledge of the effective aquifer porosity. According to the convection-dispersion solute transport model, the velocity of a solute front, $v_s$, is approximately $q / \phi$, where q is the Darcy flow velocity and $\phi$ is porosity. Assuming $q = 1.8$ m/year, and $\phi = 0.3$, $v_s \sim 6$ m/year. However, the velocity of a solute front traveling through a porous medium containing clay may be greatly increased compared to this estimate. Because the clay-rich fill/colluvium material at this site is highly heterogeneous, preferential pathways for flow probably exist in the F/C layer. Most of the pore space in the clay may be bypassed. As a result, subsurface transport of solute from the pit to the lake may occur much more rapidly. In order to gain an improved understanding of large-scale solute transport at the site, we plan to carry out tracer tests in order to measure solute travel times from the pit to the wells.

# SUMMARY AND CONCLUSIONS

As part of a multidisciplinary investigation of the impact of oil production on the environment, we are investigating the hydrology and the fate and transport of contaminants at the OSPER “B” field site, which is located at Skiatook Lake, Oklahoma. Salt and crude oil from oil-field operations have contaminated soil, ground water, and surface water at this site.

Based on analysis of soil cores, well data, and field observations, we developed conceptual models of the hydrology and solute transport mechanisms at the southern end of the site, where oil-field brine from a waste pit has killed vegetation near the lake. We propose two main mechanisms for solute transport from the waste pit to the lake. One mechanism is the relatively slow and steady flow of saline ground water in an aquifer formed by a near-surface layer formed of fill and colluvium (F/C). We hypothesize that brine from the pit flows down through the bottom of the pit and laterally in the F/C aquifer to the lake. The second mechanism for solute transport is overland flow of saline surface runoff. Evaporation from bare soil leads to high salt concentration near the soil surface. We hypothesize that during rainfall rainwater rapidly mixes with highly saline water at the soil surface and carries dissolved salt down slope in runoff. It is likely that solute transport via salt-laden runoff is much faster than via saline ground-water flow.

Using the USGS model SUTRA, we carried out preliminary computer simulations of steady-state ground-water flow and solute transport from the waste pit to the lake. Results obtained assuming homogeneous aquifer characteristics implied that there is ground-water flow and solute transport outward from the pit in all directions. The most rapid transport was toward the southeast, where the distance from the pit to the lake is minimum. In the homogeneous simulation, travel time of solute from the pit to the lake was about two years. However, field evidence suggests that there is reduced flow of brine south and west of the pit. In order to explain this discrepancy, we hypothesize that the near-surface materials have a reduced hydraulic conductivity west and south of the pit. We ran a second SUTRA simulation with assumed reduced permeability west and south of the pit. With the permeability barrier in place, most of the flow was directed to the northwest. Inserting a permeability barrier increased the simulated solute travel time from the pit to the lake to about four years.

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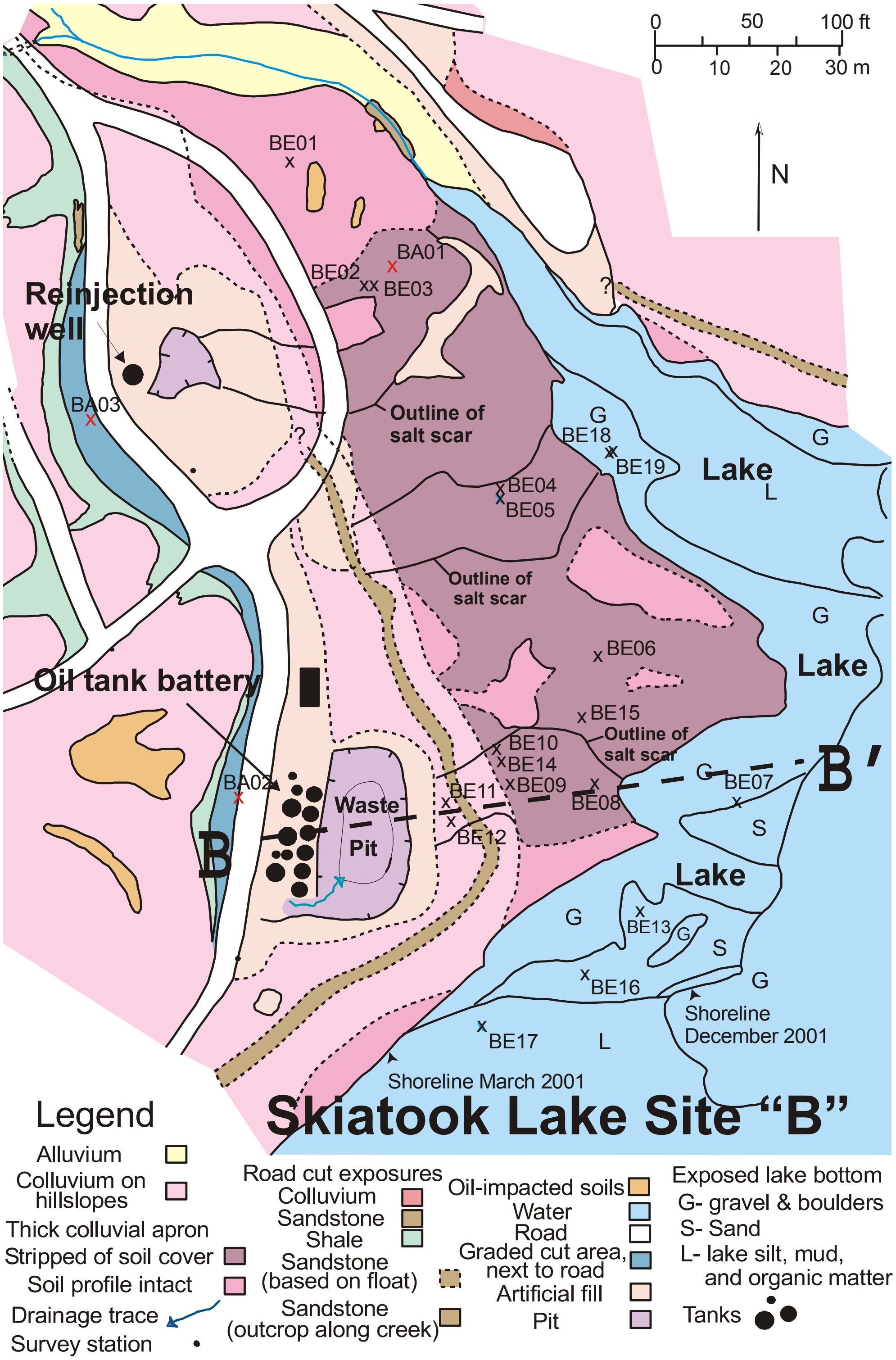

**Figure 1**. Map of Skiatook Lake research site "B."

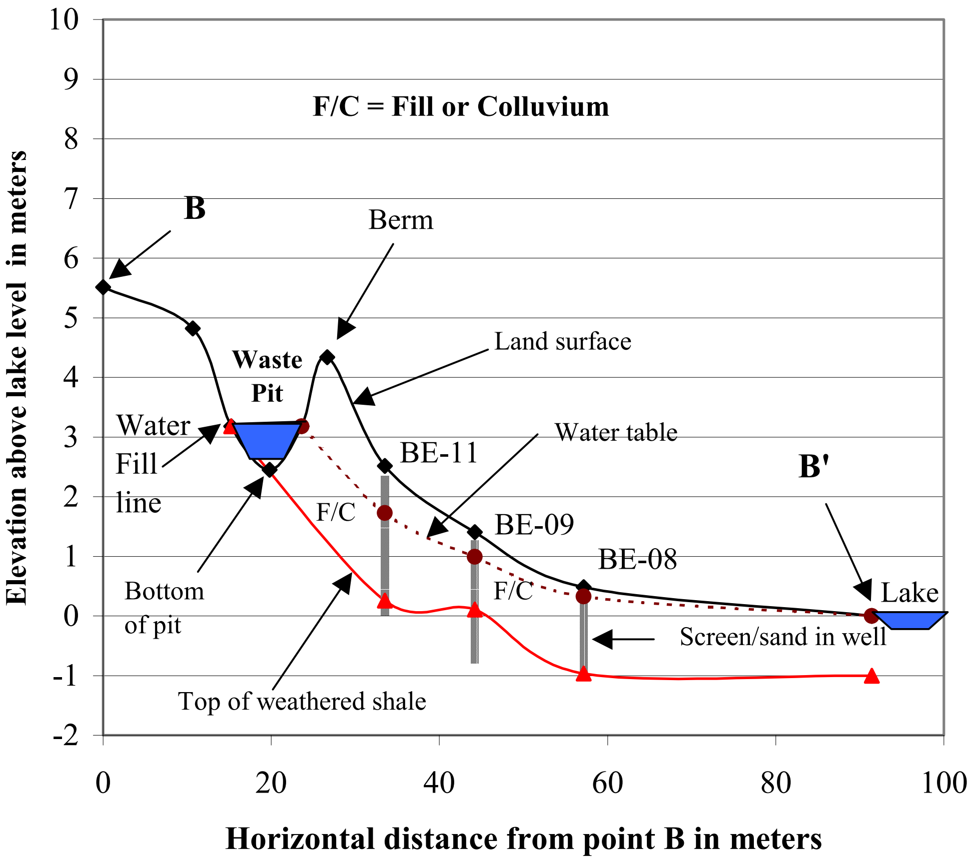

**Figure 2.** Simplified cross section beneath the B-B’ transect at Skiatook Lake site “B.”

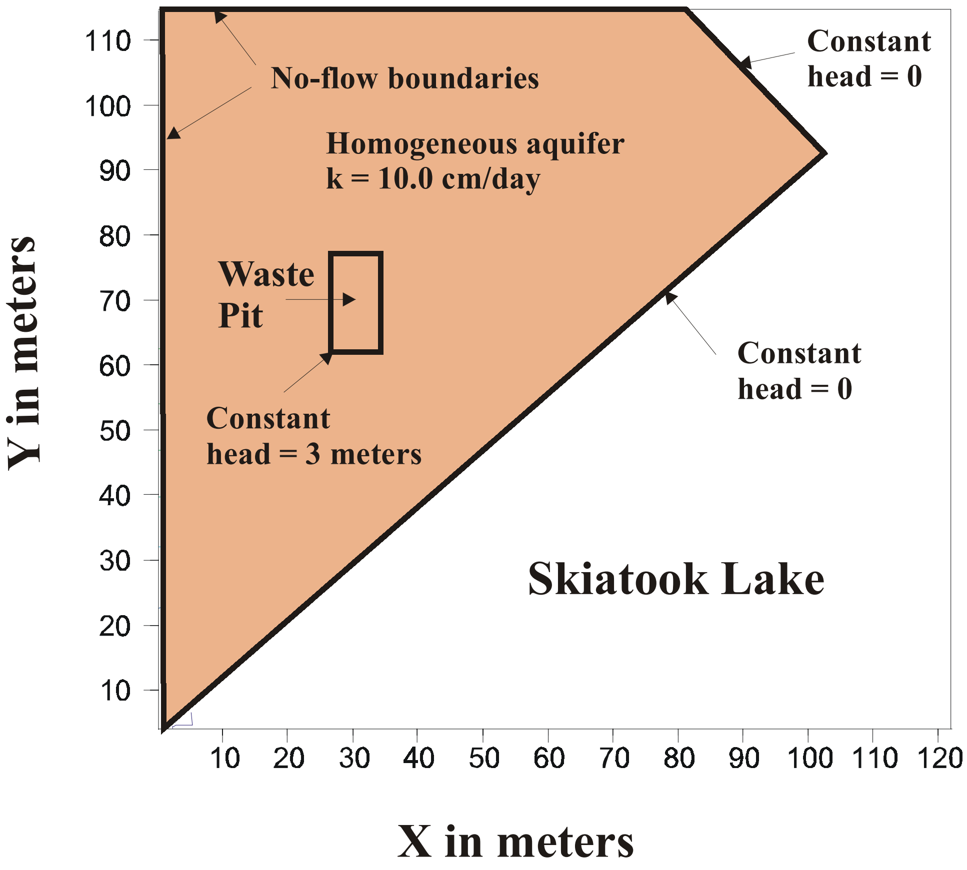

**Figure 3.** Problem layout and boundary conditions for the homogeneous, steady-state areal ground-water flow and transport problem at Skiatook Lake site "B."

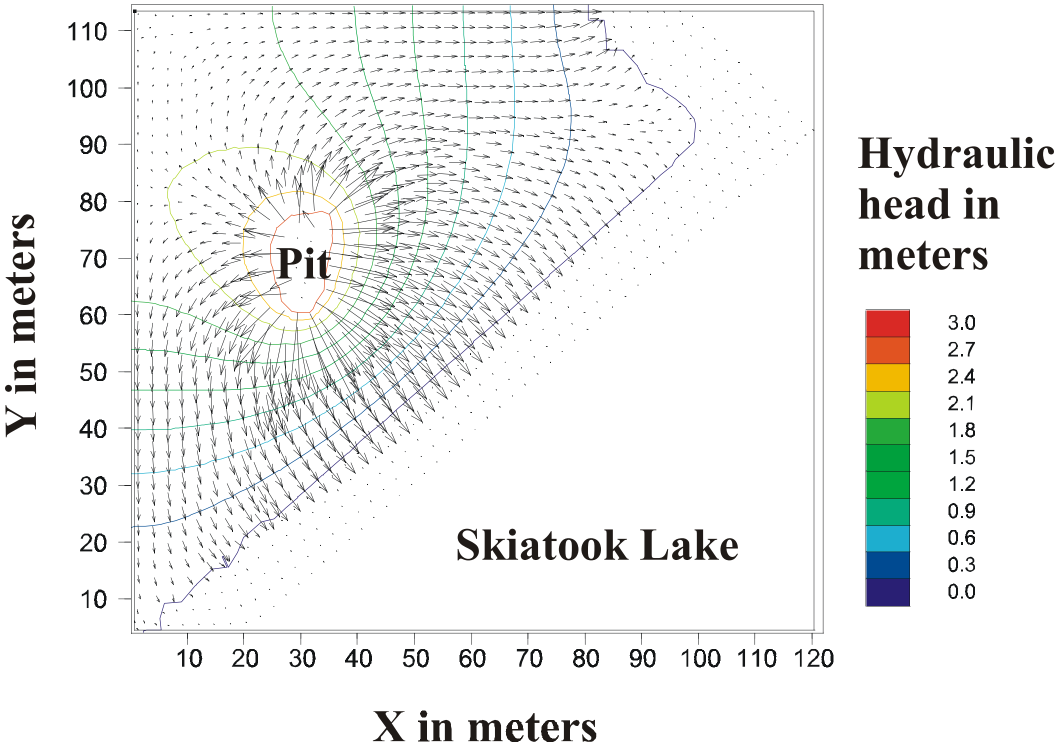

**Figure 4.** Simulated hydraulic head distribution and ground-water flow velocities at Skiatook Lake site "B." Flow velocity at a point is proportional to the length of the flow vector. In this simulation hydraulic properties were assumed to be uniform.

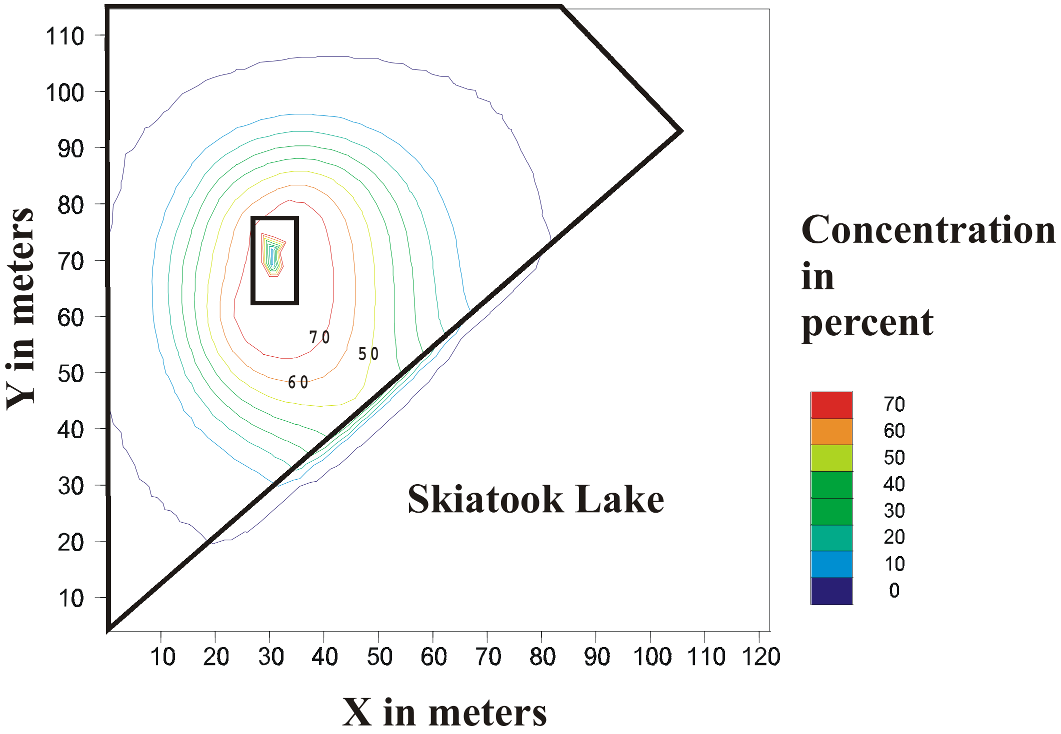

**Figure 5.** Simulated solute concentration profiles at Skiatook Lake site "B" 600 days after oil-field brine was placed in the waste pit. Concentration values are in percent of the source concentration. In this simulation the aquifer beneath the pit was assumed to be homogeneous.

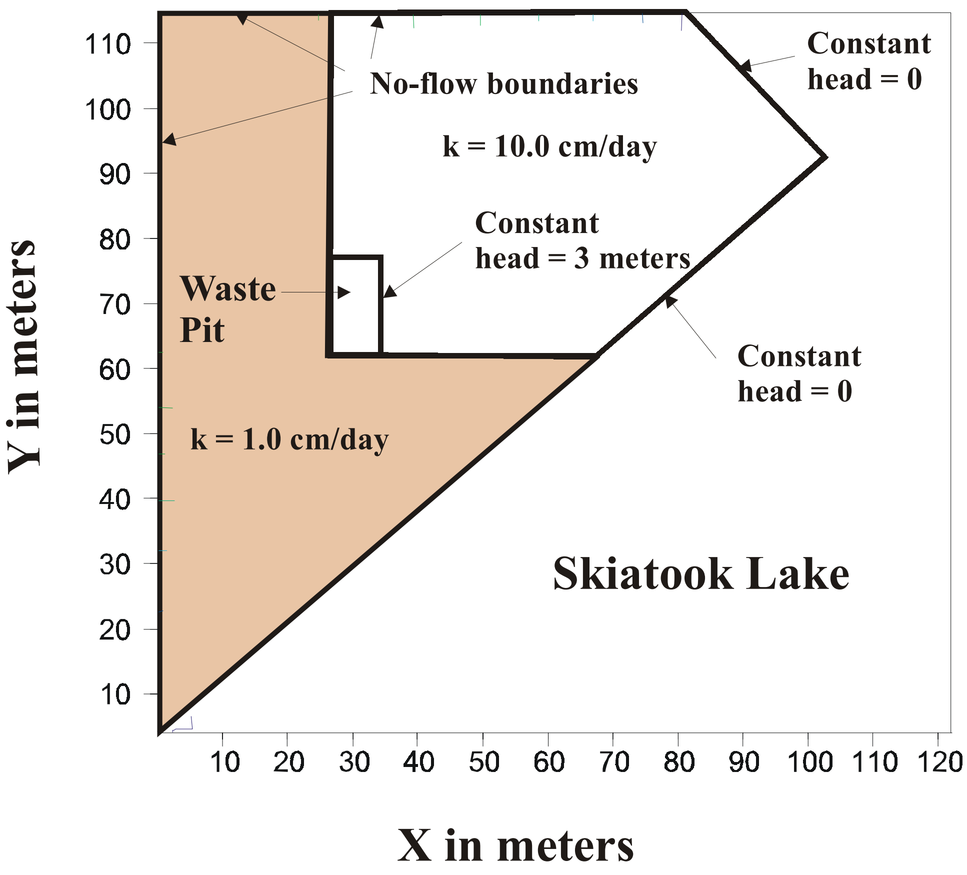

**Figure 6.** Problem layout and boundary conditions for the steady-state areal ground-water flow and transport problem with reduced hydraulic conductivity west and south of the waste pit at Skiatook Lake site “B.”

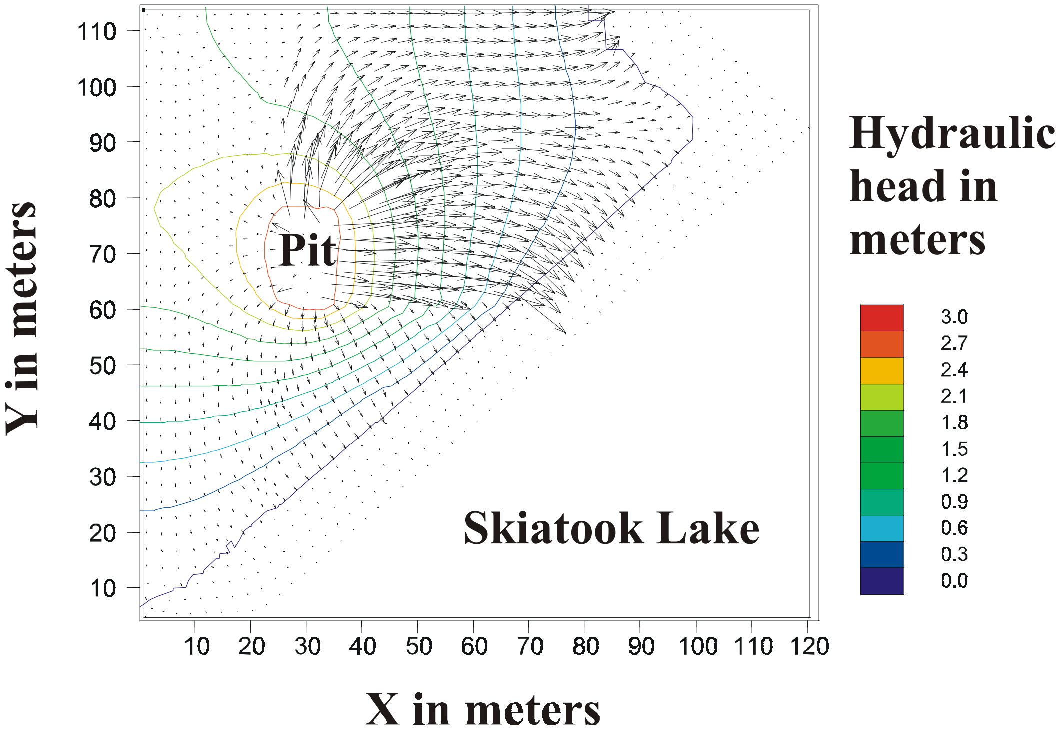

**Figure 7.** Simulated hydraulic head distribution and ground-water flow velocities at Skiatook Lake Site "B." Flow velocity at a point is proportional to the length of the flow vector. In this simulation, hydraulic conductivity west and south of the waste pit was reduced by a factor of 10.

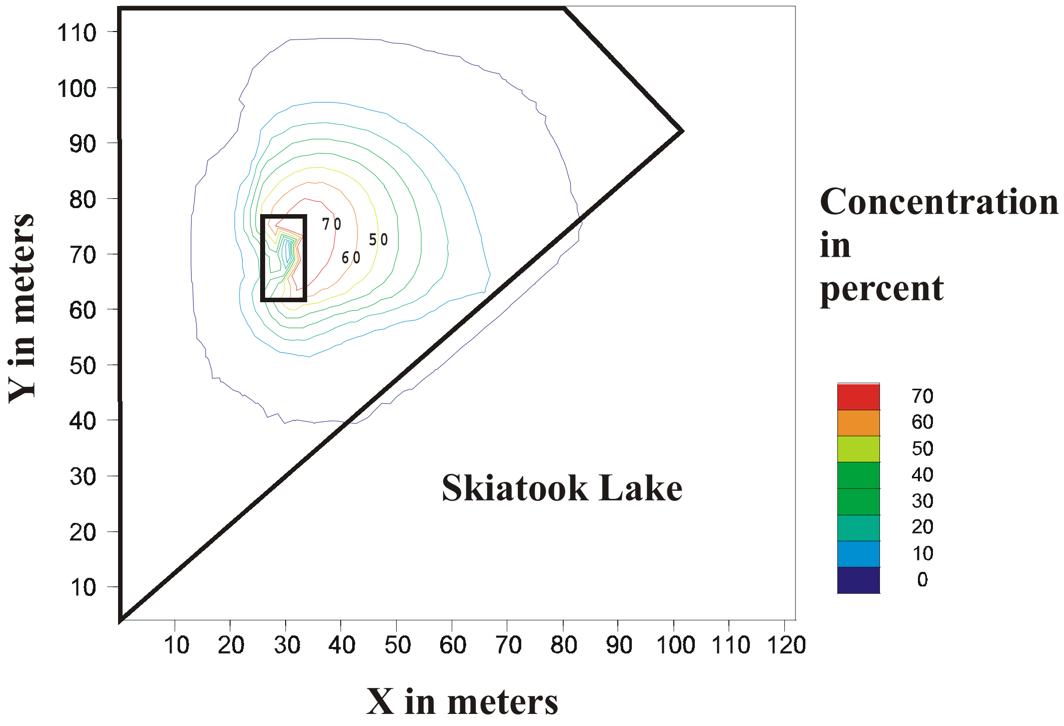

**Figure 8.** Simulated solute concentration profiles at Skiatook Lake site “B” 600 days after oil-field brine was placed in the waste pit. Concentration values are in percent of the source concentration. In this simulation the assumed aquifer permeability west and south of the waste pit was reduced by a factor of 10.