

Environmental impacts of petroleum production: Fate of inorganic and organic chemicals in produced water from the Osage-Skiatook Petroleum Environmental Research sites, Osage County, Oklahoma

Yousif K. Kharaka, James J. Thordsen, Evangelos Kakouros and Marvin M. Abbott*
U.S. Geological Survey, Menlo Park, CA 94025
* U.S. Geological Survey, Oklahoma City, OK 73116

ABSTRACT

We are involved in a multidisciplinary investigation to study the transport, fate, and natural attenuation of inorganic salts, trace metals, radionuclides and organic compounds present in produced water, and their impacts on soil, surface and ground waters and the local ecosystem at the Osage-Skiatook Petroleum Environmental Research (OSPER) 'A' and 'B' sites. The two sites, located in Osage County, OK, are within the depleted Lester and active Branstetter leases, respectively. These leases are typical of many depleted and aging petroleum fields in southern mid-continent of USA. About 1.5 and 1.0 hectare of land at the OSPER 'A' and 'B' sites, respectively are affected by salt scarring, soil salinization and brine and petroleum contamination due to the leakage of produced water and associated hydrocarbons from brine pits and accidental releases from active and inactive tank batteries. Results to date show that the produced water source is a Na-Ca-Cl brine (~150,000 mg/L dissolved solids), with high concentrations of Mg, Sr, and NH₄, but low SO₄ and H₂S. With the exception of Fe and Mn, the concentrations of trace metals are low. Eventually, the bulk of inorganic salts and some dissolved organic species in the released brine reach the adjacent Skiatook Lake, a 4,250-hectare reservoir that provides drinking water to the local communities and is a recreational fishery.

For the OSPER 'A' site, 35 water samples were obtained from an asphaltic pit and an adjacent weathered-oil pit, from a local stream channel and from 12 of 24 boreholes (1-35 m deep), recently drilled and completed with slotted PVC tubing. Results show that the salinity of water from the asphaltic pit is comparable to that of the produced water source. Also, we have mapped a plume of high salinity water (3,500-25,600 mg/L TDS) that intersects Skiatook Lake. Chemical and isotope analyses of the collected samples, water level monitoring and additional sampling are continuing. Results to date clearly show that significant amounts of salts from produced-water releases still remain in the soils and rocks of the impacted area after more than 60 years of natural attenuation.

About 60 water samples were obtained from OSPER 'B' site: from two brine pits, several brine pools and seeps in the impacted area, local streams, Skiatook Lake, and from 24 boreholes (1-71 m deep), recently drilled and completed. Results show diluted brine and minor amounts of oil flow from the brine pits through the shallow eolian sand, colluvial and alluvial deposits to the Skiatook Lake. Its chemical composition is modified further by sorption, mineral precipitation/dissolution, transpiration, volatilization and bacterially mediated oxidation/reduction reactions.

INTRODUCTION

Oil and natural gas currently are the main sources of primary energy supplying about 62% of the energy consumption in USA, and forecasts indicate that by 2020 natural gas and oil consumption will increase by 40% and 29%, respectively (1). Exploration for and production of petroleum typically involves activities such as road building, site clearing and leveling, seismic surveys, and drilling. Road building and site clearing impacts the soil and biota, and in arid environments can impact air quality by added dust to the atmosphere, and vehicle traffic can introduce invasive species to undeveloped areas. Drilling can introduce mud of various compositions into the subsurface and onto the surface, and may cause oil spills or drainage of produced waters. The volume of wastes generated from about 26,000 wells drilled in USA for oil and gas in 1993, including drilling mud, circulated cement, rock cuttings, completion fluids and produced water, is estimated at 0.13-1.0 billion bbl (2). The total number of wells drilled in the United States for the purpose of oil and gas production since 1859 is estimated to be 3.5 million in 36 states; only about 880,000 are currently in production (3). Improperly sealed abandoned wells may act as conduits allowing the flow of high salinity water to the surface and shallow aquifers.

Environmental impacts of petroleum production arise primarily from the improper disposal of large volumes of saline water produced with oil and gas, and from hydrocarbon and produced water releases caused by equipment failures, vandalism, flooding, and accidents. In 1993, about 25 billion and 0.3 billion bbl of produced water were obtained with 2.5 billion bbl of domestic crude oil and 18 trillion ft³ of natural gas, respectively (2). The volume of produced water in 1970 was about one-third as great, even though petroleum production was higher (2, 4). This increase resulted because the volume of produced water relative to petroleum increases with time, typically reaching 98% of total fluids during the later stages of field production.

The chemical composition of produced water is variable, but commonly it is highly saline with total dissolved solids (TDS) of about 5,000-350,000 mg/L (5). This water generally contains toxic metals, other inorganic chemicals, and BTEX (benzene, toluene, ethylbenzene and xylene) and other organic compounds, and may contain radium-226/228 and other NORMs (naturally occurring radioactive material) (4, 6, 7).

Currently about 65% of the produced water from onshore fields is reinjected into producing zones for pressure maintenance and enhanced oil recovery (2). Deep well injection into formations with water salinities greater than 10,000 mg/l (>3,000 mg/l, with exemption from regulations) accounts for about 30% of total produced water. The remaining water is discharged into surface waters, including coastal waterways, bayous, estuaries, streams, lakes and even evaporation and percolation sumps. Prior to the Federal regulations instituted in the 1970s, disposal of produced water was by the most economic method available. Historical methods included discharge into surface streams, storage in unlined impoundments, disposal in poorly maintained injection wells, and simply running the water over the ground. Impacts of these past practices are apparent in salt scars, dead trees and other vegetation, contamination of soil and surface water, and plumes of saline water that affect groundwater supplies.

Accidental releases of produced water and petroleum and the improper disposal of produced water are national issues that concern managers of Federal, and State lands,

as well as oil and gas producers and lessees, mineral rights and lease owners, State and Federal regulators, and surface landowners (8, 9, 10). In 1986, the U.S. Environmental Protection Agency (8) conducted a survey of states to determine the sources of groundwater pollution. Oil and gas brine pits were identified by 22 states as a significant source of groundwater pollution; two of the states identified these pits as the primary cause of pollution.

About 15 scientists from government agencies and academia are involved in a multidisciplinary investigation to study the transport, fate, and natural attenuation of inorganic salts, trace metals, organic compounds and radionuclides present in produced water, and their impacts on soil, surface and ground water and the local ecosystem at the Osage-Skiatook Petroleum Environmental Research (OSPER) 'A' and 'B' sites, located in Osage County, OK. In this report we present data on the chemical and isotopic compositions of surface and ground waters at the two sites and of oil-field brine and ground water in the region. Results from all the studies will be used to evaluate the long-term and short-term effects of produced water and hydrocarbon releases from these sites. Results are expected to guide estimates of human and ecosystem risk at such sites and the development of risk-based corrective actions (11). Corrective actions are particularly needed in aging and depleted fields, where land use is changing from petroleum production to residential, recreational, agricultural or other uses (12).

OSPER SITES

The two research sites, OSPER 'A' and 'B' are located respectively, within the Lester and Branstetter leases, and both are adjacent to Skiatook Lake, a 4,250-hectare reservoir completed in 1987 that provides drinking water to the local communities and is a major recreational fishery (Figs. 1 and 2). The sites are located in the Central Oklahoma platform in the southeastern part of the Osage Reservation in northeastern Oklahoma. Both sites are in a dissected area of modest relief, with oak forests covering the slopes and tall grass present on most ridge crests. Geological mapping by Otton and Zielinski (13) show the area to be underlain by interbedded shale, siltstone, and sandstone. Thicker resistant sandstone units typically form the hill crests. Hill slopes are underlain by shale, siltstone, and thin sandstone beds.

The geologic and climatic settings of the Lester and Branstetter leases resemble that of much of the major southern mid-continent oil- and gas-producing area of the U.S. The leases are also typical of many depleted and aging petroleum fields in Osage County, which ranks among the top oil and gas producing counties in Oklahoma with close to 40,000 wells (14). Oil and gas production has occurred in Osage county for over 100 years, but current production is mainly from stripper (<10 bbl/d) wells (averaging ~2.8 bbl/d oil and >30 bbl/d brine) that are shallow, mostly 300-700 m in depth, and produce from several sandstones of Pennsylvanian age. The six oil wells sampled for this study and located in the Barnstetter lease and from fields adjacent to the Lester lease, produced 1.5-4 bbl/d oil from Mississippi lime and Bartelsville, Cleveland and Tucker sands at depths of 333-538 m; brine production from these wells comprised 94-99% of produced fluid. The Osage Nation holds the mineral rights, the BIA has trust responsibility, and the Army Corps of Engineers owns the surface at OSPER 'A' and 'B' sites.

Site 'A' located within the Lester lease in section 13, T22N, R10E, has an area of about 1.5 hectare that is impacted by produced water and hydrocarbon releases that occurred primarily 60-85 years ago (Fig. 1). The site is underlain by 1) a surface layer of eolian sand of varying thickness (up to about 80 cm); 2) colluvium that ranges from large boulders of sandstone to thin, granule-pebble conglomerate; 3) weathered shale, siltstone, and sandstone; and 4) underlying unweathered bedrock. Much of the site appears to have been impacted by early salt-water releases that killed the oak forest, however a few oak trees persist as single trees or clumps of trees within the original kill area. The gently sloping upper part of the site is slightly eroded in places and has been mostly revegetated with grasses, forbs, sumac, and a few trees. The lower, steeper, more heavily salt-impacted portion has been eroded to depths of as much as 2 m. Seepage of salt water from a shallow sandstone aquifer continues and active salt scarring persists. This area drains into the Cedar Creek arm of Skiatook Lake.

Drilling at the Lester Lease started in 1912, and most of the over 100,000 bbl of oil produced by 1981, was obtained prior to about 1937. Production, which was entirely from Bartlesville sand at depths of 450-524 m, ended about 10 years ago (BIA, unpublished lease records, 2000). Oil and produced water collected in two redwood tanks at the top of the site was transported via ditch to two roadside pits at mid-site. Produced water and hydrocarbon (now highly degraded and weathered oil) releases from pipeline breaks and tank batteries, that are no longer present, are scattered around the site. However, one pit at this site contains relatively fresh asphaltic oil and high salinity brine.

Site 'B', located within the Branstetter lease in sections 29 and 32, T22N, R10E, is actively producing and has ongoing hydrocarbon releases and salt scars that have impacted an area of about one hectare (Fig. 2). The site includes an active production tank battery and adjacent large pit, two injection well sites, one with an adjacent small pit, and an old tank battery. The large pit is about 15 m from the shoreline of the Skiatook Lake; all the other sites are within 45 m of the lake. Three salt scars that were partly 'remediated' in 2000 by soil removal, tilling and soil amendments, extend down slope from the active tank battery, the injection well/pit, and the old tank battery to the lake edge. Two small creeks cross the northern and southern parts of the site. The upper part of the site is characterized by a thin surface layer of eolian sand mixed with sandstone-clast colluvium underlain by weathered and unweathered shale whereas the lower part of the site is underlain by 1) a surface layer of eolian sand (20-70 cm thick); 2) colluvial apron and alluvial deposits of varying thickness comprised of sandstone pebbles, cobbles, and boulders with a fine sand matrix; 3) weathered shale; and 4) unweathered bedrock.

The Branstetter lease was initially drilled in 1938 and increased activity occurred in 1947-51, when A. H. Ungerman purchased the lease. About 110,000 bbl oil was produced from the lease before water flooding started in 1953. Currently there are about 10 wells that produce 1-3 bbl/d oil, and 50-100 bbl/d brine; all the produced fluids are collected and separated in the tank battery adjacent to the large brine pit (S. Hall, oral communication, 2002). The two brine pits at this site are not lined and receive brine and hydrocarbons releases from broken pipes and tank leaks; they also receive large volumes of surface-water flow from precipitation. The brine in these pits is generally pumped into collection tanks by submersible pumps, but these occasionally fail causing filling and overflow of brine pits, as happened in December, 2001 for the large brine pit.

METHODS AND PROCEDURES

We have carried out three major sampling trips (March 2001, February 2002 and June 2002) and several short trips, where only a few samples were collected, or only few field parameters (e.g. water level, conductance, temperature and dissolved oxygen (DO)) were measured. During March 2001, 15 water, four oil and three gas samples were obtained from wells adjoining the two sites to characterize the source fluids from oil wells, groundwater, and the Skiatook Reservoir (Table 1). However water samples were also collected from several seeps, pools and shallow (~20 cm) holes mainly at the 'B' site. During February, 2002, about 60 Geoprobe, auger and rotary wells were drilled at and near the two sites, cored, completed with slotted PVC tubing and, where water was present, sampled. The water level, conductance, temperature and DO were measured in these wells in April-May 2002, and water sampling was carried out in June.

A total of about 100 water samples have been collected from the two sites and adjoining areas. For the OSPER 'A' site, 35 water samples were obtained from the asphaltic pit and adjacent weathered-oil pit, from a local stream channel and the Skiatook Lake, and from 12 of 24 boreholes (1-35 m deep) discussed above. About 60 water samples were obtained from the 'B' site, from the two brine pits, several brine pools and seeps in the impacted area, local streams, Skiatook Lake, and from about 20 boreholes (1-71 m deep) recently drilled and completed.

Laboratory Measurements

All of the water samples were analyzed at the USGS Water Resources laboratories in Menlo Park, CA. Concentration of chloride (Cl), bromide (Br), nitrate (NO₃), organic acid anions and sulfate (SO₄) were determined by ion chromatography (IC) (7, 15). Inductively coupled plasma mass spectrometry (ICP-MS) was used to determine the concentrations of calcium (Ca) and other cations, trace metals, boron (B), and silica (SiO₂). The reported concentrations for major cations and anions carry an uncertainty of ±3%. Precision values for minor and trace chemicals are generally ±5%, but could reach ±10% for values close to detection limits (15).

Water isotopes were determined in the USGS Stable Isotope Laboratory in Menlo Park. Water isotopes are reported in δ – values that are expressed in parts per thousand (per mil, ‰) relative to the Standard Mean Ocean Water (SMOW). The Standard Deviation of reported values are ±0.2 ‰ for $\delta^{18}\text{O}$ and ±2 ‰ for δD (15).

RESULTS AND DISCUSSION

Stable water isotopes and concentrations of selected inorganic and organic chemicals from surface and ground water samples from OSPER 'A' and 'B' sites and adjoining areas in Osage County, OK are listed in Table 2 and 3, respectively. The data listed for water from rotary (AR and BR) wells, drilled with fresh water that likely effected the composition of formation water, and from relatively deep auger (AA and BA) wells, that may have been subject to cross formational flow prior to well completions, are only for the last samples collected in June, 2002. Additional sampling from these and other wells will be carried out in order to distinguish chemical changes

related to drilling operations and to investigate spatial and temporal changes related to physical, chemical and biological processes.

Results show that the produced water obtained (Table 1) from the seven oil wells, one coal-bed methane well (01OS-110) and the composite reinjection tank has a relatively similar chemical composition; it is a hypersaline (115,000-185,000 mg/L total dissolved solids) Na-Ca-Cl brine, that is dominated by Na and Cl, and has relatively high concentrations of Ca, Mg (Fig. 3), Sr, Ba and NH_4 , but very low amounts of SO_4 , HCO_3 (Fig. 4) and H_2S . With the exception of Fe, the concentrations of trace metals are low, and the values of organic acid anions and other dissolved organic species are relatively low. The chemical composition of Skiatook Lake water and ground water in the area not impacted by petroleum operations (samples 01OS-111, -101, -102, 02OS-438, Table 1) shows major contrast from that of produced water. The water is fresh (153-518 mg/L total dissolved solids) and has comparable values for the equivalent concentrations of Na, Mg and Ca as well as those of Cl, SO_4 and HCO_3 ; this water, then, has much higher Mg and Ca concentrations relative to Na and much higher HCO_3 and SO_4 relative to Cl, when compared to produced water (Figs. 3 and 4). Uncontaminated ground and surface waters are generally oxic, resulting in low concentrations of metals, including Fe (reaction 3, Table 4) and Mn, as well as low DOC and organic acid anions (Fig. 5). In anoxic water environment, present in produced water and petroleum contaminated water, Fe (reactions 1, 2, Table 4) and Mn are mobilized from sediments, and organic acid anions, and thus DOC are generated by bacterial action on petroleum (7). These and other chemical properties and water isotopes that are different for produced and ground waters (Fig. 6) are used to investigate the impact of produced water on the surface and ground waters of the contaminated areas (14, 16, 17).

OSPER 'A' Site

At OSPER 'A' site, the water obtained from the asphaltic pit (02OS-324) has a salinity (110,000 mg/L TDS) and chemical composition that are comparable to that of the produced water source (Fig. 7). The salinity of water obtained from the boreholes in the adjacent pit, which has more weathered and degraded oil (18), and from those boreholes located close to the two pits, all have fresh water ($\leq 1,000$ mg/L TDS), indicating that the brine in the asphaltic pit is of limited volume and extent. Also, all the Geoprobe wells (AE designation in Table 2) located to the south and west of the two oil pits (Fig. 1) have fresh water, with compositions that indicate no mixing with produced water. If produced water was ever present in these shallow wells, then it was flushed and replaced with meteoric water from precipitation. (See also results from soil analysis (19) and geophysical surveys (20)).

The salinity and chemical composition of water obtained from all the auger wells (AA designation, Table 2) as well as from those Geoprobe wells (AE, Table 2) located to the north of the two oil pits in the salt scarred area at the 'A' site, show major impact from produced water operations (Figs. 8 and 9). A plume of high salinity water (3,500-25,600 mg/L TDS) dominated by Na and Cl, intersects Skiatook Lake near well AE-13 (Fig. 1) that has water salinity of 10,100-12,300 mg/L TDS (see also 20). The upper and lower boundaries of this plume are tentatively marked on the cross section (Fig. 9) that shows the plume apex to be within 1 m from ground surface in well AA-03, which is the closest to the oil pits that likely were also the brine pits. Chemical data for water from the deeper perforated section (13.8-15.2 m below ground level) of well (AA-02), we believe,

will ultimately delineate the bottom of the plume. The salinity and chemical composition of water for the last sample from this section (02OS-427, Table 2 and Fig. 8) indicate a non produced water source; the concentration of acetate, DOC and possibly other components (Table 2) could indicate contamination from an oil source or cross formational mixing from the shallow and contaminated section when the well was drilled.

Additional sampling from this and new deeper wells will be used to better delineate the plume boundaries from this site. Results to date, however clearly show that significant amounts of dissolved inorganic and organic chemicals and hydrocarbons from produced-water and oil releases still remain in the soils and rocks of the impacted area after more than 60 years of natural attenuation.

OSPER 'B' Site

Even though the number of boreholes drilled at the two sites is comparable, a larger number of water samples (60 vs. 35) have been obtained from the 'B' site compared to the 'A' site. This results primarily because the 'B' site is currently active and brine and associated hydrocarbons are added intermittently via the brine pits and accidental releases from broken pipes. Many of the water wells at the 'A' site, in contrast to those at the 'B' site, were found dry at the time of sampling because the oil wells in the Lester lease have been depleted for some time and no brine additions occur at this site.

The salinity (133,000 mg/L TDS) and chemical composition of water in the composite water tank (Table 3) are similar to those described earlier for the produced water from the sampled oil wells (Figs. 3 and 4). The salinity and chemical composition of water in the two brine pits (Fig. 2) vary greatly with time, reflecting primarily the mixing of produced water brine with dilute water from precipitation. The salinity of water in the small pit adjacent to the injection well, for example, was 13,000 mg/L TDS on 12/11/01 and 42,000 mg/L TDS on 2/25/02. The proportions of major anions and cations in both samples were similar and comparable to those of produced water, but the actual concentration were reduced by a factor close to 10 for the December sample and about three for the February sample. The concentration of a number of minor and trace chemicals that are sensitive to the redox state of the water (e.g. Fe, Mn, NH₄, organic acid anions) are likely to be lowered in oxic conditions (e.g. reactions 1-3 for Fe, Table 4) by factors that are greater than those listed above. The concentration of some chemicals (e.g. NH₄, BTEX, organic acid anions) may be reduced also by volatilization. On the other hand, evaporation generally increases the concentrations of dissolved species, and the relatively higher concentrations of HCO₃ in both samples likely result from bacterial degradation of oil.

All the water samples obtained from pools, seeps and boreholes at this site (Fig. 2) show variable impacts from produced water. The most saline sample, outside the brine pits, was obtained in December 2001 from a well located about 15 m down gradient and to the east from the large brine pit, which generally has from about 0.2 to 2 m (overflow) of produced water with a thin layer of oil. The well brine (01OS-201, Table 3) had a salinity (82,000 mg/L TDS) and chemical composition approaching that of produced water. Water obtained from the same well in February 2002, had a salinity of only 17,400, but the proportions of major cations and anions are similar to those of produced water. Water samples obtained in February and June 2002 from Geoprobe well BE-07 (Figs. 2 and 10) located in the littoral zone of Skiatook Lake, about 65 m down gradient

and to the east from the large brine pit, show a more uniform salinity (24,000 and 20,000 mg/L TDS, respectively). The chemical composition of water from this well has characteristics that are similar to that of produced water (Fig. 11), that together with the presence of oil globules in the water, strong oil odor and high values measured for hydrocarbon gases and other VOCs (see also 18), clearly show that brine and minor amounts of hydrocarbons from the large brine pit reach the lake. Minor contamination of Skiatook lake with brine is indicated (02OS-309 vs 01OS-111, Fig. 11), but this topic will be covered in detail in future reports.

Additional Geoprobe wells (BE designation, Fig. 2 and Table 3) and one dual completion auger well (BA-02) were drilled to investigate the flow paths of brine and associated hydrocarbons from the large brine pit. In addition to well BE-07 discussed, oil globules in the water, strong oil odor and high values measured for hydrocarbon gases and other VOCs were observed in well BE-09 and a 30 cm hand-dug well located close and down gradient from BE-11. No visible oil was observed in water from other wells, but oil odor and measured hydrocarbon gases were obtained from most of the other wells located on the salt scarred, but 'remediated' area below the brine pit. All the wells located in the salt-scarred area below the brine pit, especially those shown in Figure 10, also had saline water with chemical characteristics of produced water (Table 3, Fig. 11).

Water samples obtained from the two perforated zones of well BA-02 as well as those from wells BE-16 and BE-17 have high salinity (8,000-16,500 mg/L TDS) and chemical characteristics that could indicate a mixture of diluted produced water, high in Na and Cl and ground water, high in Mg, SO₄ and HCO₃ (Fig. 12). Geochemical modeling using the latest version of SOLMINEQ (21) indicates another possible, but less likely explanation for the chemical composition of water from these samples. It includes dilution of produced water source, followed by dissolution of gypsum and dolomite and precipitation of calcite (reactions 10, 7 and 6, Table 4). Regardless of the correct explanation, these results indicate a slower flow path from the large brine pit towards wells BA-02, BE-16 and BE-17 than towards the wells depicted in the transect A-A' (Fig. 10). Additional sampling, tracer tests and hydrologic parameter determinations and modeling (see also 22) are planned to investigate the flow in this system.

Significant amounts of produced water, but no oil, reach the wells, water pool and even the creek adjacent to the scarred, but 'remediated' area down gradient from the reinjection pit (Fig. 2). The salinity of water from BE-03 and other wells, small pools and a large pool close to the creek has varied widely, ranging from 2,500 to 13,100 mg/L TDS, but the chemical composition is that of a diluted produced water. Sample 02OS-311, which was collected from the creek to the east of BA-01 well has a salinity of 2,500 mg/L TDS and chemical properties of diluted produced water. A specific water conductance of about 20,000 μ siemens/cm (μ S/cm) was obtained with a probe from a location where this sample was obtained.

A high specific water conductance (8,000 μ S/cm) was also measured in the creek near well BE-19. This part of the creek, as well as wells BE-4, -5, -18 and -19 are located in the middle salt scarred and 'remediated' area of the 'B' site. This salt scar had a tank battery, located at its western end that was removed and the site 'remediated' in year 2000. The four Geoprobe wells on this site have generally been dry. However, some water was obtained from BE-4 and -19, that gave salinities of 19,200 and 10,100 mg/L TDS, respectively; the water is dominantly Na-Cl and has the other chemical characteristics of produced water.

SUMMARY AND CONCLUSIONS

About 100 water samples and several oil and natural gas samples were obtained from oil wells, domestic ground water wells, active and inactive brine and oil pits, seeps, pools, local streams, Skiatook Lake and from 50 boreholes (1-71 m deep), recently drilled and completed with slotted PVC tubing. Most of the samples are from OSPER 'A' and 'B' sites, located, respectively, within the depleted Lester and active Branstetter leases, in Osage County, OK. Results show that large amounts of produced water and associated petroleum from active and inactive brine pits and from accidental releases from broken pipes have impacted about 1.5 and 1.0 hectare of land at the OSPER 'A' and 'B' sites, respectively. The impacts include salt scarring, soil salinization and oil contamination, and brine and petroleum contamination of ground water and surface water, including Skiatook Lake, a 4,250-hectare reservoir that provides drinking water to the local communities and is a major recreational fishery.

At the 'A' site, results show that the salts have essentially been removed by flushing from the soil and surficial rocks; but degraded and weathered oil persists on the surface of old oil and brine pits, close to sites of old tanks, on old channels that carried oil from tanks to the oil pits and other impacted areas. Results show that a plume of high salinity water (3,500-25,600 mg/L TDS) is present at intermediate depths that extend from below the old oil and brine pits to Skiatook Lake. No liquid petroleum was found in the contaminated groundwater, but soluble petroleum byproducts, including organic acid anions and other VOCs are present. Results to date clearly show that significant amounts of salts from produced-water releases and petroleum hydrocarbons still remain in the soils and rocks of the impacted area after more than 60 years of natural attenuation.

At the 'B' site, significant amounts of produced water from the two active brine pits percolate into the surficial rocks and flow towards the Skiatook Reservoir; but only minor amounts of liquid petroleum leave the brine pits and reach the Skiatook Reservoir. The above results and conclusions are tentative and may be modified after additional sampling from existing and new wells, tracer tests, hydrologic parameter determinations and hydrologic and geochemical modeling are completed. These results, however, show that diluted produced water and minor amounts of oil flow from the brine pits through the surficial beds to the Skiatook Lake.

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Table 1. Chemical (inorganic and organic) and isotopic composition of ground water and produced water samples from Osage County, OK

Site Name Sample # Date	Ground water wells										Produced water from oil wells							TEC T1-19 01OS-110 03/10/01
	Hurn well 01OS-101 03/05/01	Bolin well 01OS-102 03/06/01	Reynolds #4 01OS-103 03/06/01	ECC #10 01OS-104 03/07/01	ECC #3 01OS-105 03/07/01	Lebow #8 01OS-106 03/08/01	Millard #3 01OS-107 03/08/01	ECC #5 01OS-108 03/09/01	Ungermann #1 01OS-109 03/09/01	ECC #5 01OS-108 03/09/01	ECC #5 01OS-108 03/09/01							
pH	6.0	7.2	6.2	6.7	6.1	6.3	6.4	6.4	6.3	6.4	6.4	6.3	6.3	6.8				
T (°C)	18	18	15	22	23	34	21	22	25	22	25	25	24					
Li	0.016	0.008	36	8.0	38	11.5	6.0	27	7.1	27	7.1	7.1	6.9					
Na	69	36	51700	42400	55000	48600	38100	47000	39200	47000	39200	39200	34100					
K	0.96	0.97	690	100	650	270	110	480	150	480	150	150	190					
NH ₄ ⁺	<0.1	0.5	38	79	45	78	56	48	59	48	59	59	59					
Mg	25	19	1980	2350	2070	1830	1530	1910	1510	1910	1510	1510	1830					
Ca	57	36	11200	5400	11900	9960	6250	9980	6940	9980	6940	6940	5870					
Sr	0.24	0.33	500	905	514	504	521	505	502	505	502	502	565					
Ba	0.14	0.21	451	339	461	879	311	309	396	309	396	396	12					
Mn	0.002	0.35	6.0	2.8	10.0	0.93	1.28	7.5	0.95	7.5	0.95	0.95	5.4					
Fe	0.01	0.12	50	27	31	67	28	24	38	24	38	38	126					
Cl	216	24	110000	82100	113000	99500	75400	101000	78500	101000	78500	78500	70100					
Br	0.86	0.13	346	285	364	346	335	320	338	320	338	338	257					
SO ₄	45.1	18.3	0.32	0.23	0.37	0.69	0.16	0.37	0.23	0.37	0.23	0.23	81					
HCO ₃	72	269	109	244	105	185	146	118	182	118	182	182	280					
NO ₃	5.2	<0.02	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1					
H ₂ S	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4	2.5					
SiO ₂	26	14	<16	<16	<16	<16	<16	<21	<21	<16	<21	<21	<16					
B	0.018	0.070	8.8	2.9	8.7	3.6	1.8	6.9	1.8	6.9	1.8	1.8	2.4					
TDS	518	420	177000	134000	185000	162000	123000	162000	128000	162000	128000	128000	114000					
DOC	0.4	0.4	5	3	3	3	2	6	7	6	7	7	4					
Phenols (total)			0.10	0.11	0.11	0.12		0.18	0.07	0.18	0.07	0.07	0.12					
Benzene			0.77	0.70	0.70	0.49		0.90	0.23	0.90	0.23	0.23	0.34					
Acetate	<0.02	<0.02	0.9	2.2	0.5	2.4	0.6	5.2	1.5	5.2	1.5	1.5	1.4					
Formate	0.03	0.05	0.3	0.1	0.4	0.4	0.4	0.3	0.4	0.3	0.4	0.4	0.3					
δ ¹⁸ O (‰)	-5.72	-5.73	-2.03	-2.95	-1.77	-2.57	-3.51	-2.18	-3.38	-2.18	-3.38	-3.38	-2.92					
δD (‰)	-35.16	-34.89	-9.91	-13.00	-9.32	-10.60	-19.06	-10.05	-17.09	-10.05	-17.09	-17.09	-14.36					

T, temperature; TDS, total dissolved solids; DOC, dissolved organic carbon; solute concentrations in mg/l; <, less than.

Table 2. Chemical (inorganic and organic) and isotopic composition of selected water samples from OSPER site A

Site Name	AA-01d	AA-02d	AA-02s	AA-03d	AA-03s	AA-04d	AA-04s	AE-04	AE-05	AE-06
Sample #	02OS-430	02OS-427	02OS-426	02OS-429	02OS-428	02OS-425	02OS-424	02OS-434	02OS-332	02OS-435
Date	06/13/02	06/12/02	06/12/02	06/12/02	06/12/02	06/12/02	06/12/02	06/13/02	03/03/02	06/13/02
pH	6.5	6.9	6.2	6.7	6.6	7.0	5.7			
T (°C)	16	18	19	16	19			22		23
Li	0.16	0.05	0.07	0.13	0.04	0.08	0.04	0.001	0.001	0.002
Na	2180	525	3400	3250	1110	1150	1670	60	11.8	4
K	27	6.8	16	25	3.2	28	5.3	1.0	0.03	0.8
Mg	2520	102	272	166	41	234	63	0.4	0.03	1.1
Ca	3460	176	564	419	98	567	202	2.1	0.18	5.9
Sr	8.6	2.9	8.4	5.2	3.4	4.9	7.7	0.07	0.004	0.26
Ba	0.3	0.1	0.6	1.2	1.9	1.3	6.3	0.026	0.003	0.25
Mn	5.1	0.49	1.7	14.5	2.2	4.3	12.5	0.013	0.001	0.23
Fe	<10	3	<5	6	6.5	<2.5	<2.5	0.1	0.07	0.2
Cl	16100	436	7020	5630	1860	3410	3240	76.7	3.3	2.2
Br	56	1.5	23	19.3	6.4	11.6	11.7	0.27	0.08	0.12
SO ₄	696	668	137	23.4	5.7	56.8	5.9	10.2	14.2	6.0
HCO ₃	445	824	255	894	301	279	54	ND	ND	ND
NO ₃	<1	<0.2	<1	<0.2	<0.2	<0.5	1.8	1.2	1.1	0.32
SiO ₂	<43	24	<21	<21	19	18	29	11	10	16
B		0.4			0.1			0.04	0.023	0.033
TDS	25500	2760	11700	10500	3450	5760	5310	180	50	62
DOC	99	113	2	203	53	2	4			
Acetate	171	200	0.08	517	101	<0.04	<0.04			
Formate	<0.08	<0.08	0.09	<0.08	<0.08	<0.08	<0.04			
Propionate	<0.2	<0.2	<0.2	0.7	3.3	<0.1	<0.05			
Butyrate	<0.2	<0.2	<0.2	0.5	<0.2	<0.1	<0.05			
$\delta^{18}\text{O}$ (‰)										
δD (‰)										

T, temperature; TDS, total dissolved solids; DOC, dissolved organic carbon; solute concentrations in mg/l; <, less than.

Table 2. Chemical (inorganic and organic) and isotopic composition of water samples from OSPER site A -- continued

Site Name	AE-07 well	AE-08 well	AE-10 well	AE-12 well	AE-13 well	AE-13 well	AE-15 well	AE-19 well	AR-01 well	AP-01* well
Sample #	02OS-334	02OS-326	02OS-331	02OS-328	02OS-329	02OS-431	02OS-437	02OS-433	02OS-438	02OS-324
Date	03/03/02	03/01/02	03/03/02	03/03/02	03/03/02	06/13/02	06/13/02	06/13/02	06/13/02	02/28/02
pH	5.3	6.4	5.7	7.3	5.6	5.6	5.6	6.5	6.5	5.8
T (°C)										
Li	0.002	0.048	0.025	0.032	0.024	<0.025	0.09	0.01	0.011	3.2
Na	23	341	24	179	1980	2250	4030	50	23	32900
K	0.13	1.6	0.74	1.7	2.8	3	4	0.5	1.6	89
Mg	0.21	4.8	0.57	1.8	629	808	484	1.4	23	1600
Ca	0.81	19	2.9	8.3	738	1020	1000	5.7	58	5880
Sr	0.037	1.2	0.19	0.59	23.3	25.4	16.9	0.25	0.36	454
Ba	0.066	0.19	0.081	0.023	0.41	0.41	1.2	0.040	0.56	15.5
Mn	0.007	0.39	0.086	0.029	105	87.8	2.8	0.14	2.1	6.3
Fe	0.15	<0.05	0.02	0.05	2.0	6	<10	0.1	0.2	595
Cl	20.0	580	17.4	37.6	6300	7770	9120	58.8	76.8	68100
Br	0.17	1.3	0.07	0.39	22.0	26.6	30.9	0.41	0.57	244
SO ₄	20.6	14.3	28.5	4.9	92.3	248	115	16.8	5.6	43.1
HCO ₃	3	ND	13	457	14	57	11	ND	221	239
NO ₃	1.2	0.08	0.25	3.1	10	<1	11	0.38	<0.02	<4
SiO ₂	11	11	10	2.9	9.6	25	<43	12	23	<32
B	0.012	0.14	0.021	0.34	<0.025			0.08	0.02	1.9
TDS	81	1000	97	700	9930	12300	14800	181	436	110000
DOC			11	69	5	5			4	
Acetate		0.3	0.2	0.5	0.3	0.04	0.07		0.07	210
Formate		0.3	0.1	1.2	0.2	<0.04	<0.08		0.07	3
Propionate		<0.25	<0.05	<0.2	<0.05	<0.05	<0.2		<0.1	44
Succinate		<0.1	0.04	0.3	0.1	<0.12	<0.12		<0.02	1.4
δ ¹⁸ O (‰)		-5.18	-5.92	-3.06	-5.31					-2.77
δD (‰)		-27.79	-38.29	-18.65	-29.04					-13.58

(*) AP-01 well - butyrate = 4.2 mg/l, malonate = 0.17 mg/l.

Table 3. Chemical (inorganic and organic) and isotopic composition of selected water samples from OSPER site B

Site Name	BA-01d	BA-01s	BA-02d	BA-02s	BA-03d	BA-03s	BE-03	BE-04	BE-06	BE-07	BE-08
Sample #	02OS-405	02OS-403	02OS-401	02OS-318	02OS-402	02OS-320	02OS-411	02OS-408	02OS-409	02OS-305	02OS-422
Date	06/10/02	06/10/02	06/10/02	02/26/02	06/10/02	02/26/02	06/11/02	06/11/02	06/11/02	02/21/02	06/12/02
pH	7.1	5.4	6.8	7.5	6.7	7.3	5.0			6.2	6.7
T (°C)	19	22	18	17	19	16	27	28	24	12	25
Li	0.11	0.010	0.19	0.22	0.13	0.19	<0.013	0.04	0.012	0.21	0.13
Na	1550	2080	831	1220	863	1410	2430	5640	1280	6800	2450
K	16	4.5	19	35	12	30	6	15	1.5	13	11
NH ₄ ⁺										10	
Mg	315	174	793	723	538	463	172	388	296	525	1430
Ca	410	509	433	416	477	399	564	1100	195	1410	794
Sr	16.2	17.7	7.0	7.4	12.2	9.9	22.3	51.2	4.0	78.3	15.2
Ba	0.023	0.60	0.010	0.055	0.010	0.042	1.3	1.8	0.46	14.2	0.046
Mn	1.8	21	0.057	0.38	0.20	0.79	25.2	36.0	25.7	89.3	3.5
Fe	<0.13	0.8	<0.13	<0.25	0.9	<0.25	<2.5	<0.25	<0.13	138	<5
Cl	2050	4660	1140	1540	999	1800	5090	12000	3150	14600	5690
Br	8.1	20.3	4.4	6.3	3	7.1	23	49	11	69	24
SO ₄	2420	99.0	3700	3910	3080	2840	61	76	96	15.7	4780
HCO ₃	424	33	1030	990	808	829	17			178	820
NO ₃	<0.4	<0.5	<0.2	0.3	<0.2	<0.1	<0.5	6	<0.5	3	<1
H ₂ S										0.9	
SiO ₂	16	16	15	16	16	19	11	12	13	8.6	<21
B	4.6	0.11	1.9	1.7	5.1	3.9	0.27	0.06	0.06	0.11	0.4
TDS	7245	7635	7990	8880	6840	7830	8430	19300	5080	24000	16000
DOC	1	8	12		1		8			28	8
Acetate	<0.04	0.9	0.03		<0.08		<0.04		<0.04	0.3	<0.04
Formate	<0.04	<0.04	<0.04		<0.2		0.05		0.06	0.4	<0.04
Succinate	<0.15	<0.08	<0.02		<0.1		<0.04		<0.15	0.08	<0.12
δ ¹⁸ O (‰)				-5.54		-5.52					-5.45
δD (‰)				-32.38		-32.08					-35.50

T, temperature; TDS, total dissolved solids; DOC, dissolved organic carbon; solute concentrations in mg/l; <, less than.

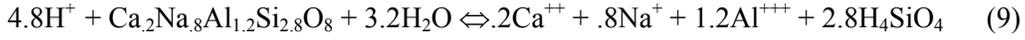
Table 3. Chemical (inorganic and organic) and isotopic composition of selected water samples from OSPER site B -- continued

Site Name	BE-09	BE-10	BE-11	BE-12	BE-13	BE-15	BE-16	BE-17	BE-18	BR-01d	BR-02d
Sample #	02OS-412	02OS-413	02OS-420	02OS-421	02OS-307	02OS-410	02OS-417	02OS-418	02OS-407	02OS-406	02OS-404
Date	06/11/02	06/11/02	06/12/02	06/12/02	02/21/02	06/11/02	06/11/02	06/11/02	06/11/02	06/10/02	06/10/02
pH	6.0	4.4	6.4	6.7	6.3	6.4	6.1	7.1	6.2	6.4	6.9
T (°C)	24	23	22	22	12	24	23	35	23	18	20
Li	<0.025	<0.025	<0.050	<0.050	0.01	<0.013	0.04	0.08	0.018	0.12	0.13
Na	3300	3060	4860	4000	3520	1180	2140	2030	2780	2360	1270
K	4	5	5	6	5.9	2	5.9	12	7.6	7.1	10
NH ₄ ⁺					3						
Mg	145	624	1140	1360	974	313	1360	1700	253	347	171
Ca	309	840	1140	1190	874	360	500	502	552	681	271
Sr	16.0	29.8	36.7	25.4	29.8	4.8	8.7	8.5	22.1	11.3	10.9
Ba	0.90	0.51	0.49	0.076	0.23	0.17	0.035	0.037	0.58	1.7	0.42
Mn	51.1	65.2	22.6	3.4	284	9.2	108	15.6	45.4	3.9	0.32
Fe	5	<5	<10	<10	116	<2.5	11	<2.5	32	<0.13	0.3
Cl	6300	8180	12500	10500	9900	3090	3130	2020	5800	5570	2460
Br	29	38	56	49	48	12	15	8	24	26	10
SO ₄	125	470	277	2520	583	385	6910	8860	290	96.6	353
HCO ₃	185	0	232	447	181	142	325	1260	275	252	493
NO ₃	<0.5	<0.5	<1	1.2	<0.5	4	<0.5	<1	<0.5	<0.5	<0.5
H ₂ S					1.8						
SiO ₂	<21	19	<43	<43	4.9	11	<21	15	11	31	15
B					0.04				0.16	0.13	5.2
TDS	10500	13300	20300	20100	17400	5500	14400	16400	10100	9380	5100
DOC	21		9	12	12	19	14	9	18	7	5
Acetate	<0.02	<0.04	<0.04	<0.04	0.6	<0.02	0.04	<0.1	<0.04	0.04	0.1
Formate	0.03	<0.04	<0.04	<0.04	0.7	0.04	0.05	<0.1	0.09	0.06	0.07
Succinate	<0.03	<0.04	<0.04	<0.06	0.04	<0.15	<0.2	<0.2	<0.04	<0.5	<0.02
δ ¹⁸ O (‰)											
δD (‰)											
					-5.12						
					-33.16						

Table 3. Chemical (inorganic and organic) and isotopic composition of selected water samples from OSPER site B -- continued

Site Name	EPA-1 well	injection pit	main pit	small pool at BA-01	large pool at BA-01	stream, at BA-01	Skiatook Lake near ACE	Skiatook Lake at BE-07	reinjection tank
Sample #	01OS-201	02OS-316	02OS-317	01OS-113	01OS-114	02OS-311	01OS-111	02OS-309	02OS-314
Date	12/11/01	02/25/02	02/25/02	03/13/01	03/13/01	02/22/02	03/10/01	02/22/02	02/24/02
pH	4.3	8.5	6.6	7.1	7.3	6.7	6.7	8.1	6.5
T (°C)	12.1	11	7	13	11	11	7	12	24
Li	2.9	1.1	1.4	0.015	0.002	0.029	0.002	0.002	8.5
Na	22700	12500	10600	1930	641	1190	14	21	40400
K	56	37	36	5.4	2.4	4.3	2.2	2.5	230
NH ₄ ⁺			20	<0.1	0.1				70
Mg	1250	444	442	56	57	129	5.0	6	1590
Ca	5270	2450	1980	288	173	333	20	23	7700
Sr	343	172	141	13.2	4.66	10.0	0.19	0.27	473
Ba	113	88.4	100	4.4	0.56	0.27	0.050	0.072	460
Mn	16.1	0.43	2.9	2.9	3.1	13.8	0.003	0.085	0.79
Fe	130	<1	40	<0.13	<0.05	17	<0.006	<0.01	35
Cl	52000	26200	21600	3560	1470	2550	25	39.7	82100
Br	227	124	100	13.0	6.3	12	0.11	0.20	328
SO ₄	12.3	5.1	11.2	9.2	22.5	271	10.0	11.6	2.5
HCO ₃	0	57	146	143	134	273	74	80	139
NO ₃	<2	<1.5	<1	<0.4	0.7	<0.15	0.8	0.7	<0.5
H ₂ S			0.4						<0.2
SiO ₂	<16.0	<6	4.6	2.0	4.0	8.8	2.8	1.5	<32
B	0.57	0.5	0.6	0.109	0.024	0.05	0.023	0.03	2.9
TDS	82100	42100	35300	6020	2520	4810	153	186	134000
DOC			43	14	9	4	4	4	5
Acetate	0.05		0.6	1.1	0.06				0.7
Formate	<0.08		0.3	0.1	0.2				0.3
Succinate	<0.1		0.06	<1	<0.4				<0.1
δ ¹⁸ O (‰)	-3.54	-2.44	-4.30	-5.23	-5.83	-5.79	-2.46	-1.75	-3.07
δD (‰)	-21.25	-26.45	-26.66	-31.50	-32.41	-37.70	-15.27	-13.66	-17.23

Table 4. Important water-mineral interactions at OSPER sites that modify the chemical composition of water from various sources.



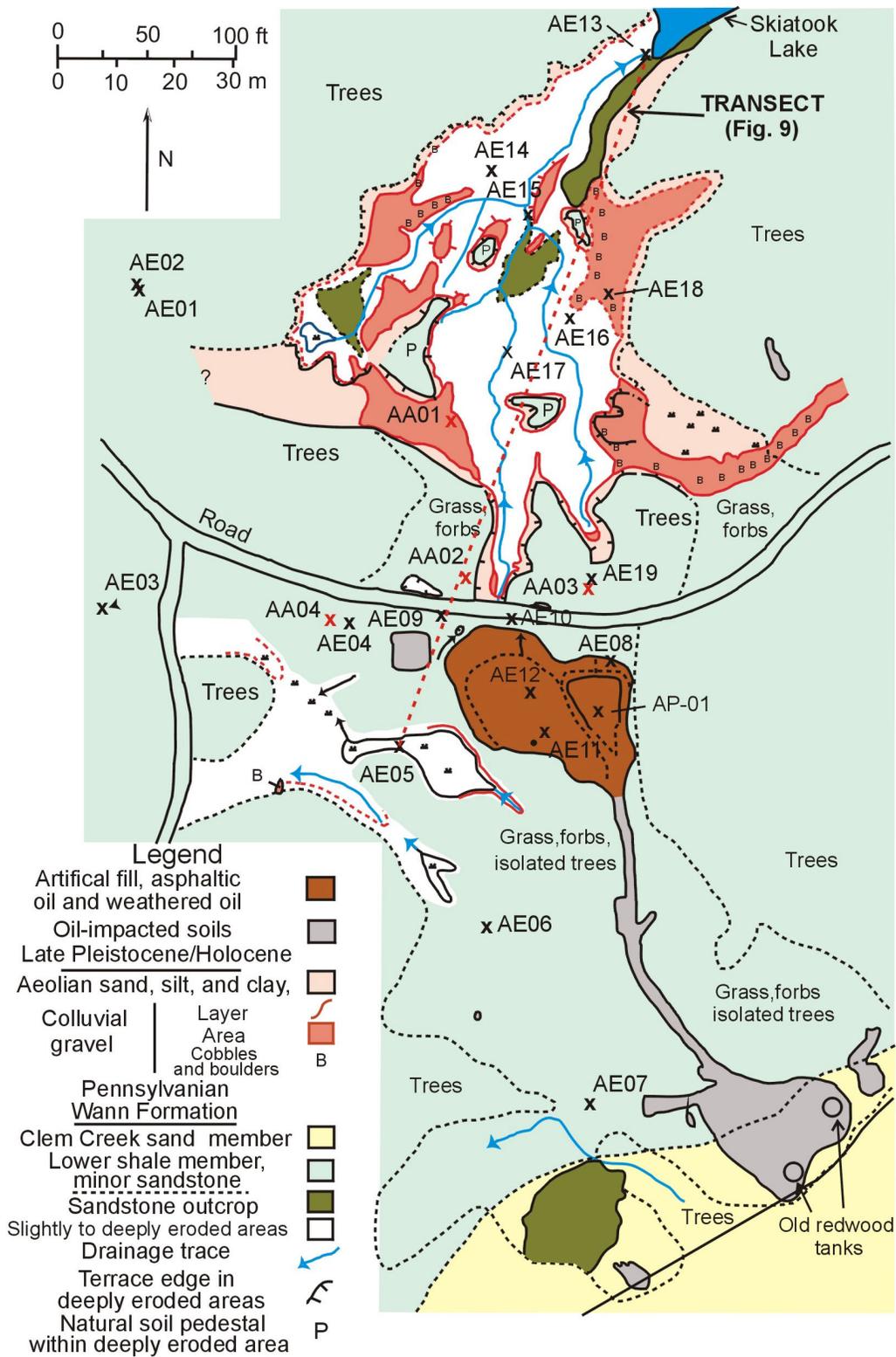


Figure 1. Geologic map of the OSPER 'A' site showing the locations of the oil pits, other production features, drilled water wells and outline of the impacted area.

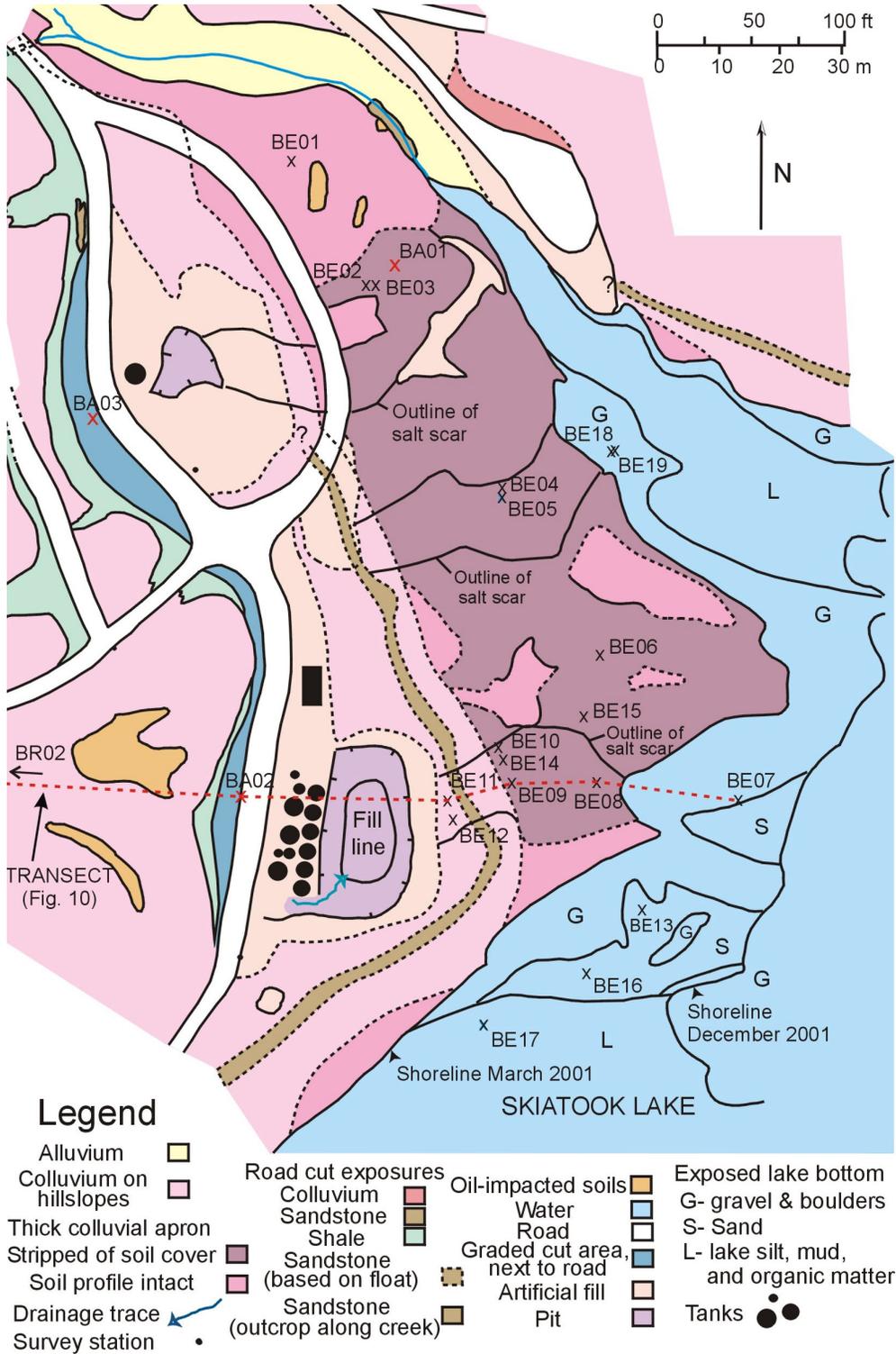


Figure 2. Geologic map of the OSPER 'B' site showing the locations of the large oil pit adjacent to the tank battery, the smaller pit at reinjection well, outlines of the three scarred and remediated areas, other production features, drilled water wells and several shorelines for the Skiatook Lake.

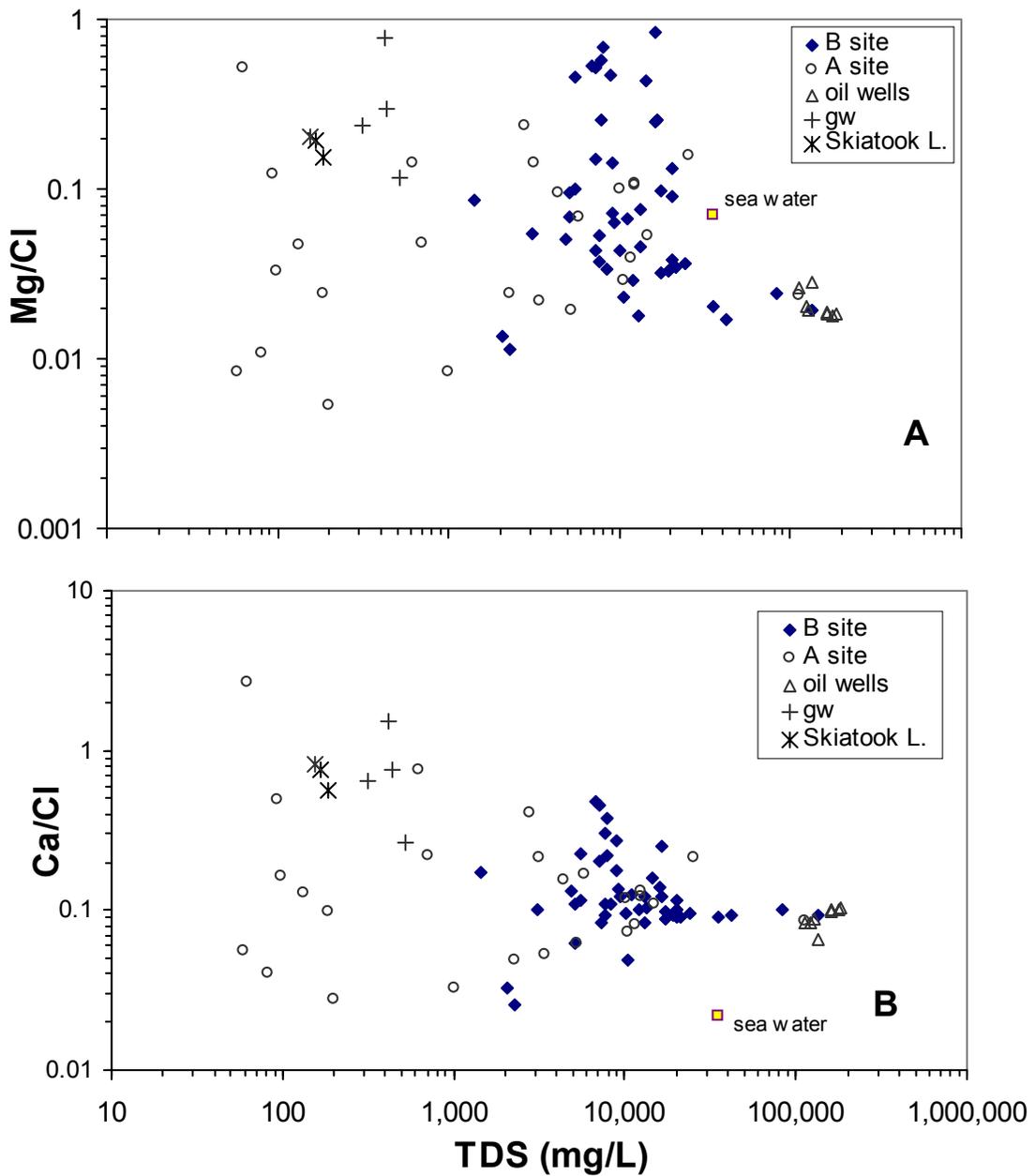


Figure 3. The Ca/Cl and Mg/Cl ratios as a function of water salinity for the oil-field brines, regional ground water (gw), Skiatook Lake and surface and ground waters from the impacted areas in the OSPER 'A' and 'B' sites. Note the generally lower ratios for the oil-field brines and diluted produced water.

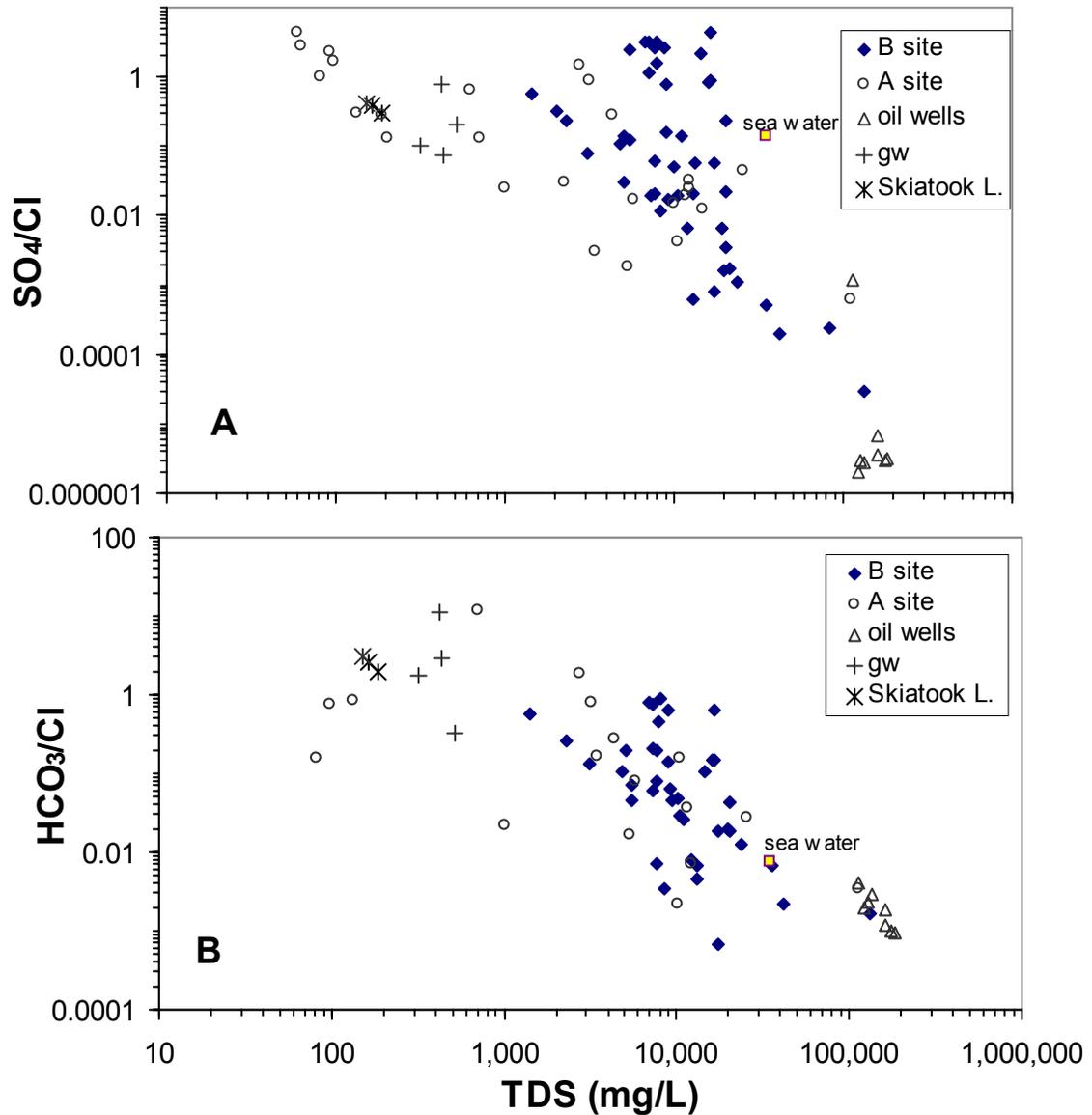


Figure 4. The SO_4/Cl and HCO_3/Cl ratios as a function of water salinity for the oil-field brines, regional ground water (gw), Skiatook Lake and surface and ground waters from the impacted areas in the OSPER ‘A’ and ‘B’ sites. Note the much lower ratios for the oil-field brines and diluted produced water.

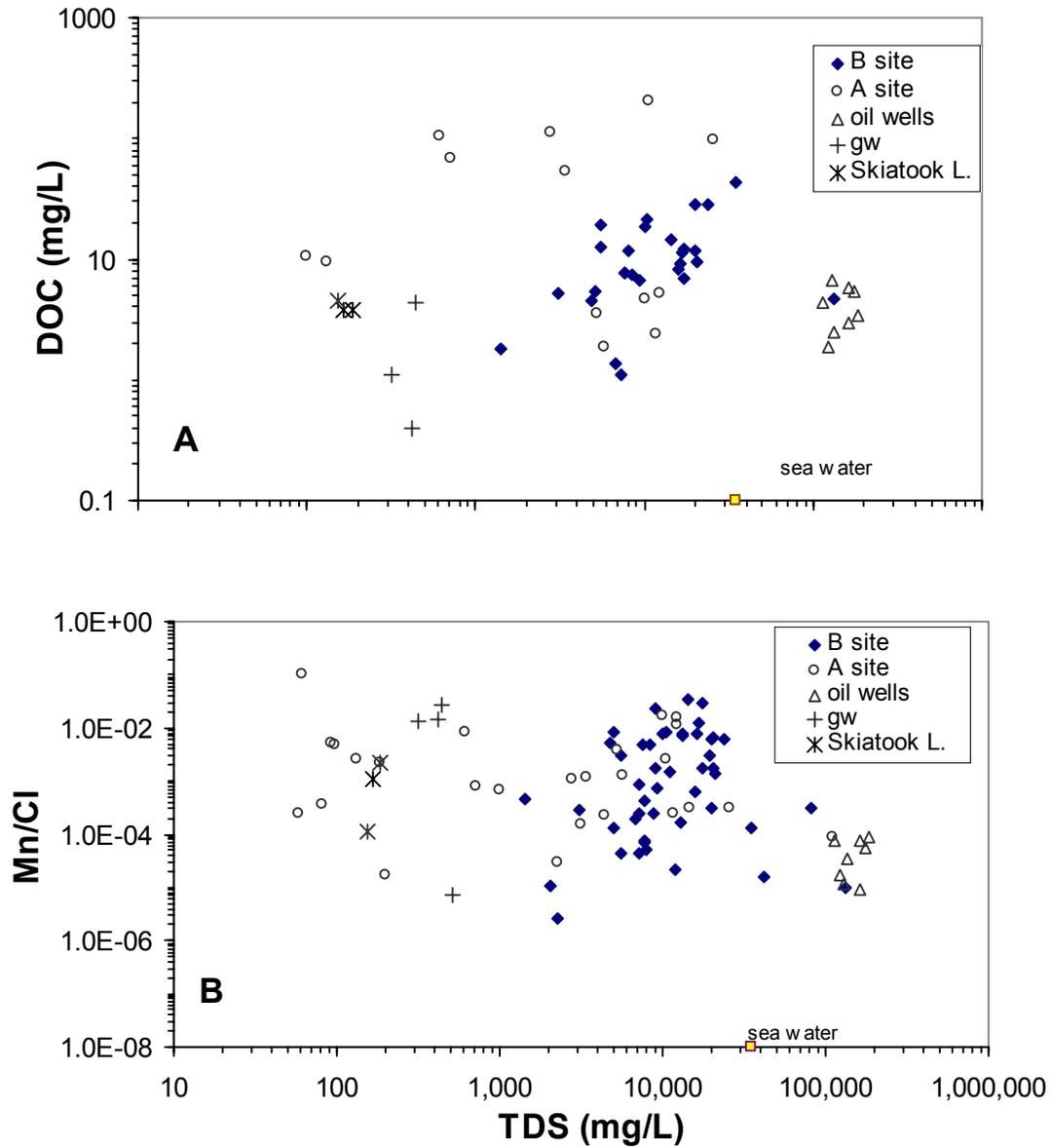


Figure 5. The concentrations of DOC and the Mn/Cl ratios as a function of water salinity for the oil-field brines, regional ground water (gw), Skiatook Lake and surface and ground waters from the impacted areas in the OSPER ‘A’ and ‘B’ sites. Note the much higher DOC and Mn/Cl values for ground water from the impacted wells, especially at the ‘A’ site.

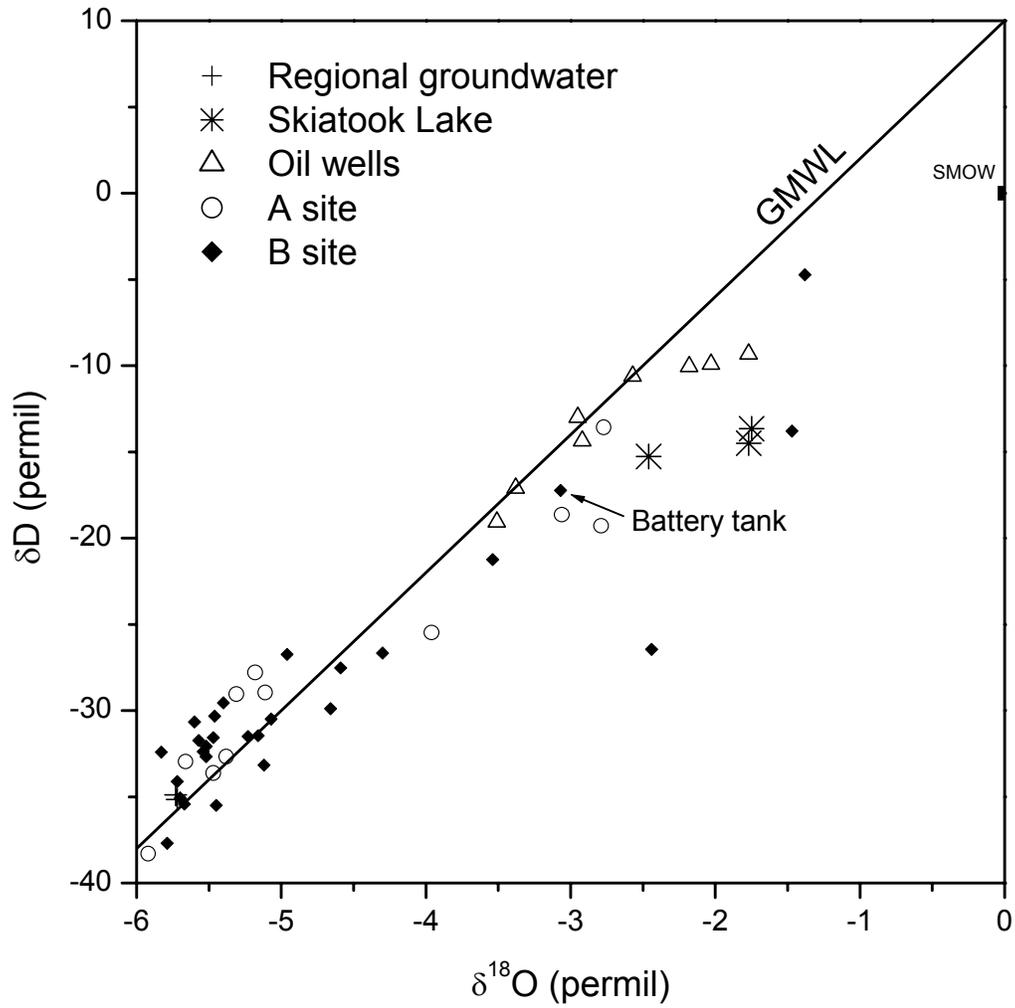
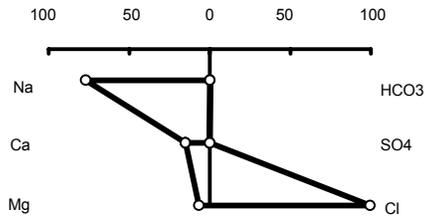


Figure 6. Isotopic composition of water for the oil-field brines, regional ground water (gw), Skiatook Lake and surface and ground waters from the impacted areas in the OSPER 'A' and 'B' sites. Note the major differences in the isotope values of the produced water relative to ground water.

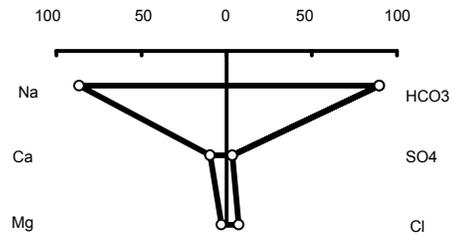
02OS-324 - AP-01 well

02/28/02 pH = 5.79 TDS = 111851 mg/l



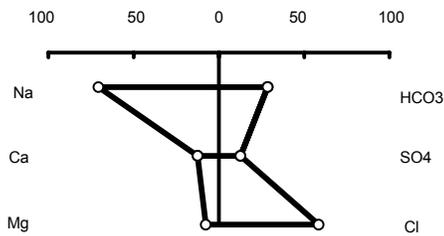
02OS-436 - AE-12

06/13/02 pH = TDS = 619 mg/l



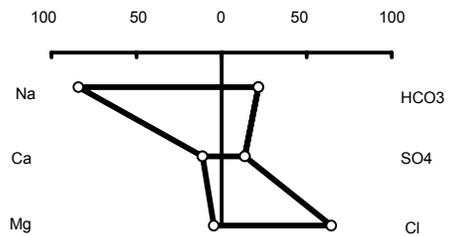
02OS-432 - AE-08

06/13/02 pH = 6.04 TDS = 131 mg/l



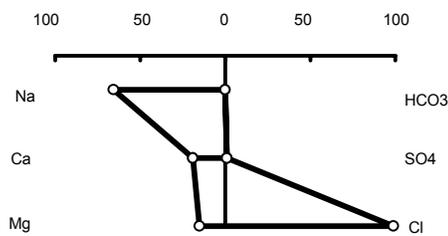
02OS-433 - AE-19

06/13/02 pH = TDS = 186 mg/l



02OS-437 - AE-15

06/13/02 pH = TDS = 14818 mg/l



02OS-431 - AE-13

06/13/02 pH = 5.63 TDS = 12302 mg/l

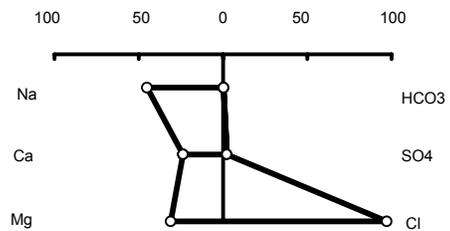


Figure 7. Modified Stiff diagrams showing the salinity of water and the relative concentrations (in equivalent units) of major cations and anions in a transect from the asphaltic pit to Skiatook Lake at the OSPER 'A' site.

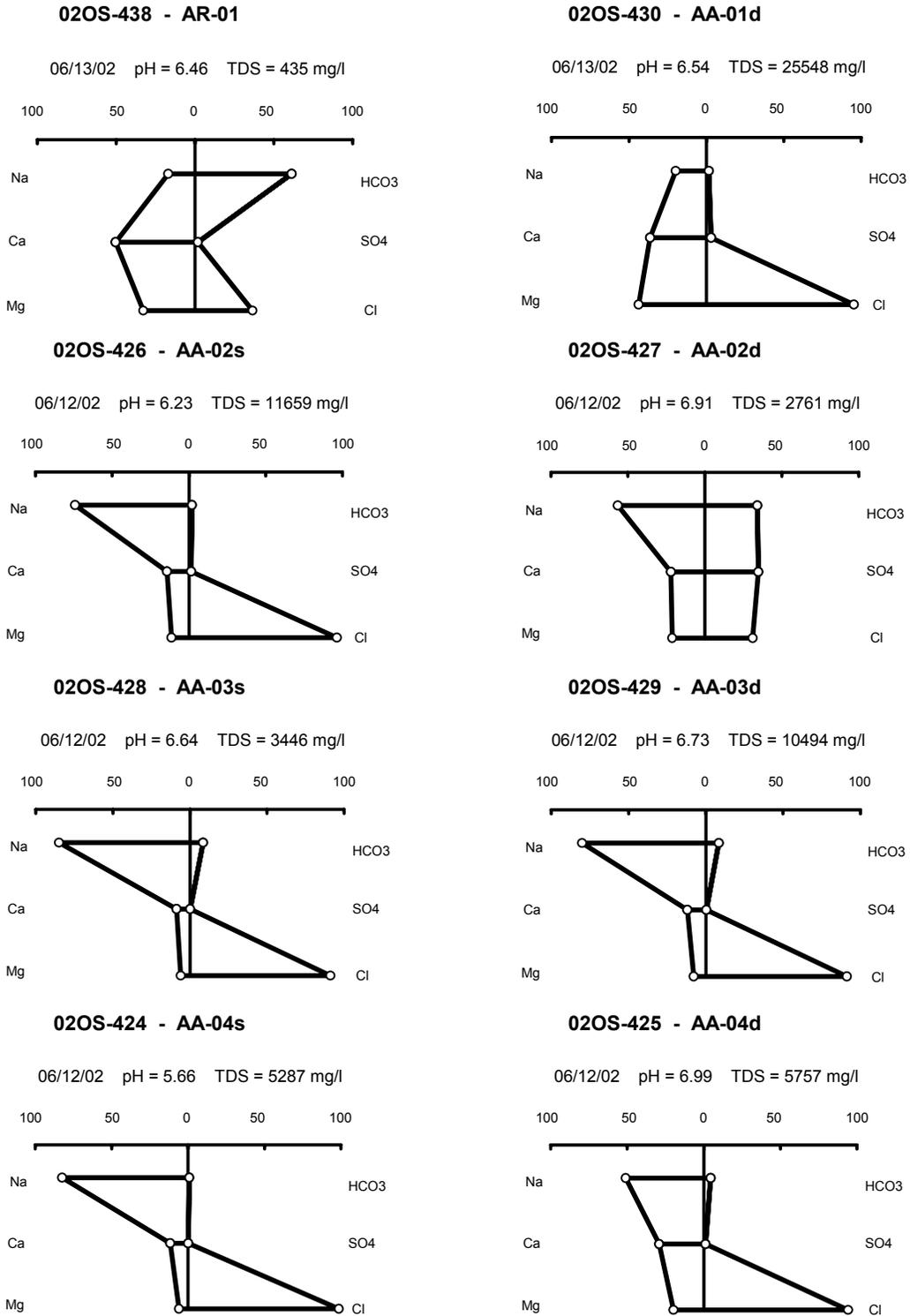


Figure 8. Modified Stiff diagrams showing the salinity of water and the relative concentrations (in equivalent units) of major cations and anions from the relatively deep rotary (AR) and auger (AA) wells in and near the OSPER 'A' site.

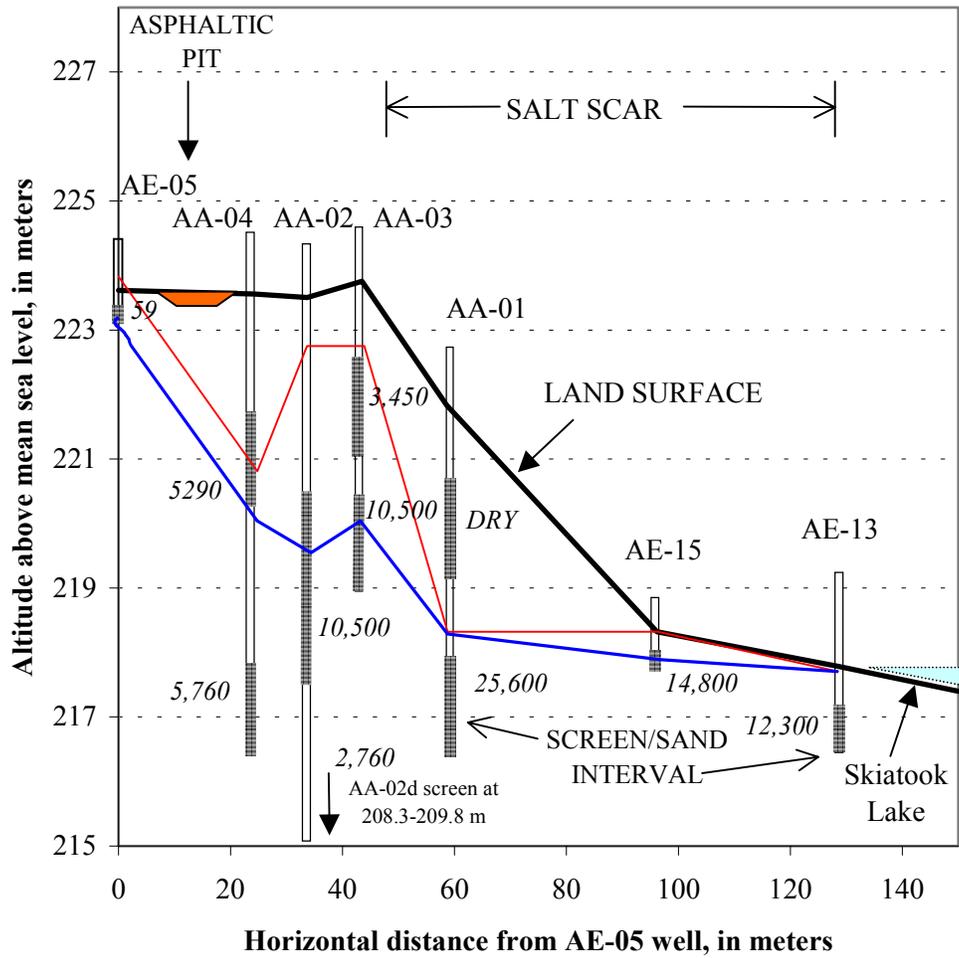


Figure 9. Water levels and salinity of water in wells along a transect from well AE-5 to AE-13, located in the littoral zone of Skiatook Lake at the OSPER 'A' site. A plume of relatively high salinity water is present at intermediate depths in wells located below the asphaltic pit.

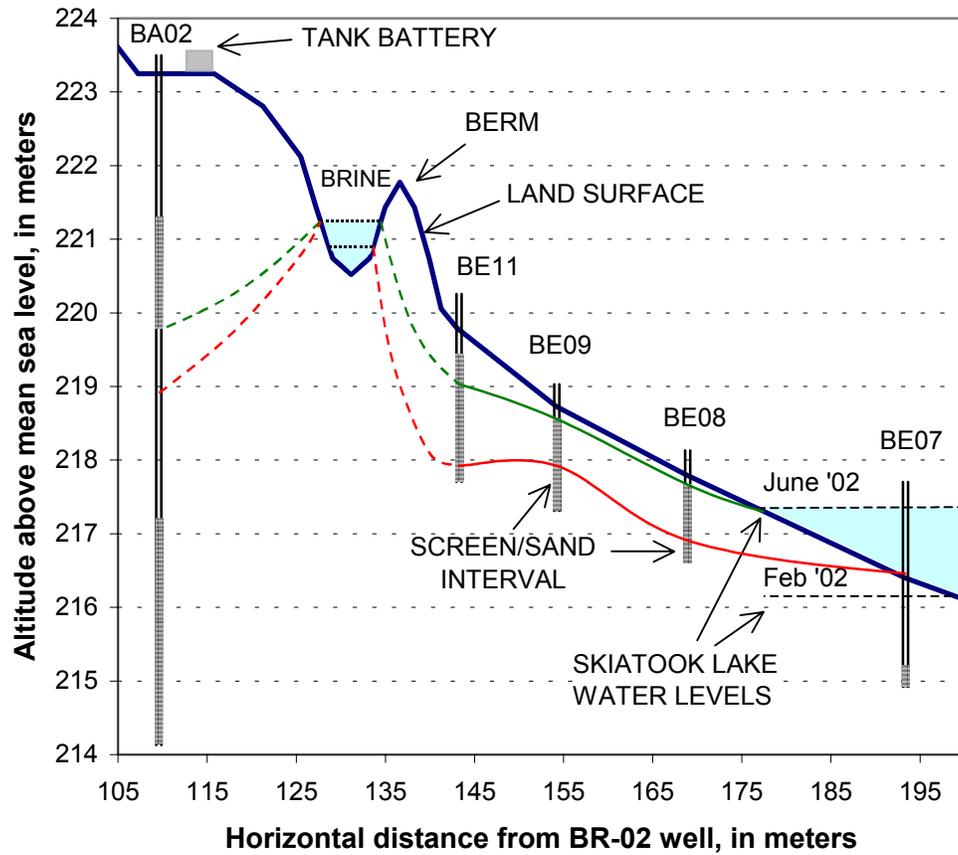
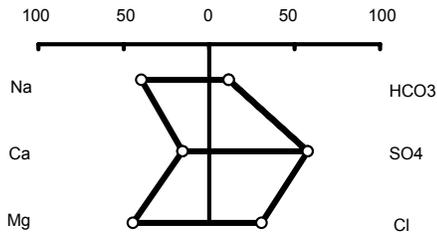


Figure 10. The high and low water levels measured wells in the transect A-A', from well BA-02 to well BE-07, located in the littoral zone of Skiatook Lake at the OSPER 'B' site.

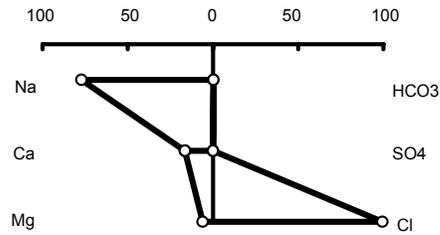
02OS-318 - BA-02 well (sh)

02/26/02 pH = 7.48 TDS = 8870 mg/l



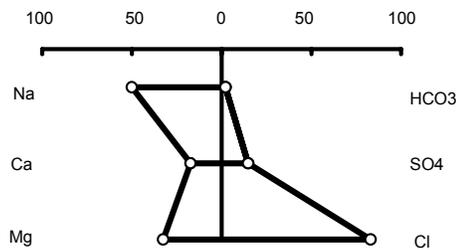
02OS-317 - main pit

02/25/02 pH = 6.62 TDS = 35241 mg/l



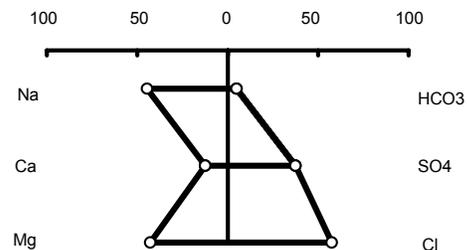
02OS-421 - BE-12

06/12/02 pH = 6.65 TDS = 20075 mg/l



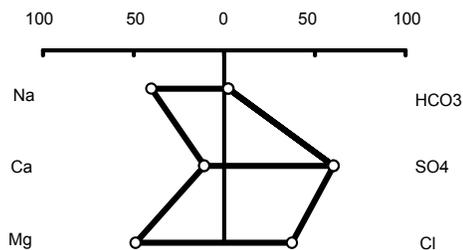
02OS-416 - BE-13

06/11/02 pH = 6.59 TDS = 16544 mg/l



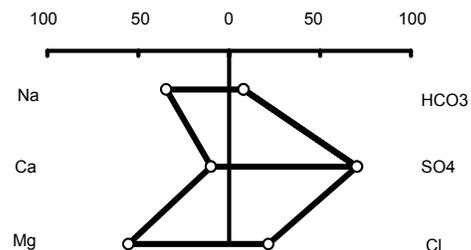
02OS-417 - BE-16

06/11/02 pH = 6.14 TDS = 14428 mg/l



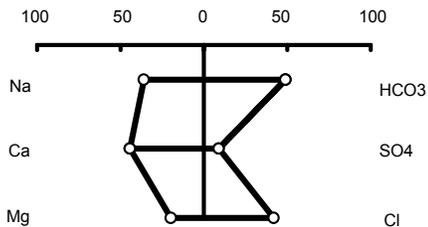
02OS-418 - BE-17

06/11/02 pH = 7.06 TDS = 16388 mg/l



02OS-309 - Skiatook Lake nr.BE-07

02/22/02 pH = 8.08 TDS = 186 mg/l



01OS-111 - Skiatook Lake nr. ACE

03/10/01 pH = 6.71 TDS = 153 mg/l

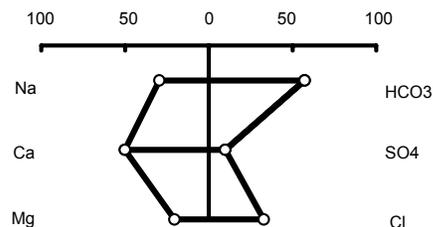
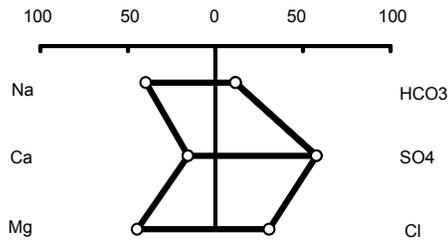


Figure 11. Modified Stiff diagrams showing the salinity of water and the relative concentrations of major cations and anions in a transect from the BA-02 well to well BE-07, located in the littoral zone of Skiatook Lake at the OSPER 'B' site.

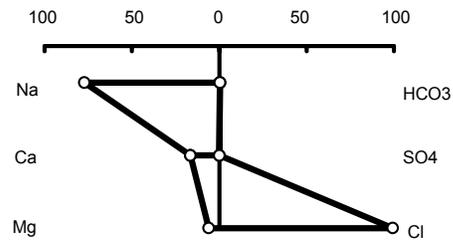
02OS-318 - BA-02 well (sh)

02/26/02 pH = 7.48 TDS = 8870 mg/l



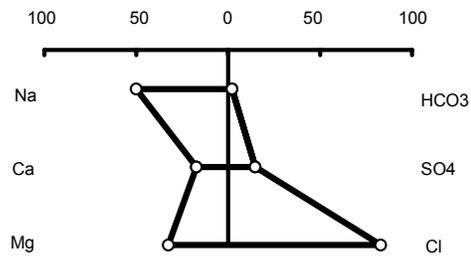
02OS-317 - main pit

02/25/02 pH = 6.62 TDS = 35241 mg/l



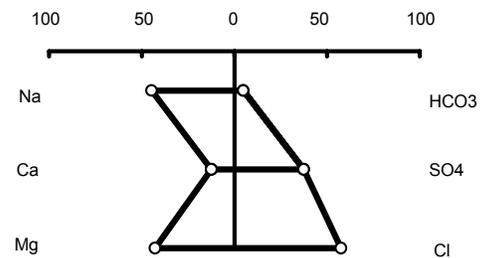
02OS-421 - BE-12

06/12/02 pH = 6.65 TDS = 20075 mg/l



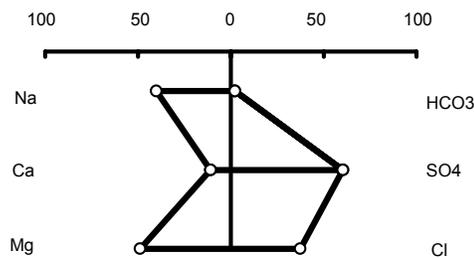
02OS-416 - BE-13

06/11/02 pH = 6.59 TDS = 16544 mg/l



02OS-417 - BE-16

06/11/02 pH = 6.14 TDS = 14428 mg/l



02OS-418 - BE-17

06/11/02 pH = 7.06 TDS = 16388 mg/l

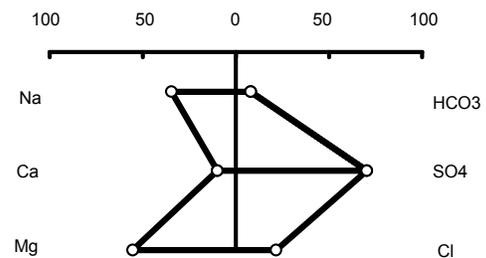


Figure 12. Modified Stiff diagrams showing the salinity of water and the relative concentrations (in equivalent units) of major cations and anions from the main brine pit and Geoprobe wells located to the southeast of this pit; the latter wells appear to have a mixture of produced water and local ground water.