TOPOGRAPHIC AND GEOLOGIC CONTROLS ON THE DISTRIBUTION AND MOVEMENT OF PRODUCED WATER AND HYDROCARBONS AT THE OSAGE SKIATOOK PETROLEUM ENVIRONMENTAL RESEARCH SITE "A"

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Topography, surficial geology, and bedrock geology exert critical control on the distribution and movement of released produced water and hydrocarbons on the landscape at the research site "A". Major point sources for NaCl-bearing produced water and for hydrocarbons at the site appear to be two adjacent pits in which these fluids were stored separately. The two pits sit near the crest of a northwest-trending drainage divide. The northeast sector drains northward into the Cedar Creek arm of Skiatook Lake and the southwest sector drains northwest, west, and then south into the main trunk of the lake. Although it was a primary source for contaminants within the site, a small tank battery upslope and a manmade channel between it and the pits were minor sources of releases to the sector southwest of the drainage divide. Colluvium and bedrock contaminated by produced water salt (NaCl) are remarkably widespread on the site in positions that are topographically below the level of the two pits. The outlet of the produced water pit drained to the north; thus, most salt water was apparently released in that direction. Seepage through pit walls and overflow from the pit probably transported some lesser amounts of salt into the drainage southwest of the divide. Surficial sediments composed of a permeable eolian sand surface layer (20 to 120 cm thick), permeable sandstone-clast-rich slopewash, and clayey to conglomeratic colluvial deposits overlie weathered bedrock (sandstone, clayey sandstone, sandy claystone, and shale). Pathways for produced water movement include 1) topographic lows on the contact between the permeable surficial deposits and the underlying less permeable bedrock units; 2) permeable conglomeratic facies in the colluvial deposits; 3) laterally discontinuous, clean sandstone units in the bedrock; and 4) fractures in bedrock. Shale and dolomite-cemented sandstone might have acted as aquitards. On the outcrop scale, produced waters and hydrocarbons followed permeable zones caused by vertical burrows in bioturbated sandstone. The burrows commonly have a bleached halo around them caused by the dissolution and movement of iron. At one site beneath a pit, hydrocarbon fills an individual vertical burrow.

THE CHEMICAL COMPOSITION AND DISTRIBUTION OF GROUNDWATER IMPACTED BY PETROLEUM PRODUCTION OPERATIONS: THE OSPER A SITE, OSAGE COUNTY, OK

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We are involved in a multidisciplinary investigation to study the transport, fate, natural attenuation and impacts of released petroleum compounds and inorganic salts in produced water at the Osage-Skiatook Petroleum Environmental Research (OSPER) A and B sites in Oklahoma. In this report, we summarize the impacts on the groundwater at the OSPER A site, where ~1.5 hectare of land has been affected by oil operations that started in 1913 and were largely terminated by 1937. Groundwater impacts are being investigated by repeated sampling of 35 wells (1-36 m deep), completed with slotted PVC tubing. The well locations were based on: (1) The presence of salt scars, excessive soil and rock erosion, brine and asphalt pits, degraded oil, dead trees and shrubs and other visible surface features; (2) results of electrical conductance, Cl, Br and SO_4 measurements on aqueous leachates from samples of shallow soil (0-15 cm), selected soil profiles (0.5-1.7 m) and core samples from prior drilled wells; and (3) results of shallow penetrating (<10 m) electromagnetic (EM) and deeper (30-60 m) DC resistivity surveys used to map the subsurface distribution of saline water, soil and bedrock.

Results of water analysis are in general agreement with those obtained from soil and core samples and the geophysical surveys. We are mapping a 3-D plume of high salinity water (5,000-30,000 mg/L TDS) with chemical and isotopic characteristics similar to those of the source produced water. The depth of this plume is not currently well defined; the one well that penetrates into a deeper aquifer has lower salinity (~2,000 mg/L TDS), but high Fe, Mn and dissolved organics. The horizontal plume boundaries are also not well delineated, since all wells deeper than 2 m at the site encounter the plume. A background well, drilled 0.6 km to the NW of the site has freshwater (450 mg/L TDS) and other characteristics of the pristine local groundwater, but also has relatively high dissolved organics, including BTEX. Results to date clearly show that large amounts of salts and organics remain in the local groundwater after more than 65 years of natural attenuation.

NATURAL REMEDIATION OF GROUNDWATER IMPACTED BY PETROLEUM PRODUCTION OPERATIONS: THE OSPER A SITE IN OSAGE COUNTY, OK

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The Osage-Skiatook Petroleum Environmental Research (OSPER) A site, located within the depleted Lester lease, has an area of about 1.5 hectare that is impacted by produced water and hydrocarbon releases that occurred primarily 65-90 years ago. In addition to groundwater contamination, impacts include salt scars, excessive soil and rock erosion, brine and asphalt pits, degraded oil, dead trees and shrubs and other visible surface features. Eventually, the bulk of inorganic salts and dissolved organic species will reach the adjacent Skiatook Lake, a 4250-hectare reservoir that provides drinking water to local communities and is a recreational fishery. Water samples from nearby oil wells indicate that the produced water source was a Na-Ca-Cl brine (~150,000 mg/L total dissolved solids), with relatively high concentrations of Mg, Sr, Fe, Mn and NH_4, but low concentrations of SO_4, H_2S and dissolved organics.

Results of detailed analysis of water samples, periodically obtained from 35 wells (1-36 m deep), were used to map a 3-D plume of high salinity groundwater (5,000-30,000 mg/L TDS) with chemical and isotopic characteristics that are similar to those of the produced water. These and future results will be used also to investigate the natural processes that modify the chemical composition of the plume-groundwater, including mixing with pristine groundwater and percolating water from precipitation, sorption, mineral precipitation/dissolution, evapotranspiration, volatilization and bacterially mediated oxidation/reduction reactions. The rate of salt removal from the site by surface runoff is being determined by measuring the volume and chemical composition of water flowing over a weir installed close to the Skiatook reservoir in a location that captures most of the surface and base flow from this site following precipitation. Results to date show that the natural salt-removal processes at this site are slow, thus providing a valid explanation for the fact that large amounts of salts from produced-water releases still remain in the groundwater plume after more than 65 years of natural attenuation.

TOPOGRAPHIC MAPPING USING GPS RECEIVERS AND GIS SOFTWARE AT THE OSAGE-SKIATOOK PETROLEUM ENVIRONMENTAL RESEARCH SITES IN OKLAHOMA

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Survey-grade Global Positioning System (GPS) receivers were used at the two Osage-Skiatook petroleum environmental research sites to obtain data for detailed topographic mapping. A real-time kinematic GPS method was used because it is stable, fast, and accurate (±1 centimeter horizontal, ±2 centimeters vertical).

The GPS antenna was mounted on a modified 2-meter measuring wheel because of its high mobility and to maintain a constant instrument height above the ground. The GPS receiver recorded data points every 1.5 meters along traverses of the sites. The traverses were initially spaced evenly across the sites. Traverses were then added where ground features, such as rapid slope changes, needed to be mapped. Approximately 8,600 data points were logged in 30 hours.

The data points were incorporated in a digital elevation model (DEM) using the ARC/INFO® GIS software. The software uses an interpolation method specifically designed for the creation of DEMs for comparatively small areas that have well defined elevation. The software assumes a surface drainage system model on the area. The software uses an iterative finite difference interpolation technique that has been modified to allow the fitted DEM to follow abrupt changes in terrain. This model of an assumed drainage condition produces more accurate surfaces with less input data. The program acts conservatively in removing closed low areas and will not impose the model of an assumed drainage in locations that would contradict the input elevation data.

The DEM grid-cell elevations were compared to known ground-level data across the sites for quality assurance and quality control. Sixty-nine grid cells were near control points. The mean difference between the grid cells and the control points was -2.4 centimeters and the interquartile range was -6.4 to +1.1 centimeters.

The DEMs were computed with a cell size of 0.6 meter. A smaller cell size did not illustrate closed depressions in the smaller pits at the B-site. The DEMs were used to produce topographic contour maps of the sites with a contour interval of 10 centimeters. These topographic maps will be used in contaminant-flow and sediment-erosion modeling at the research sites.

THE FATE OF PETROLEUM RELEASES FROM THE OSAGE-SKIATOOK PETROLEUM ENVIRONMENTAL RESEARCH (OSPER) SITES, OSAGE COUNTY, OKLAHOMA

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We are involved in a multidisciplinary investigation to study the transport, fate, natural attenuation and impacts of hydrocarbons, inorganic salts, trace metals, and radionuclides present in petroleum and produced-water releases at the OSPER A and B sites, located adjacent to the 4250-hectare Skiatook Lake, that provides drinking water to local communities and is a recreational fishery. More than one hectare of land at each site is affected by salt scarring, soil salinization and brine and petroleum contamination. Petroleum wells at the A site are inactive; the bulk of the hydrocarbon (now degraded and weathered oil) and produced water releases occurred 65-90 years ago. The B site includes an active production tank battery and adjacent brine and oil pit, an inactive tank battery and an injection well with a small brine pit. For this study, oil, soil, gas and/or water samples were obtained from several oil wells located at and adjoining the sites, from active pits at the B site, from inactive pits and surface accumulations at the A site and from several of the 60 boreholes, that are 1-71 m deep. Characterization of the resident microbial populations was completed for a number of these samples.

Results show that the local source oils are paraffinic-naphthenic light crude, containing n-alkanes as the dominant components. These oils, though obtained from shallow (300-600 m depth) sandstones, are not significantly impacted by biodegradation, probably because of the high salinity (~150,000 mg/L total dissolved solids) of the associated brine. The oils at the inactive A site are similar to each other although they do vary widely in stages of biodegradation. Some nearby oils at the active B site do not correlate with other site B oils, suggesting that there is not significant subsurface transport of the spilled oils. Microbial populations at both sites are degrading the water-soluble crude oil compounds. Concentrations of organic species, Fe, Mn, SO_4, and other geochemical evidence, and make-up of the microbial populations at both sites indicate that the systems are slightly different but based on free energy yields, are both poised at the level of iron reduction.

ELECTRICAL GEOPHYSICAL CHARACTER OF AREAS OF SHALLOW BRINE CONTAMINATION, OSAGE CO. OKLAHOMA

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Ground electrical geophysical surveys of areas where surface salt contamination has taken place indicate specific subsurface areas of very high electrical conductivity. These areas in part correspond to surface salt scars. Subsurface water and geochemical sampling indicates saline waters occur in a much wider area than indicated by surface scarring. Electromagnetic (EM) subsurface images help refine the areas of contamination and possible subsurface controls for distribution of saline waters. Shallow borehole natural gamma and electrical induction logs help constrain the interpretation of the ground EM surveys.

HYDROLOGY AND SUBSURFACE TRANSPORT OF OIL-FIELD BRINE AT THE OSAGE-SKIATOOK PETROLEUM ENVIRONMENTAL RESEARCH (OSPER B) SITE, OKLAHOMA

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As a part of a multidisciplinary study of the impact of oil wells and oil production on the environment, we are investigating the hydrology of the OSPER B site, which is located at Skiatook Lake in Osage County, Oklahoma. Salt and crude oil from oil well brine pits and accidental releases from oil-tank batteries have contaminated soil, ground water, and surface water at this site. Coring near a brine pit at the site showed that low permeability shale underlies 0.5-2 meters of surficial deposits (fill, soil, colluvium, and alluvium). The land slopes down from the pit at about a 1:10 slope to the lake, which is located about 20 meters from the pit. More than 40 shallow wells were installed at site B in order to enable periodic ground-water sampling for chemical analysis, to monitor water table elevations, and to delineate the subsurface contamination plume at the site. Five wells were instrumented with pressure transducers in order to continuously monitor water table elevation. Dielectric probes were installed to monitor soil water content. Probes were installed in the brine pit in order to continuously monitor pit water depth and electrical conductivity. A tracer test was carried out in order to estimate travel time from the pit to nearby observation wells. Results of computer simulations and field measurements indicate that subsurface brine flows slowly from the pit to the lake in a shallow saturated zone above the shale layer. Little brine has penetrated into the shale. In response to rainfall, the water table rises rapidly to the soil surface and runoff begins. Soil moisture content is very high at all times; there is little capacity to absorb rainfall, and recharge and mixing of rainwater with subsurface brine is limited. Breakthrough of tracer to observation wells was not observed, apparently because of very slow recharge through the pit bottom and high adsorption of rhodamine and fluorescein tracer in the surficial deposits.