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Leachate Generated by an Oil-and-Gas Brine Pond Site in North Dakota

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ABSTRACT

Two unlined ponds were used for holding and evaporation of brines produced with oil and gas at a well site in north-central North Dakota. The brine-evaporation ponds were in use from 1959 up to the late 1970s when they were backfilled and leveled. Continued salt-water migration at this site since closure has decreased crop yields in surrounding fields and has killed trees in a shelterbelt within an area of approximately 10 acres.

An apparent resistivity survey delineated a 360,000-ft^2 area of extremely low resistivity. Isoconcentration maps indicate that a highly saline leachate plume extends laterally in a 500-foot radius around the ponds and vertically to a depth of 70 feet below the surface.

Ground-water recharge at this site is low because of the semiarid climate and the low hydraulic conductivity of the near-surface sediments and, as a result, very little flushing of the brine from the sediment beneath the ponds has occurred. Pore water within the unsaturated zone beneath the reclaimed ponds contains essentially the same ionic concentrations as that of brine impounded in these pits 10 to 25 years ago.

Based upon the results of this research, we estimate that brine leachate will continue to migrate at slow rates from this site for tens and possibly hundreds of years if no action is taken. The construction of a mound over the site and/or an infiltration gallery around the perimeter would minimize the spread of brine and make it possible to return this land to production in the foreseeable future.

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INTRODUCTION

Brines typically are produced along with crude oil at oil-well sites. These brines are recognized as the major source of potential environmental contamination associated with oil production (Knox and Canter, 1980). The issue of how to properly dispose of oil-field brines has been considered in the State of North Dakota since oil production first began in 1951. North Dakota has benefited from the experiences of earlier oil-producing activities in other states and avoided problems such as the direct dumping of brines into streams which occurred in Illinois in the 1930s (Reed *et al.,* 1981).

As early as 1932, it was recognized in Kansas that brine-holding facilities were causing serious environmental problems (Grandone and Schmidt, 1943). However, clear documentation of the problems associated with surface brine disposal did not appear in the literature until the 1960s. Many of these 1960s studies document the decline in surface- and ground-water quality around producing oil fields (Krieger and Hendrickson, 1960; Shaw, 1966; and Boster, 1967). A number of studies over the last 20 years have focused upon the rate of movement of the brine plumes, the length of time needed for the natural restoration of water quality in a degraded aquifer, and the cost effectiveness of different methods of disposal-site and aquifer reclamation (Boster, 1967; Pettyjohn, 1973; Fryberger, 1972; Baker and Brendecke, 1983). The purpose of our study was to document brine migration within a unit of low hydraulic conductivity and to suggest methods of site reclamation.

Initially, salt water at North Dakota drilling sites was primarily disposed of in evaporation ponds and injection wells. These ponds were so

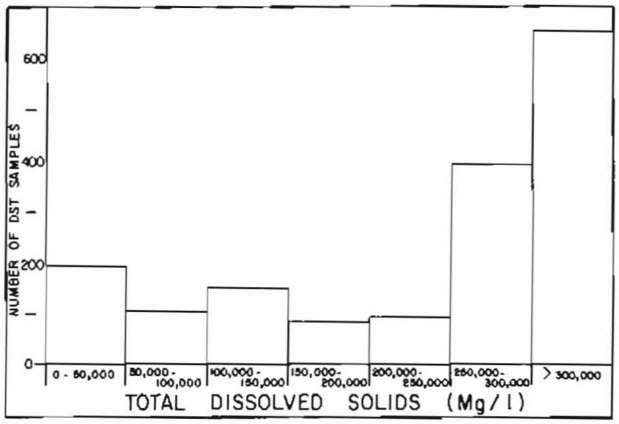

Fig. 1. Total dissolved solids concentration in Williston Basin brines.

named because it was believed that all of the salt water in these brine-holding ponds evaporated. The ponds were generally unlined, and ranged from dimensions of 45 × 60 feet up to 90 × 180 feet with depths of 4 to 9 feet. The ponds received brine at rates varying from ½ to 420 barrels per day.

The cumulative production of oil in North Dakota, during the period from 1951-1986, was 889,985,722 barrels. Salt-water production during this same period was 955,694,692 barrels. The ratio of crude oil-to-brine production varies significantly from well to well and will generally increase over the life of a given well. The chemistry of subsurface brines varies widely between and within geologic formations in the Williston Basin of North Dakota. However, chemical analyses of 1,956 oil-field drill-stem tests have demonstrated that the majority of brines within the Basin are characterized by TDS concentrations of greater than 250,000 mg/l; 12 percent of the brines contain less than 50,000 mg/l of TDS (Figure 1).

In 1969, the North Dakota Geological Survey began to require permits for all salt-water-handling facilities. During the period from 1969 to 1981, 206 permits for evaporation ponds were issued. The total number of evaporation ponds that operated within the State prior to 1969 is unknown. Brine-holding ponds are no longer allowed to operate within the State of North Dakota. Therefore, current environmental concern is no longer focused on active ponds, but rather is now focused on abandoned brine-holding ponds. Migration of brine from these abandoned ponds had been recognized as a potential source of soil degradation and surface- and subsurface-water contamination. The salt that remains in the pond sites after they have been leveled will generate leachates at a rate dependent upon the local precipitation, topography, and the hydraulic conductivity of the near-surface sediments.

In order to evaluate the long-term impacts of brine ponds, a reclaimed brine-holding pond site was chosen for study within the Wiley Field near the town of Maxbass in Bottineau County, North Dakota (Figure 2). This site was chosen because of obvious salt damage to crops and a shelterbelt adjacent to the pond site and because it was representative of many pond sites in North Dakota. The oil well at this site was drilled in 1959 and produced until 1970; it was later converted to a salt-water disposal well (Stratton SWD #1) by Phillips Petroleum in 1978. Two brine-holding ponds were located at this site from 1959 through at least 1976 (Kallestad, personal communication, 1986). The amount of brine that was disposed in these ponds during that 17-year period is not known.

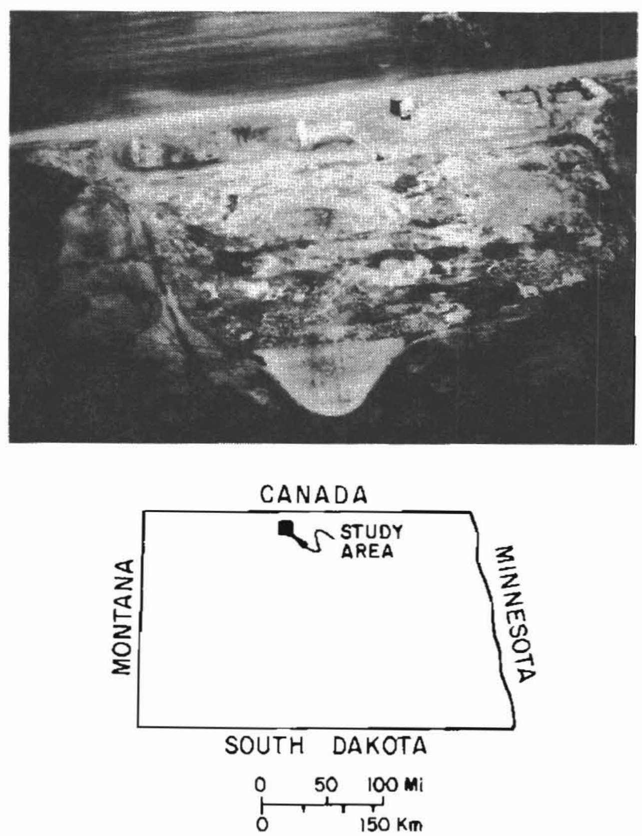

Fig. 2. Oblique aerial photograph of the study site and study site location map (photo taken June 1984 by John Foss).

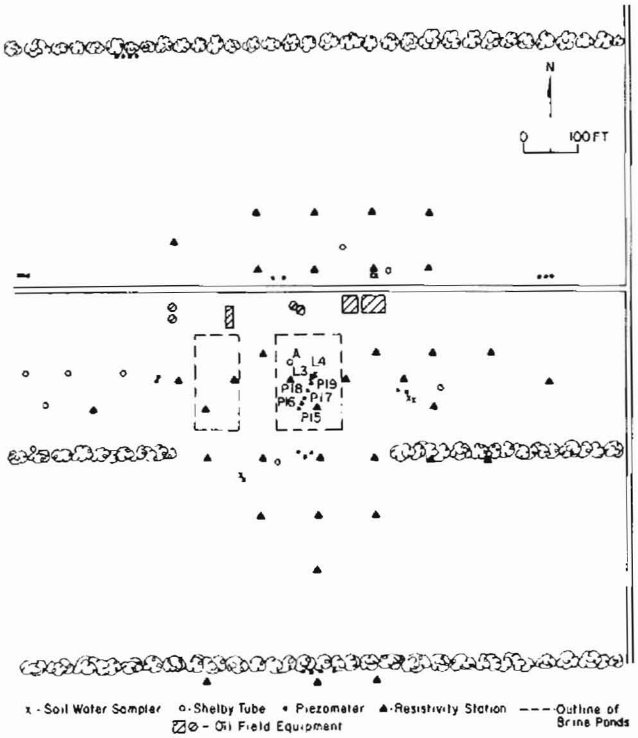

Fig. 3. Locations of earth resistivity survey stations, pore-water and ground-water sampling equipment, and Shelby-tube holes at the study site.

FIELD METHODS

An electrical earth resistivity survey, using the Wenner electrode configuration, was conducted at the Stratton SWD #1 site during June 1984. The Vertical Electrical Sounding method (VES), which was used at this site, involves a fixed center of the electrode array (resistivity station) and expansion of the electrodes about this point. Thirty-six resistivity stations were surveyed in and adjacent to the brine pits (Figure 3). Readings were taken at successive electrode spacings ("a") of 3, 5, 8, 10, 12, 16, 20, 24, 30, 40, 50, 60, 80, and 100 feet. The results of the earth resistivity survey were used to determine placement of the ground-water and pore-water monitoring instruments.

Shelby-tube sediment samples were taken using the North Dakota Geological Survey's truck-mounted, hollow-stem 8-inch auger. A total of 198 feet of Shelby-tube sediment core was retrieved from 10 holes drilled within and adjacent to the brine ponds (Figure 3). The maximum coring depth reached was 32.5 feet.

Eight pressure-vacuum lysimeters (soil-water samplers) (Soil Moisture Equipment Corp. Model 1920) were used to obtain water samples from the unsaturated zone. These were installed in pairs at depths of 4 and 9 feet. Twenty-eight piezometers were installed (Figure 3) to provide water samples from within the zone of saturation and to determine the elevation and gradient of the water table. Single well response tests (slug tests) were also performed to estimate the hydraulic conductivity of the sediment adjacent to the screened interval (Hvorslev, 1951). The piezometers were screened within four general zones: at depths less than 40 feet, between 40-55 feet, between 70-80 feet, and at 160 feet. One piezometer was installed in the Fox Hills Formation, which lies beneath the Pleistocene drift. Where possible, rotary-rig borings were drilled with air. When this proved difficult, fresh water was used and, where necessary, a bentonite mud fluid was used. In order to minimize the effects of the bentonite drilling mud, these piezometers were backwashed with fresh water injected by the drill-rig pumps until they flowed relatively clear water (approximately 20 minutes).

Water samples were collected on December 9, 1984, and June 12, 1985. The first set of samples was analyzed for both trace-metal and major-ion content, and the second set was analyzed only for majors. Temperature, pH, and electrical conductivity of the water samples were determined in the field at the time of sample collection. A minimum of two volumes of water was removed from each piezometer prior to sampling.

The ground-water and pore-water chemistry were determined by the Chemistry Department Laboratory of the North Dakota State University. Selected portions of the Shelby-tube sediment samples were also analyzed for major ion content by saturated paste extract at the North Dakota State University Land Reclamation Research Center Laboratory. The lab procedure used is described in Sandoval and Power (1977).

GEOLOGY AND GEOHYDROLOGY OF THE SITE

The Stratton SWD #1 site is situated upon approximately 220 feet of Pleistocene till which overlies the Cretaceous Fox Hills Formation (Figure 4). Surficial deposits in the area consist of Pleistocene sediments of Late Wisconsinan Age, including till, glaciofluvial, and glaciolacustrine units. Topographically, the site lies upon a low relief, hummocky till plain.

The till at this site is a mixture of clay, silt, sand, pebbles, cobbles, and boulders. The mean grain-size percentages of 66 till samples from this site are: sand 35.6%, silt 37.9%, and clay 26.5%. Numerous sand and gravel zones, with thicknesses

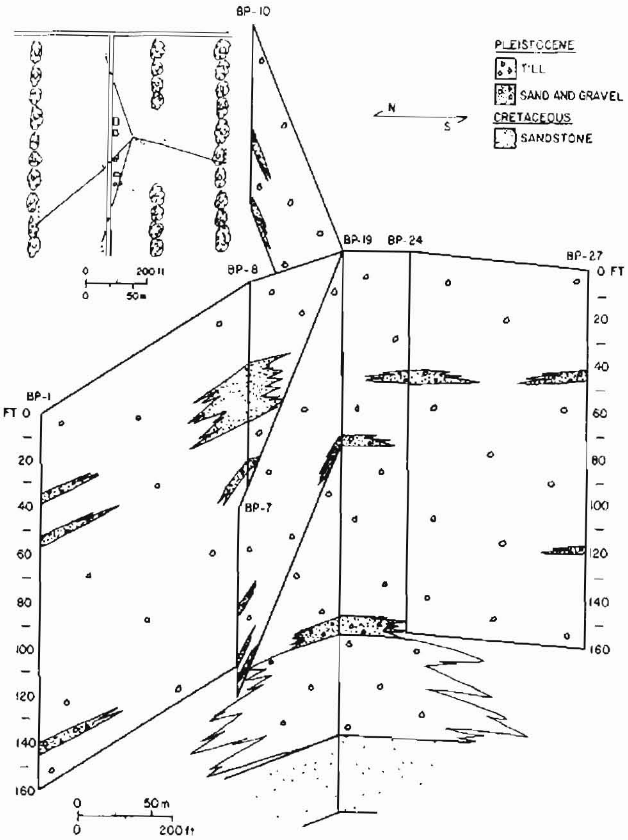

Fig. 4. Geologic fence diagram of the study site.

of 5-15 feet, were encountered within the till. These zones could not be traced between boreholes and therefore appear to be discontinuous lenses (Figure 4).

Glacial drift in the vicinity of the study site is an aquitard and, therefore, there are no farm wells completed within either the till or the discontinuous sand and gravel lenses. However, numerous unconfined and confined aquifers occur in surficial or buried glaciofluvial deposits throughout the region. The Stratton well (SWD #1) is situated near the northern extent of one of these major glaciofluvial aquifers (Randich and Kuzniar, 1984), although this aquifer was not encountered during our drilling project. The underlying Fox Hills Formation is the most extensive bedrock aquifer system in north-central North Dakota and commonly is the only aquifer system that yields sufficient quantities of water for domestic or stock use (Randich and Kuzniar, 1984).

The water table, which lies at a depth of approximately 17 feet is mounded below the brine ponds to within 10 feet of the surface. Mound boundaries may extend as far as 500 feet beyond the ponds and may be affecting the water levels in all of the shallow piezometers. It is difficult to determine the direction of ground-water flow in the study area due to the local effects of the ground-water mound.

The slug-test results gave a range of hydraulic-conductivity values of 1.6 to 3.2×10^{-6} ft/s with a mean of 2.4×10^{-6} ft/s for the glacial drift. Sediment-core observations indicate that the till is highly fractured. Presumably, these fractures have a significant effect upon the bulk hydraulic conductivity of the till unit.

APPARENT RESISTIVITY

An area of low resistivity measuring approximately 360,000 ft^2 was delineated at all of the "a" spacings down to 100 feet around and beneath the brine ponds (Figure 5). The resistivity values increase radially from the pits.

The ratio of depth-to-electrode spacing using the Wenner electrode configuration is approximately 1:1 for an isotropic, homogeneous medium. Electrode spacing and depth of current penetration are sometimes considered to be equal, especially for electrode spacings of less than 100 feet (Soiltest, 1968). However, the presence of sedimentary layers with greatly differing resistivities and/or saline pore water has been shown to distort the electrical field and reduce the depth of current penetration (Reed *et al.*, 1981). In this study, the current may have been concentrated in

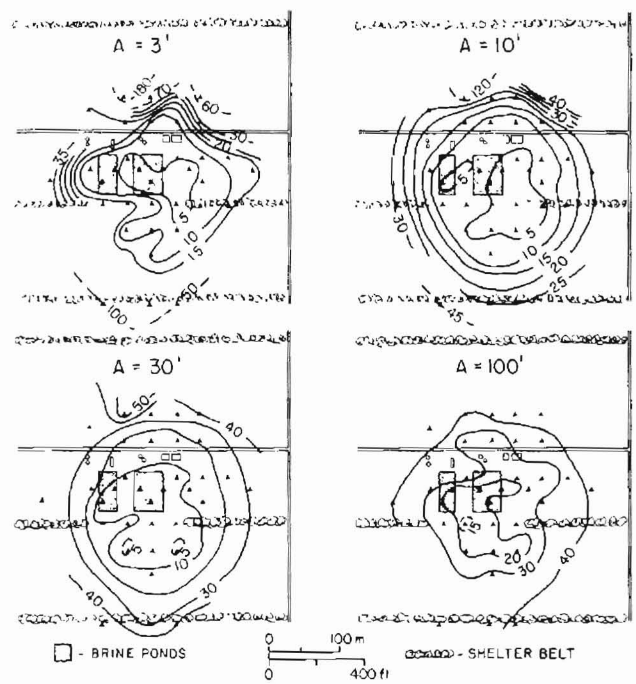

Fig. 5. Apparent isoresistivity maps (ohm-ft) of the study site for electrode spacings of 3, 10, 30, and 100 feet.

Table 1. Chemical Composition (mg/l) of Brine from Wiley Field and Selected Lysimeters (L-3 and -4) and Piezometers (P-15 to -19) at the Study Site. The Interval Is the Depth of the Lysimeters or the Depths of the Piezometer Screen. Piezometer and Lysimeter Data from Samples Taken on 6/12/85

Well or Sample	Interval (ft)	Temp °C	pH	TDS	Ca	Mg	Na	K	HCO_3	SO_4	Cl
Wiley High	-	20	7.1	268,036	5,510	2,310	96,823	-	440	3,634	163,000
Wiley Low	-	20	5.3	21,287	1,348	302	6,141	-	82	1,102	10,250
Mean	-	20	6.3	182,414	4,338	1,298	64,535	-	227	2,132	109,686
L-3	4		6.5	214,470	5,597	1,923	60,766	1,652	212	759	119,920
L-4	9		6.6	100,590	2,542	2,082	32,143	403	412	1,263	67,760
P-15	25-35		6.5	127,490	5,517	1,546	35,764	621	222	1,895	75,390
P-16	35-40		6.8	50,010	3,727	588	8,008	146	343	2,040	20,871
P-17	76-81		7.4	2,670	86	172	445	12	465	1,112	158
P-18	156-161		7.6	2,590	91	146	467	11	469	682	579
P-19	215-220		8.0	3,290	22	34	1,118	9	560	6	1,512

the zone of lowest resistivity which is the highly concentrated brine in the near-surface. This hypothesis was supported by the failure of two-thirds of the apparent resistivity soundings to be interpreted by the resistivity program developed by Zohdy and Bisdorf (1975). This program calculates layer thicknesses and resistivities but cannot interpret VES curves that exceed a slope of 45°. Interpreted resistivity data could be obtained by this program for only 11 of the 36 resistivity stations. These stations are all located along the edges of the grid, which indicates that the current at the interior stations was greatly affected by the near-surface brine. Therefore, the interpreted resistivity data were not useful in our study. Although evidence suggests that at least a portion of the current is not reaching a depth equal to the electrode spacing, the results of the apparent resistivity survey were useful in delineating the lateral extent of brine movement and guiding the placement of ground-water instrumentation.

GROUND-WATER CHEMISTRY

Unsaturated zone water at a depth of 4 feet below the reclaimed brine-pond surface (L-4, Table 1) is chemically very similar to the mean concentrations of brines produced from the Wiley Field (Table 1). The exception to this is the generally lower sulfate concentrations in the pore water at the site in comparison to the brine. This may be the result of removal of sulfate from the aqueous system by the precipitation of gypsum ($CaSO_4 \cdot 2H_2O$) in the unsaturated zone. Large concentrations of gypsum crystals were observed in Shelby-tube sediment cores from the unsaturated zone. A parallel reduction in the calcium concentrations within this same interval is not evident. This is assumed to be due to the release of Ca^{++} by cation exchange as Na^{+} is adsorbed onto the smectitic clays.

Pore water at a depth of 4 feet in the reclaimed pond has essentially the same chemistry as that of the brines disposed of in the pond 10 to 25 years ago (Figure 6). Apparently, minimal

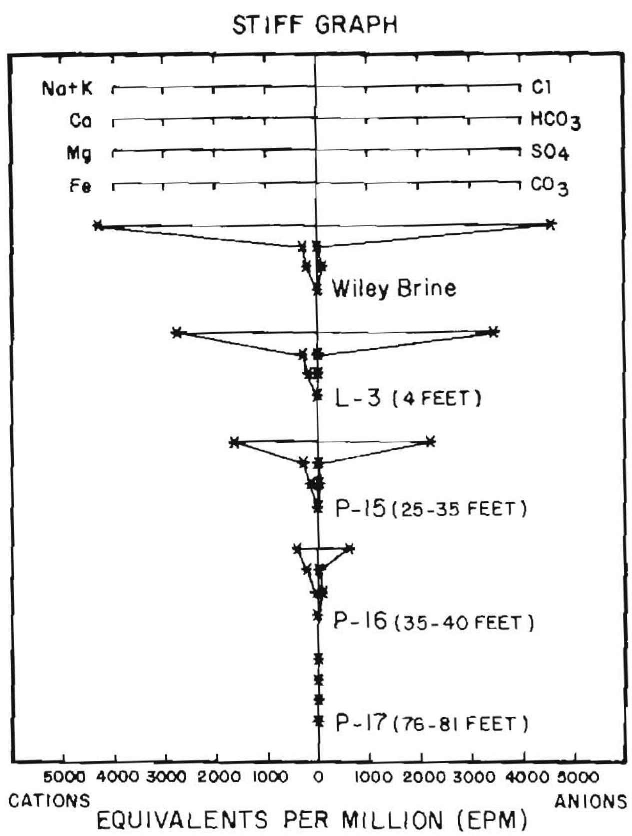

Fig. 6. Stiff diagrams of a Wiley Field brine (Wiley) and pore water (L-3) and ground water (P-15, P-16, and P-17) beneath the brine ponds.

flushing has occurred in the shallow subsurface at the site. The semiarid climate in this region generally results in few major recharge events per year (Rehm *et al.*, 1982). In addition, this water is restricted from moving through the subsurface by the reduction of sediment permeability as a result of the exchange of sodium from the brine to the clays.

The high ion concentrations in the pore water may also result from the original evaporative concentration of salts at the base of the pond. Although salt was observed macroscopically throughout the sediment cores, it did not occur in a concentrated layer in the unsaturated zone. These sediments may have become supersaturated with salts because of the evaporation of the brine and now constitute a source of leachate when fresh water infiltrates from the surface.

Chemical analyses of ground-water samples from the study site define a brine-generated leachate plume that extends laterally beneath an area of 250,000 ft^2 around the brine ponds. This plume extends down to a depth of approximately 70 feet (Figure 7). An area of high chloride that occurs at a depth of 160 feet beneath the pond

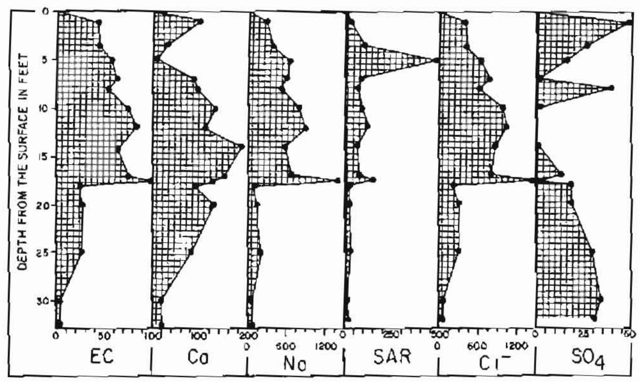

Fig. 8. Ionic concentration profiles from sediment samples beneath the brine ponds (Shelby Tube Hole #A).

appears to be the result of upward leakage from the Fox Hills Formation. The Fox Hills Aquifer in this area contains naturally occurring Cl^- concentrations of up to 4000 mg/l in this area (Kuznair and Randich, 1982).

The movement of salts in the subsurface is further documented by analysis of sediment from beneath one of the brine ponds (Hole No. A, Figure 3). A sharp decrease in the Na^+ and Cl^- ion concentrations occurs at a depth of 18 feet (Figure 8). This depth corresponds to the color contact between oxidized and unoxidized till and is assumed to represent the water-table position prior to mounding caused by fluid disposal in the ponds.

This reduction in Na^+ and Cl^- ion concentrations may be due to the initial greater movement of leachate through the unsaturated zone. The alternate wetting and drying in this zone promotes greater fracture permeability in contrast to below the water table where the expansion of saturated smectitic clays decreases fracture permeability and reduces leachate movement.

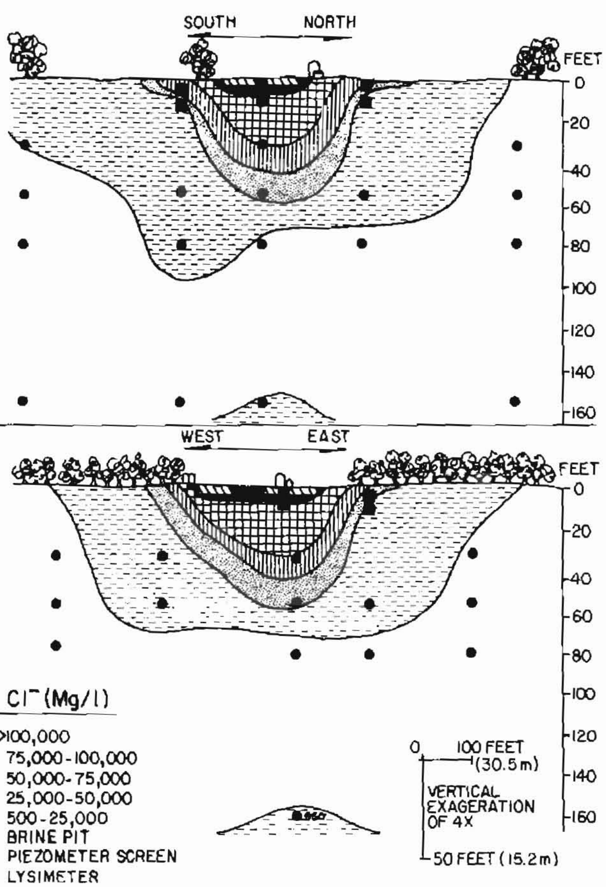

Fig. 7. Profiles of chloride concentrations at the study site.

DISCUSSION

A major question at this site is how long, and to what depth, the reclaimed brine ponds will impact subsurface water. Powell *et al.* (1963) documented widespread contamination of shallow aquifers by brine-evaporation ponds in Alabama. A study of these same areas 10 years after the closure of the ponds documented rapid cleansing of the impacted aquifers (Powell *et al.*, 1973). The same environmental conditions which had created rapid and widespread migration by brines at these sites, i.e., high annual precipitation, shallow water table, and permeable sediments, also contributed to the rapid water-quality improvement of the aquifers.

In contrast, the semiarid climate (15-19 inches of annual precipitation) and low hydraulic conductivity of the sediments at the Stratton SWD #1 site have resulted in limited movement of brine leachate in the shallow subsurface. The results of the earth resistivity surveys and ground-water chemistry indicate that the brine contamination is restricted to the till aquitard and has not affected any usable ground-water supply. The minimal flushing that has occurred at this site indicates that the amount of salt remaining at the site today is not significantly different from the amount at the time of pond abandonment.

The horizontal component of leachate migration is seven times that of the vertical component (500 vs. 70 feet) (Figure 7). It is this lateral surface and near-surface component of brine migration which is of most concern at this site. Salt migration is causing soil sterility, decreasing crop yields, and the death of trees in a shelterbelt within a 250,000-ft^2 area around the ponds. Interpretation of aerial photographs of this and other brine ponds taken over the last 25 years has documented the gradual lateral spread of brine in the plant-growth horizon from these sites over time (Foss *et al.,* 1985).

The heavily concentrated brine in the shallow subsurface within the reclaimed brine ponds at the study site is evidence that little dilution has occurred over the last 10 years. If no remedial action is taken, this site will continue to generate highly saline leachate for tens and possibly hundreds of years. The area of brine contamination will continue to grow slowly as ground water flows laterally away from the water-table mound and runoff flows freely from the site.

The study site is typical of many sites situated upon drift in the glaciated portion of North Dakota. The results from this study can be applied to leveled brine ponds situated in drift and other low permeable sediments throughout the oil-producing states.

RECOMMENDATIONS

The key to controlling or limiting the near-surface spread of brine at this site is to control infiltration in and out of the immediate pond areas. This can be done by either mounding soil above the old ponds or constructing an infiltration gallery around the site. Mounding the site is the least expensive method and would minimize the spread of brine from the area. Precautions would have to be taken to prevent capillary rise from bringing salts up through the mound. The construction of an infiltration gallery with a sump pump and the periodic use of artificial irrigation with $CaCO_3$ or $CaCl_2$ around the site would have an initial cost of between $20,000 to $30,000. This method is costly but would lead to the eventual flushing of brine from the shallow subsurface and make it possible to return this land to crop production in the foreseeable future. The land which has been taken out of production due to brine contamination is capable of generating gross annual revenue of $1250.00 (based upon 25 bushels of wheat to the acre and a $2.50 per bushel price). The cost of this remedial action is not extravagant when you consider that a jury in Oklahoma awarded a landowner $4,000,000 in damages ($2,000,000 in actual damages) from a brine pond that had been abandoned for 25 years (Hall, pers. comm., 1987).

As we have previously discussed, we predict that the area of brine contamination at the Stratton SWD #1, and at other brine ponds in similar geologic settings, will continue to spread. Therefore, as time goes by, these sites will become more expensive to reclaim. We are currently searching for sources of funding to enable us to implement our suggested methods of reclamation at both the study site and an additional brine pond. We plan to monitor the local ground-water and pore-water conditions over an extended period of time following reclamation.

We hope to use the information obtained from this study, and any future studies, to encourage oil companies to voluntarily reclaim the abandoned brine pond sites in North Dakota. It is in the companies' best interests to reclaim these sites because of the increasing tendency of juries to award huge sums of money to landowners for damages resulting from improperly reclaimed brine ponds in Oklahoma and other oil-producing states (Hall, 1986).

ACKNOWLEDGMENTS

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REFERENCES

Baker, F. G. and C. M. Brendecke. 1983. Seepage from oil-field brine disposal ponds in Utah. Ground Water. v. 21, no. 3, pp. 317-324.

Boster, R. S. 1967. A study of groundwater contamination due to oil-field brines in Moscow and Delaware Counties, Ohio with emphasis on detection utilizing electrical resistivity techniques. M.S. Thesis, Dept. of Geology, Ohio State University, Columbus. 191 pp.

Foss, J. E., J. L. Richardson, L. D. Prunty, M. D. Sweeney, D. K. Cudworth, and B. K. Hoag. 1985. Identification of salt-seepage areas from oilfield brine pits. North Dakota State University, Fargo, ND. Final Report to North Dakota Water Resources Research Institute, Grant no. 5850-4138-6671. 31 pp.

Fryberger, J. S. 1972. Rehabilitation of a brine-polluted aquifer. U.S. Environmental Protection Agency. EPA-R2-72-014. 61 pp.

Grandone, P. and L. Schmidt. 1943. Survey of subsurface brine-disposal systems in western Kansas oil fields. U.S. Dept. of Interior-Bureau of Mines Rept. of Inv. no. 3719. 20 pp.

Hall, R. A. 1986. Mud: It's the pits. In Proceedings of a National Conference on Drilling Muds. Environmental and Ground Water Institute, University of Oklahoma, Norman, OK, May 29-30. pp. 410-418.

Hall, R. A. 1987. Personal Communication. Consulting Geologist, Water and Soil Consultants, Norman, OK. July 10.

Hvorslev, J. M. 1951. Time lag and soil permeability in groundwater observations. Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi. U.S. Army Bulletin 36. 47 pp.

Kallestad, K. 1986. Personal Communication. Reclamation Supervisor, Oil and Gas Division of the North Dakota Industrial Commission. March 7.

Knox, R. C. and L. W. Canter. 1980. Effects of oil and gas field activities on ground water quality. National Center for Ground Water Research, University of Oklahoma, Norman, OK. Rept. no. NCGWR 80-30. 109 pp.

Krieger, R. A. and G. E. Hendrickson. 1960. Effects of Greensburg oilfield brines on the streams, wells, and springs of the Upper Green River Basin, Kentucky. Kentucky Geological Survey Rept. of Inv. no. 2. 36 pp.

Kuzniar, R. L. and P. G. Randich. 1982. Groundwater data for Bottineau and Rolette Counties, North Dakota. North Dakota Geological Survey Bulletin 78—Part 2. 742 pp.

Pettyjohn, W. A. 1973. Hydrogeologic aspects of contamination by high chloride wastes in Ohio. Water, Air, and Soil Pollution. v. 2, no. 1, pp. 35-48.

Powell, W. J., C. E. Carroon, and J. R. Avrett. 1963. Water problems associated with oil production in Alabama. Geological Survey of Alabama Circular no. 22. 63 pp.

Powell, W. J., M. E. Davis, B. L. Bailey, and E. R. German. 1973. Water resources monitoring and evaluation—a key to environmental protection in Alabama oil fields. Alabama Geological Survey. Info. Series no. 44. 82 pp.

Randich, P. G. and R. L. Kuzniar. 1984. Groundwater resources of Bottineau and Rolette Counties, North Dakota. North Dakota Geological Survey Bulletin 78, part 3, 41 pp.

Reed, P. C., K. Cartwright, and D. Osby. 1981. Electrical earth resistivity surveys near brine holding ponds in Illinois. Illinois State Geological Survey Environmental Notes. no. 95, 30 pp.

Rehm, B. W., G. H. Groenewold, and W. M. Peterson. 1982. Mechanisms, distribution and frequency of groundwater recharge in an upland area of western North Dakota. North Dakota Geological Survey Report of Investigation. no. 75, p. 72.

Sandoval, F. M. and J. F. Power. 1977. Laboratory methods recommended for chemical analysis of mined-land spoils and overburden in western United States. U.S. Department of Agriculture. Agriculture Handbook no. 525. 31 pp.

Shaw, J. E. 1966. An investigation of ground water contamination by oil-field brine disposal in Morrow and Delaware Counties, Ohio. M.S. Thesis, Department of Geology, Ohio State University.

Soiltest Inc. 1968. Earth Resistivity Manual. Soiltest Inc., Evanston, IL. 52 pp.

Zohdy, A.A.R. and R. J. Bisdorf. 1975. Computer programs for the forward calculation and automatic inversion of Wenner Sounding Curves. U.S. Department of Commerce. NTIS Publication PB-247 265. 47 pp.

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