Remediation of Oilfield Brine-impacted Soil Using a Subsurface Drainage System and Hay

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ABSTRACT

This study involved a demonstration of a novel remediation technology for brine-impacted soil at a site in Osage County, OK, which was recently contaminated with produced

water brine from a leak in a steel line leading to a saltwater disposal well. At this site topsoil was underlain by clay-rich subsoil which had resulted in leaching and transport of brine components from the site to an environmental receptor (farm pond) downgradient. Encouraging further movement of brine components using natural drainage patterns would have only further contaminated the pond. A subsurface drainage system (SDS) was installed to intercept brine components, enhance the lateral subsurface transport (LST) process, and prevent further contamination of the pond. Chloride and sodium concentrations in the soil were reduced by an average of 93 and 78%, respectively, in the 4 years after the SDS was installed. More importantly, approximately 95% of the site revegetated during this time period. This is in stark contrast to the complete lack of vegetation before the current work was initiated.

A thick layer of prairie hay was applied across the surface of this site after the SDS was installed. In addition to limiting the rate of evaporation from the site this organic material appears to have also played a significant role in desalination and revegetation of the site. The fibrous hay enhanced leaching after mechanical disruption of the soil and provided soil organic matter that helped to build soil structure and sustain the soil ecosystem.

Based on the results from this study, a two-step remediation strategy for brine-impacted topsoil, is proposed. The first step involves the tilling of hay and fertilizer into the soil, while the second step involves a subsurface drainage system, if necessary.

Key Words:

Produced brine, impacted soil, cost-effective remediation, gypsum, subsurface drainage system

INTRODUCTION

During the production of petroleum, saline produced water is also brought to the surface. At one time it was common practice for this fluid to be discharged at the surface. Today, oilfield brine is usually re-injected into a deep geological formation, often the one from which it was withdrawn. Nevertheless, brine spills at the wellhead or tank battery are a frequent occurrence.

An oilfield brine spill will convert the soil to a saline condition (Harris, 1998). This causes established plants to perish because a high concentration of ions in the soil solution

makes it difficult for plant roots to absorb water by osmosis. Contamination with oilfield brine may also produce a sodic soil. Sodic soils exhibit poor structure, characterized by a low hydraulic conductivity, because the aggregation of clay particles is inhibited when sodium ions displace other ions (notably calcium ion) from cation exchange sites. Dispersed clay particles are free to migrate in the soil water until they become lodged in, and plug off, the smaller pores in the soil.

Soil that is unable to support plant life, as result of either salinity or sodicity, will eventually succumb to erosion. The resultant "salt scar" is very costly to remediate. Therefore, it is an economic imperative that brine-impacted soil be remediated as soon as possible after the spill has occurred. On the other hand, since oilfield brine does not represent a threat to human health unless it impacts drinking water, and the contaminated land may not be that valuable (from an economic perspective), the means by which the brine components are removed from the soil must be relatively inexpensive.

In 1997, the American Petroleum Institute (API) published a field manual concerning the remediation of brine-impacted soil (Carty et al., 1997). This manual describes three separate remedial activities. The first, excavation of the contaminated soil (with appropriate disposal elsewhere), is utilized when the brine components represent a significant threat to nearby surface water (or groundwater). However, this approach should be used as a last resort because it is very expensive. The second activity involves the addition of amendments (e.g. gypsum) to improve the structure of the topsoil and encourage the downward movement of brine components through the soil profile (driven by rainfall or surface irrigation). The success of this approach is critically dependent on the characteristics of the subsoil (or underlying geologic materials); if the hydraulic conductivity of these materials is low, the brine components will remain concentrated in the topsoil. The third activity utilizes halophytes, plants capable of surviving in highly saline soil, to stabilize the topsoil. Unfortunately, the knowledge base required to match known halophytes to local climatological and ecological conditions is not yet available.

The purpose of this research project was to demonstrate a cost-effective remediation strategy specifically for oilfield brine-impacted sites at which the downward movement of the contaminants through the soil profile is inhibited and lateral movement of brine components threatens an environmental receptor. In this study a recent brine spill site in Osage County, OK (referenced here as *Site B*) was remediated. The site is located in the Tallgrass Prairie Preserve (TGPP), which is owned and operated by The Nature Conservancy, a non-profit organization dedicated to the preservation of native habitats. The mineral rights to this area belong to the Osage Nation. On the site a subsurface drainage system (SDS) was utilized. Commonly used for the draining of waterlogged cropland (Jeffords, 1976), SDS's have been applied to a limited number of oilfield brine–impacted sites (Weathers et al., 1994; Sewell et al, 2000). Lateral subsurface transport is enhanced by an SDS.

EXPERIMENTAL METHODOLOGY AND SITE INFORMATION

Site B is located at NE Sec. 12 T27N R8E. The soil survey for Osage Co., Oklahoma (United States Soil Conservation Service, 1979) provides some information on the characteristics of the soil at this site. The dark brown topsoil is classified as silt loam, while the tan-colored subsoil is silty clay. *Site B* is mapped as the Steedman-Coweta complex, with a slope between 3 and 15%. The Steedman soil exhibits a topsoil depth of approximately 8 inches (20 cm), medium water capacity, slow water permeability and a seasonal water table 6-12 inches (15-30 cm) below the surface. The subsoil exhibits a gray color at greater depth, indicative of weathered or diagenetically altered shale. Shale was not encountered in a 2-m deep excavation at the northwest corner of the site; thus, the lowest subsoil layer for the Steedman can be quite thick. The Coweta soil is typically thinner than the Steedman, has a lower water capacity, and is derived from sandstone. There is a sandstone outcrop just above the contaminated area on this site, suggesting that Coweta soil is present at the top of the site.

In the late winter of 1995, a 2-in (5-cm) steel pipe connecting a tank battery to the produced water re-injection well failed in two places due to corrosion, resulting in the loss of approximately 400 bbl (64 m^3) of brine. The brine flowed 60 meters downhill to a shallow ditch,

then rainfall conveyed brine components to a stock pond approximately 500 m downgradient. Migration of brine components over the next two years (by overland transport and lateral subsurface transport) resulted in approximately 2 acres (0.8 hectares) of contaminated soil and a continual source of contamination for the pond.

Site B was treated for the first time approximately two months after the spill. The choice of remedial treatment(s) was made by the operator of the lease in consultation with Tallgrass Prairie Preserve officials but not the authors. The contaminated area was first ripped with a bulldozer and then divided into four quadrants, with each quadrant receiving a different amendment applied to the surface (Fig. 1). Details of these early remedial treatments are provided in Table 1.

Three growing seasons after this initial remediation, the site was still almost completely bare. Consequently, in December 1997, a subsurface drainage system (SDS) was installed. This system featured four lateral lines of 4-in (10-cm) slotted polyethylene drainage pipe buried approximately 1 m beneath the surface, just below the topsoil-subsoil interface. The pipe was surrounded by approximately 3 inches (7 cm) of limestone gravel with an average particle diameter of 1/2 inch (1.3 cm). The dirt from the ditches was used to construct berms immediately downgradient of the drainage lines, as well as a dam across the shallow ditch noted above to encourage infiltration of rainfall. *Site B* and the SDS are illustrated schematically in Fig. 2. It can be seen that the four drainage laterals effectively divided the site into four sections.

The upper three drainage lines were connected to a collection line, constructed of unslotted pipe that traversed the north side of the contaminated area. This line and the lowest lateral line were connected to a sump buried in the lowest corner of the site. Initially, a 1000 L open-top polyethylene tank served as the sump. In February, 1998 this was replaced with a 25-bbl (4-m^3) steel tank. A gasoline-powered pump and connecting line were used to transfer the contents of the SDS sump to the lease's produced water disposal system (saltwater holding tank). A cumulative flow meter in the connecting line was used to record this transfer, which occurred

each day that the "pumper" was able to include this activity in his schedule. A sample of the fluid being transferred was collected manually by the pumper on a weekly basis.

Soon after installation of the SDS most of the site was disked. Twenty large round bales of hay were then unrolled, providing a 4-inch (10-cm) thick layer over most of the site. Subsections L1S1 and L1S2, as well as the entire L4 section, were too wet to allow disking or the application of hay at that time. Permanent sampling stations designated by steel pins were established on the site at this time (see Fig. 2).

Subsections L1S1 and L1S2, being closest to the origin of the spill, initially exhibited the highest levels of contamination initially (see below). When revegetation did not occur in this area during the first growing season following installation of the SDS and hay treatment, further remedial activities were undertaken. Subsection L1S1 was treated with gypsum following API guidelines (Carty et al., 1997) and then tilled, while subsection L1S2 was covered with a 4-in (10-cm) thick layer of prairie hay and then tilled.

Site B is within 2 miles (3.2 km) of the Foraker weather monitoring station of the Oklahoma Mesonet (Oklahoma Climatological Survey). Thus, rainfall amounts for the time period addressed in this paper are known to a high degree of accuracy.

Sample Collection and Analysis

Routine sampling of the site involved the collection of surface soil only. Using a shovel, soil to a depth of 10 cm was collected from four locations chosen randomly from within a circle with a radius of 1 m centered on the rebar pin designating the sampling station. The soil was placed on a clean sheet of plastic and composited thoroughly before a representative sub-sample was transferred, using a clean trowel, to a polyethylene bag with Ziploc® closure.

Since one objective of this study was to monitor the salt concentration in the soil over time, the "1:1 extract" was employed instead of the saturated paste extract (Harris et al., 1998). The 1:1 extract was prepared by combining a mass of high purity water (HPW) produced with a Milli-Q system (Millipore) equal to that of a soil sample (approximately 100 g) dried overnight in an oven at 110 °C. After allowing the soil and water to equilibrate overnight in a sealed

container, the extract was recovered by vacuum filtration through qualitative filter paper (Millipore).

The soil extracts, leachate samples from the SDS, and a sample of produced water from the site were analyzed for major anions (chloride and sulfate) and cations (sodium, calcium and magnesium). A DX-100 (Dionex) ion chromatograph, employing an IonPac AS4A-SC column and a sodium bicarbonate/carbonate buffer solution (concentrate purchased from Dionex) as the mobile phase, was used to quantify the anions. Most of the samples required dilution (with HPW) to reduce the chloride concentration within the dynamic range of the instrument. Standard solutions prepared from commercial reference solutions (SPEX) and HPW were used for calibration. A Plasma 2000 (Perkin-Elmer) inductively-coupled plasma atomic emission spectrophotometer was used to determine the concentrations of major cations. The samples were diluted with 1 vol.% nitric acid, prepared from trace metal-grade concentrate (Fisher Scientific), to minimize matrix effects

RESULTS

As noted above, *Site B* received remedial treatment(s) shortly after the spill occurred. That portion of the site above the shallow ditch was ripped with a bulldozer and then divided into quadrants, each receiving a different treatment. These treatments included two commercial products, Salt Away II, a calcium nitrate solution, and Adsee 799, a surfactant, both of which were applied by spraying after dilution with fresh water. Neither the source of these products, nor the concentration of the calcium nitrate in the Salt Away II, is known. A third quadrant was treated with sulfur, fertilizer (ammonium phosphate), and a relatively small amount of hay. Despite this effort, after three growing seasons the extent of revegetation was minimal.

The ineffectiveness of the initial remediation at *Site B* is likely due to two factors. First, the concentrations of brine components in the soil were extraordinarily high initially. For example, a surface sample collected in August, 1995 in the vicinity of sampling station L1S1 provided a saturated paste extract electrical conductivity value of 33,000 µmhos/cm. A second factor as illustrated in Fig. 3. During the nearly three years between the initial treatments and

installation of the SDS, the brine components had only begun to penetrate the subsoil, approximately 0.7 m beneath the surface. The samples corresponding to the data in Fig. 3 were collected from the walls of two of the ditches excavated for the subsurface drainage system (SDS), as well as a control ditch approximately 30 m down gradient from the spill. The control ditch noted above was relatively close and downgradient to the contaminated area. Given this, it is perhaps surprising that the concentrations of brine components in the soil at that location were so low. However, overland transport (OT) to this area was effectively blocked by a shallow ditch that runs along the upgradient side of a lease road. Given the shallowness of the topsoil at this site, lateral subsurface transport (LST) may also have been impeded by the bed of this road.

Nearly 1,400 bbl (5.6×10^6 L) of leachate were transferred from the SDS sump to the lease's produced water disposal system during the first 6 months of operation. However, this volume is estimated to be only 20% of the total volume of leachate collected by the SDS during this time. As can be seen in Fig. 4a, the sump, with a volume of only 25 bbl (4 m^3), was full virtually every day that it was pumped out. On those days when it was not pumped out, leachate overflowed into the shallow ditch that runs along the up gradient side of the lease road, eventually ending up in a stock pond approximately 500 meters down gradient from the site. During periods of heavy rainfall this pond overflowed into a creek.

The concentrations of chloride and sodium ion in the leachate transferred from the sump to the produced water disposal system varied over time (Fig. 4b). The lower concentrations were probably the result of dilution with uncontaminated run-off from the adjacent hillside. This run-off collected behind the berms below sections L3 and L4 of the SDS, creating small ponds. This additional water was expected to enhance LST, and thus the pace of soil desalination and re-vegetation.

Based on the average concentrations of these ions, and the estimated total volume of leachate that passed through the SDS (including the estimated sump overflow), approximately 1,400 kg of salt was removed during this time. If it is assumed that 400 bbl (64 m^3) of brine containing 120,000 mg/L of chloride ion and 60,000 mg/L of sodium (based on produced water

taken from the tank battery in June, 1998) were spilled at this site, this amount of salt corresponds to only 3% of the amount that was released initially. This indicates that a significant fraction of the salt had been leached from the site via OT prior to installation of the SDS.

The concentrations of chloride ion and sodium ion in surface soil samples collected at this site over a 4-year period are presented in Fig. 5. Each column of values corresponds to a particular sample location; the values in each column correspond to samples collected in 1998 (top) through 2001 (bottom). It can be seen that the concentrations of these brine components decreased significantly across the entire site during this time period. However, the concentrations at some of the sample locations actually increased in the first year following installation of the SDS. This transitory effect was due to LST, since OT was blocked by the berm adjacent to each subsurface drainage lateral. This phenomenon was most pronounced in subsection L4S1, where ponding occurred both up gradient and down gradient to the sampling station (Fig 2).

On the whole, *Site B* experienced significant revegetation as a result of this remediation (Fig. 6). Knotweed and ragweed were most plentiful initially. After the first growing season the densest vegetation was found on the berms, consistent with efficient leaching of the brine components from the immediate vicinity of the drainage lines. The vegetation in subsequent growing seasons was both more widespread and more diverse.

Subsections L1S1 and L1S2, which were closest to the origin of the spill, exhibited the highest levels of contamination initially. These subsections also failed to revegetate during the first growing season after installation of the SDS. Consequently, in July 1999 these subsections were treated with gypsum or prairie hay, respectively, and then tilled to a depth of 6 inches (15 cm). It can be noted in Fig. 5 that both treatments produced similar, dramatic reductions in the chloride ion concentration. However, the subsection that was treated with hay (L1S2) exhibited a much greater reduction in sodium ion concentration during next year. In addition, subsection L1S2 was effectively revegetated during the next growing season, while subsection L1S1

remained mostly barren even after the 2001 growing season. These observations suggest that hay, tilled into the brine-impacted soil, can reduce the salinity and the sodicity to the same extent as gypsum. In addition, it is clear that hay provides an additional incentive for revegetation relative to gypsum.

DISCUSSION

The American Petroleum Institute (API) field manual (Carty, et al., 1997) recommends three different strategies for the remediation of oilfield brine-impacted soil. Only one of these approaches, the addition of amendments (e.g. gypsum) to the soil, is commonly used. This treatment is designed replace some exchangeable sodium with magnesium of calcium to facilitate the downward movement of brine components through the soil profile. However, this transport process can be inhibited by a clay-rich subsoil.

A rainfall sufficient to produce run-off can leach brine components from the soil near the surface and then transport them off-site. This process, referred to as overland transport, is clearly evident in the data from site A presented above. Scientists concerned with the soil desalination have recognized the effectiveness of OT previously (Bohn et al., 1985). The basin-furrow design, in which berms are constructed at 45° to the down gradient direction, encourages the run-off to meander across the surface, thus enhancing the leaching of brine components.

It has been demonstrated in at least one other field study (Carter and Fanning, 1964) that the downward movement of brine components through the soil profile can be negated by periods of dryness. This occurs because evaporation draws salty leachate back toward the surface through capillary action. This phenomenon may be beneficial to a remediation based on the OT process: salt that has crystallized out in the first centimeter of soil is particularly susceptible to leaching by run-off. This approach should be particularly successful in regions where spring rainfall events are intense.

Based on the results presented above (Figs. 4 and 5), the SDS was both effective and efficient. With the exception of those subsections that received some brine components through lateral subsurface transport, chloride and sodium ion concentrations in the soil were reduced by

an average of 93% and 78%, respectively, by the fourth year after the SDS was installed. In addition, approximately 95% of the site revegetated during that time period.

The leachate collected by the SDS during the first year of operation was relatively concentrated (Fig. 4b). This indicates that special disposal of the leachate produced by an SDS may be required. Re-injection at the lease, preferably through the use of an existing produced water re-injection well, would be the most cost-effective means of leachate disposal. The presence of dispersed clays in the leachate may present a barrier to this approach. Fortunately, the re-injection well at *Site B* was completed in a high-permeability formation; thus, the presence of minor amounts of suspended solids in the leachate was of no concern to the operator.

It was noted above that limestone gravel was applied around the drainage pipe, to provide a region of enhanced permeability around the pipe, and possibly to limit soil particles from entering the drainage system. It is conceivable that calcium ion released from the limestone gravel will assisted in this endeavor. Calcium ion promotes the agglomeration of clay particles, by exchanging for sodium onto the surface of the clay particles and compressing the electrical double layer (Harris, 1998).

It is likely that lateral subsurface transport dominates contaminant movement in an SDS. Undoubtedly, this process accounted for the revegetation of the berms observed during the first growing season following installation of the SDS, as well as the increase in brine component concentrations observed in some subsections (e.g. L4S1) during this time period. However, it is difficult to believe that LST alone could reduce brine component concentrations at the sampling stations (located 10 meters from the nearest drainage line) to the extent indicated in Fig. 5. It is more likely that the OT process also played a role, by rapidly conveying leachate to the downgradient berm, where it then permeated a relatively short distance through soil to the drainage line.

A thick layer of prairie hay was applied across the surface of the contaminated soil after the SDS was installed. This material was expected to limit the rate of evaporation, thus encouraging LST toward the drainage laterals during periods of intermittent rainfall (Carter and

Fanning, 1964). However, the hay appears to have played a more significant role in support of desalination and revegetation, as indicated by the effect of the additional remedial treatments that were applied to two subsections. These subsections, L1S1 and L1S2, had been too wet to allow disking or the application of hay following installation of the SDS. The additional treatment involved amendments, gypsum alone (L1S1) or hay alone (L1S2), tilled into the soil. During the next year, the sodium ion concentration decreased more rapidly in subsection L1S2 relative to L1S1 (Fig. 5b). In addition, significant revegetation was observed on L1S2 during the next growing season, while L1S1 remained barren. By the 2001 sampling date the brine concentrations in the two subsections were comparable, but subsection L1S1 was still only sparsely vegetated.

There are several potential explanations for the beneficial effect of hay on the remediation of brine-impacted soil. The introduction of a fibrous material to the topsoil should extend the time period over which enhanced leaching occurs after mechanical disruption of the soil. Presumably, this effect will be realized only if the organic matter is tilled into the soil. In addition, the rapid decrease in the sodium ion concentration in the soil suggests that organic matter enhances the leaching of this ion. This may occur as a result of the presence of products of the microbial biodegradation of the hay which are known to help build soil structure and increase hydraulic permeability. Another effect is the production of CO_2 from biodegradation of organic matter which will increase the solubility of calcite and thus calcium concentrations. (Robbins, 1986).

Organic matter added to the soil may also have a direct effect on the revegetation of brine-impacted soil as has been observed in at least two previous studies (McFarland et al., 1987; Sewell et al., 2000). Soil microorganisms are essential to the growth and well-being of plants; thus, their population must be sustained if revegetation is to be realized. In other work we have observed reductions in soil microbes of about 50% following a brine spill (Moralwar et al., 2004). While some part of this decline may be due to the effect of elevated salinity on the microorganisms, it may also be related to a reduction in the soil organic matter. In the absence

of brine contamination, growing and dying plants provide most of the organic matter that sustains the soil ecosystem. This ecosystem maintains the structure of the soil, which benefits both plant life and the leaching of salts from the soil. When a brine spill kills the plants the amount of soil organic matter becomes finite, and diminishes rapidly during periods of high microbial activity. The structure of the soil will degrade further during this time. The addition of hay to the soil should sustain the microbial population and the structure of the soil until revegetation occurs.

Finally, the use of gypsum as a soil amendment should be discussed. Gypsum is one of the cheapest sources of readily available calcium ion. As noted above, calcium ions encourage the agglomeration of clay particles, and thus enhance the permeability of the soil (and the pace of desalination). However, based on the results from the second remedial treatment applied to *Site B*, gypsum was not as effective as prairie hay for enhancing the rate of the leaching of brine components from the soil (Fig. 5), or enhancing the pace of revegetation.

Another issue of concern is the amount of gypsum that must be applied to a brine-impacted site. The API field manual (Carty, et al., 1997) provides a calculation for determining this amount; it is based on the sodium absorption ratio and the cation exchange capacity of the soil (determined to be approximately 20 meq/100 g of soil). The gypsum requirement predicted by this calculation for various subsections of *Site B* decreased dramatically during the four years following installation of the SDS. For example, based on the results of the cation analysis of surface soil samples collected at sampling station L1S2 (only the sodium ion data are presented in Fig. 5), the gypsum application rate decreased from 0.25 to 0.05 pounds per square foot (0.010 to 0.002 kg/m^3). This suggests that the application of gypsum to a relative new brine spill could be much more expensive than the hay plus tilling treatment. Gypsum typically adds considerably to the cost of the remediation of a brine spill both in the cost of the gypsum and the cost of transportation and spreading. However, the effect of gypsum in mobilizing sodium from clays is manifested only to the depth to which it is applied (Robbins, 1986). Further, the addition of large amounts of gypsum to the soil has the potential to interfere with phosphorous cycling.

It can be noted in Fig. 1 that a calcium-containing product, “Salt-Away”, was utilized in the initial remediation of *Site B*. Neither this product nor the other amendments added at that time were able to achieve even limited revegetation. It is conceivable that the failure of this approach at *Site B* was due to the very high level of contamination initially. On the other hand, since this remediation did not include the application of hay across the entire contaminated area, one may also conclude that hay is the key to remediating sites where the downward movement of brine components is blocked by impermeable subsoil.

Approximately $7,000 was spent on the installation of this SDS. This translates into a capital cost of $3,500/acre, which is much higher than the $200/acre cost estimated for the SDS installed at the Texon Scar (Weathers, personal communication). However, several extraordinary expenses (e.g. weather-related construction delays, high-integrity fencing to keep bison off the site, replacement of the system’s first sump) accounted for over one-half of this amount. The limestone gravel used to create a “gravel pack” around the perforated drainage pipe was by far the most expensive material used to construct the system.

RECOMMENDATIONS

This study specifically addresses the remediation of relatively new brine spills on topsoil underlain by impermeable subsoil. Scars resulting from historical spills are a clear manifestation of subsurface impermeability, as well as a visual reminder of the ease with which the topsoil will erode in the absence of vegetation. Thus, if scars are present in the vicinity of a lease, it is imperative that any new brine spill be remediated as soon as possible.

Based on the results of the field demonstration presented above, a two-step remediation strategy is proposed. The first step involves the tilling of hay into the soil, while the second step involves a subsurface drainage system with limestone gravel. Both steps require only rainwater to leach the salt from the soil. This strategy is applicable even in semi-arid areas.

The first step in this remediation strategy is based on the overland transport of the brine components from the contaminated site. Hay, tilled into the soil, enhances this process by maintaining the enhanced permeability provided through mechanical disruption (e.g. tilling) of

the soil. The products of the microbial degradation of the hay may also assist in the transport of sodium from the soil by improving soil structure and increasing the solubility of calcite in the soil. Fertilizer addition may enhance these effects since hay is deficient in nitrogen. This remedial treatment should be performed in the late fall or winter in order to make full use of spring rains and the subsequent growing season. The treatment may be repeated if significant revegetation is not achieved after the growing season. The hay also provides a direct benefit to revegetation, by maintaining both the soil microbial population and the soil structure. Once any revegetation occurs the penetration of roots into the subsurface further improves hydraulic conductivity (and, therefore, the leaching of brine components) by releasing organics and CO_2 into the soil. These effects have been shown to be manifested throughout the root zone (Robbins, 1986).

The second step in this remedial strategy is the installation and operation of a subsurface drainage system. While this approach is significantly more expensive, it will greatly accelerate the pace of revegetation. In addition, an SDS can protect nearby surface water and groundwater resources from secondary contamination, through collection and disposal of the leachate produced. This option, which may be mandated by some regulatory agencies, will be cost-effective only if there is an existing produced water disposal system on the lease, and both the operator and the state allow the leachate to be transferred into it.

REFERENCES

Bohn, H.L., B.L. McNeal, and G.A. O'Connor,1985, Soil Chemistry: New York, John Wiley and Sons, p 217-246.

Carter, D.L., and C.D. Fanning, 1964, Combining surface mulches and periodic water applications for reclaiming saline soils: Soil Science Society of America Proceedings, v. 28, p. 564-567.

Carty, D.J., S.M. Swetish, W.F. Priebe, and W. Crawley, 1997, Remediation of salt-affected soils at oil and gas production facilities: Washington, American Petroleum Institute.

Harris, T.M., 1998, *Brine impacted soils, remediation*, Ed. R.A. Meyers, in: Encyclopedia of Environmental Analysis and Remediation: New York: John Wiley and Sons, p. 823-829.

Harris, T.M., J. McConnell, and K. Schulte, 1998, Physicochemical characterization of brine-impacted soil. in: Proceedings of the 5th International Petroleum Environmental Conference, Albuquerque, NM. [CD available from the Division of Continuing Education, University of Tulsa, Tulsa, Oklahoma.]

Jeffords, O.D., 1976, *Advanced drainage systems*, Drainage Handbook *(*2nd Edition): Bellview, Washington.

McFarland, M.L., D.N. Ueckert, and S. Hartmann (1987) Revegetation of oil well reserve pits in west Texas: Journal of Range Management, v. 40, p. 122-127.

Moralwar, A., K.L. Sublette, L. Ford, K. Duncan, G. Thoma, J. Brokaw, 2004, Remediation of a spill of crude oil and brine without gypsum: Environmental Geosciences, submitted.

Oklahoma Climatological Survey, Oklahoma Mesonet. http://www.mesonet.ou.edu/public.

Robbins, C.W.,1986, Sodic calcareous soil reclamation as affected by different amendments and crops: Agron J., v. 78, p. 916-920.

Sewell, H.J., W.A. Hamilton, G. Deeley, K.W. Farrish, E.S. Anderson, L.E. Deuel, Jr., and D. Moore, 2000, Remediation and re-vegetation of brine-impacted soil: A case study. in: Proceedings of the 7th International Petroleum Environmental Conference, Albuquerque. [CD available from the Division of Continuing Education, University of Tulsa, Tulsa, Oklahoma.]

United States Soil Conservation Service, 1979, Soil Survey of Osage County, Oklahoma: Washington, Department of Agriculture, Soil Conservation Service.

Weathers, M.L., 1998, personal communication.

Weathers, M.L., K.R. Moore, D.L. Ford, and C.K.Curlee, 1994, Reclamation of saltwater-contaminated soil in Big Lake Field: Transactions of the Gulf Coast Association of Geological Societies, v. 44, p. 737-743.

Dr. Tom Harris received his Ph.D. in metallurgy from the Massachusetts Institute of Technology in 1989. From 1989 to 2001 he was a faculty member in the Department of Chemistry and Biochemistry at the University of Tulsa. He also has 8 years of experience in industry, including 3 years in his current position with Delphi Catalyst.

Dr. Bryan Tapp is Chairman of the Geosciences Department at The University of Tulsa. Trained in structural geology, he has worked in deformation mechanisms, mathematical geology and finite element analysis. His research emphasis has shifted to environmental analysis and application of Geographical Information Systems in geosciences. Current research involves application of GIS and FEA understand surface and subsurface brine contaminant flux.

Dr. Kerry Sublette is Professor of Chemical Engineering and Geosciences and Sarkeys Chair of Environmental Engineering at the University of Tulsa. He also serves as the Director of the Integrated Petroleum Environmental Consortium (IPEC), an EPA Research Center. His research interests include the remediation of oil and brine contaminated sites and ecological indicators of the restoration of damaged soil ecosystems.

FIGURE CAPTIONS

Figure 1. Schematic illustration of *Site B* spill scar describing the initial remediation involving amendments. *Site B* is located in northeastern Oklahoma at N 36° 50.019', W 96° 23.223'.

Figure 2. Schematic illustration of *Site B* displaying the subsurface drainage system and sampling station locations. Dashed lines correspond to perforated drainage pipes. Thick textured lines correspond to berms. The shaded areas indicate where seasonal ponding occurred.

Figure 3. Chloride and sodium ion concentrations as a function of depth at *Site B*. Two locations along the L1 and L2 drainage lines were sampled; samples were also collected from a control location 30 meters east of the lease road.

Figure 4. a. Volume of leachate pumped from the subsurface drainage system sump to the produced water disposal system at *Site B* on selected dates. b. Chloride and sodium ion concentrations in samples of the leachate collected on those dates.

Figure 5. Spatial display of surface soil sample data for *Site B* corresponding to the schematic illustration in Fig. 2. Fig. 5a corresponds to chloride ion concentrations (ppm); Fig. 5b corresponds to sodium ion data. Each column of values corresponds to one station sampled in 2/98 (top), 3/99, 7/00 and 5/01.

Figure 6. Photographs of *Site B* taken in 8/95 (six months after the brine spill) and in 6/00 (third growing season after installation of the subsurface drainage system). The photographs were taken from the north side of the contaminated area, facing south. Sampling station L2S1 and L3S1 are in the foreground.

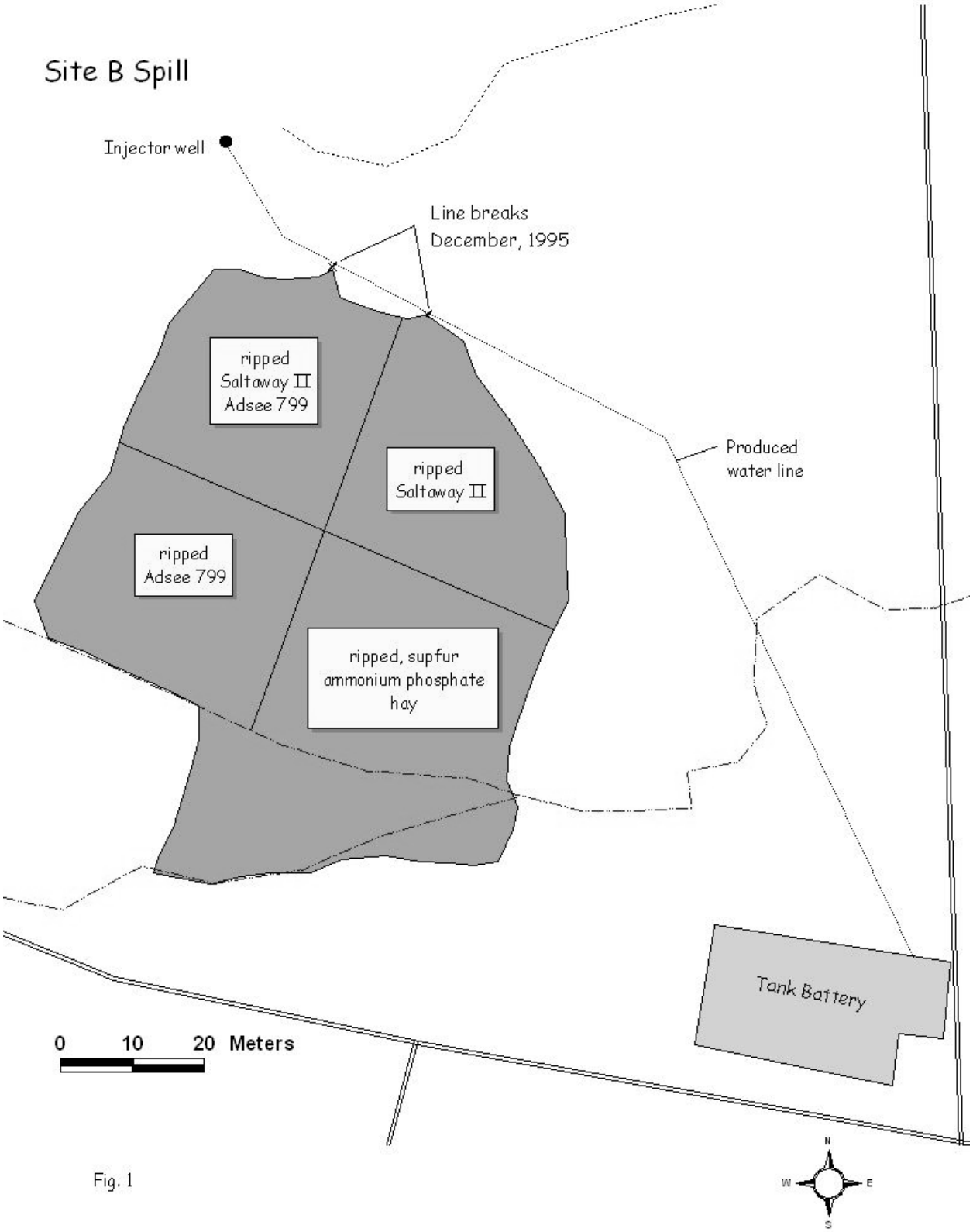

Site B Spill
Injector well
Line breaks
December, 1995
ripped
Saltaway II
Adsee 799
ripped
Saltaway II
ripped
Adsee 799
ripped, supfur
ammonium phosphate
hay
Produced
water line
Tank Battery
0 10 20 Meters
N
W
E
S

Fig. 1

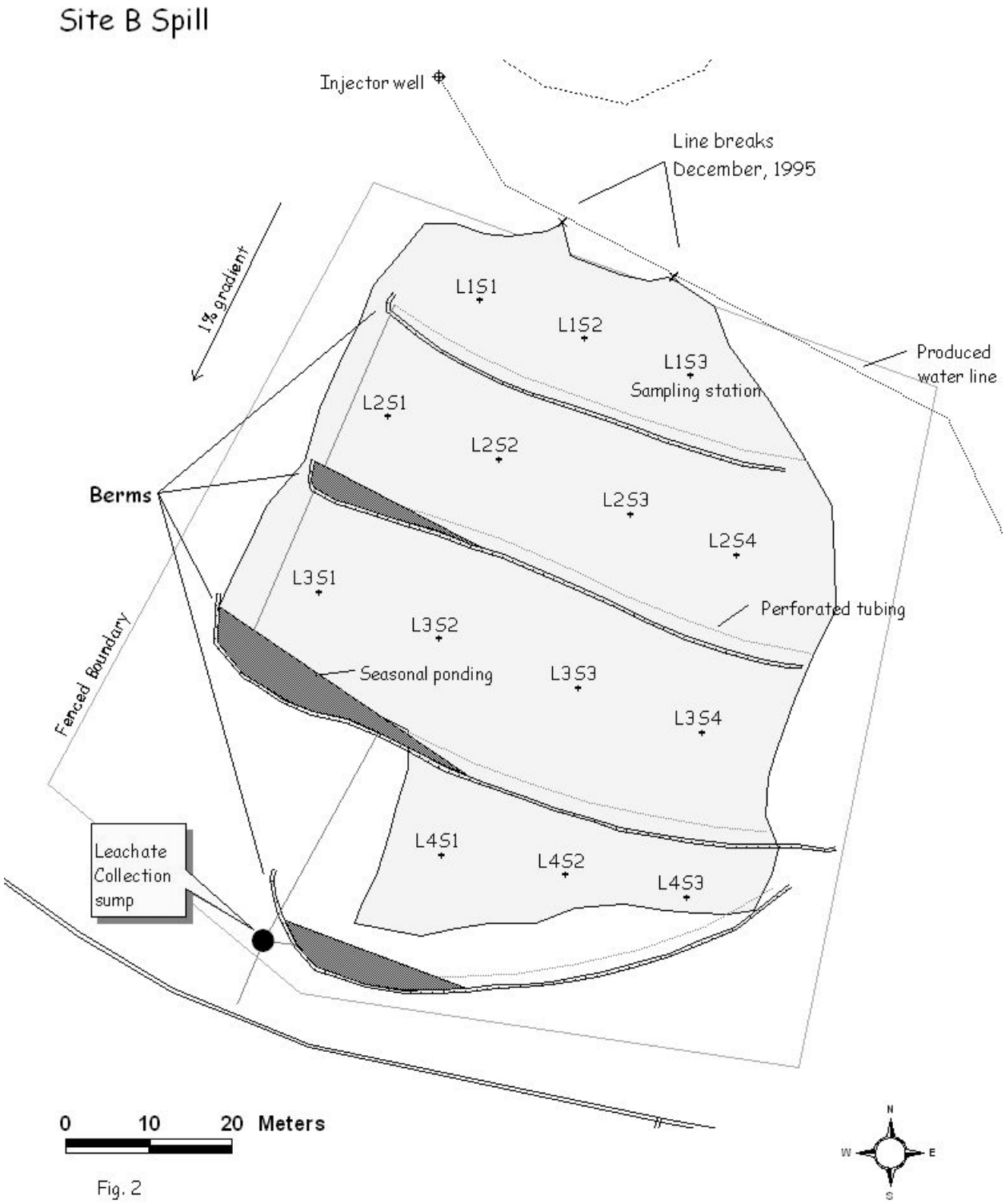

Site B Spill
Injector well
Line breaks
December, 1995
1% gradient
L1S1
L1S2
L1S3
Sampling station
Produced
water line
L2S1
L2S2
Berms
L2S3
L2S4
L3S1
Perforated tubing
L3S2
Fenced Boundary
Seasonal ponding
L3S3
L3S4
Leachate
Collection
sump
L4S1
L4S2
L4S3
0
10
20
Meters
N
W
E
S

Fig. 2

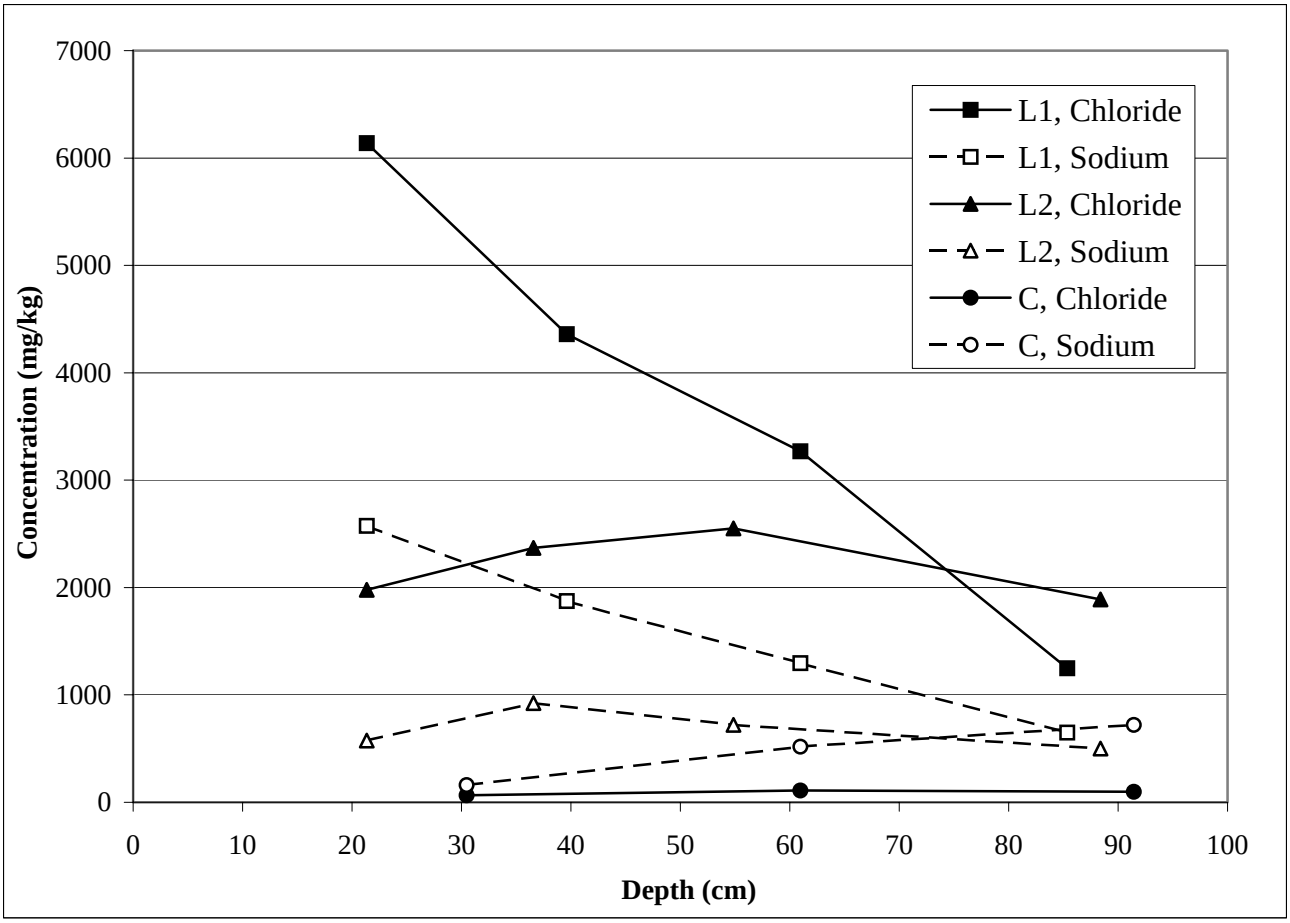

7000
6000
5000
4000
3000
2000
1000
0
Concentration (mg/kg)
0
10
20
30
40
50
60
70
80
90
100
Depth (cm)
L1, Chloride
L1, Sodium
L2, Chloride
L2, Sodium
C, Chloride
C, Sodium

Figure 3

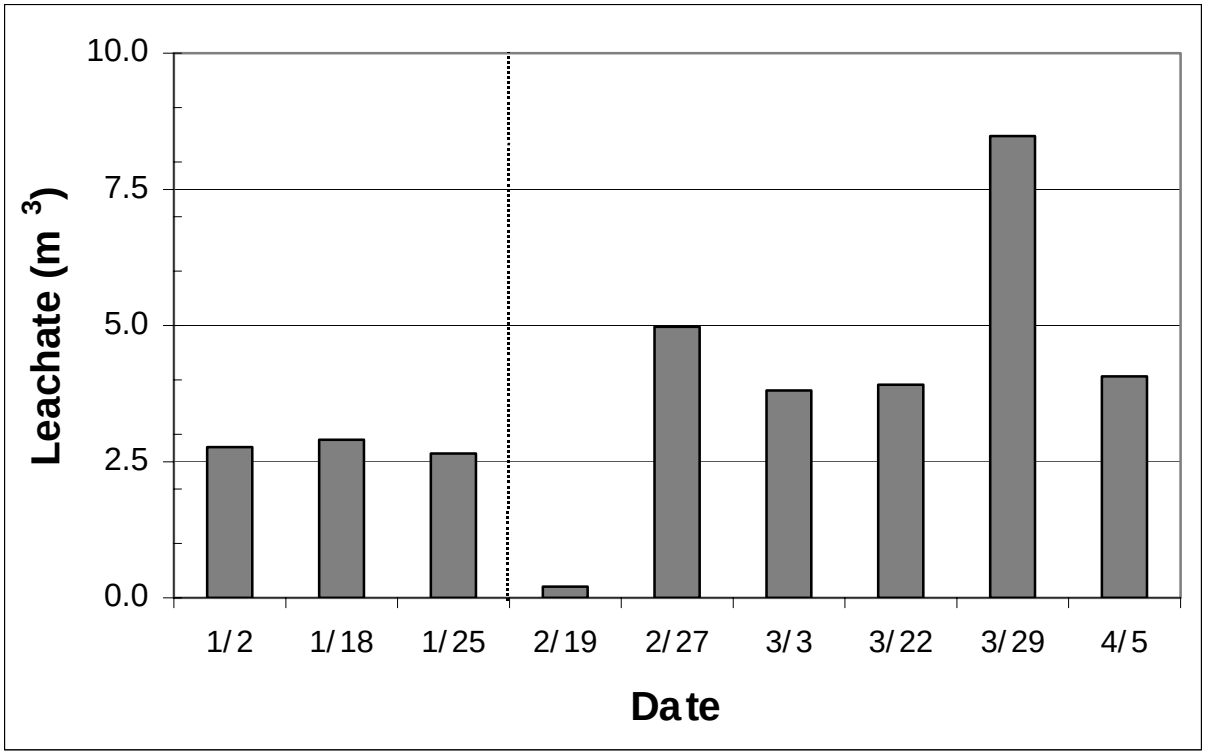


Figure 4a

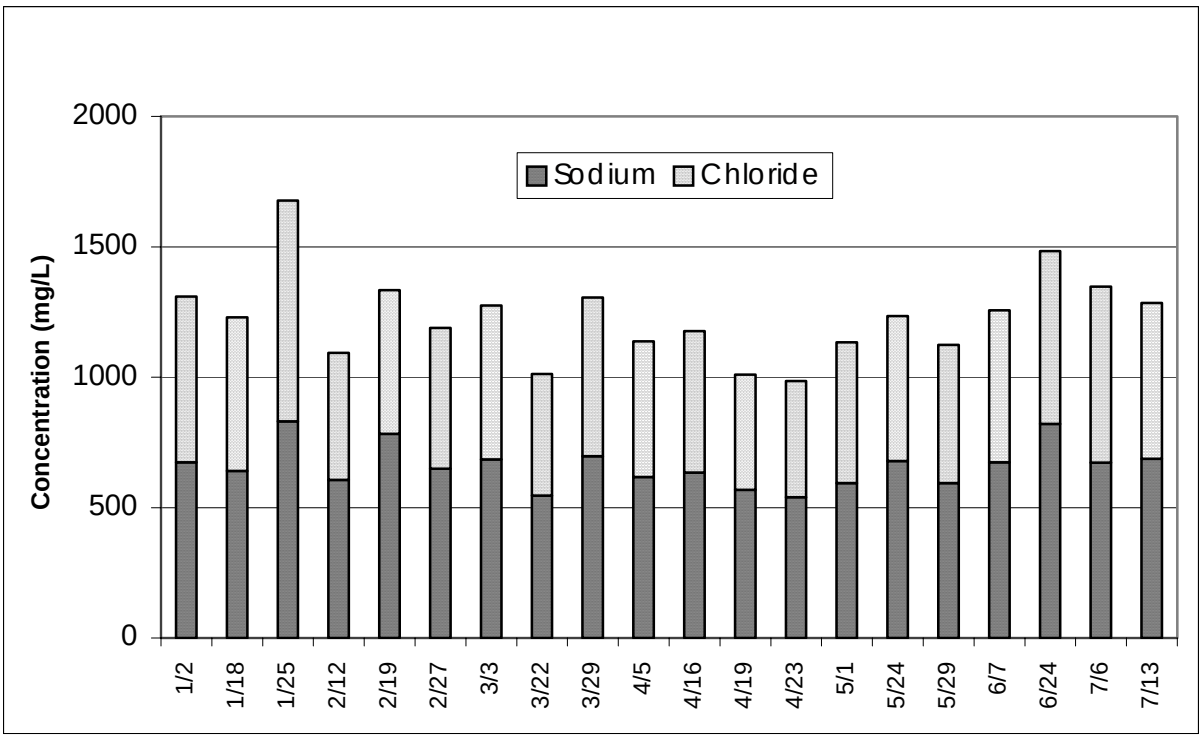
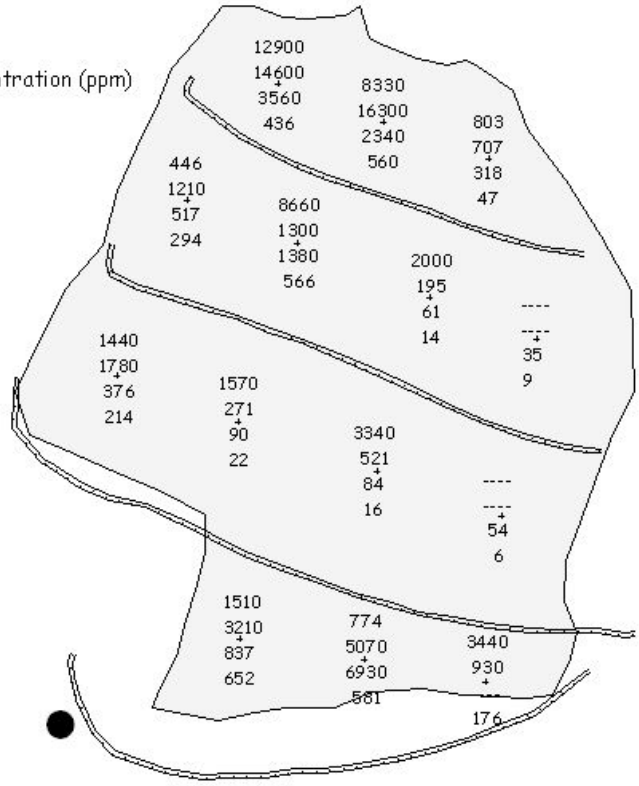


Figure 4b

a. Chloride Ion Concentration (ppm)



b. Sodium Ion Concentration (ppm)

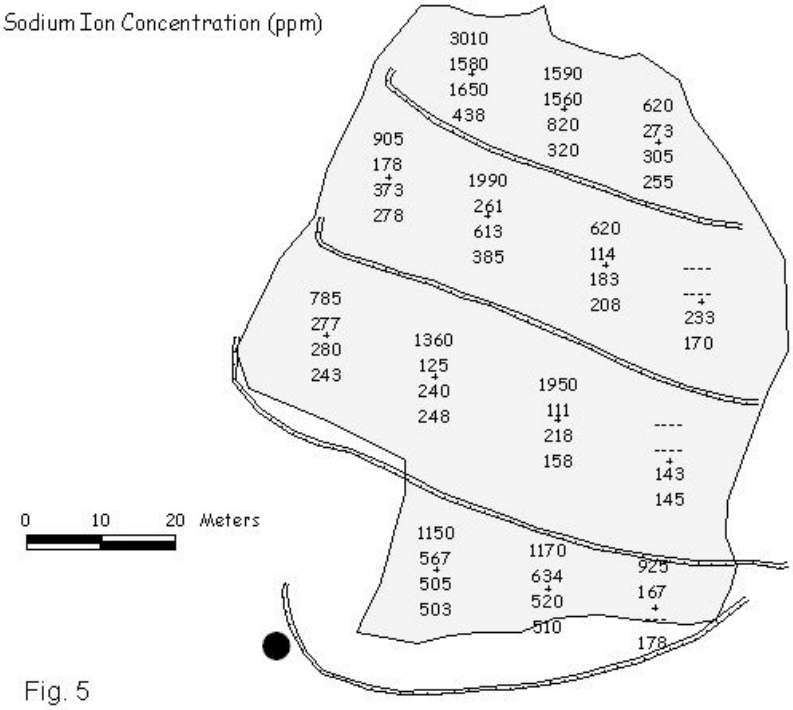


Fig. 5

Figure 6a

Figure 6b

TABLES

Table 1. Details of the remediation treatments applied to *Site B* two months after the brine release. All treatments included ripping to 30 cm in depth with a bulldozer.

Treatment #	Salt Away II	Adsee 799	sulfur	fertilizer	hay	FW
1	105 L / 4.8 m^3 FW	19 L / 1.0 m^3 FW				
2	105 L / 4.8 m^3 FW					
3			136 kg	11 kg	65 bales	6.1 m^3
4		38 L / 2.1 m^3 FW				

(Salt Away II: commercial calcium nitrate solution; Adsee 799: commercial wetting agent solution; fertilizer: 10-20-10-7 pellets; hay: small rectangular bales; FW = freshwater)