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Remediation Study for a Salt-affected Soil Impacted by the Oil and Gas Industry

by

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Abstract

An agricultural land was adversely affected by salt released by the oil and gas industry. Remediation was needed to recover the land to agricultural productivity. Field-scale and laboratory-scale experiments were conducted to identify a practical and reliable remediation technique that could be used to treat the salt-contaminated farmland. Different approaches, including leaching and drainage interventions, gypsum application, zeolite application, alluing or ripping, sanding and combinations of these approaches, were tested to evaluate the removal of sodium and chloride from salt-affected soils. Electrical conductivity (EC), sodium adsorption ratio (SAR) and remediation time were three important diagnostic parameters in the evaluation. It was found that the integrated application of alluing, gypsum addition and leaching achieved the best remediation for the fine textured soil containing a high concentration of sodium and chloride. Chemical amendments must be applied prior to leaching when treating severely sodic soils.

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1 Introduction

1.1 Introduction

Soil salinity is of concern in agriculture because it can restrict plant growth and degrade soil structure. In Alberta, there are approximately 1.6 million acres of soil affected by salinity (Alberta Agriculture, 1991). With the oil and gas industry fast expanding in Alberta, this situation could become more serious. Salt, especially high concentrations of sodium and chloride, is introduced into soils through produced water spills and leaking pipelines from the petroleum industry. These salt spills cause concerns to agriculture and degrade farmlands (Brushett, 1975; EUB, 1996a; American Petroleum Institute, 1997; Alberta Environment, 2001). In southern Alberta, a sodium brine spill could cause potentially disastrous results for farmers because many oil and gas production and treatment facilities are located on land which is predominantly used for grazing and agriculture (Currie, 1997).

In addition to produced water spills and leaking pipelines, another two common sources of salt in the environment in Alberta are drilling fluids and flare pits. Drilling fluids which are used during the process of exploitation at drilling sites may contain high concentrations of sodium, calcium, potassium and nitrogen salts and petroleum hydrocarbons (Alberta Environment, 2004). The Alberta Energy and Utility Board set *Guide 50: Drilling Waste Management* to deal with the disposal of drilling waste (EUB, 1996b). If the drilling waste is not treated and disposed of correctly, soil may become contaminated and treatment options need to be used (Currie, 1997). The upstream oil and gas industry in Alberta has used flare pits for decades to store or burn produced fluids generated at well sites and compressor stations up until 1996. As produced fluids contain liquid hydrocarbons, chemicals, and salt water, the soils under flare pits are heavily contaminated by hydrocarbons and salts (Amatya *et al.*, 2002; Arocena and Rutherford, 2005). It is estimated that there are about 30,000 flare pits in Alberta needing remediation (Amatya *et al.*, 2002).

Soils containing salts exceeding a certain limit are called salt-affected soils (Stebutt, 1930; Szabolcs, 1989; Chhabra, 1996; Qadir *et al.*, 2000). These soils are broadly divided into three categories: saline, sodic and saline-sodic. These categories are defined by electrical conductivity (EC), sodium adsorption ratio (SAR) and pH (U.S. Salinity Laboratory Staff, 1954; American Petroleum Institute, 1997; Qadir *et al.*, 2000; Alberta Environment, 2001). Saline soils contain a large amount of soluble salts, which cause the electrical conductivity of the saturated paste extract (ECe) to be greater than 4dS/m and the pH to be less than 8.5. A sodic soil is defined as a soil with a sodium adsorption ratio (SAR) of more than 13, indicating excess sodium in the soil that can cause deterioration in the soil structure. Saline-sodic soils contain sodium and other soluble salts in such concentrations that the ECe is greater than 4dS/m and the SAR is more than 13.

Compared to hydrocarbons, salt is non-biodegradable and very mobile. It may easily move with water if the soil structure allows, causing long-term and detrimental effects (Edwards and Blauel, 1975; Evans and Barck, 1995). Typical problems associated with excess salt in soil are degradation of soil physical characteristics, such as low permeability and soil dispersion; impairing crop growth, reduction of yield and poor groundwater quality due to the change in soil properties and the high concentration of sodium and chloride ions (Qadir *et al.*, 2000; Alberta Environment, 2001).

Current technologies to remediate salt-affected soils include: leaching without amendment application, leaching with chemical amendments or physical amendments, chemical amendments alone, modifying the soil profile through mechanical activities, passing an electrical current through the soil (i.e. electrokinetic remediation) and growing salt-resistant crops to ameliorate calcareous soil (i.e. phytoremediation) (Robbins, 1986; De Villiers, 1995; Qadir *et al.*, 2000; Qadir *et al.*, 2001; Akhter *et al.*, 2003; Jayasekera and Hall, 2007). The selection of the appropriate method depends on many factors such as soil properties, water supply, salt types, required remediation time, drainage system and others.

When reclaiming an agricultural soil contaminated by salt released from petroleum industry, three major problems are encountered: 1) the sodium in soil is in large amount and extremely high concentration; 2) the associated chlorides are present in extremely high concentrations and are very mobile, highly toxic to plants; and 3) the soil is often fine-textured (silt and/or clay) and has low permeability. Large amounts of sodium in clay soils could make remediation more difficult compared to general dryland salinity remediation because of the interaction between dissolved salts (including exchangeable sodium ions) in the soil solution and the exchange phase of the clay minerals. This interaction will cause variations in clay mineral behaviour and thus leads to a deteriorated soil structure or dispersion (Sumner, 1993; Jayasekera and Hall, 2007). Soil dispersion can cause poor water infiltration, low permeability, surface crusting, water logging and soil strength reduction, not only adversely affecting agricultural productivity, but also threatening the long-term satisfactory performance of built infrastructure (Jayasekera and Hall, 2007)

1.2 Objectives

The purpose of this research is to investigate treatment technologies for a highly salt-contaminated soil. Six remediation technologies were conducted to compare the effectiveness. These six remediation technologies are leaching alone, leaching with physical amendment (alluing), leaching with alluing and chemical addition (gypsum or zeolite), leaching with alluing and sand addition, leaching with ripping and gypsum addition. Electrokinetic remediation was not chosen because it is a relatively new technology that is seldom used to remove sodium and chloride in the field and it is relatively complicated to conduct in the field. Phytoremediation was not considered in this project since the salt concentration on the site was too high for plants to grow, and the period of phytoremediation is considered to be long.

This research emphasized on how much sodium and chloride can be removed from the soil and in what time frame, and how the salts migrate during leaching of the soil by each treatment. Two important parameters in this research are EC and SAR, which determine the quality of treated soil and end time of the experiment.

The objectives of this research are to:

1. assess the extent and severity of salt-contamination in a cultivated agricultural land that was contaminated by the oil and gas industry,
2. investigate soil remediation treatment options in removing salts from a saline-sodic soil at both lab-scale and field-scale, and
3. based on results of the above investigation, suggest a suitable remediation option for the study site.

The study area is located on private land, which is for agricultural production. Preliminary soil survey results indicated that the site contained high salt and petroleum hydrocarbon concentrations. The salt-contaminated site was divided into 36 plots for the field-scale treatment study. Soil from the site was collected and transported to University of Alberta for lab-scale experiments.

This thesis will present a review of the relevant literature and a description of the experimental materials and methods used for the research project. Results of experiments are presented and discussed. Summary and conclusions are drawn from the results and suggestions for further work are proposed.

2 Literature Review

This chapter introduces the principle concepts used in this project: sources of salt in soil, major classification of salt-contaminated soils, factors affecting remediation of salt contaminated soils and remediation technologies used for these soils.

2.1 Sources of Salt

Salts are naturally existing minerals in the earth. They occur naturally in many bedrock deposits and the exposed rocks of the earth's crust. In addition to natural movement that carries salts from one location to another, anthropogenic activities may introduce salts into local soils.

2.1.1 Natural sources of salt in soil

Salts are components of natural minerals on the earth surface. They originally exist in bedrock deposits and exposed rocks of the earth's crust. Chemical weathering, which involves hydrolysis, hydration, oxidation, and carbonation, gradually releases salt ions from minerals and rocks into the surroundings (U.S. Salinity Laboratory Staff, 1954). Groundwater flowing through the area then carries these dissolved salts from one location to another. Under certain conditions, salts are left behind on or in the soils when water evaporates. Some soils have high salt contents due to the parent material that may consist of marine deposits that were left during earlier geologic periods. Irrigation water may also bring salts into soils. In arid and semi-arid regions, where rainfall is less than evaporation, salts are more likely concentrated in soils and surface water. (U.S. Salinity Laboratory Staff, 1954; Abrol *et al.*, 1988; Sumner and Naidu, 1998)

In Alberta, salts occur naturally in many bedrock deposits and in some deposits that lie on top of the bedrock. Groundwater dissolves and carries the salts from bedrock and glacial drift from one location to another, and evapo-transpiration concentrates salts on or in soils under certain conditions (Alberta Agriculture, Food and Rural Development, 2000; Alberta Environment, 2001). Most Alberta soils do not have salt problems naturally except Solonetzic soils, which have poor soil structure and permeability resulting from high sodium concentrations on the cation exchange complex (Alberta Environment, 2001).

2.1.2 Anthropogenic source of salt in soil

In addition to natural sources, anthropogenic activity will also introduce salts into soils. In Alberta, salt contamination in soil is typically the result of four major sources: former flare pits, salt water or salt-contaminated waste produced at industrial facilities, spilling of salt during transportation of saline material and runoff from snow removal dumps (Alberta Environment, 2001). Until 1996, the upstream oil and gas industry in Alberta has used flare pits for decades to store and/or burn produced fluids generated at well sites, compressor stations and batteries. Since produced fluids contain liquid hydrocarbons, process chemicals or salt water, the soils under these flare pits are heavily contaminated by hydrocarbons and salts (Amatya *et al.,* 2002; Arocena and Rutherford, 2005). It is estimated that there is about 30,000 flare pits in Alberta needing remediation

(Amatya *et al.*, 2002). In other activities related to the petroleum industry, the spills and disposal of brine and oilfield waste may contaminate soils with salts (EUB, 1996a; Alberta Environment, 2001). In the winter in Alberta, large amounts of salts are applied with sand to roads to enhance snow melting. These salts can enter the environment (soil and water) via leaching and runoff. Spills and leaks from salt storage facilities or during transportation of saline materials can also result in contaminated soil and water (Alberta Environment, 2001).

2.2 Classification of salt-contaminated soils

Salt-contaminated soils can be classified as saline soils, sodic soils or saline-sodic soils depending on the EC, SAR and types of salts present. This classification is described in the following sections.

2.2.1 Saline soils

Saline soils have high levels of soluble salts except sodium. A saline soil is defined as a soil with the electrical conductivity (EC) of the saturated paste extract greater than 4dS/m (at 25°C) and a pH usually less than 8.3 (American Petroleum Institute, 1997), or 8.5 (Alberta Environment, 2001). Saline soils may be recognized by the presence of a white crust at the surface soil, or damp oily-looking surfaces, stunted growth of crops with considerable variation in size, and sometimes tip burn of the leaves of crops growing in the saline soil (Abrol *et al.*, 1988). The major problem with saline soils is that high concentrations of total soluble salts in the soils prevent plants from absorbing water from the soils even though there may be substantial water present. This problem is correlated to the osmotic potential in the plant root zones. *"Osmotic potential is the force which causes dissolved constituents to try to retain water molecules."*(American Petroleum Institute, 1997) A high osmotic potential due to presence of excessive salts in soils, can cause plants to exhibit drought stress even when there may be substantial water present in soils (American Petroleum Institute, 1997; Plaster, 1997).

2.2.2 Sodic soils

The principal characteristic of sodic soils is the high sodium content. Sodium is often measured by SAR or exchangeable sodium percentage (ESP). A sodic soil is defined as a soil containing an ESP of 15% or more (SAR of 13 or more) (American Petroleum Institute, 1997; Alberta Environment, 2001). The problems associated with sodic soils vary with soils and crops. The pH of sodic soils is generally higher than 8.2 (Abrol *et al.*, 1988; Plaster, 1997), which can limit the growth of many crops. The major problem associated with sodic soil is soil dispersion. When sodium ions saturate cation exchange sites, the colloids will mutually repel and disperse soil aggregates. After irrigation or rainfall, due to the dispersion, these tiny soil particles in the soil pores seal the soil surface and may stop seed germination. Fine-textured soils (clay, for example), are more affected by sodium than coarse soils (sand, for example). Appreciable sodium taken up by plants can also injure plant tissues (American Petroleum Institute, 1997; Plaster, 1997).

2.2.3 Saline-sodic soils

Saline –sodic soils contain high levels of both soluble salts and sodium. Saline-sodic soils are defined as soils with an ESP greater than 15% and an ECe greater than 4dS/m (American Petroleum Institute, 1997; Plaster, 1997; Alberta Environment, 2001). Saline-sodic soils have both osmotic stress and dispersion problems. Saline-sodic soils may be prone to becoming sodic soils after periods of heavy rain or irrigation with low-salt concentration water. Appreciable quantities of water may wash soluble calcium and magnesium out of the soil, leaving behind sodium salts. The soil may then become sodic, with poor physical structure and drainage (Plaster, 1997).

2.3 Alberta Regulations related to salt-contaminated soils

Remediation of salt-contaminated soils must meet the requirements set out in federal and provincial acts and regulations. In Alberta, the *Environmental Protection and Enhancement Act* and its subsequent regulations provide the guiding principles for industrial activities, substance release reporting, remediation efforts and objectives (Alberta Environmental, 2001).

Two basic approaches are used in Alberta to determine remediation objectives for a specific site: a Guideline-Based Approach and Site-Specific Risk Assessment Approach (Alberta Environmental, 2001).The Guideline-Based Approach directly adopts the accepted soil remediation guidelines as objectives, while the Site-Specific Risk Assessment Approach involves an evaluation of the existing and potential hazard to receptors and the resulting risk at a specific site. The project described in this thesis used Guideline-Based Approach to determine the remediation objectives. After remediation, the soil quality will fall within the good rating categories of unrestricted land use, which are provided by Alberta Environment and Canadian Council of Ministers of the Environment (CCME). These rating categories are determined by the electrical conductivity (EC) and sodium adsorption ratio (SAR). The requirement of topsoil is stricter than that of subsoil. Table 1 presents the guidelines for unrestricted land use in Alberta and Table 2 provides the guidelines for commercial and industrial land uses in Alberta which use the Commercial/Industrial Criteria from the Canadian Council of Ministers of the Environment (CCME) *Interim Canadian Environmental Quality Criteria for Contaminated Sites*. Table 3 is Alberta Tier 1 salt remediation guidelines, which are consistent with the guidelines presented in Table 1 and Table 2.

Table 1: Soil quality guidelines for unrestricted land use in Alberta

(from Alberta Environment, 2001)

Parameter		Rating Categories			
		Good	Fair	Poor	Unsuitable
Topsoil[a]	EC (dS/m) (salinity[b])	<2	2 to 4	4 to 8	>8
	SAR (sodicity[c])	<4	4 to 8	8 to 12	>12
Subsoil[a]	EC (dS/m) (salinity)	<3	3 to 5	5 to 10	>10
	SAR (sodicity)	<4	4 to 8	8 to 12	>12

Notes:

a. Topsoil: surface A horizons on the control area, or the equivalent surface soil on the reclaimed site.
Subsoil: B and C horizons and the upper portion of the parent material.

b. Salinity: the amount of soluble salts in a soil. The conventional measure of soil salinity is the EC of a saturated paste extract.

c. Sodicity: The accumulation of exchangeable Na, estimated from the SAR of a soil-water extract.

Table 2: Soil quality guidelines for commercial/industrial land use in Alberta

(from Alberta Environment, 2001)

Parameter	CCME Soil Criteria
EC	4dS/m
SAR	12

Table 3: Alberta Tier 1 salt remediation guidelines
(from Alberta Environment, 2008)

Rating Categories	Good	Fair	Poor	Unsuitable	Commercial/ Industrial
Topsoil[a]					
EC (dS/m)	<2[b]	2 to 4	4 to 8	>8	4
SAR	<4	4 to 8	8 to 12	>12[c]	12
Subsoil[a]					
EC (dS/m)	<3	3 to 5	5 to 10	>10	4
SAR	<4	4 to 8	8 to 12	>12	12

Notes:

a. Topsoil: surface A, L, F, H, and O horizons on the control area, or the equivalent surface soil where these horizons are not present
Subsoil: B and C horizons and the upper portion of the parent material
b. Some plants are sensitive to salts at EC < 2dS/m
(e.g., flax, clover, beans, some wheat varieties, peas, some garden crops).
c. Material characterized by SAR of 12 to 20 may be rated as poor if texture is sandy loam or coarser and saturation % is less than 100.

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2.4 Salt-affected Soil remediation techniques

The objective of all salt-affected soil remediation technologies is to remove excess salts from the root zone and recover the soil self-sustaining vegetative ability. Two basic steps to reclaim salt-affected soil are to leach out the salts and then to ensure a good drainage to allow salted water leaving the soil profile. After the proper drainage installation, the next steps depend on the type of problems: a high water table, hardpans or fine soil texture (Plaster, 1997).

Compared to sodic soils, saline soils are more easily reclaimed. Flooding the soil surface could leach salts out of the soil profile via percolation. High-quality water works best, but saline water will also work well as long as it is low in sodium. Application of organic mulches was found to improve the remediation of saline soils because mulches reduce evaporation of water from the surface. Mulches also keep the soil loose to facilitate the movement of water downwards (Plaster, 1997).

Saine-sodic and sodic soils can not be ameliorated simply by leaching because the sealed soil surface will restrain leaching and drainage. Removal of excess sodium is usually necessary beforehand, which may be done by treating the soil with calcium containing amendments. When calcium replaces sodium on the cation exchange sites, the soil slowly begins to aggregate and the soil structure is improved (Oster, 1993; Plaster, 1997).

Remediation techniques are often applied in a combination. For example, a physical activity is performed to break up the impermeable layer, then gypsum is added into the soil and finally leaching is conducted to wash salts below the root zone. Some techniques are site-specific while some techniques (e.g. leaching) are applicable to most types of soil.

2.4.1 Leaching

Leaching is to transport salts downward through the soil to below the root zone by water. It is the most common technique for salt-affected soil remediation. If there is not sufficient water to leach salts to a safe depth, the salt may move back to the soil surface by capillary rise and evaporation.

According to Qadir *et al*. (2000) and U.S. Salinity Laboratory Staff (1954), "*the fraction of the irrigation water that must pass through the root zone to control* *soil salinity within an acceptable level is referred to as the leaching requirement (LR)*". The leaching requirement depends on the salt concentration of the irrigation water and the acceptable salt concentration in the drainage water. Since, under field conditions, the applied water may not all pass through the root zone, the fraction of the irrigation water that actually percolates to the required soil layer is called leaching fraction (LF) (Qadir *et al*., 2000). The leaching fraction can be calculated as the ratio of the depth of the drainage water (D_{dw}) to the depth of irrigation water (D_{iw}). Under steady-state conditions without salts contribution or loss, the ratio is equal to the ratio of salinity in irrigation and drainage water (EC_{iw}/EC_{dw}) (U.S. Salinity Laboratory Staff, 1954; Qadir *et al*., 2000), that is:

$$LF=D_{dw}/D_{iw}=EC_{iw}/EC_{dw}$$

Leaching water can be applied by three methods: continuous ponding, intermittent ponding and sprinkling irrigation. Continuous ponding is the fastest way to move salt down through the soil profile, yet the sprinkling irrigation is the most effective method (Oster *et al.,* 1972; Warren, 1987). An experiment conducted by Babel and Purohit (1988) indicated that high rate sprinkling saved approximately 35% water compared to ponding to achieve a similar removal of salt but need more time. Intermittent ponding of water is more effective in leaching salts than continuous ponding, but needs more time to achieve the similar results (Miller *et al.,* 1965; Oster *et al.,* 1972).

In an area where irrigation water is not sufficient, saline solutions may be used as leaching water. Vander-Pluym *et al.* (1973) found that the hydraulic conductivity of the soil changes in the same direction as the SAR of the leaching water when a highly saline solution (800meq/L) is used. Leaching water with low SAR produced soils with low hydraulic conductivity, most likely due to large amounts of sodium that leached from the surface soil into the subsurface, where the sodium caused an increase in the swelling of the clay soil and an irreversible reduction in the soil's hydraulic conductivity.

2.4.2 Chemical amendments

The major mechanism of action of chemical amendments is ion exchange, which involves the in-situ displacement of sodium from soil cation exchange sites and then permanent removal of produced soluble salts to a suitable location. Soils have a preference for cations with more than one positive charge, so adsorbed cations of lower valence, such as Na^+, tend to be replaced by cations of higher valence, such as Ca^{2+} in a dilute solution, such as soil-water solutions (Helfferich, 1992; Mitchell, 1993). Therefore, calcium products are the most common chemicals used in chemical remediation. For calcareous sodic soil, some acids or acid formers, e.g. H_2SO_4 or sulfur, are used to dissolve $CaCO_3$, which then provides soluble Ca^{2+} to replace Na^+ (Miyamoto *et al.*, 1975; Qadir *et al.*, 2001).

2.4.2.1 Calcium Application

Calcium sources include gypsum ($CaSO_4 \bullet 2H_2O$), calcium chloride ($CaCl_2$), calcium nitrate ($Ca(NO_3)_2$,), and lime (CaO). When the pH is between 5.5 and 8.5, gypsum, calcium chloride or calcium nitrate may be applied to reclaim sodic soil. Although $CaCl_2$ and $Ca(NO_3)_2$ are faster and more effective in sodic soil remediation due to their high solubility, gypsum is still the most popular calcium source because $CaCl_2$ and $Ca(NO_3)_2$ are expensive and may cause potential contamination of the groundwater and soil by introducing nitrates or yet more chloride (American Petroleum Institute, 1997; Alberta Environment, 2001; Qadir *et al.*, 2001). The chloride and nitrate anions from $CaCl_2$ and $Ca(NO_3)_2$ amendments can be problematic since too much chloride in soil is toxic to plants and some jurisdictions have restrictions on chloride and nitrate levels. Even small concentrations of nitrate in water may cause oxygen depletion, algal blooms, and may be very harmful to infants who may ingest it (American Petroleum Institute, 1997; Alberta Environment, 2001).

Lime can be applied to counteract soil acidity if the pH of soil is less than 5.5 (American Petroleum Institute, 1997). It can not only provide calcium to displace sodium but it can also adjust pH of soil. Lime provides additional benefits of improving crop response to fertilizers by increasing uptake of nutrients and removing aluminum toxicity. The problem with lime application is that lime might raise the pH to higher than 7.0 (Plaster, 1997).

2.4.2.2 Sulfur/ H_2SO_4 Application

Sulfur is applied to sodic soil when there is the presence of calcium carbonate in the soil (Miyamoto *et al.*, 1975; Loveday, 1984; American Petroleum Institute, 1997). The mechanism is listed as follows:

$$2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4 + \text{energy.}$$

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2O + CO_2 \text{ (gas)}$$

These equations show that sulfur is used to produce acid that introduce soluble calcium into soils. Hence, alternatives to sulfur could also achieve the same objective. These alternatives include aluminum sulfate, iron sulfate, and sulfuric acid (Miyamoto *et al.*, 1975; Loveday, 1984; American Petroleum Institute, 1997). Sulfuric acid can also be applied directly into soils. The methods of acid application include sprinkling of concentrated acid and water-applied acid(Miyamoto *et al.*, 1975). It was found that compared to water-applied acid, sprinkling of H_2SO_4 may result in less destruction of soil aggregates (Miyamoto *et al.*, 1974), faster movement of leaching water (Miyamoto *et al.*, 1973) and greater leaching of salts with the same amount of water (Miyamoto *et al.*, 1975).

Some experiments in calcareous sodic soils found that H_2SO_4 increased water penetration into the soils with the removal of Na^+ more effectively than gypsum (Prather *et al.*, 1978) or crop yields from H_2SO_4 treatment site were higher than the gypsum treatment sites although Na^+ removal was nearly same (Ahmad *et al.*, 1986; Ghafoor *et al.*, 1986).

Compared to the alternatives, application of elemental sulfur is less effective and restricted to sites where topsoil is rich of sulfur-oxidizing bacteria (Plaster, 1997) because the oxidation of sulfur to sulfate requires the presence of the soil-borne bacterium (American Petroleum Institute, 1997). However, sulfur is preferred for longer lasting pH reduction and for larger areas (Plaster, 1997).

Other chemicals used to reclaim sodic soils include various polymers added to irrigation water for the purpose of stabilizing the hydraulic properties of sodic soils (El-Morsy *et al.*, 1991) and polyacrylamide (PAM) to promote flocculation of mildly sodic soils at low EC values (Aly and Letey, 1990) and to increase the hydraulic conductivity (El-Morsy *et al.*, 1991).

Usually, chemical addition is not by itself sufficient to reclaim salt-contaminated soil. In order to succeed in chemical remediation, salts must be permanently leached below the root zone, at least 1.5 to 1.8 m below the surface (Chang *et al.*, 1991; Oster, 1993; American Petroleum Institute, 1997). Therefore, the following activities are usually included when performing chemical amendments:

- Improve drainage
- Apply and incorporate chemicals and other soil additives, like organic materials
- Install facilities for erosion control and irrigation
- Irrigation (leaching)
- Follow by bioremediation or revegetation

In addition, chemical amendments are best applied to the soil before any leaching commences. It is critical to monitor the change in EC during the leaching process because it is difficult to predict the rate of salt leaching from soils and the potential for inadvertently inducing dispersion due to lack of chemical amendment (American Petroleum Institute, 1997).

2.4.3 Physical amendments

Physical amendments involve mechanical activities that are performed to increase the hydraulic conductivity of soil. When there are impermeable layers in soils, physical amendments may be more cost effective and necessary to promote good soil drainage and adequate removal of soluble salts (American Petroleum Institute, 1997). Impermeable layers can be broken up by heavy-duty deep plowing, tillage or by hydraulic fracturing (American Petroleum Institute, 1997; Sumner and Naidu, 1998; Qadir *et al.*, 2001).

Physical remediation includes in-situ and ex-situ methods. Ex-situ remediation involves excavation and relocation of the salt-affected soil to a suitable treatment cell or ultimate disposal. It is most often selected for sites with very high salt-levels; near surface usable or sensitive groundwater; shallow soils; and where regulatory, lease, or other legal considerations favor mechanical remediation (American Petroleum Institute, 1997).

In-situ physical remediation involves physical activities (for example tillage) to break up impermeable layers that are formed due to excess sodium ions in soils. In-situ physical remediation increases the physical and hydraulic characteristics of soils. When the soil is loosened by tillage or alluing, the total porosity is increased and macropores are formed (Qadir *et al.*, 2001). This increased porosity results in an increase in plant-available water at water contents after irrigation. Under this situation, both saturated and unsaturated hydraulic conductivity at high water potentials are increased. These changes could lead to faster infiltration and improve aeration of sodic soils. However, physical activities at unfavorably high soil water contents may cause smearing and compaction, resulting in negative changes in the physical and hydraulic properties of the treated soil (Sumner and Naidu, 1998).

The problem with physical remediation in sodic soils is that the physical improvements are often not permanent. The reason for this is that wet soils have little strength and they tend to reconsolidate under their own weight, which is faster in sodic soils. Consequently, the hydraulic characteristics will deteriorate again (Sumner and Naidu, 1998). Another problem with physical remediation is that macroporosity created by physical activities is often reduced by in-field traffic compaction. Carter (1985) found that cotton fields without traffic had between 21% and 32% better water penetration than those with normal traffic.

2.4.4 Electrokinetic remediation

Electrokinetic remediation refers to treating salt-affected soils with electric current (Qadir *et al.*, 2001). The principles of electrokinetic remediation involve applying an electric current to the soil via electrodes inserted in the soil (Jayasekera and Hall, 2007). The passing of the electric current through a soil will cause charged ions to migrate towards an oppositely charged electrode and accumulate around the electrodes. The concentrated ions around the electrodes can then be removed by methods of electroplating, precipitation at the electrode or pumping near the electrode (Pamukcu *et al*., 1997 cited by Jayasekera and Hall, 2007). Another function of electrical current is to increase solubility of CaCO3 in calcareous sodic soils during remediation and thus to supply Ca^{2+} for soil amelioration (Qadir *et al*., 2001).

Electrokinetic remediation is most used to remove heavy metals such as arsenic, zinc, lead and copper (Jayasekera and Hall, 2007). Although the studies of electrokinetic remediation on saline-sodic soils have shown promising potential, it did not replace the commonly used chemical or physical remediation (Qadir *et al*., 2001).

2.4.5 Phytoremediation

Salt-affected soils can be ameliorated through phytoremediation, which is the use of salt-tolerant crop plants to uptake salts. Phytoremediation may remediate salt-affected soils via three mechanisms: plant root action to dissolve some native $CaCO_3$, providing Ca^{2+} (Qadir *et al*., 2001); improving the soil structure via plant roots penetrating the soil and increasing the pressure of CO_2 in soils; and accumulation of salts in plant shoots or leaves that can be removed by harvest (Robbins, 1986; Qadir *et al.*, 1996; Qadir *et al*., 2002).

Experiments conducted in the field and in the laboratory have shown that phytoremediation can remove significant amounts of salts (Robbins, 1986; De

Villiers, 1995; Akhter *et al.,* 2003; Qadir *et al.,* 2003). Qadir *et al.,* (2002) found that phytoremediation and chemical amendment resulted in similar decreases in soil salinity and sodicity. In comparison with gypsum amendment, phytoremediation was more persistent in terms of soluble salts and maintenance of electrolyte concentration in leachates. The advantages of phytoremediation include low initial capital investment, increased availability of some nutrients in the soil during and after amelioration and financial benefits from crops grown (Qadir *et al*., 2002). However, phytoremediation often requires much longer time to achieve a similar result as chemical amendment. Since the cost of chemical amendment is affordable, the long remediation time for phytoremediation makes phytoremediation less attractive as a remediation option (Qadir *et al*., 2001).

Prior to phytoremediation, plant selection must be made carefully. It should be ensured that the crop to be used for phytoremediation can survive and grow in the site conditions where poor soil physical properties and Na-induced nutrient deficiency may inhibit crop growth (Maas and Grieve, 1987; American Petroleum Institute, 1997).

2.5 Factors affecting soil remediation

Soil remediation is affected by many important factors, including soil properties such as soil texture, pH, major ions present in the soils, salt movement in the soil profile and the soil drainage system.

2.5.1 Soil properties

Soil remediation requires detailed information on the soil physical characteristics, chemical characteristics, texture, horizons, slope, erosion, and drainage (American Petroleum Institute, 1997).

2.5.2 Soil texture

The ratios of sand, silt and clay in soils have a close relationship with soil permeability, water retention and ions retention. In general, soils with high sand content have better permeability and aeration, while soils with high clay content have a better ability to hold water but less aeration and permeability. Clay content is important to soil reclamation because it influences the stability of the soil structure and the hydraulic properties. Moreover, clay particles have a large surface area, thin platy shape and negative lattice charge, which absorb exchangeable cations. Some types of clay swell when wet and shrink when dry (Plaster, 1997).

Figure 1 describes how soil texture affects the permeability of a soil. The top line shows the total amount of pore space in soil. Clay has the greatest total pore space. The lower line presents how much space is in the form of large pores. It can be seen that sand has the most large pore space. However, permeability depends not only on the amount of pore space in soils, but more on the size and continuity of the pores. Large and continuous pore spaces, or macropores, lead to a higher permeability (Plaster, 1997).

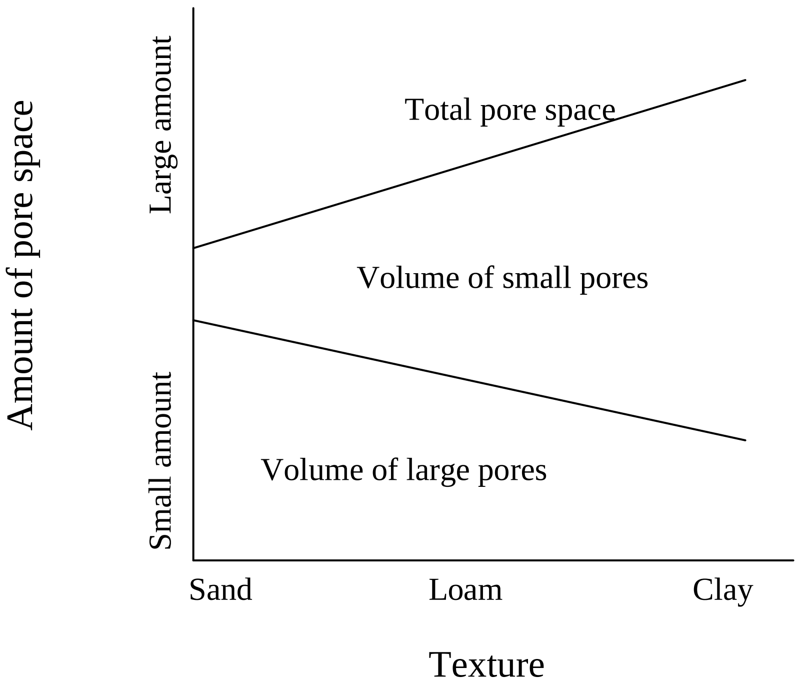


Figure 1: Amount of pore space and approximate pore size distribution as a function of soil texture
(from Plaster, 1997)

2.5.3 pH and ions

It is known that each plant grows best in a specific pH range. Soil pH affects plant growth on the following aspects: (1) nutrient availability; (2) the build-up of toxic levels of aluminum or other metals; and (3) on soil microbes (Plaster, 1997). Rather than changing pH of soils, it is cost-effective and simple to grow crops that match the present soil pH (Plaster, 1997).

A relationship exists between remediation methods and soil pH. American Petroleum Institute (1997) suggests that for the soil with pH below 5.5, lime ($CaCO_3$) and $MgCO_3$ are effective for remediation. If a soil has a pH greater than

8.5, and contains appreciable quantity of calcium and magnesium carbonate, acid or sulphur may be more cost-effective. Gypsum application would be suggested to treat sodic soils having a pH between 5.5 and 8.5.

Soil pH results from the interaction of soil minerals, ions in solution and cation exchange. Plaster (1997) states high pH is caused by reaction of water and the bases (calcium, magnesium and sodium) to form hydroxyl ions. For example, the pH of sodic soils results from the reactions of carbonates with water to form hydroxyl ions, according to the following reactions:

$$CaCO_3 + 2\ H_2O \rightarrow Ca^{2+} + H_2CO_3 + 2OH^-$$

$$Na_2CO_3 + 2H_2O \rightarrow 2Na^+ + H_2CO_3 + 2OH^-$$

The hydrolysis of calcium carbonate results in a pH about 8.0-8.5. When abundant sodium is present (i.e. SAR>13), the hydrolysis of sodium produces sodium hydroxide, which can raise the pH to 10.0.

In zones with sufficient precipitation, leaching removes excess basic mineral. When the concentration of these minerals is reduced, hydrolysis of exchangeable bases will control the pH between 7.0 and 8.0 (Plaster, 1997):

$$\text{micelle-}Ca^{2+} + 2H_2O \rightarrow H\text{—micelle—}H + Ca^{2+} + 2OH^-$$

When pH declines to below 6.0, the aluminum ions start to be released from the structure of silicate soil and react with water to form hydrogen ions and aluminum hydroxide compounds (Plaster, 1997).

$$\text{micelle—Al}^{3+} \rightarrow \text{Al}^{3+} + \text{micelle}$$

$$\text{Al}^{3+} + 2\text{H}_2\text{O} \rightarrow \text{Al(OH)}_2^{+} + 2\text{H}^{+}$$

The above reaction is the major cause of most acidic soils.

The soluble ions of greatest concern in soils are sulfates, bicarbonates, carbonates, nitrate, chlorides, calcium, magnesium, and sodium. In a dry soil system, some cations are tightly adsorbed by negatively charged clay particles to neutralize the electronegativity of clay particles and associated anions, and some are present as salt precipitates. When clay is wet, the precipitated salts dissolve into solution and try to diffuse away because of high concentration near the surface of clay produced by adsorbed cations. The salts are also attracted by the negative electrical field originating in the clay particle surfaces (Mitchell, 1993). Usually, all other things equal, multivalent cations have greater attraction to the soil than monovalent cations. The preference exchangeable series for the most common cations is as follows (Helfferich, 1992; Mitchell, 1993):

$$\text{Al}^{3+} > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^{+} > \text{NH}_4^{+} > \text{Na}^{+}$$

This series is suggested as a result of various force competition. One is repulsive force between colloidal particles, which relates to the double layer. The more compressed the double layer becomes, the smaller the repulsive force between the colloidal particles. Another is the attractive force between colloidal particles due to Van der Waals forces, which decreases with the second power of the distance between the particles. Therefore, this force is only important when colloidal particles are approaching each other closely (Van Olphen, 1963). Ionic potential and size also influence the adsorption of salts to soil. Calcium is preferred to sodium due to its higher ionic potential and more compressed diffuse double layer. In addition calcium forms much more stable complexes with organic matter (Sumner, 1998).

Excess cations will cause soil dispersion and enhance soil swelling. With respect to dispersion, sodium has the most effect, potassium and magnesium at intermediate positions, and calcium least dispersive among common cations in soils (Sumner, 1993). At low SAR levels, effect of sodium on swelling would not cause soil degradation appreciably. However, when SAR is higher than 13, swelling due to sodium becomes important (Sumner, 1993). Figure 2 shows Ca^{2+} and Na^{+} exchange on soil structure.

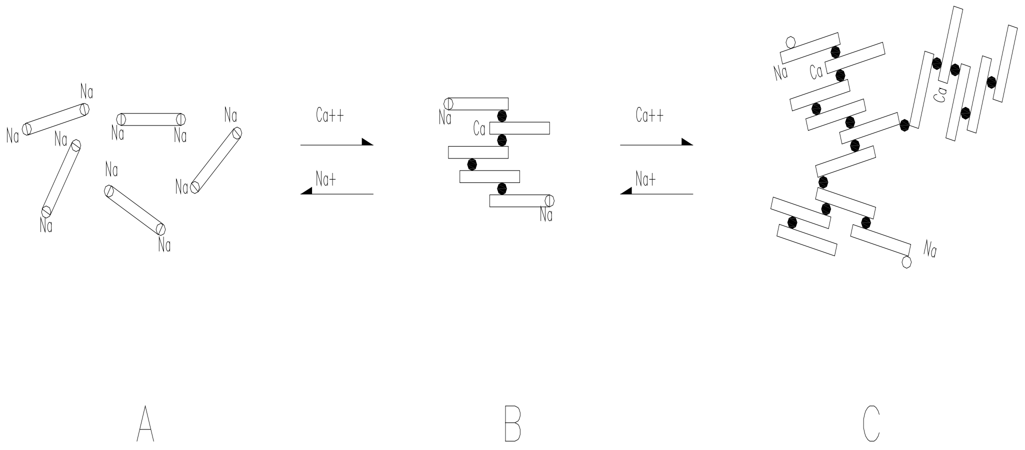


Figure 2: The effect of Ca and Na exchange on soil structure showing dispersed clay (A) , flocculated clay (B) and stable aggregates (C) (from Rengasamy *et al.*, 1984)

When the exchange complex of the soil is occupied by greater than 15% sodium, the clay is dispersed (A), resulting in a poor soil structure. When calcium ions replace enough sodium ions from the exchange complex, the clay is flocculated (B); and stable soil aggregates are formed that create a good soil structure (C). **(**Rengasamy *et al.*, 1984)

2.5.4 Organic matter

Organic matter is beneficial to improve and maintain soil structure, prevent soil erosion, increase the cation exchange capacity of soils and the selectivity of exchange sites for Ca over Na, and thus hasten reclamation process. Organic matter could help to cement the loose aggregates that are formed when soil particles stick together, making the weak aggregates strong. Thus, the intrusion of sodium may be more difficult into soils if the organic matter occurs in conjunction with clay particles rather than into clay alone (Chhabra, 1996; Plaster, 1997).

Organic matter in soils increases the soil water-holding abilities. When salt-affected soils dry and are then saturated with water again, there is a potential for the soil particles to disperse. The water-holding ability of the organic matter component in the soil inhibits the soil from drying out, improving soluble salt exchange during treatment. Through the increase of cation exchange capacity (CEC) and organic matter's ability to donate protons, organic matter may retard the degree to which a soil becomes sodic or reduce the soil sodicity (Sumner and Naidu, 1998). Therefore, frequent addition of organic matter to soils can enhance the stability of soil structure and reduce remediation time. It was found that organic exchange sites tend to hold more calcium and less sodium than their clay counterparts (Frenkel *et al.*, 1992; Gu and Doner, 1993; Sumner and Naidu, 1998).

2.5.5 Moisture

The effect of soil salinity on plants is related to the moisture content of the soil. The moisture content at which EC and SAR are measured is very important. The higher the moisture content is, the greater the ratio of less soluble salts (calcium and magnesium salts) to more soluble salts (sodium salts) is. Saturation percentage is measured to represent the maximum moisture content at which dissolved salts are available, and at which enough soil water can be extracted from the soil to allow measurements of salts (U.S. Salinity Laboratory Staff, 1954; American Petroleum Institute, 1997).

2.5.6 Salt-movement in the soil profile

2.5.6.1 Leaching

Leaching is the predominant mechanism to move salts vertically down to deeper soil, although soluble salts can move in any direction by leaching through the soil (Finlayson, 1993). The amount and rate of leaching are influenced by many factors, such as the quantity of water applied to the soil and hydraulic conductivity of the soil (Finlayson, 1993). Leaching is the major action to remove salt out of the required depth of soil profile.

2.5.6.2 Capillary action

Soluble salts are able to move upward with water via capillary action. Capillary rise is an important mechanism by which soils become saline. When water moves upward and then transpires and/or evaporates at the soil surface, salts carried by water are left behind and accumulate in the upper and surface soil. Figure 3 presents salt build up by capillary action and evaporation. The amount of water and salts that reach the soil surface through capillary rise depends on the soil texture, the depth of water table, and the concentration of salts in the soil water and groundwater (Chhabra, 1996). The following equation mathematically defines capillary rise (Chhabra, 1996).

$$\text{hc}= 2\psi \times \frac{\cos\theta}{r} \times \ \rho_W \times g$$

where hc is equilibrium height of capillary rise, ψ is surface tension, θ is wetting front, r is radius of capillary tubes, ρ_W is density of water, and g is acceleration due to gravity.

This equation predicts that more water will rise in high clayey soils that have finer pores (i.e. smaller value of r) than in sandy soils that have wider pores (i.e. higher value of r). However, capillary rise often occurs within the top one meter of the soil profile (Finlayson, 1993).

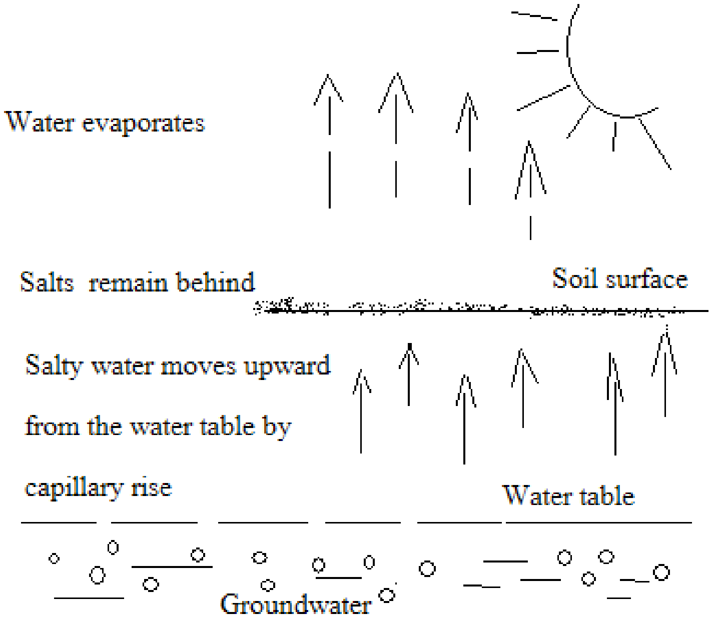


Figure 3: **Salts build up by capillary action and evaporation**

(Modified from Alberta Agriculture, Food and Rural Development, 2000)

Since capillary rise may bring salts to the surface of the soil, it will not be useful to cover a layer of clean soil at the surface and allow reclamation and/or vegetation for those soils with high salinity. To avoid capillary rise carrying more salts into top soil, a layer of barrier material may work. Rooney *et al.* (1998) found capillary barriers of 8 cm prevented upward migration of salt into the topsoil, thus allowing vegetation to be established although capillary barriers did not provide complete hydraulic isolation of the saline soil.

2.5.6.3 Evaporation

Water at the surface soil tends to evaporate quickly when the surrounding temperature is high, leaving the salts to accumulate at or near the surface. Salts will accumulate at the surface when the amount of water leaving the soil surface via evaporation exceeds the amount of water entering the soil by precipitation, irrigation and runoff (Henry et al., 1987).

2.5.6.4 Chemical diffusion

Chemical diffusion may introduce salts to soils and thus cause salinization. Chemical diffusion is affected by sharpness of gradient between non-saline soil materials and underlying strongly saline materials, and hydraulic conductivity of the materials (Finlayson, 1993). However, movement of salt by chemical diffusion generally occurs within the upper 30 cm soils (Finlayson, 1993).

2.5.7 Drainage

Drainage is the major pathway for salts to migrate out of soil profiles. Proper soil drainage is critical to the success of salt-affected soil remediation. Poor design and installation of soil drainage might be the most common reason for failure of reclamation projects (American Petroleum Institute, 1997).

2.6 Summary

Salt enters into soil through two routes: natural existing sources and anthropogenic activities. Anthropogenic activities introduce salt into soils via many pathways, such as production water spills and pipeline leaks from oil and gas production, flare pits, or runoff from snow removal dumps. To protect farm lands from the adverse impact of salts and to reclaim salt-affected soil back to a cultivated soil, Alberta Environment has set out a series of regulations and requirements under Environmental Protection and Enhancement Act to assist those involved in prevention, assessment, remediation and management of salt-contaminated sites.

Problems with high salt concentrations in soils include (1) hastening drought stress due to increased soil osmotic potential as salts compete with plants for water; and (2) unwanted soil dispersion occurring when negatively charged clay colloids mutually repel and clog macropores, which severely restricts the ability of water and air to move through the soil.

Current treatments for salt-affected soils can be categorized into leaching, chemical amendments, physical amendments, electrokinetic remediation and phytoremediation. The following factors are taken into consideration when determining a remediation technology for a specific salt-contaminated soil: soil texture, major ions in soil, soil pH, soil organic matter content, soil moisture, movement of salts in soil and soil drainage situation. When practicing remediation for a highly salt-affected clay soil, the interaction between Na^+ in the soil solution and the exchange phase of the clay minerals can cause challenge for salt removal from soils. Under high sodium conditions (sodium adsorption ratio $SAR > 13$), this interaction can cause clay colloids to repel each other and thus result in a poor soil structure. Leaching is the predominant mechanism to move salts downward to deeper soil, while capillary action and evaporation are able to bring salts upward to upper and surface soil. A proper soil drainage system is critical to the success of salt-affected soil remediation.

3 Materials and Methods

The experimental program carried out in this thesis involved both field experiments and laboratory experiments. The materials and experimental methods used to investigate the use of gypsum, sand, zeolite and physical methods to remediate salt-contaminated soil are described in the following sections.

3.1 Materials

3.1.1 Experimental site

The studied site is located on private land that is used for cultivated agriculture. A creek flows through the quarter-section approximately 150m west of the site. The site included three above ground storage tanks, an evaporation pond, a flare pit, a well and associated flow lines (Soil Solutions Environmental Consulting Ltd., 2005). Preliminary soil surveys indicated that the site was a saline-sodic clay loam. Topsoil (upper 0.2m surface soil) EC values have good to fair ratings. SAR values for topsoils have good ratings, but the SAR values for subsoils have fair to poor ratings.

3.1.2 Soil

Soil for use in laboratory experiments was collected from the plow layer (upper 15 cm) of the contaminated site. The soil was transported to the lab in the Department of Civil and Environmental Engineering at the University of Alberta and stored in the cold rooms until use. Before use in the experiments, the soils were air-dried, ground, passed through a No.10 sieve (Canadian Sieve Series-

2mm opening) and mixed thoroughly. A sample of the soil was analyzed in the Department of Civil and Environmental Engineering at the University of Alberta to determine particle size distribution, organic matter content, water content, cation exchange capacity (CEC), electrical conductivity (EC), and pH. The determination of particle size distribution was accomplished using the American Society for Testing and Materials (ASTM) methods. Other properties were determined using procedures outlined in Table 4. Details of analytical methods are presented in Section 3.4.

Table 4: Analytical methods

Parameters	**Analytical Method**
Electrical Conductivity (EC) (dS/m)	Thermo Orion Models 130A, 131S portable conductivity meter
pH	Thermo Orion 290 A+ pH meter
Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} ,NO_3^-	Ion Chromatography (IC),Dionex 2500
Water content	Oven-dry at 105°C, by Fisher Isotemp®500 series
Organic matter content	Oven-dry at 550°C, , by Fisher Isotemp®500 series
Cation Exchangeable Capacity	Ammonium Acetate method
Sodium Adsorption Ration (SAR)	SAR= $meqNa^+ / \sqrt{\left(meqCa^{2+} + meqMg^{2+}\right)/2}$
Density	Designation:D698-78 (ASTM,1996a)
Specific gravity	Designation:D854-83 (ASTM,1996b)
Particle size analysis	Hydrometer, Designation: D 422-63 (ASTM,1996c)

3.1.3 Gypsum

Gypsum (Baker Analyzed'® Reagent) was purchased from the Department of Chemistry at the University of Alberta (Edmonton, Alberta).

3.1.4 Zeolite and sand

Zeolite (Bear River Zeolite, Edmonton, Alberta) and sand were taken from the field, and transported to the Department of Civil and Environmental Engineering at the University of Alberta, where they were washed with deionized water before use. The properties of the zeolite are summarized in Table 5. Sorption and desorption tests of zeolite were performed to determine how much Na^+ and Cl^- would be sorbed or desorbed from surrounding solutions of high and low concentration.

Table 5: Specification of zeolite used in the experiments

Physical Characteristic					
Cation Exchange Capacity:	1.5 to 1.8 meq/gram (as ammonium,-N)				
Maximum Water Retention:	>55 %weight				
Overall Surface Area:	24.9 m^2/g				
Bulk Density	Approx. 881.1-961.2 kg/m^3				
Color	Pale green				
Chemical Composition					
Cations: Potassium, 3.47%; Calcium, 1.60%; Sodium, < 0.5%.					
MgO	0.45%	Al_2O_3	10.6%	Fe_2O_3	1.7%
K_2O	4.19%	CaO	2.23%	Na_2O	0.59%

3.2 Field-scale experiment

3.2.1 Experimental design

The site was divided into 36 plots: 3 blocks of 12 plots each (Figure 4). Each plot was 5m by 5m, and the distance between each block is 6.5m. A drainage system was installed at 5m spacing and at a 2.3m depth across the site. The main drainage pipe was 15cm inner diameter and the sub-drainage pipe was 10cm inner diameter. A circular sump of 90cm diameter and 2.5m was installed at northeast.

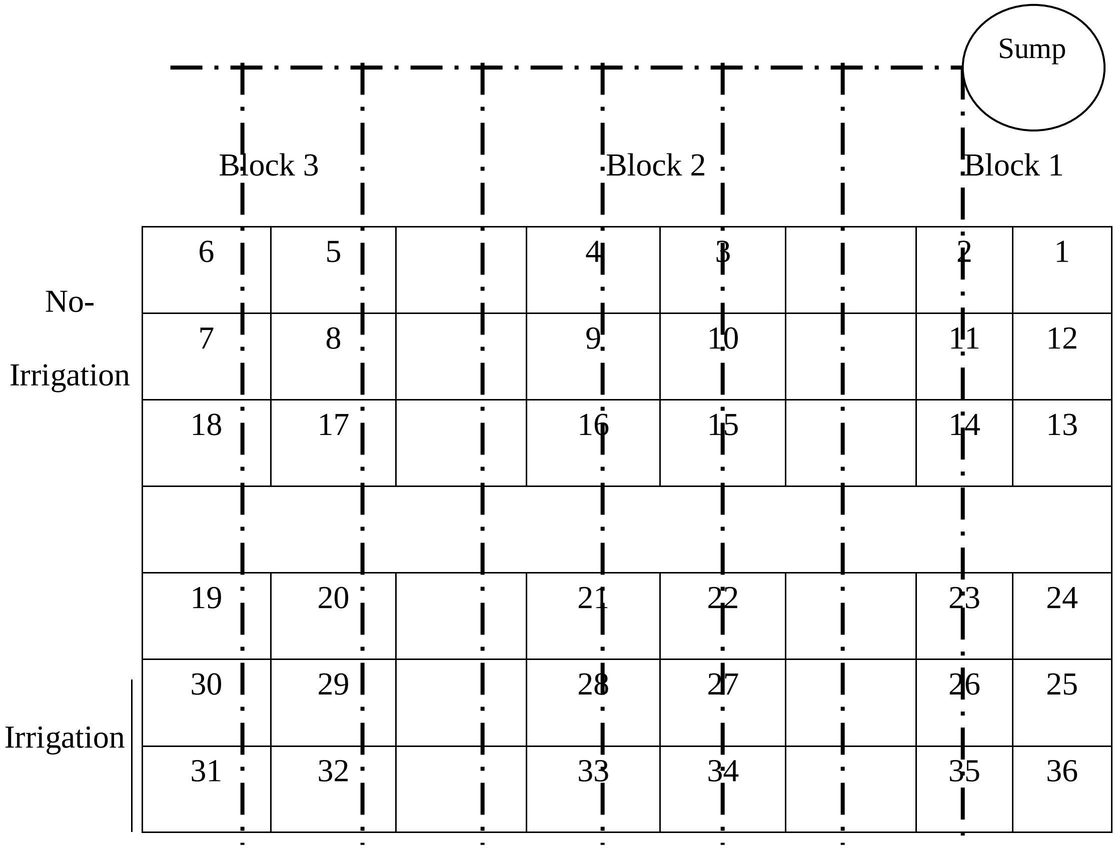


Figure 4: Field design with ▬ · ▬ indicating the placement of the drainage system

3.2.2 Treatments

Five treatments and control were applied to the plots in triplicate, with and without irrigation. The selection of plots for a specific treatment was based on a completely randomized design. Table 6 shows the treatments and plots where the treatments were applied.

Table 6: Treatment description

Treatment Name	Treatment Abbreviation	Plots	Treatment Description
Control	C	6,12,16*, 22,30,36**	No chemical addition or physical activities
Allu	A	5,11,15*, 21,29,35**	Soils were dug out, well mixed and then placed back on site.
Allu and Sand	AS	4,8,14*, 24,28,32**	Soils were dug out, mixed with sand thoroughly and then placed back on site (Sand: Soil=1:10, in volume).
Allu and Gypsum	AG	2,10,18*, 20,26,34**	Soils were dug out, mixed with gypsum thoroughly and then placed back on site. (0.4ton gypsum/plot)
Allu and Zeolite	AZ	3,7,13*, 23,27,31**	Soils were dug out, mixed with zeolite thoroughly and then placed back on site. (Zeolite: Soil=1:10 in volume)
Ripping and Gypsum	RG	1,9,17*, 19,25,33**	0.15ton gypsum was spread uniformly on the surface of the plot and then the upper 0.4 m of the soil was ripped.

* Non-irrigated plots
** Irrigated plots

3.2.3 Soil sampling

A randomized sampling template (Figure 5) was used to determine the soil sampling location in each plot, and each plot was small and assumed to be uniform. Three sampling locations were determined from the data generated by the computer using the random function in Excel. The randomized sampling template was designed as follows.

- Set up coordinates for each plot by establishing two base lines at right angles to each other which intersect at the northwest corner of the plot;
- Establish 0.5m scale interval along each base line;
- Draw lines perpendicular to the base lines at interval points. The perpendicular lines of one base line will intersect with the perpendicular lines of the other base line. Three intersections will be randomly selected as sampling locations. The distance of any two sampling locations should be more than 3m.

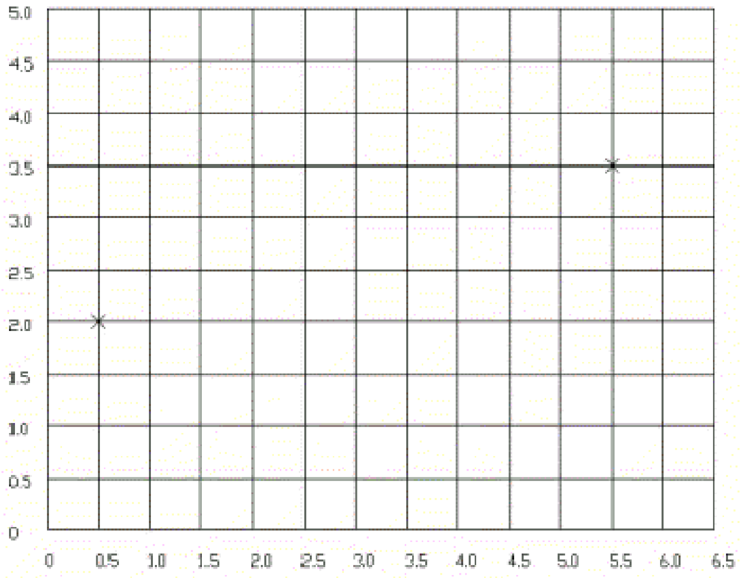


Figure 5: A randomized sampling template

3.2.4 Sampling depth and time

Soil sampling was carried out at 0.3m, 0.6m, 1.0-1.3m, and 2.0m depths at three randomly selected locations using Figure 5 in each plot. The drainage collection pipes were placed at the depth of 2.3m.

Soil was sampled with a machine auger and a sampling knife. To avoid any cross-contamination, the auger and knife were cleaned between samples.

Before the initiation of the experiment, soils were sampled once, in June, 2005. After the initiation of experimentation, soils were sampled right after the physical treatment, in August, 2005, and November, 2005.

3.2.5 Sampling quantity

Approximately 1 kg of soil was collected at each depth and sampling site. This approximate mass was determined based on suggested values given by U.S. Salinity Laboratory Staff (1954) for the required analysis (Table 7).

3.2.6 Samples preservation

Soil samples from each depth were placed in heavy duty Ziplock^{TM} bags. Groundwater and soil water samples were preserved in clean, dry glass sample bottles. All the samples were stored in coolers while on site, and then transported immediately after sampling to the University of Alberta, where they were stored in cold rooms. All samples were labelled with the following information:

sampling date, identification number, sampler's name, sampling site, depth, sample type and relevant sample site observations.

Table 7: Recommended sampling size for soil analysis
(from U.S. Salinity Laboratory Staff, 1954)

Analysis	Amount of Soil Required (g)
EC of saturated paste extract, Saturation (%), pH	250
Soluble ion analysis	250
Gypsum & alkaline-earth carbonates	50

3.2.7 Soil samples analysis

The soil was taken from the site in June (before treatment), August (immediately after treatment) and November (three months after treatment). Soil samples taken at three locations of each plot in June were analyzed in Department of Civil and Environmental Engineering at University of Alberta. Detail procedures are presented in Section 3.4. Samples in August and November were only taken at one location in each plot due to economic reasons and then sent to commercial labs by Soil Solutions Environmental Consulting Ltd. for analysis. The data of August and November are provided for the discussion in this thesis.

3.3 Lab-scale soil column experiments

A series of laboratory-scale packed soil columns were set up to determine salt removal, pH change and salt movement in saline-sodic clay loam using different treatments.

3.3.1 Soil column setup

Columns were made of 45cm high clear acrylic tubing with a 10.2cm internal diameter. The bottom of each column was packed with a 5cm bed of washed gravel and sand to facilitate water leaching. The sand and gravel were held in place by two layers of geotextile stick to the bottom of the column. A Fisherbrand powder funnel with 130mm top diameter was attached to the bottom of each column to collect leachate into a covered beaker (Figure 6). Two groups of columns were set up. One group of columns was packed with 35cm of soil which was named as 35cm soil columns and the other group of columns was packed with 10cm of soil which was named as 10cm soil columns. The soil in the columns was packed to obtain the density of approximately 1.33 or 1.50g/cm^3 for the 35cm soil columns and 1.18g/cm^3 for the 10cm soil columns. Packing was achieved by adding 5cm lifts of a pre-weighed amount of soil for both 35cm soil columns and 10cm soil columns. Figure 7 showed the packed columns.

The packing procedure can be summarized as follows.

- The mass of air dry soil needed for each 5cm lift was pre-weighed in clean beakers. This mass was calculated to achieve the desired bulk density.
- 4cm of gravel was added into the empty column and then sand was added to obtain a 5cm high bed of gravel and sand.
- The soil was then added to the column by 5cm lifts and packed by gently tapping the side of columns until it occupied the desired volume. This process was repeated until the desired column length was achieved.

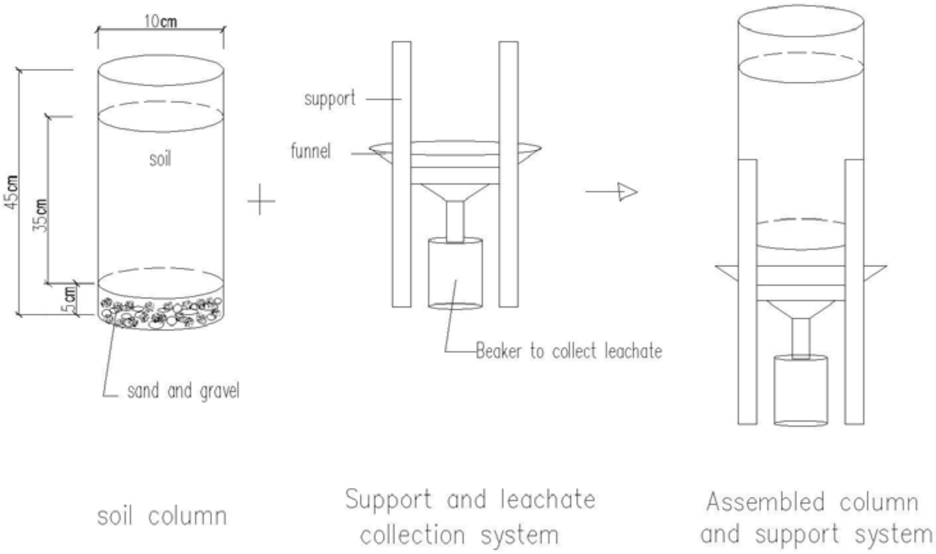


Figure 6: Schematic of soil column setup

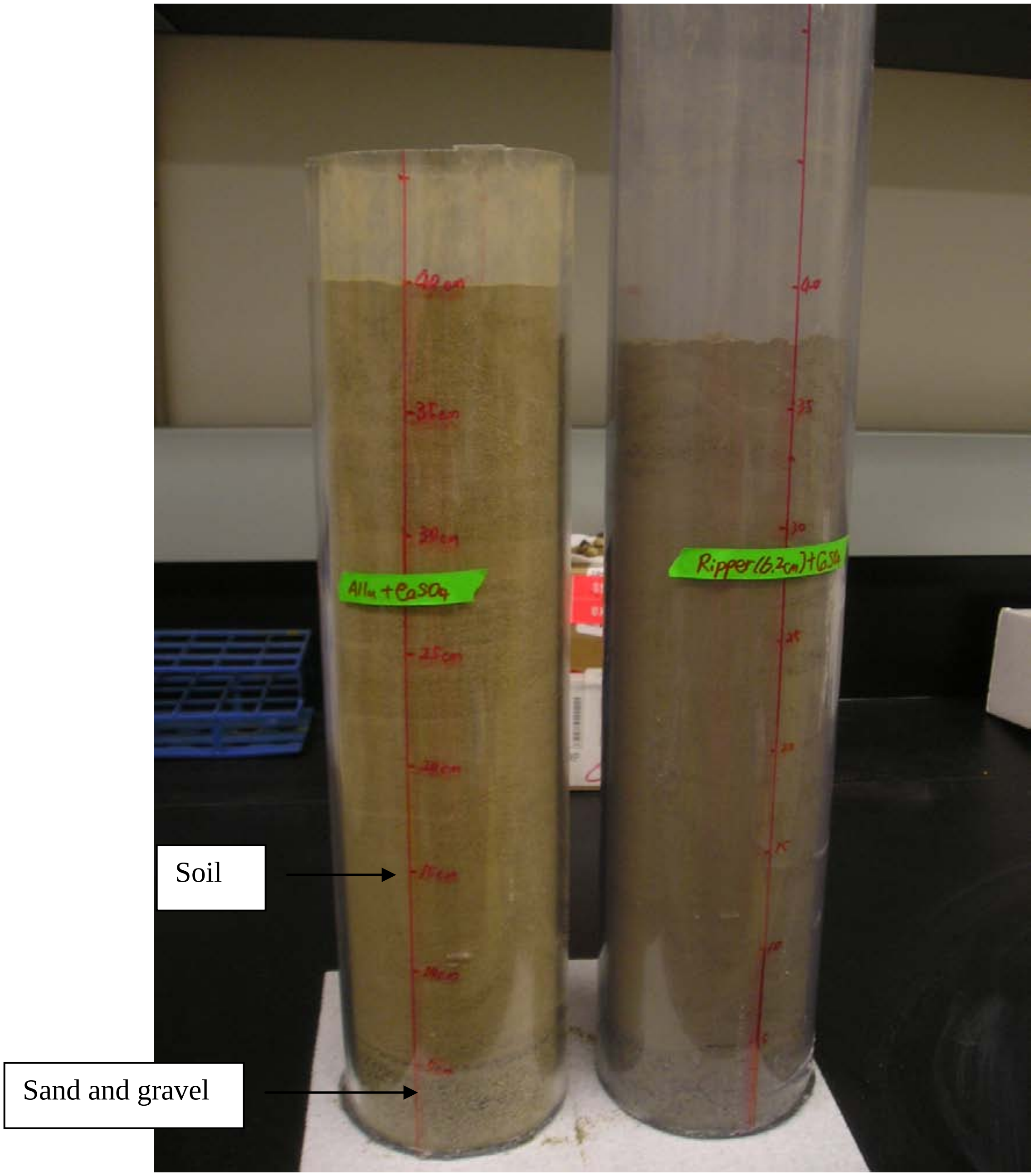


Figure 7: **Packed soil columns**

3.3.2 Experiments with the 35cm soil columns

Five 35cm columns were prepared by packing 35cm of soil into each column (as described in Section 3.3.1). One column for control was packed with 30cm of soil. Each column received one of the six treatment described in Table 8. A 4cm hydraulic head was maintained in all columns by adding tap water at least once every day.

Table 8: Experiments with the 35cm soil columns

Column Name	Treatment	Treatment Description
Control	Control	Soil column was leached with tap water without any chemical or physical treatment to the soil. The soil density of the column was 1.50g/cm^3.
Allu	Allu	The soil in the column was loosely compacted into the column with a density of 1.33g/cm^3, followed by leaching with tap water without any chemical addition.
Allu+Sand	Allu and Sand	10% volume (3.5cm) of sand was mixed thoroughly with the same quantity of soil as the allu column prior to packing. The soil column was leached with tap water.
Allu+Gypsum	Allu and Gypsum	24.3g gypsum was mixed thoroughly with the same quantity of soil as the allu column prior to packing. The soil column was leached with tap water.
Allu+Zeolite	Allu and Zeolite	10% volume (3.5cm) of zeolite was mixed thoroughly with the same quantity of soil as the allu column prior to packing. The soil column was leached with tap water.
Ripping +Gypsum	Ripping and Gypsum	8.58g gypsum was mixed with the upper 6.2cm soil layer. Soil density was 1.52g/cm^3

Figure 8 shows the set-up of the 35cm soil columns. All columns were leached and ponded for 12 months. The leachate in the beaker was removed when the volume reached at least 20mL (a minimum volume needed for analysis), until the end of the experiment.

Figure 8: 35cm soil columns

3.3.3 Experiments with the 10cm soil columns

Based on the preliminary results with the 35cm soil columns, 10cm soil columns were set up to speed up the experiment and to do a mass balance analysis. In this group of columns, the soil layer in each column was decreased to 10cm. Only four columns were run in parallel in this group due to small layer of soil. Each column received one of the four treatments provided in Table 9. During the leaching process, a high hydraulic head of 30cm was maintained to increase the infiltration for control, sand and zeolite columns. Only a 10cm hydraulic head was maintained for the gypsum column because infiltration was too fast to record at a 30cm hydraulic head. The quantity of added water was recorded for mass analysis. When the volume of leachate collected in the beaker was 20mL or more, the leachate was moved into 50mL clean tubes for ion concentration analysis. At the end of the experiment, the soil column was taken apart into three segments: top, middle and bottom. The salt concentration was determined on a segment basis in duplicate. An average value of salt concentration was calculated and used to evaluate the effectiveness of the treatments. The soil analysis is described in Section 3.4 and the leachate analysis is described in Section 3.5.

Table 9: Experiments with the 10cm columns

Column Name	Treatment	Treatment Description
Control	Allu	Soils were packed into the column by tapping the side of the column. The soil column was leached with deionized water without any chemical or physical treatment to the soil. The soil density of the column was 1.18g/cm^3.
Sand	Allu + Sand	10% volume (1cm) of sand was mixed thoroughly with the same quantity of soil as the control column prior to packing and then packed into the column without any compaction. The soil column was leached with deionized water.
Gypsum	Allu + Gypsum	6.5g gypsum was mixed thoroughly with the same quantity of soil as the control column prior to packing and then packed into the column without any compaction. The soil column was leached with deionized water.
Zeolite	Allu+ Zeolite	10% volume (1cm) of zeolite was mixed thoroughly with the same quantity of soil as the control column prior to packing and then packed into the column without any compaction. The soil column was leached with deionized water.

3.4 Soil analysis

Soil was analyzed before and after leaching experiments. Following the leaching experiments, the 10cm soil columns were taken apart for analysis. Soil samples were analyzed for the following parameters: EC, soil pH, SAR, CEC, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, NO_3^-, moisture, particle distribution, porosity and percent saturation (%). Moisture was determined by weight loss before and after oven-drying soil samples at a temperature of 105°C in a Fisher Isotemp® 500 series oven.

3.4.1 Particle size distribution

The analysis of the soil particle size distribution was performed by Christine Hereygers, the technologist of the Department of Civil and Environmental Engineering at the University of Alberta, using ASTM standard methods (Designation: D421-85 and D422-63).

3.4.2 Cation exchange capacity

The exchangeable cations (i.e. Ca, Mg, Na, K) were determined by displacing these ions from soil with NH_4. This displacement was done by shaking the soil with 1N NH_4OAc adjusted to pH=7.0 and the extract was analyzed using ion chromatography (IC). This method does not correct for Ca and Mg extracted from free carbonates (Sheldrick, 1984; Carter, 1993). The procedure was as follows.

- Weigh 2.5g of dry soil into a 50mL centrifuge tube and add 25mL of 1N ammonium acetate.
- Close the tube, use a Wrist Action™ shaker (Burrell) to shake the tube for 1 hour and leave overnight.
- Centrifuge on a Multifuge 3 L-R (Heraeus) for 15 minutes at 4150rpm to obtain a clear extract for easier filtration.
- Filter the extract using a 0.22µm filter into 10mL Dionex IC vials.

- Dilute an aliquot of the extract with distilled water at least 10 times to prevent overloading of IC system with ammonium. Adjust dilution factor based on the IC calibration range.
- Put extract vials into the Dionex 2500 IC system to determine the cation concentration.
- Calculate exchangeable cations in meq/100g using the following equation:

  Exchangeable cations in meq/100g = (mg/L IC measured /eq weight of cation) * (0.025L/2.5g sample)*100

3.4.3 Saturated paste extract

The analysis of EC, pH and ion concentration in the soil samples was performed on the saturated paste extract. This extract was prepared using a modified method of Rhoades (1982) (as cited in Carter, 1997). The modified saturated paste extract preparation method is as follows.

- Weigh approximately 120g of soil with a known moisture content into a container with a lid. Record the total weight of the container and the soil sample.
- Add sufficient deionized water while mixing to saturate the soil sample. According to Carter (1997), saturation is defined as "*when the soil paste glistens, flows slightly when the container is tipped and slides cleanly from the spatula. A trench carved in the soil surface will readily close when the container is shaken*".
- Allow the sample to stand for at least 4h and ensure that the saturation criteria are still met.

- Weigh the container again. Record the increase in weight, which corresponds to the amount of water added and calculate the saturation percentage (SP) as follows:

$$SP = \frac{(\text{weight of } H_2O \text{ added} + \text{weight of } H_2O \text{ in sample})}{\text{oven - dry weight of soil}} \times 100$$

- After allowing the paste to stand for at least an additional 4h, transfer it into a 50mL Fisher centrifuge tube and close the tube.
- Centrifuge on Multifuge 3 L-R (Heraeus) for 45 minutes at 4150rpm to obtain clear extract.
- Transfer the upper extract into a clean dry 50mL tube for EC and pH measurement.

3.4.4 pH

A thermo Orion 290 A+ pH meter was used to read the pH of the saturated paste extract. Calibration was performed before each set of measurement using three calibration buffers (pH of 4.01, 7.00 and 10.00) and the calibration procedure provided by the user manual. Electrode was rinsed with deionized water before immersing into new solution.

3.4.5 EC

The saturated paste extract EC was determined by reading a stable value on a thermo Orion Models 130A and 131S portable conductivity meter after the electrode was immersed in the sample. Calibration was conducted before every set of measurements. 0.010*M* KCl and 0.100*M* KCl solutions were used to standardize the EC meter. At 25°C, the EC of 0.010*M* KCl is 1.412dS/m, and the EC of 0.100*M* KCl is 12.90dS/m. The calibration procedure was as follows.

- Use 0.010*M* KCl and 0.100*M* KCl solutions as calibration solutions.
- Pour approximately 20mL of the calibration solution into the measuring bottle.
- Rinse the EC meter probe with deionized water.
- Put the EC meter probe into the solution, allowing time for it to adjust for temperature.
- Adjust the meter to the know salinity of the calibration solution: at 25°C, the EC of 0.010*M* KCl is 1.412dS/m, and the EC of 0.100*M* KCl is 12.90dS/m.
- Discard the calibration solution.
- Rinse the EC meter probe with distilled water before immersing it into a new solution.

For the conductivity meter used here, the error of the EC measurements does not exceed 1% or 0.001dS/m (Carter and Gregorich, 2008).

3.4.6 Ion concentration

Ion concentrations (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, NO_3^-) in the extract were measured by taking a 10mL sample and analyzing this sample by Ion Chromatography (IC). Pre-treatment was conducted on the saturated paste extract from Section 3.4.3 before being run on the IC. The pre-treatment was as follows.

- Using a B-D 60mL syringe to take approximately 10mL of sample from the saturated paste extract.

- Filter the sample into a 10mL Dionex IC vial using a 0.22µm filter.
- If needed dilute an aliquot of the extract with deionized water 10 times or 100 times due to high salt concentration.
- Store extracts at 4°C prior to analysis by IC.

3.4.7 Determination of ion concentration by IC

The pre-treated extract was analyzed by Ms. Jela Burkus using the Dionex 2500 in the Department of Civil and Environmental Engineering at the University of Alberta. The sample was injected by an AS50 autosampler into the stream of eluent (8.0mN Na_2CO_3/1.0mN $NaHCO_3$ for anions or 22mN H_2SO_4 for cations) stored in a 2L plastic container and then pumped with a GP50 gradient pump through the following columns:

For anions: a sample loop (25µL), IonPac® AG14A guard column, IonPac® AS14A anion-exchange column, a ASRS® Ultra II 4-mm suppressor and a CD25 conductivity detector.

For cations: a sample loop (25µL), IonPac® CG12A guard column, IonPac® CS12A cation-exchange column, CSRS® Ultra II 4-mm suppressor and a CD25 conductivity detector.

The method detection limit of this analysis was 1ppm for cations and 1ppm for anions except chloride. The detection limit for chloride was 0.2ppm. The calibration used 5 working standards to create the calibration curve. The working standards were made from stock solutions containing 200mg/L Na^+, 500mg/L K^+, 250mg/L Mg^{2+} and/or 500mg/L Ca^{2+} for cations and 500mg/L Cl^-, 100mg/L SO_4^{2-}, 100mg/L NO_3^- and/or 100mg/L NO_2^- for anions. All stock solutions were purchased from Dionex. One check standard was prepared and run after every 10th sample to check for the retention time shifts or any change in the instrument response. The analyte concentration in the check standard was approximately in the middle of calibration curve. Every sequence was run with 5 standards, 1 check standard every 10 samples, 1 blank and duplicates for quality control.

3.5 Leachate analysis

Leachate was removed from the leachate collection beaker when the volume was more than 20mL. The leachate was analyzed for: pH, EC, Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, and NO_3^-. The measurement of these parameters was as described previously.

3.6 Zeolite sorption and desorption test

Sorption and desorption tests of the zeolite were performed to give an idea how much Na^+ and Cl^- might be sorbed to the zeolite when exposed to solutions of high salt concentration and how much Na^+ and Cl^- would be desorbed when the zeolite is exposed to solutions of low salt concentration.

Sorption tests were conducted as follows and listed in Table 10:

- Wash and air dry the zeolite taken from the site.
- Weigh 8.00g and 14.00g zeolite in 50mL tubes.
- Add 40mL of NaCl solution of known concentration.

- Take a 10mL sample from each tube after 24h and 72h of shaking on the Wrist Action™ (Burrell) shaker.
- Measure Na^+ and Cl^- concentrations by the Dionex 2500 IC system.
- Calculate sorbed mass and percentage of Na^+ and Cl^- sorbed.

Table 10: Tube arrangement for zeolite sorption tests

Tube No.	**Zeo 1**	**Zeo 2**	**Zeo 3**	**Zeo 4**	**Zeo 5**	**Zeo 6**
Weight of zeolite (g)	8.00	8.00	8.00	8.00	8.00	8.00
Concentration of added NaCl (mg/L)	1000	1000	2000	2000	0	0
Volume of added NaCl (mL)	40	40	40	40	40	40
Tube No.	**Zeo 7**	**Zeo 8**	**Zeo 9**	**Zeo 10**	**Zeo 11**	**Zeo 12**
Weight of zeolite (g)	14.00	14.00	14.00	14.00	14.00	14.00
Concentration of added NaCl (mg/L)	1000	1000	2000	2000	0	0
Volume of added NaCl (mL)	40	40	40	40	40	40

The procedure for the desorption test was as follows:

- Centrifuge the 72h-shaken 50mL tubes on a Multifuge 3 L-R (Heraeus).
- Remove the solution from the centrifuge carefully.
- Add 40mL deionized water (the concentration of Na^+=0mg/l).
- Use the Wrist Action™ shaker (Burrell) to shake the tubes for 72h.
- Take 10mL of solution from each tube and measure the Na^+ concentration in the solution by IC.
- Calculate the percentage of Na^+ desorbed.

4 Results and Discussion

This chapter presents the results and discussion of the soil analysis, the field experiments and laboratory experiments. Raw data and detailed calculations can be found in Appendix A to F.

4.1 Soil properties

Table 11 presents the measured properties for the soil used in this study. The soil was collected from the contaminated site, transferred to the lab in the Department of Civil and Environmental Engineering at the University of Alberta and then analyzed according to the methods described in Chapter 3. Appendix A presents the plot of particle size distribution and the data of CEC.

Table 11: Measured soil properties

Characteristic	Unit	Value
Sand	% weight	5
Silt	% weight	60
Clay	% weight	35
pH of saturated paste extract	-	7.3-7.5
EC of saturated paste extract	dS/m	20.50
SAR of saturated paste extract		20.38
Cation exchange capacity (CEC)	meq/100g	34.33
Organic matter	% weight	10.61
Moisture	% weight	4.1

Based on these data, the soil is saline-sodic alkaline silty clay loam (Plaster, 1997) with a high CEC.

4.2 Field data

Five treatments and a control were conducted on site in triplicate: allu only, allu+sand, allu+zeolite, allu+gypsum and ripping+gypsum. In order to investigate the effect of irrigation, each treatment was tested with irrigation and without irrigation. Figures 9 to 14 present the EC variation at 36 sampling plots under various treatments, and Figures 15 to 20 present the SAR variation at 36 sampling plots under various treatments. Soil samples were taken from sites three times: before treatment (June, 2005), immediately after treatment (August, 2005), and three months after treatment (November, 2005). Three different locations were sampled in each plot during the June 2005 sampling event while only one location was sampled in the August and November 2005 sampling events (due to financial constraints).

4.2.1 EC measurements for field samples

EC measurements were conducted for soil samples taken from the site in June, August and November. For the June sampling event, the standard deviation for the EC of soil samples at the three locations of each plot ranged from 0.06 to 2.18 at a depth of 0.2m; from 0.17 to 2.59 at a depth of 0.6m; from 0.51 to 7.36 at a depth of 1.3m and from 0.88 to 7.00 at a depth of 2.0m. For the August and November data, standard deviations could not be calculated since only one location was sampled. The data for all EC measurements are provided in Appendix F.

4.2.1.1 EC measurements in control plots

Figure 9 presents the change in EC as a function of depth in control plots without irrigation (a) (Plots 6, 12, 16) and with irrigation (b) (Plots 22, 30 and 36). It is noticed that there is no difference between (a) and (b).

The value of EC in control plots varied from 1.18 to 17.14dS/m, indicating a saline soil. Highest values of EC were found at a depth of 1.2 to 2.0m. A possible reason for this contamination at depth is that, at the initial time of contamination, rainfall and/or irrigation for crops leached ions from the soil surface down to the deep soil. Irrigation did not apparently decrease the EC of the soil. Given the SAR and type of soil, it is possible that the soil became dispersed and sealed as the large amount of sodium adsorbed on the clay. This dispersed clay would not allow irrigation water to flow through the contaminated soil and therefore irrigation would not be effective at decreasing the EC.

4.2.1.2 EC measurements in allu plots

Figure 10 presents the change in EC as a function of depth in allu treated plots without irrigation (Plot 5, 11, and 15) and with irrigation (Plot 21, 29, 35) in June (before treatment), in August (immediately after treatment) and in November (three months after treatment).

The values of EC in June varied from 1.58 to 22.60dS/m. Highest values of EC were found at a depth of 1.2 to 2.0m. After alluing, a physical treatment which removes the soil, breaks it down and then puts it back into the site, the value of EC in August was quite similar as a function of depth. Without irrigation, the value of EC in November did not decrease. Irrigation seemed to have led to a slight decrease in EC in the allued plots after three months: from 10.10 to 7.88dS/m at 0.2m, from 11.80 to 9.56dS/m at 1.0m, and from 11.60 to 9.59dS/m at 2.0m in Plot 29-2; from 6.51 to 4.60dS/m at 0.2m in Plot 35-2, and from 9.0 to 7.7dS/m at 2.0m in Plot 21-2.

4.2.1.3 EC measurements in allu and sand-added plots

Figure 11 presents the change in EC as a function of depth in allu-treated and sand-added plots without irrigation (Plot 4, 8, and 14) and with irrigation (Plot 24, 28, 32) in June (before treatment), August (immediately after treatment) and November (three months after treatment).

The initial values of EC varied from 1.85 to 24.70dS/m. As with the control and allu plots, the highest values of EC were found at a depth of 1.2 to 2.0m. Immediately after alluing and sand addition, soluble salts were redistributed uniformly. The value of EC was similar along the depth. In November, three months after treatment, the value of topsoil EC in plots without irrigation decreased slightly, from 7.84 to 6.80dS/m at sample location 4-2, from 10.30 to 8.87dS/m at sample location 8-2, and from 9.76 to 8.37dS/m at sample location 14-2. The value of EC at 2.0m increased from 10.70 to 12.50dS/m at sample location 4-2, from 5.84 to 15.10dS/m at sample location 8-2. The value of EC in plots with irrigation had a distinct decrease compared to allu plots, especially for topsoil. The value of EC decreased from 15.20 to 12.30dS/m at 0.2m, from 16.30 to 12.30dS/m at 1.0m and from 14.90 to 13.60dS/m at 2.0m at sample location 28-2; from 12.60 to 4.55dS/m at 0.2m, from 11.60 to 9.28dS/m at 1.0m, and from 13.00 to 11.80dS/m at 2.0m at sample location 32-2. This result indicates that sand addition appeared to improve soil permeability and thus irrigation was helpful to wash soluble salts down to deeper soil and then out of studied soil profile.

4.2.1.4 EC measurements in allu and zeolite-added plots

Figure 12 provides the change in EC as a function of depth in allu treated and zeolite-added plots without irrigation (Plot 3, 7, and 13) and with irrigation (Plot 23, 27, 31) in June, August and November.

The initial values of EC varied from 2.68 to 22.50dS/m. As with the control and allu plots, the highest values of EC were found at a depth of 1.2 to 2.0m. Immediately after alluing and zeolite addition, soluble salts were redistributed uniformly. The value of upper soil EC increased and the value of deeper soil EC decreased. In November, three months after treatment, the EC value of soils above 0.6m in plots without irrigation decreased slightly and the value of EC at 2.0m increased a very small degree. The value of EC in plots with irrigation had a slight decrease at all depth, better than the change of EC in allu plots. The value of EC at 0.2m decreased from 7.30 to 5.97dS/m at sample location 23-2, from 13.30 to

12.10dS/m at sample location 27-2, and from 9.90 to 6.60dS/m at sample location 31-2. The decrease was less than the change of EC in allu+sand plots, but more than the decrease of EC value in control plots. This result seems to indicate that zeolite addition did have an effect on salt removal and irrigation led to only a slight decrease in EC in the allu+zeolite plots.

4.2.1.5 EC measurements in allu with gypsum-added plots

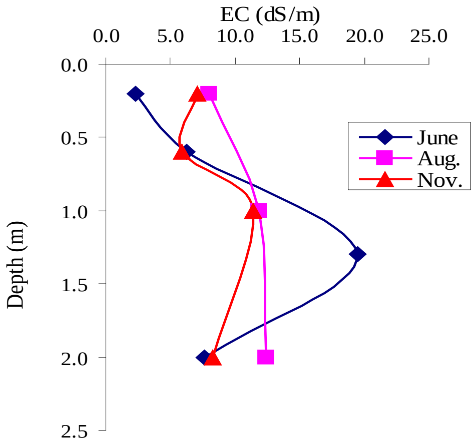
Figure 13 provides the change in EC as a function of depth in allu-treated and gypsum-added plots without irrigation (Plot 2, 10, and 18) and with irrigation (Plot 20, 26, 34) in June, August and November.

The values of EC in June varied from 1.69 to 15.97dS/m. As with the control and allu plots, the highest values of EC were found at a depth of 1.2 to 2.0m. In November, three months after treatment, the values of EC in plots without irrigation decreased slightly at three depths (0.2m, 1.0m, and 2.0m) except for at sample location 18-2. The values of EC in plots with irrigation decreased from 10.40 to 7.48dS/m at the depth of 0.2m, from 11.20 to 9.52dS/m at 1.0m and from 13.30 to 11.40dS/m at 2.0m in sample location 20-2; from 11.60 to 7.43dS/m at 0.2m in sample location 26-2; and from 14.10 to 11.50dS/m at 1.0m and from 13.40 to 11.40dS/m at 2.0m in sample location 34-2. Since five out of six sample locations have a noticeable EC decrease and all three locations with irrigation achieved EC decrease, it indicated that allu with gypsum addition treatment may improve the soil permeability and thus irrigation led to a decrease in EC.

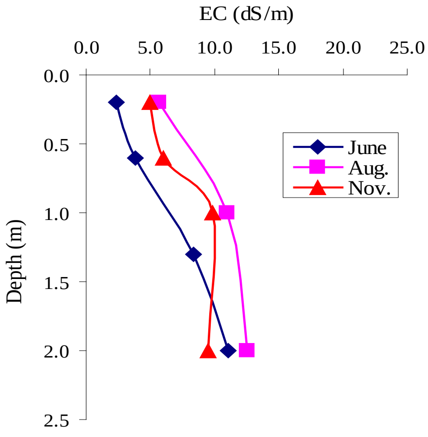
4.2.1.6 EC measurements in ripping with gypsum-added plots

Figure 14 provides the change in EC as a function of depth in ripping-treated and gypsum-added plots without irrigation (Plot 1, 9, and 17) and with irrigation (Plot 19, 25, 33) in June, August and November.

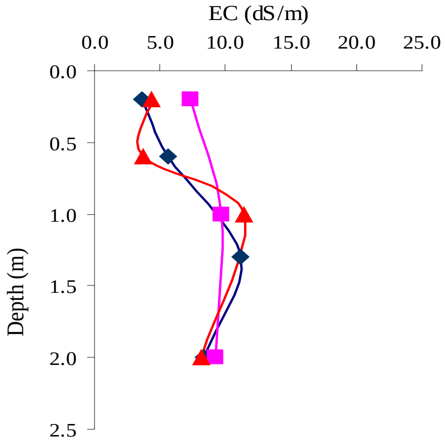
The values of EC in June varied from 1.77 to 16.01dS/m. The highest values of EC were found at a depth of 1.2 to 2.0m. Because ripping was performed only to the upper 0.4m soil, the value of EC at a depth of 0.2m increased immediately after treatment (August). The values of EC below 0.4m did not appear to change at some locations (17-2, 25-2, 33-2). At other sample locations (9-2 and 19-2), the value of EC increased at a depth greater than 0.4m. The reason for this increase is not known yet. In November, three months after treatment, the values of EC in plots without irrigation decreased in the upper 0.6m, from 10.40 to 3.26dS/m at a depth of 0.2m, from 13.20 to 7.60dS/m at 1.0m, and from 13.80 to 12.40dS/m at 2.0m in sample location 9-2; from 8.69 to 4.97dS/m at 0.2m, from about 10.00 to 3.81dS/m at 0.6m in sample location 17-2. In plots with irrigation, the values of EC dropped at two locations (19-2 and 25-2) but did not change at location 33-2. The values of EC in plots with irrigation decreased from 7.47 to 3.27dS/m at the depth of 0.2m, from 9.02 to 2.95dS/m at 1.0m and from 6.64 to 2.39dS/m at 2.0m in sample location 19-2; from 9.86 to 7.48dS/m at the depth of 0.2m, from 11.00 to 8.97dS/m at 1.0m and from 10.80 to 9.40dS/m at 2.0m in sample location 25-2. Since gypsum was distributed in the upper 0.4m soil, the EC value of the upper 1.0m decreased more than the values of EC at a depth of 1.0-2.0m. Generally, ripping with gypsum addition achieved EC decrease at all sample locations, especially for soil above 1.0m, better than other treatments. Ripping with gypsum addition reclaimed soils above 0.6m in some plots to non-saline, and reclaimed one plot soil in terms of EC to be in the fair category of Alberta soil quality guidelines for unrestricted land use.



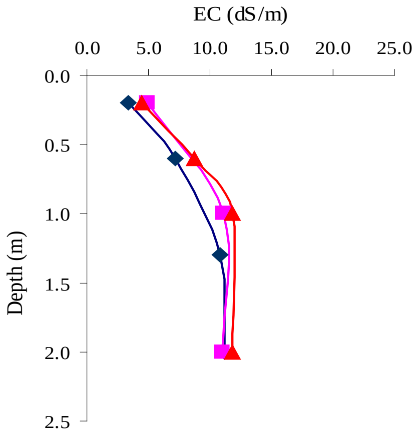
Sample location 6-2



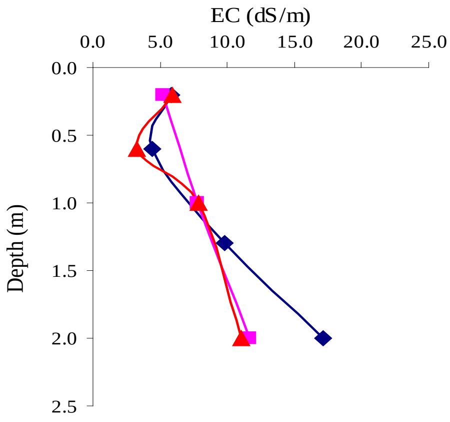
Sample location 22-2



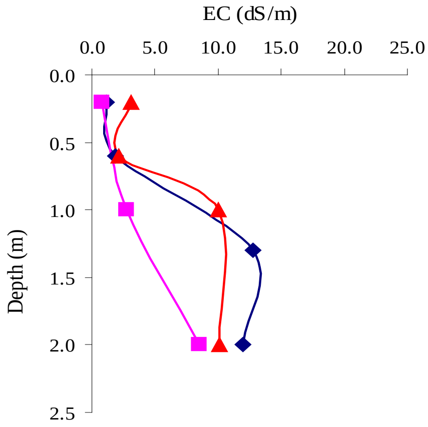
Sample location 12-2



Sample location 30-2



Sample location 16-2

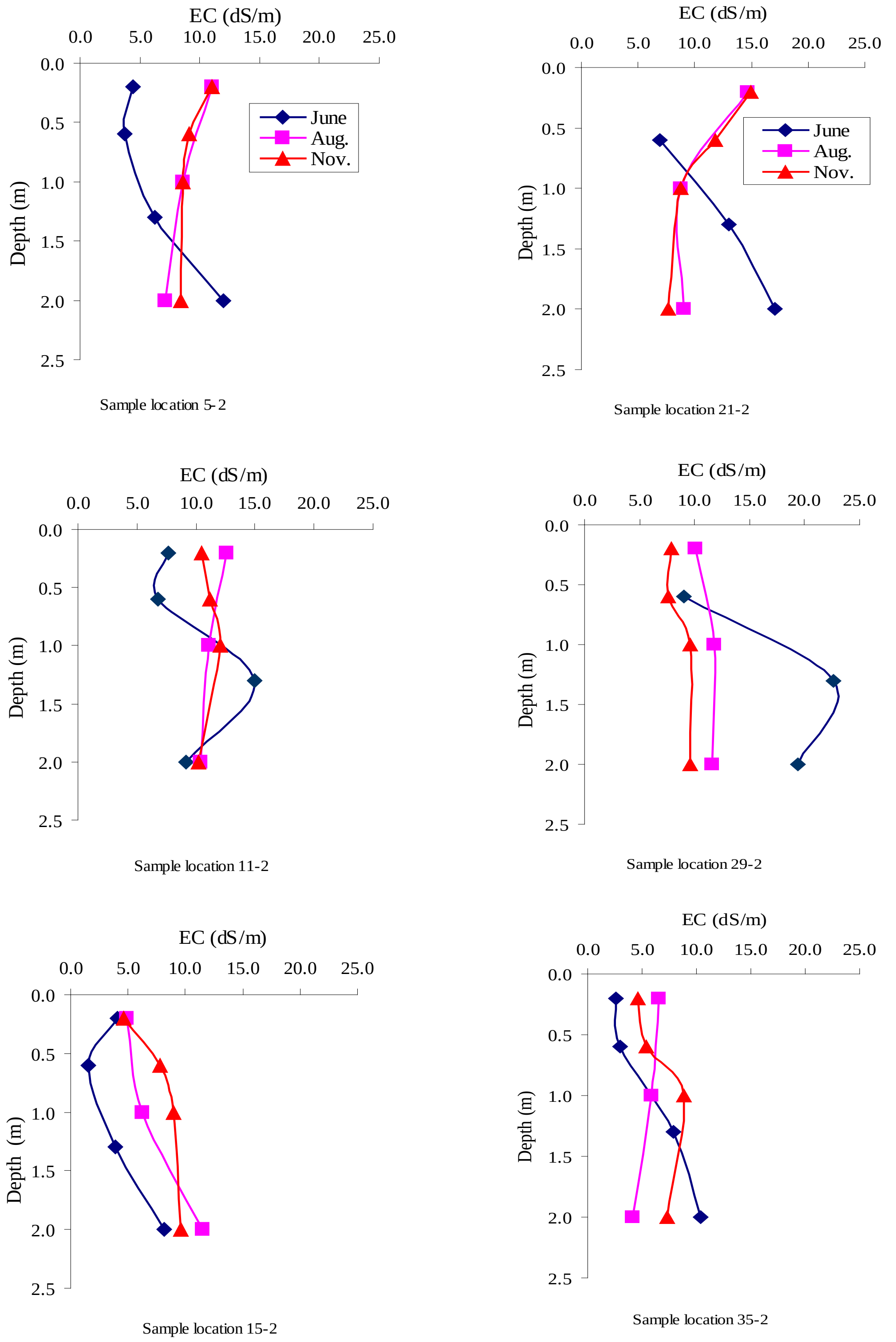


Sample location 36-2

(a) control plots without irrigation

(b) control plots with irrigation

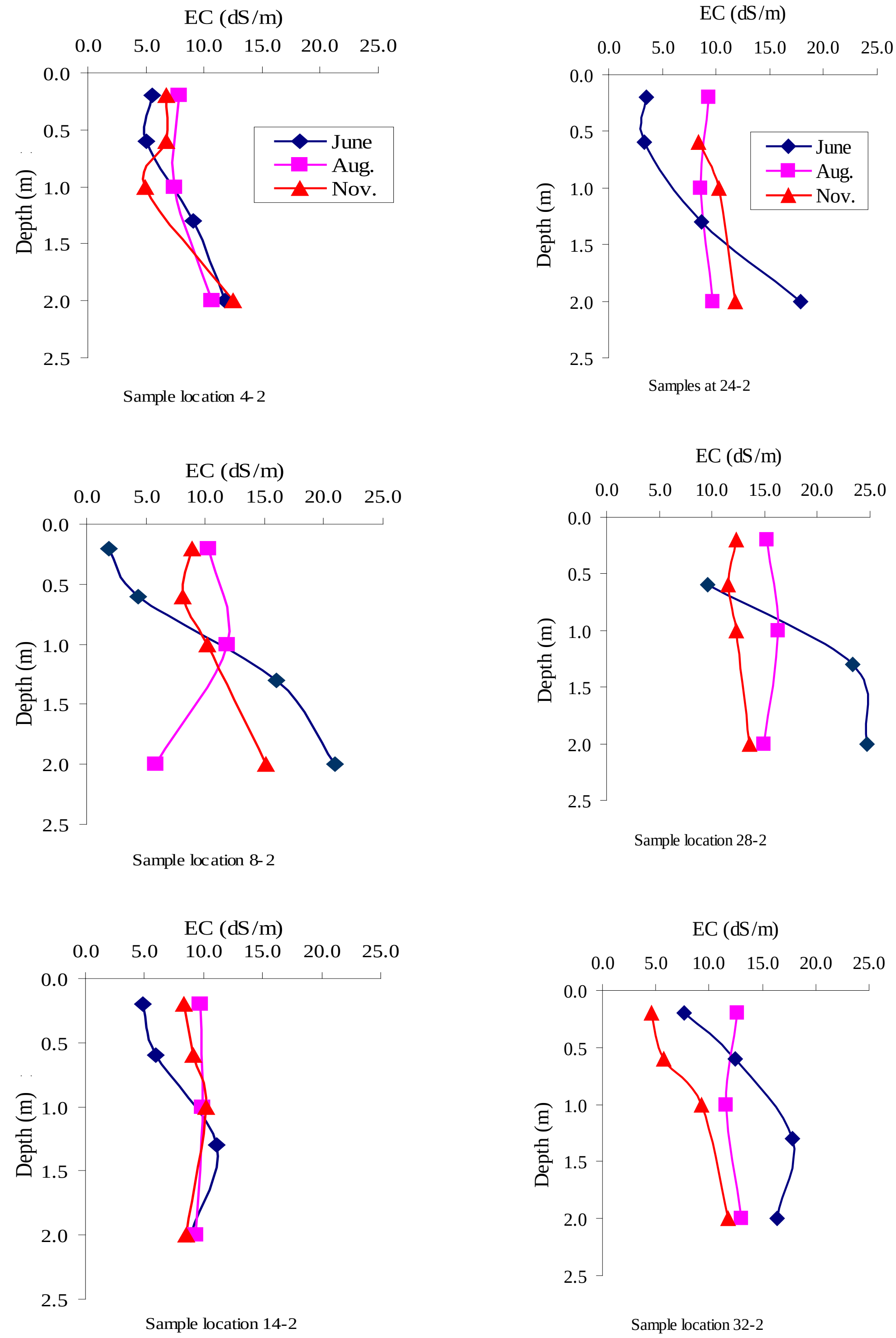
Figure 9: EC measurements as a function of depth at various sampling points in control plots (a) without irrigation, (b) with irrigation



(a) allu plots without irrigation

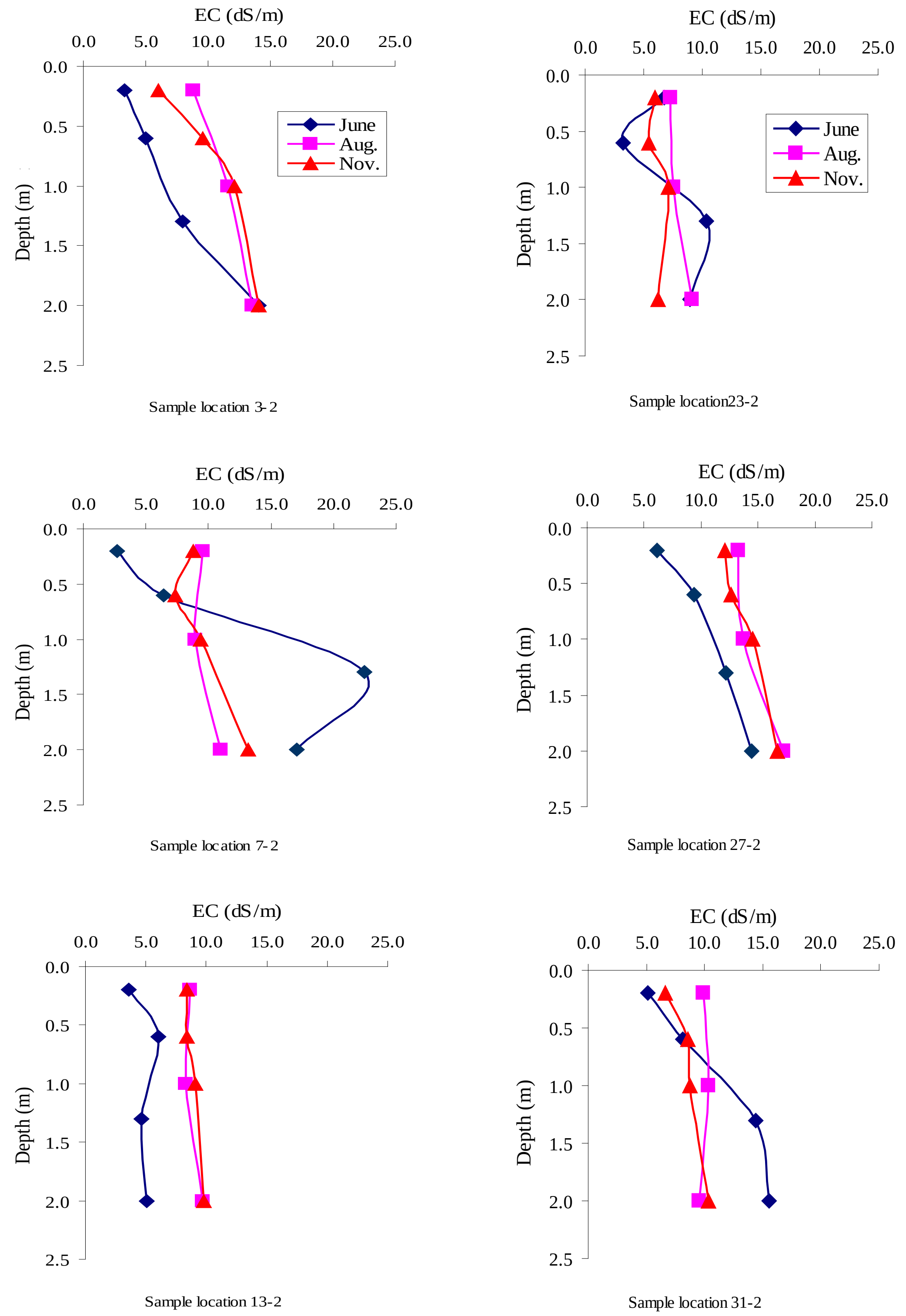
(b) allu plots with irrigation

Figure 10: **EC measurements as a function of depth at various sampling points in allu plots (a) without irrigation, (b) with irrigation**



(a) allu+sand plots without irrigation (b) allu+sand plots with irrigation

Figure 11: EC measurements as a function of depth at various sampling points in allu+sand plots (a) without irrigation, (b) with irrigation



Sample location 3-2

Sample location23-2

Sample location 7-2

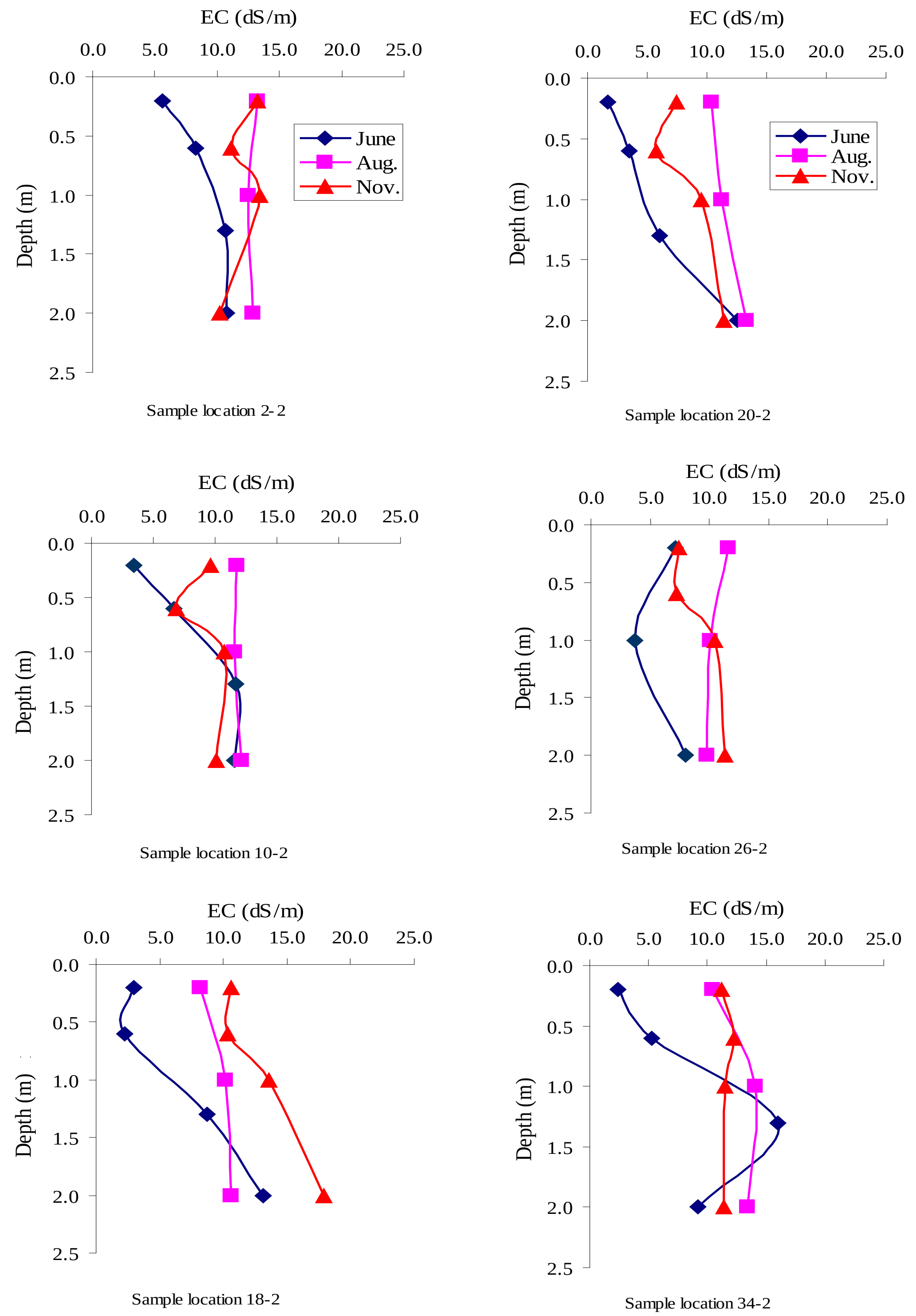
Sample location 27-2

Sample location 13-2

Sample location 31-2

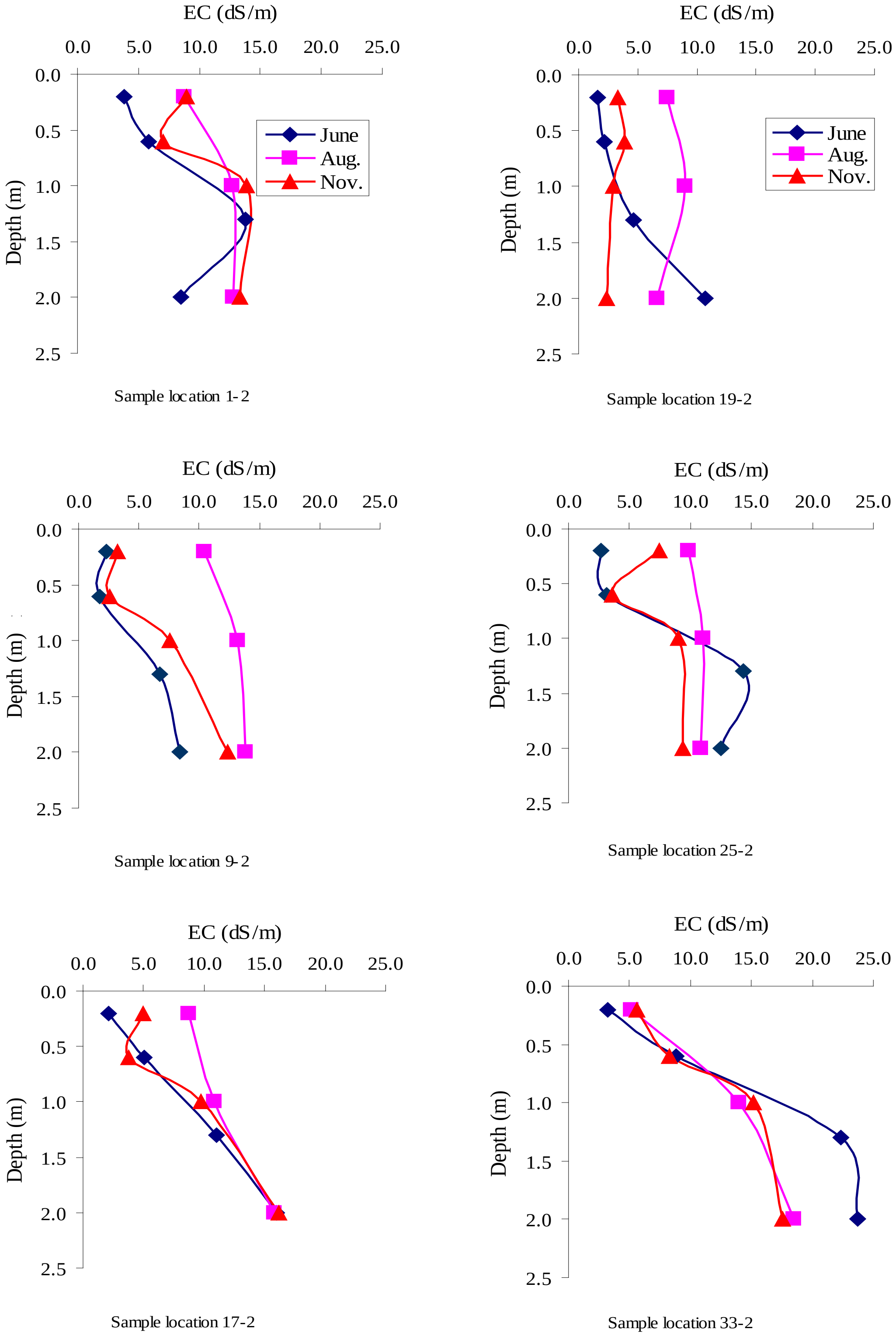
(a) allu+zeolite plots without irrigation (b) allu+zeolite plots with irrigation

Figure 12: EC measurements as a function of depth at various sampling points in allu+zeolite plots (a) without irrigation, (b) with irrigation



(a) allu+gypsum plots without irrigation (b) allu+gypsum plots with irrigation

Figure 13: EC measurements as a function of depth at various sampling points in allu+gypsum plots (a) without irrigation, (b) with irrigation



Sample location 1-2

Sample location 19-2

Sample location 9-2

Sample location 25-2

Sample location 17-2

Sample location 33-2

(a) ripping+gypsum plots w/o irrigation (b) ripping+gypsum plots with irrigation

Figure 14: EC measurements as a function of depth at various sampling points in ripping+gypsum plots (a) without irrigation, (b) with irrigation

4.2.2 SAR of soil samples from field sites

The SAR of soil samples was calculated by the equation provided in Section 3.1.2 and the data are presented in Appendix F. For the June data, the standard deviation for SAR varied from 0.59 to 15.31 at a depth of 0.2m; from 0.78 to 15.38 at a depth of 0.6m; from 0.89 to 26.15 at a depth of 1.3m and from 0.65 to 16.11 at a depth of 2.0m. Generally, the standard deviation at all depths is below 10.00 except for Plot 19 where the standard deviation at all depths is more than 20.00. For the soil samples at a depth of 0.2m, the SAR standard deviation in 32 of the 36 plots is less than 10.00, for the samples at 0.6m, the SAR standard deviation in 29 of the 36 plots is less than 10.00, for the samples at 1.3m, the SAR standard deviation in 28 of the 36 plots is less than 10.00, and for the samples at 2.0m, the SAR standard deviation in 29 of the 36 plots is less than 10.00. Standard deviations for SAR were not calculated for August and November data since only one soil sample at each depth was analyzed.

4.2.2.1 SAR in control plots

Figure 15 presents the change in SAR as a function of depth in control plots without irrigation (Plots 6, 12, 16) and with irrigation (Plots 22, 30 and 36) in June, August and November. The value of SAR in control plots in June varied from 7.26 to 76.39, indicating a severely sodic soil. The highest values of SAR were found at a depth of 1.2 to 2.0 m. The values of SAR in August were in the range of 5.60 to 31.70, slightly lower than the values of SAR in June. The reason for this was unknown. The decrease in SAR may have been due to the rain leaching through the plots, whose soils were loosened during the last sampling event. The values of SAR in November varied from 9.4 to 45.1, slightly higher than the values in August. It is believed that capillary action and evaporation resulted in sodium moving up in the soil profile. Irrigation did not appear to decrease the soil sodicity, for which SAR is an indicator.

4.2.2.2 SAR in allu plots

Figure 16 presents the change in SAR as a function of depth in allu treated plots without irrigation (Plot 5, 11, and 15) and with irrigation (Plot 21, 29, 35) in June (before treatment), August (immediately after treatment) and November (three months after treatment). The values of SAR in allu treated plots varied from 1.58 to 71.49 in June. The values of SAR in August varied from 13.50 to 26.60 after alluing, and the values of SAR in November ranged from 11.50 to 39.20. Alluing appeared to have redistributed sodium along the depth, minimizing the SAR variation across the soil profile. Compared to the change of SAR in control sites, the increase of SAR in allu sites in November was less than the increase in control sites. Irrigation in location 29-2 slightly decreased the SAR after three months treatment, but overall irrigation did not appear to be better at reducing the SAR than no irrigation.

4.2.2.3 SAR in allu+sand plots

Figure 17 presents the change in SAR as a function of depth in allu-treated and sand-added plots without irrigation (Plot 4, 8, and 14) and with irrigation (Plot 24, 28, 32). The values of SAR varied from 13.53 to 58.29 in June, from 14.40 to 23.90 in August, and from 15.40 to 41.40 in November. It can be seen that without irrigation, the SAR increased after three months. In plots with irrigation, the situation was better. Irrigation inhibited the influence of capillary action and evaporation. The addition of sand improved the drainage of water, which could carry some sodium out of the studied soil profile.

4.2.2.4 SAR in allu with zeolite-added plots

Figure 18 provides the change in SAR as a function of depth in allu-treated and zeolite-added plots without irrigation (Plot 3, 7, and 13) and with irrigation (Plot 23, 27, 31) in June, August and November. The values of SAR varied from 12.04 to 59.06 in June, from 11.60 to 30.50 in August, and from 10.60 to 39.60 in November. There does not appear to be a big change in SAR in plots without irrigation. However, SAR increased slightly in plots with irrigation after three months of leaching.

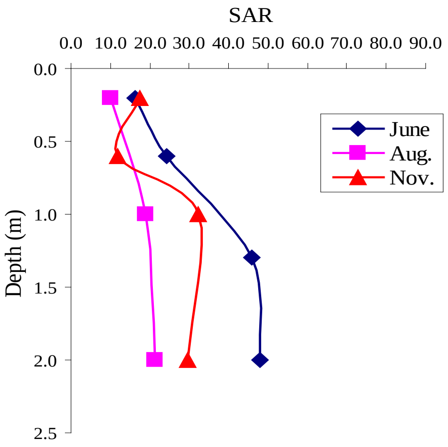
4.2.2.5 SAR in allu with gypsum-added plots

Figure 19 provides the change in SAR as a function of depth in allu-treated and gypsum-added plots without irrigation (Plot 2, 10, and 18) and with irrigation (Plot 20, 26, 34) in June, August and November.

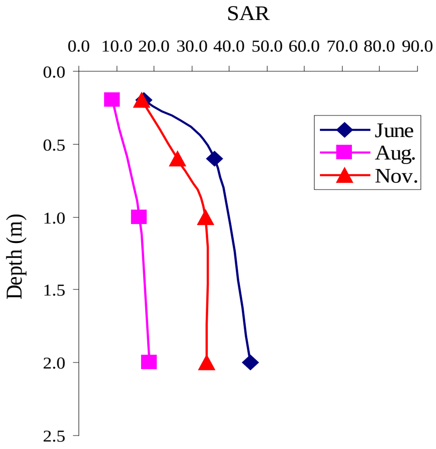
The values of SAR in June ranged from 5.90 to 65.66. Similar to the other sites with alluing, the values of SAR as a function of depth in August were similar in each plot, varying from 10.20 to 28.30. After three months treatment, the values of SAR ranged from 8.70 to 49.30. The value of SAR has an increase over three month’s treatment at location 10-2 and 18-2 where no irrigation was applied. With irrigation, SAR has a slight decrease, but not appreciable.

4.2.2.6 SAR in ripping with gypsum-added plots

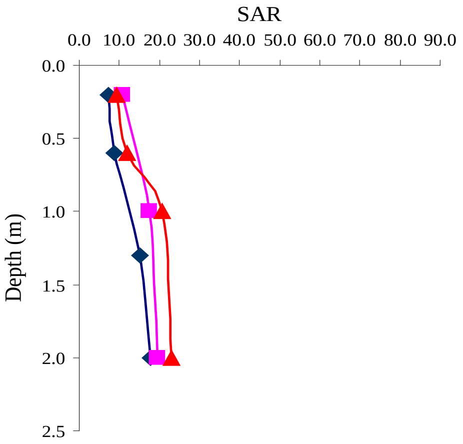
Figure 20 provides the change in SAR as a function of depth in ripping-treated and gypsum-added plots without irrigation (Plot 1, 9, and 17) and with irrigation (Plot 19, 25, 33) in June, August and November. The values of SAR are in the range of 7.39 to 88.60 in June, 8.50 to 27.90 in August, and 6.90 to 53.90 in November. Over the period of August to November, three months after treatment, a small decrease in the SAR of soils above 0.6m occurred in all ripping with gypsum added locations except 17-2, where the value of SAR increased. The value of SAR decreased from 8.5 in August to 6.9 in November at 0.2m, 11.5 to 9.5 at 0.6m in sampling location 1-2; 14.9 in August to 9.5 in November at 0.2m, and 19 to 14.7 at 0.6m in location 9-2; 11.3 in August to 8.7 in November at 0.2m of location 19-2, and 19.7 in August to 16.6 in November at 0.2m in location 25-2. Soils below 0.6m showed an increase in SAR in all ripping with gypsum added plots except sample location 19-2 where irrigation was applied. It should be noted that the increase in SAR at depths below 0.6m in plots with irrigation is less than in plots without irrigation. With the treatment of ripping with gypsum addition, the soil above 0.6m in most plots are reclaimed to be non-sodic, some falling into the fair category of Alberta soil quality guideline for unrestricted land use.



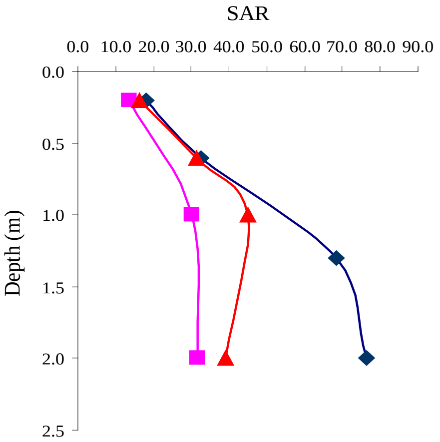
Sample location 6-2



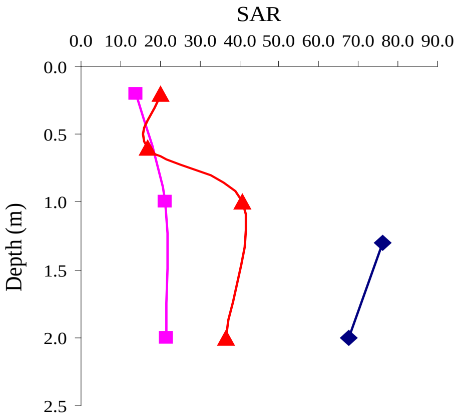
Sample location 22-2



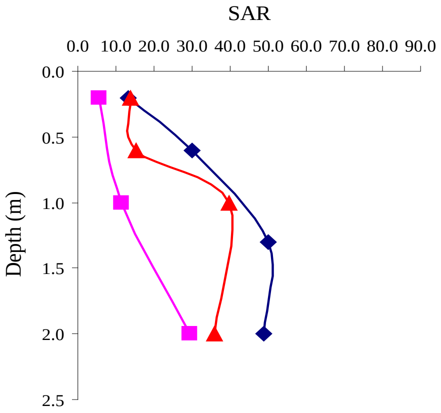
Sample location 12-2



Sample location 30-2



Sample location 16-2

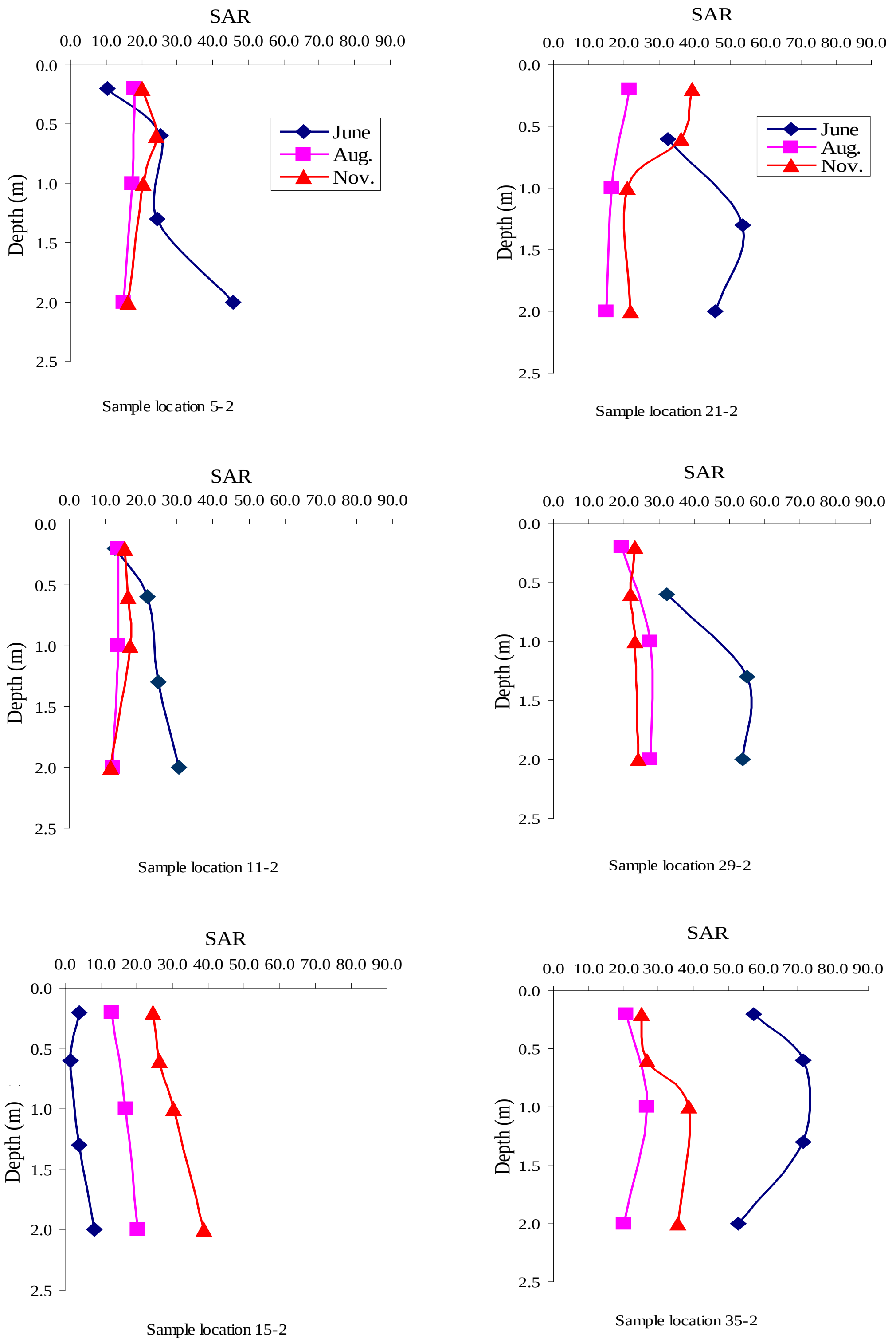


Sample location 36-2

(a)control plots without irrigation

(b) control plots with irrigation

Figure 15: SAR as a function of depth at various sampling points in control plots (a) without irrigation, (b) with irrigation



Sample location 5-2

Sample location 21-2

Sample location 11-2

Sample location 29-2

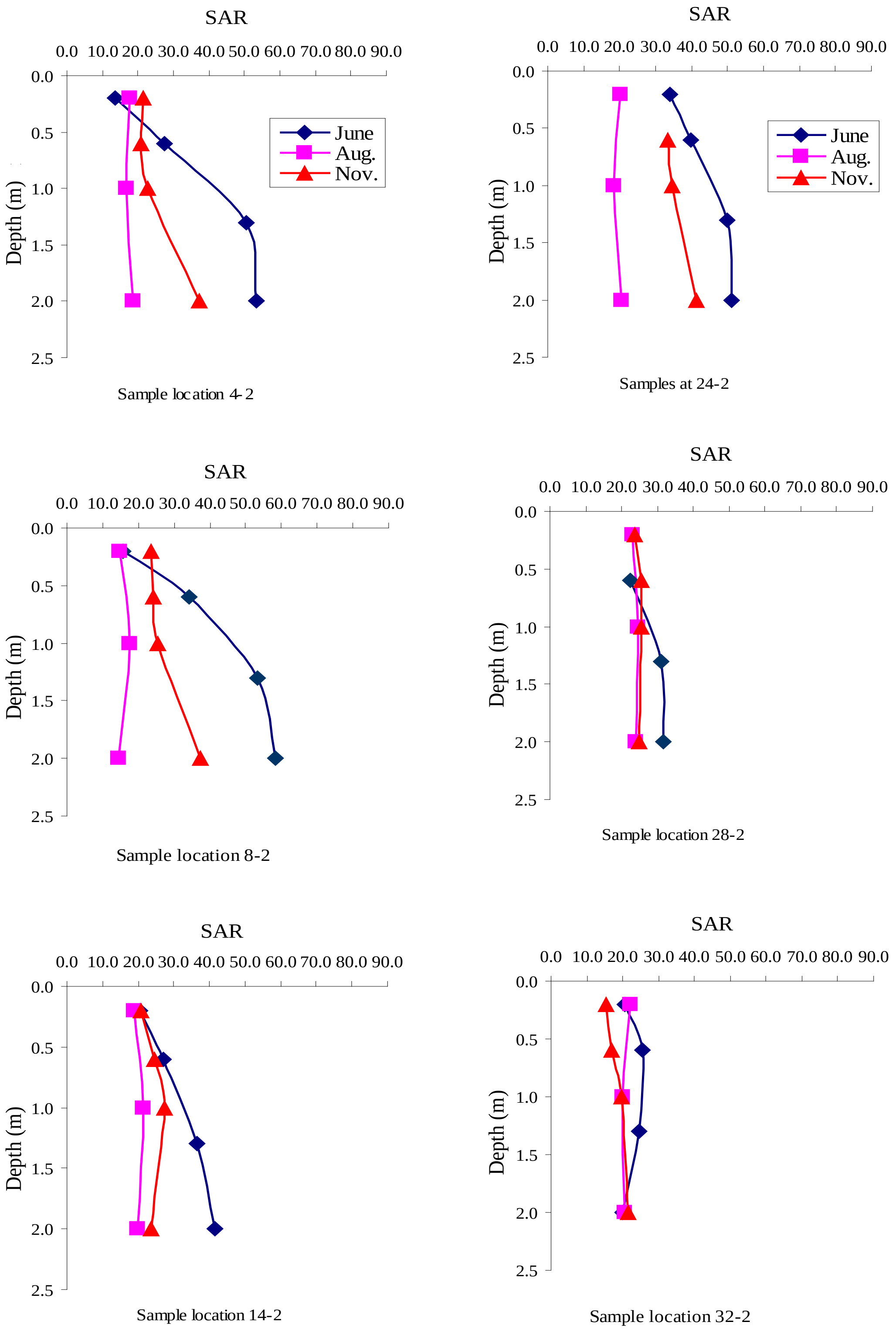
Sample location 15-2

Sample location 35-2

(a)allu plots without irrigation

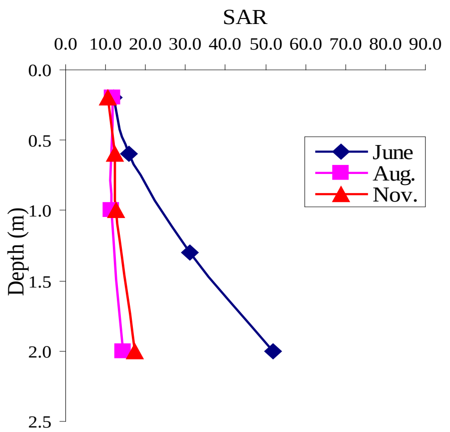
(b) allu plots with irrigation

Figure 16: SAR as a function of depth at various sampling points in allu plots (a) without irrigation, (b) with irrigation

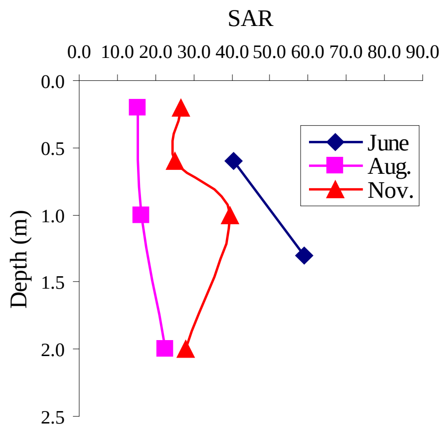


(a)allu+sand plots without irrigation (b) allu+sand plots with irrigation

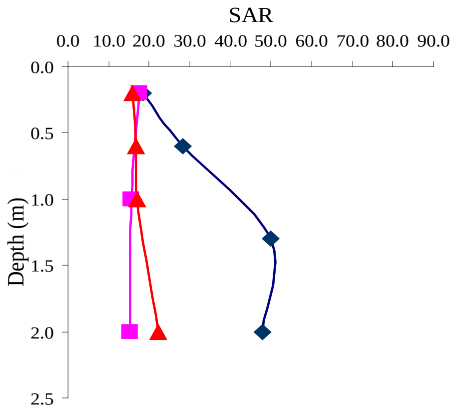
Figure 17: SAR as a function of depth at various sampling points in allu+sand plots (a) without irrigation, (b) with irrigation



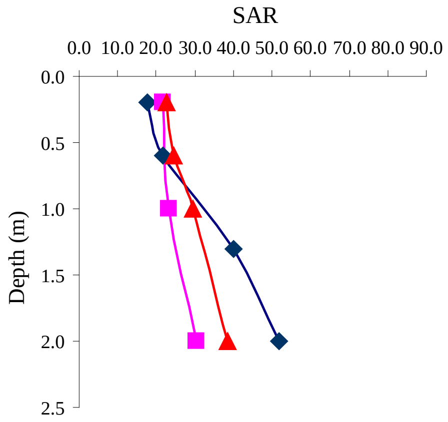
Sample location 3-2



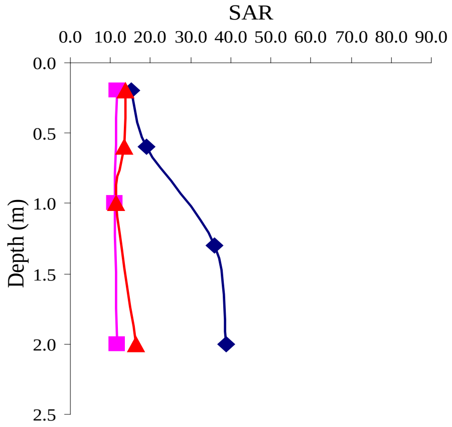
Sample location23-2



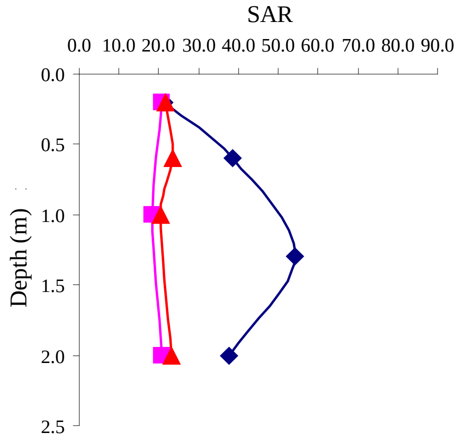
Sample location 7-2



Sample location 27-2



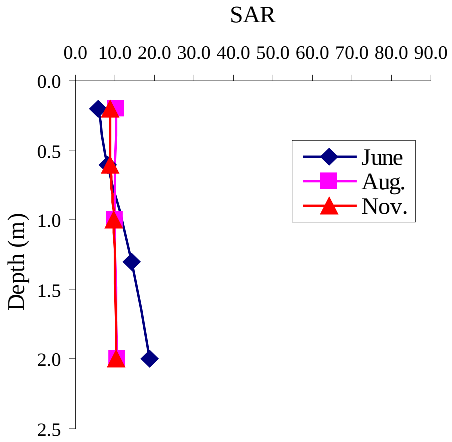
Sample location 13-2



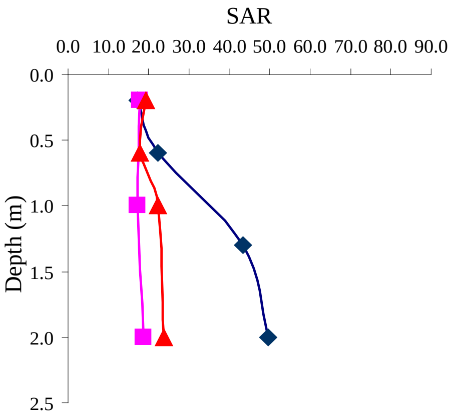
Sample location 31-2

(a)allu+zeolite plots without irrigation (b) allu+zeolite plots with irrigation

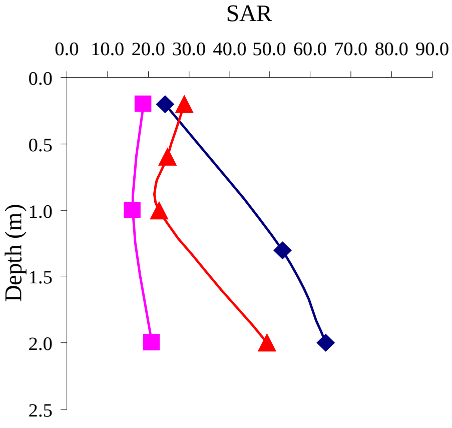
Figure 18: SAR as a function of depth at various sampling points in allu+zeolite plots (a) without irrigation, (b) with irrigation



Sample location 2-2

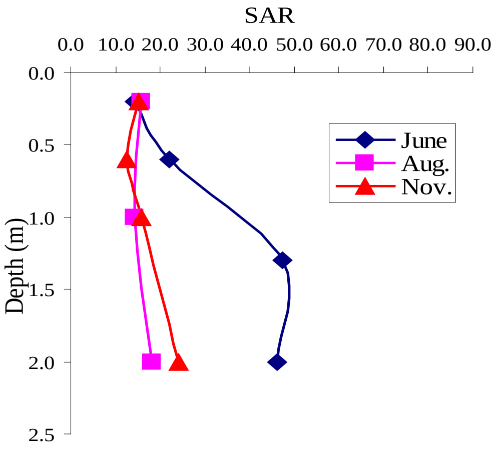


Sample location 10-2

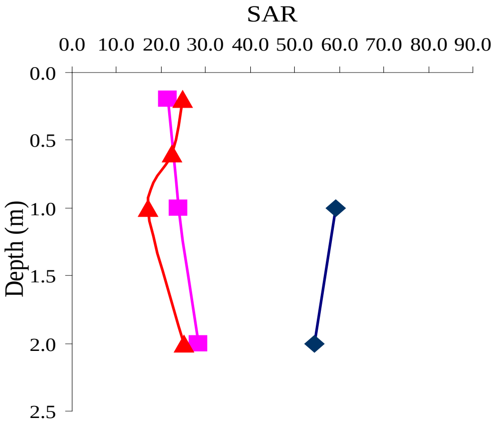


Sample location 18-2

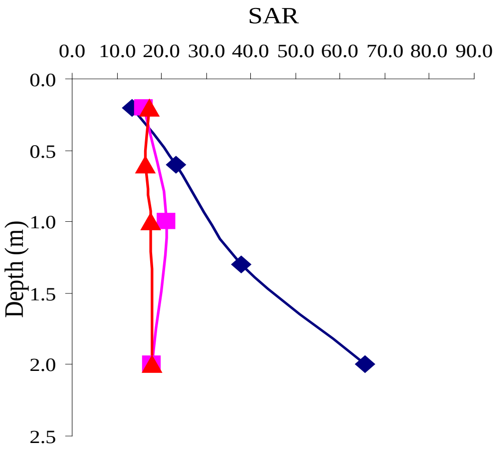
(a)allu+gypsum plots without irrigation



Sample location 20-2



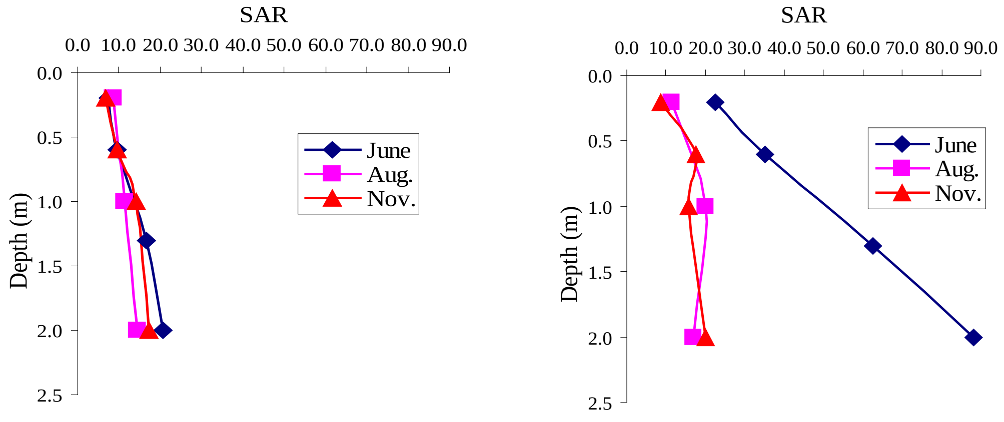
Sample location 26-2



Sample location 34-2

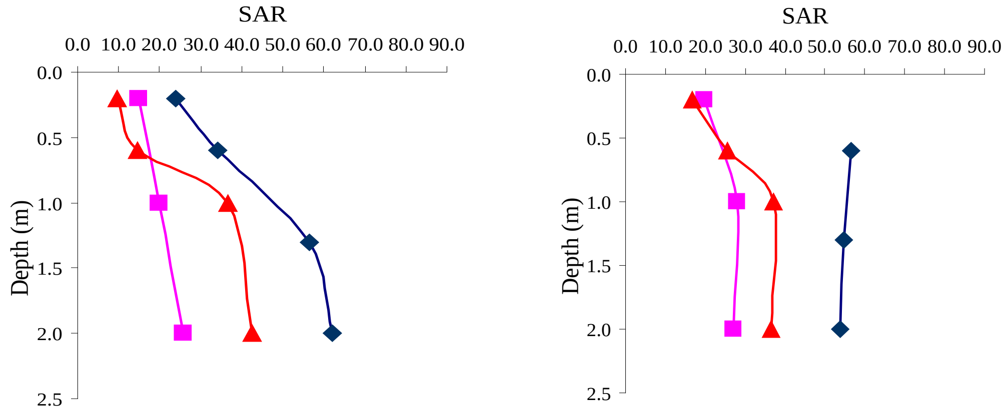
(b) allu+gypsum plots with irrigation

Figure 19: SAR as a function of depth at various sampling points in allu+gypsum plots (a) without irrigation, (b) with irrigation



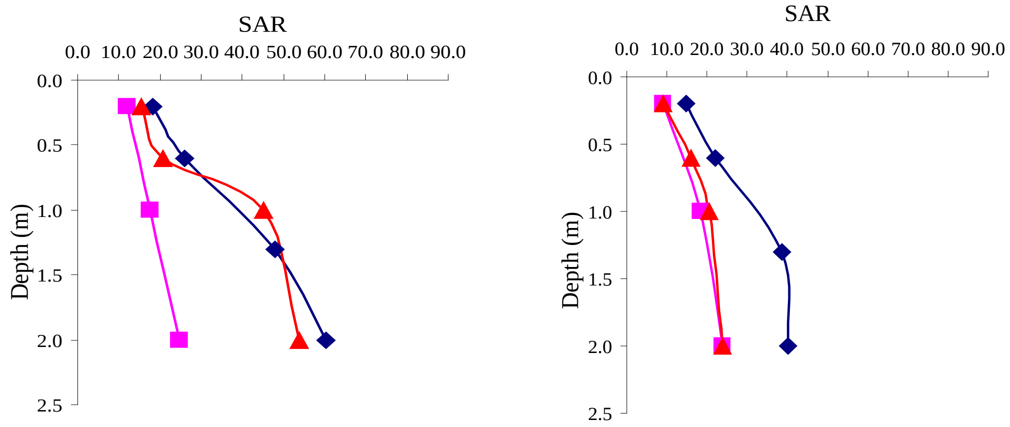
Sample location 1-2

Sample location 19-2



Sample location 9-2

Sample location 25-2



Sample location 17-2

Sample location 33-2

(a)ripping+gypsum plots w/o irrigation (b) ripping+gypsum plots with irrigation

Figure 20: SAR as a function of depth at various sampling points in ripping+gypsum plots (a) without irrigation, (b) with irrigation

4.3 Lab data

Two groups of columns were set up in the laboratory. One group consisted of 6 columns: five treatments (allu, allu+sand, allu+gypsum, allu+ zeolite and ripping +gypsum) and one control. 4cm hydraulic head was maintained during the experiment. The other group of columns consisted of four columns to compare three treatments with one control which represented allu-treated soil: allu+sand addition (sand column), allu+gypsum addition (gypsum column), and allu+zeolite addition (zeolite column). 3000mL water was added into each 10cm soil column. The lab data presented in this section includes quantitative and qualitative data for infiltration, leachate volume, leachate color, leachate EC, leachate pH and removal of Na^+, Ca^{2+} and Cl^-. The complete data are provided in Appendix B, C and D.

4.3.1 Water infiltration and soil permeability

The ability of water to infiltrate the soil will affect the remediation results. The soil permeability will provide an indication of how easily water can enter the deep soil profile and successfully leach abundant salt out of the soil and into a drainage system.

4.3.1.1 Infiltration rates in the 35cm soil columns

The infiltration depths of the 35cm soil columns were recorded every day until water reached the bottom of the soil layer. Leachate from each soil column was collected in a beaker attached to the bottom of each soil column. Figure 21 shows the infiltration rate in the 35cm soil columns, each column representing one treatment. The infiltration rates in the 35cm gypsum columns (allu+gypsum column and ripping+gypsum column) were much faster than in the other columns. This phenomenon indicated that gypsum addition improved the permeability of soil. Thorough mixing of gypsum with soil resulted in a faster infiltration than surface mixing of gypsum with soil. Water penetrated the 35cm allu+zeolite column slightly faster than the 35cm allu+sand, allu and control columns. No difference was observed among the 35cm allu+sand, allu and control columns. In the case of the allu+sand, it was expected that the infiltration rate would be higher than in the allu and control due to the addition of sand. The fact that infiltration rates were the similar for the three treatments may be due to the fact that small amount of sand was added and this amount may not have been sufficient to cause a noticeable effect. Leachate was collected on day 13 and day 39 from the 35cm allu+gypsum and ripping+gypsum columns, respectively. Only after 10 months of water ponding, leachate was collected from the 35cm allu+zeolite column. There was no leachate collected from the 35cm allu+sand, allu or control columns at the end of the experiment, after 12 months of water ponding.

Similar to the 35cm soil columns, infiltration rates in the 10cm gypsum column was the fastest. The leachate was collected from the 10cm gypsum column on the first day of leaching. Irrigation water flowed through the 10cm zeolite soil column faster than the 10cm sand column and 10cm control column. After 8 days, leachate was collected from the 10cm zeolite column. Generally, the infiltration rate in the 10cm sand column was similar to that in the 10cm control column. It took 21 days to obtain the first drop of leachate from the 10cm sand column, and 22 days to obtain leachate from the 10cm control column. The infiltration rate in the 10cm sand column was slightly slower than that in the 10cm control column for the first 20 days, but then it was similar for both columns.

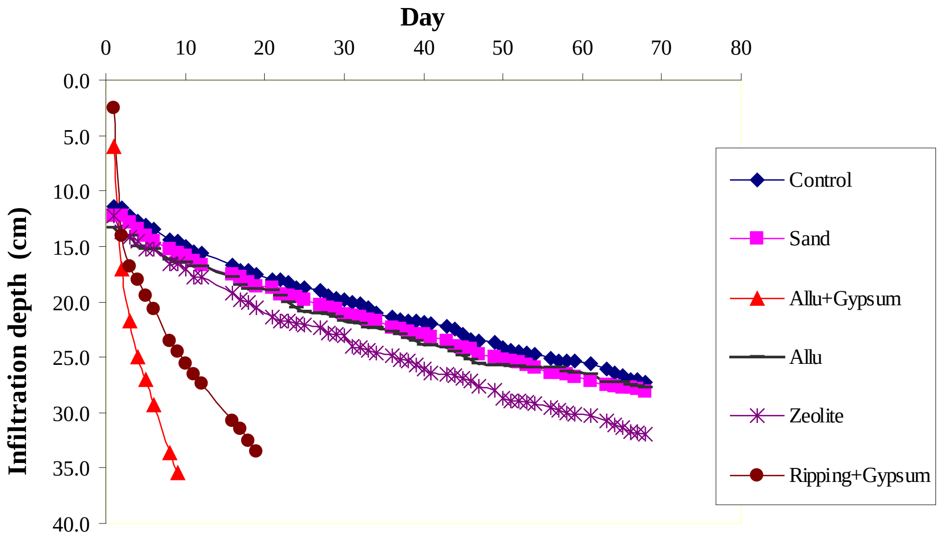


Figure 21: Infiltration in the 35cm soil columns

4.3.1.2 Leachate volumes of the 10cm soil columns

The leachate volume variation of each column in the group of 10cm soil columns is presented in Figure 22. The initial leachate volumes were around 400mL/day, 27.5mL/day, 14mL/day and 10mL/day respectively from the 10cm gypsum, zeolite, control and sand columns, respectively. The infiltration rate in the 10cm gypsum column was too high so that the leachate volume from the gypsum column could not be plotted in Figure 22. The leachate volumes of other columns in the group of 10cm columns decreased with time, fluctuated and finally dropped to less than 16mL/day in the zeolite column, 7mL/day in the control column and

7.7mL/day in the sand column at the end of the experiment. These were affected by the water pressure above the soil media decreasing with total leaching volume. The other possibility was the soil dispersion during leaching due to salt loss.

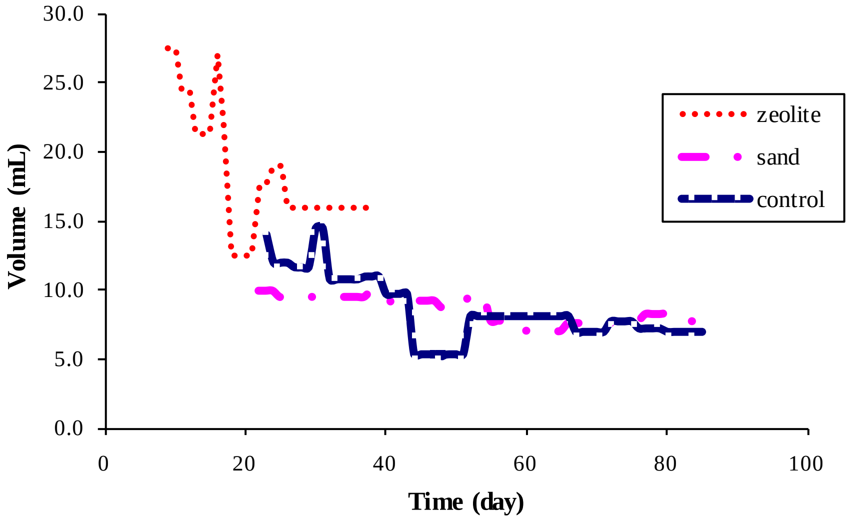


Figure 22: Leachate volume variation over leaching time from the 10cm soil columns

4.3.1.3 Soil permeability

The soil used in this experiment was collected from the contaminated site, air dried, ground and then passed through 2mm sieve. The texture of soil is 35% silt and 60% clay, which leads to a relatively impermeable soil under sodic situation. Therefore, permeability was a concern for this experiment. In the group of 35cm columns with 4cm hydraulic head, no leachate was collected from sand, allu and control columns at the end of the experiment period (12 months). The first drop of leachate from the 35cm zeolite column was collected only after 10 months water ponding. While, for gypsum columns, leachate was collected at shorter irrigation times; 13 days and 39 days for allu+gypsum and ripping+gypsum, respectively.

These results indicate that ordinary leaching methods would not work well in high-silt-clay soils since the limiting factor is permeability. In these soils, clay dispersion caused sealed pores and impeded water infiltration (Donahue *et al.*, 1983).

In the group of 10cm soil columns, hydraulic head was increased to 30cm in zeolite, sand and control columns. The additional positive pressure counterbalanced the resistance and forced water to percolate through soil layer of four columns. The hydraulic head of the 10cm gypsum column was only 10cm rather than 30cm and it took only 2 hours for water to drain out from the 10cm gypsum column. Under 30cm hydraulic pressure, the 10cm zeolite column needed 8 days to produce leachate. The 10cm sand column and the 10cm control column needed 21 days and 22 days, respectively. In terms of time to remove salt from the soil, it took only 4 days to decrease the EC of the leachate solution in the gypsum column to below 2dS/m, and to decrease the EC of soil less to 1dS/m. Zeolite application appeared to be the second most effective treatment to remove excess salt from the soil: 23 days to decrease the leachate of the 10cm zeolite column to 1.85dS/m. It took 75 days to decrease the leachate EC of the 10cm control column from 85.4dS/m to 1.96dS/m and 87 days to decrease the leachate EC of the 10cm sand column from 94dS/m to 1.93dS/m (Appendix B). The similar EC variation over time indicated that sand addition did not improve the permeability of soils.

However, looking only at salt removal during leaching, both zeolite addition and sanding succeeded at removing salt from the studied soil. Results of the 10cm soil columns, where water could percolate through soil, were in agreement with theory that gypsum addition is less effective at remediation if the soil is permeable (Donahue *et al.*, 1983).

Both the results of the 35cm and 10cm columns suggest that loose packing and sanding did not improve the permeability of field soil (high clay) significantly. In the group of 35cm soil columns, no water leached from the control column, allu column (loose packing) and allu+sand column at the end of experiment. In the group of 10cm soil columns, no obvious difference was observed between the infiltration rates of the sand column and control column. This result may be explained that the amount of added sand was not enough to cause a noticeable change in the soil texture (Qadir *et al.*, 2001). Clay contents of 35% in the soil may also destroy the macropores created by sanding when wetting the soil. Although loose packing, as with alluing, may break down impermeable layers, if the soil is still sodic, loose clay particles may be easily dispersed again after wetting and may reseal the created soil pores. The results are consistent with literatures that leaching alone with water is not suggested to treat saline-sodic soils because of their extremely low permeability (Donahue *et al.*, 1983; Carty *et al.*, 1997; Qadir *et al.*, 2001). For saline-sodic high-clay content soils, chemical application is required for an effective leaching process.

It was observed in the group of 10cm soil columns that the leachate volume initially decreased, fluctuated and finally dropped from 27.5mL/day to less than 16mL/day in the zeolite column, from 14mL/day to 7mL/day in the control column and from 10mL/day to 8mL/day in the sand column at the end of the experiment (Figure 22). This decrease in leachate volume may be due to the decrease in water pressure above soil media. Another possibility is that leaching cause a drastic drop in soil permeability (Mojallali and Dregne, 1969; Dregne, 1976; American Petroleum Institute, 1997). A drop in permeability may be caused by soil dispersion during the process of leaching Na^+ from the soil (American Petroleum Institute, 1997). In early leaching, the soil did not disperse since it was still saline. Due to the high salt content and little dispersion, water may quickly pass through the soil columns without interaction with salts (Costa *et al.*, 1991). The sodium cations were still closer together and the charge density was high enough to resist soil dispersion (American Petroleum Institute, 1997). With salinity decreasing, the sodium saturation of clay cation exchange sites increases. The soil thus became susceptible to dispersion. The sodium cations continued to migrate deeply into micropores and internal cation exchange layers of the clay minerals. As a result, the clay became dispersed and the soil surface was sealed so that water could not move effectively into the soil profile. Therefore, maintaining an effective pore size distribution during and after remediation is another important objective in reclaiming salt-affected soil (American Petroleum Institute, 1997).

The low permeability of soil will adversely affect in situ reclamation efforts by greatly decreasing the rate at which salts and sodium can be leached from the soil. Experiments conducted herein indicated that gypsum application would be useful to maintain and improve soil pore size distribution. Calcium introduction can remove exchangeable sodium from the soil and make it leachable. With calcium instead of sodium predominant in soil, the soil would not disperse and thus permeability could be maintained or even increased.

4.3.2 Leachate pH of the 10cm soil columns

Leachate pH for the group of 10cm soil columns experiments can be observed in Figure 23. The pH in the leachate of the gypsum column rose steeply from 6.95 to 8.12 as the experiment preceded, with little fluctuation, then increasing to 8.28 at the end of the experiment. In the column with zeolite application, the leachate pH started at 6.18, increasing rapidly to 8.99, then remained almost constant until the end of the experiment. The pH variations were similar in the leachate of the control and sand addition columns, starting at 7 and increasing slowly to over 9.

The trend of leachate pH increasing rather than decreasing over time is different from the observation of Courtney and Timpson (2005). At the end of the experiment, the leachate pH of all columns with treatment increased almost one unit, never decreasing. This change in pH must be taken into consideration when reclaiming field soil since the growth of plants is dependent on soil pH. Dregne (1976) stated that the removal of excess soluble salts during rapid leaching would cause a rise in pH, especially in sodic soils with high sodium concentrations. This rise is due to the hydrolysis of Na^+ in the absence of electrolytes in the soil solution. Sodium hydroxide and sodium carbonate will form when rapid leaching occurs (Dregne, 1976; Qadir *et al.*, 2000).

When soil leaching occurs without gypsum or calcium addition, there are no cations to replace the exchanged sodium ions. Sodium ions react with water to make sodium hydroxide and produce hydrogen ions in the soil (Equation 1). Sodium hydroxide continues to react with carbon dioxide in the soil to form sodium carbonate (Equation 2). Sodium carbonate is then leached into the drainage solution, increasing the pH of the leachate (Equation 3) (Tantataemie, 1984):

$$Na^+\text{-Clay} + H_2O \rightarrow H^+\text{-Clay} + NaOH \qquad 1$$

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \qquad 2$$

$$CO_3^{2-} + H_2O \rightarrow HCO_3^- + OH^- \qquad 3$$

If Ca^{2+} is present and if Ca^{2+} concentration decreases with leaching, a rise in pH may occur as a result of the hydrolysis of Na^+ and then equilibrium with calcite. Al-Barrak and Rowell (2006) found in their gypsum solubility experiments that the pH in the extracts increased from 7.5 to 9.4 when the Ca^{2+} concentration decreased.

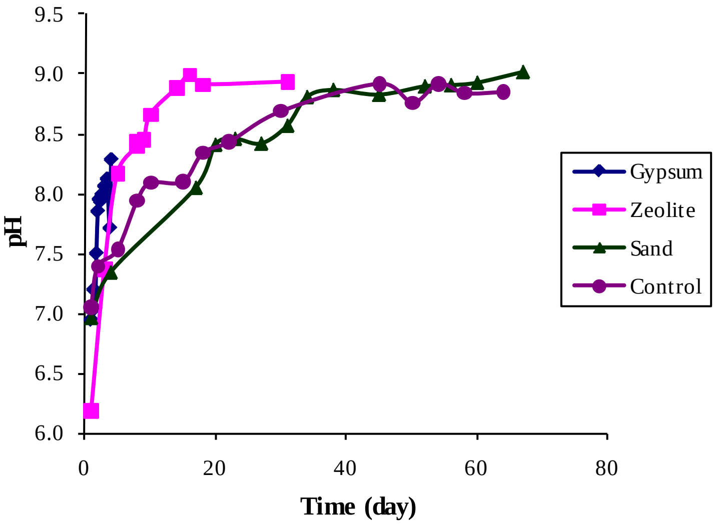


Figure 23: Leachate pH variation in the 10cm soil columns as a function of time

4.3.3 Leachate color of the 10cm soil columns

Leachate from the 10cm gypsum column was clear with a light yellow color. The color of the leachate from the gypsum column did not change over the duration of the experiment. The leachate color from the 10cm sand column changed from slightly yellow to yellow/brown, when the leachate pH was roughly 8.5 or higher. In the 10cm zeolite column, the leachate color was also clear light yellow at the beginning, and gradually changed from yellow to brown and remained so until the end of the experiment. The leachate from the 10cm control column behaved similar to the leachate from the zeolite column. Figure 24 shows the color of the leachate collected from the 10cm columns. Figure 25 shows the color change of the leachate from the 10cm sand column over time.

The possible explanation of the yellow to brown color change is that iron salts dissolved from the soil into solution when water of high pH leached through the soil layer. There was yellowish and reddish spot observed in these soil samples, which indicated that iron compounds were present in the soil. Fe^{3+} ions could react with SO_4^{2-} to form soluble $Fe_2(SO_4)_3$. When the pH is higher than 4, $Fe_2(SO_4)_3$ dissolved in water presents a yellow color. Brown color in the leachate could be due to the presence of $FeCl_3$.

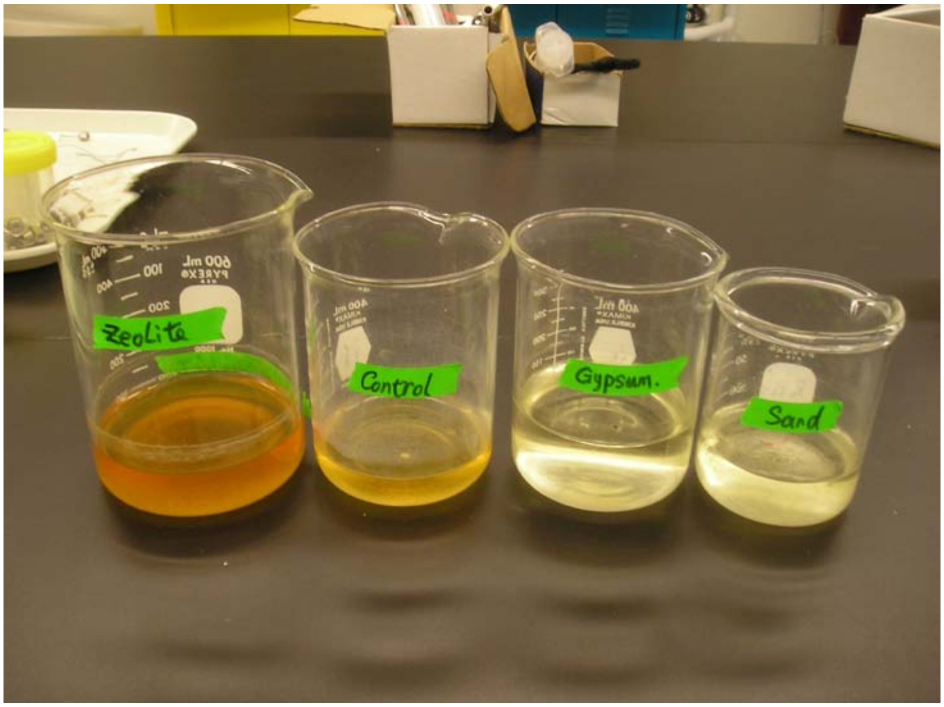


Figure 24: Color of leachate from the 10cm soil columns

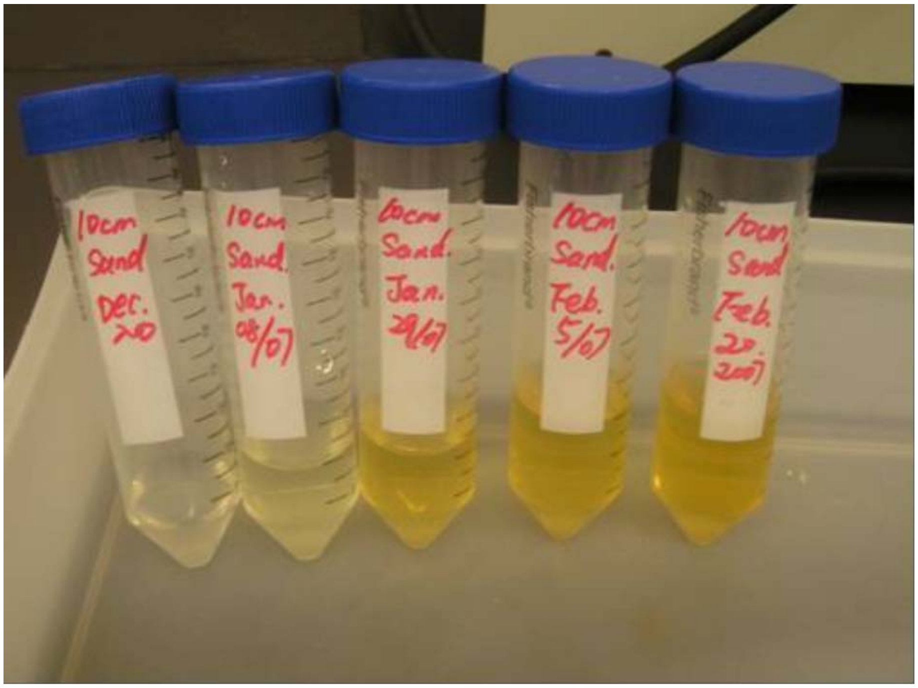


Figure 25: Color change over time for leachate collected from the 10cm sand column

4.3.4 EC variation of leachate from the 10cm soil columns

Figure 26 shows the decreasing trend in leachate EC for all 10cm columns. The initial values of leachate EC were 102.2dS/m, 105.5dS/m, 94.0dS/m and 85.7dS/m from the 10cm soil columns of gypsum, zeolite, sand and control, respectively. During the first few collecting days, the values of leachate EC from all columns decreased sharply, and then tended to decrease slowly over time when the EC was below 10dS/m. The rate of decrease in the leachate EC (before EC dropped to 10dS/m) was in the order of gypsum column>zeolite column>control column>sand column. When the value of leachate EC dropped below 10dS/m, the decreasing rate changed to be in the order of gypsum column>zeolite column > control column=sand column. Since EC is used as an indicator of salinity and the amount of soluble salts present in the leachate, the rate of leachate EC decreasing suggests that gypsum application removed soluble salts faster than zeolite and sand application.

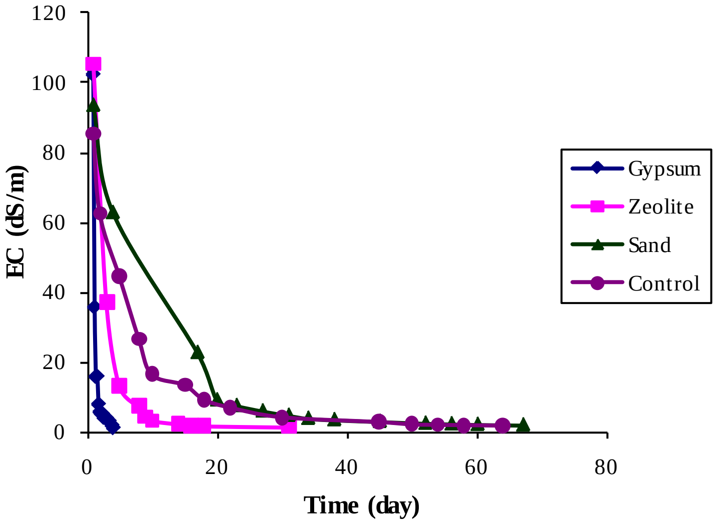


Figure 26: Change in leachate EC as a function of time for the 10cm soil columns

The change in leachate EC (sharp decrease followed by a levelling off) seems to be related to the observed trend in soil permeability as measured by infiltration rate. Early in leaching, the soil was saline-sodic, having high salinity and a high concentration of sodium and the soil was not dispersed yet. As leaching removed the soluble salts, the sodium saturation of the clay cation exchange sites increased. The soil thus became susceptible to dispersion. The sodium cations migrated into micropores and internal cation exchange layers of the clay minerals. As a result, the clay dispersed and the soil permeability decreased and salts were difficult to remove from the soil. The rate of leachate EC decrease from the sand column was similar to or slightly less than the rate of leachate EC decrease from the control column. This result indicates that 10% sand addition does not fasten the removal of salts when water can penetrate through the soil profile.

Figure 27 presents the change in EC of the leachate as a function of pore volumes (PVs) of water added. Figure 27 shows a decreasing trend of leachate EC with increasing leaching water PVs in the 10cm soil columns. 1.2PVs water was enough to decrease the EC from over 80dS/m to below 2dS/m for the 10cm control, sand and zeolite columns. Although gypsum application could decrease the salinity of soil the fastest, it required more water (3.97PVs) than the other treatments to decrease the solution EC to less than 2dS/m.

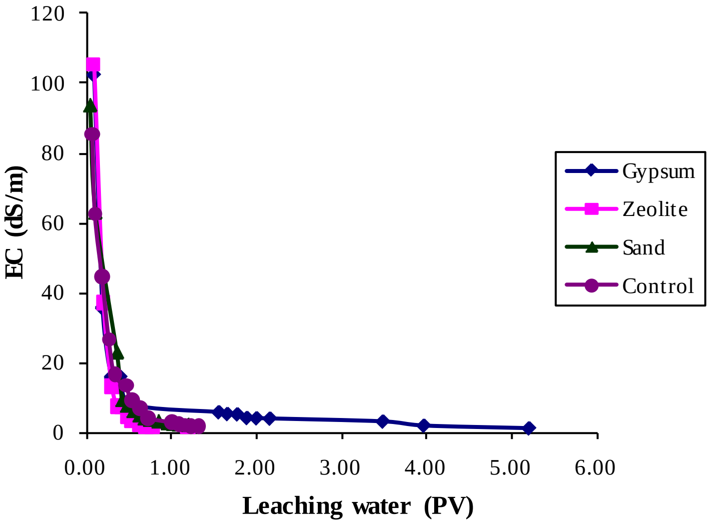


Figure 27: **Decrease of leachate EC as a function of leaching water pore volumes (PVs) from the 10cm soil columns**

Figure 28 is leachate EC curve from the allu+gypsum column in the group of 35cm soil columns. It indicated that 2.8PVs was needed to decrease the leachate

EC from 189.2dS/m to 7.43dS/m. Sufficient leachate for analysis was not collected from the 35cm allu+zeolite column and no leachate drained out of the 35cm control, allu, allu+sand columns until the end of the experiment (12 months ponding). There was leakage found on the bottom wall of the 35cm ripping+gypsum column when the experiment reached 6 months. Therefore, the data of the 35cm ripping+gypsum column was not considered in this discussion.

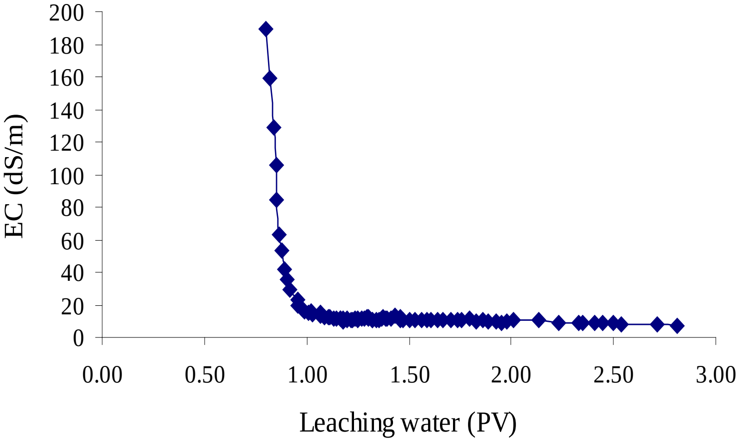


Figure 28: **Decrease of leachate EC as a function of leaching water pore volumes (PVs) from the 35cm gypsum column**

4.3.5 Salt removal from the 10cm soil columns

The removal of Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, SO_4^{2-}, NO_3^- from the 10cm soil columns was calculated and the data are presented in the this section. In the following sections, the discussion will focus on the removal of Na^+, Ca^{2+}, Cl^- and SO_4^{2-}.

4.3.5.1 Na^+, Ca^{2+}, Cl^- and SO_4^{2-} variation in leachate from the 10cm soil columns

Figure 29, 30 and 31 represent the change in sodium, calcium and chloride concentrations in the leachate from the 10cm soil columns as a function of time, respectively. In general, one key trend can be seen in the figures, that is, for all treatments, sodium, calcium and chloride decreased sharply during the first few collecting days.

The initial leached Na^+ concentration from the 10cm gypsum column was much higher than that from the 10cm zeolite, sand and control columns. This high initial Na^+ concentration in the leaching water was the consequence of a greater part of Na^+ being displaced from the cation exchange sites by Ca^{2+} during the initial phase of leaching. It is noticed that the Na^+ concentration decreased in the first leachate samples collected from all four 10cm columns. In later leachate samples, the Na^+ concentration decreased very slowly. One aspect is that most of the exchangeable Na^+ had been removed from the soil, leaving behind small amounts to be washed from the soil. Another reason is that the high-clay content soil became dispersed in zeolite, sand and control columns, which impeded the water drainage and salt removal. It is obvious that sand addition did not distinctly improve the removal of salts from the soil. The Na^+ and Ca^{2+} concentration curves of the sand column are overlapped by those of the control column.

The highest Ca^{2+} concentration occurred in the initial leachate collected from the zeolite column, but not in the initial leachate collected from the gypsum column although gypsum was added to the soil. The added Ca^{2+} replaced Na^+ on the exchangeable sites and then remained in soil.

Cl^- is very easily washed out of soil since it does not interact with the soil (i.e. conservative ion). A little higher concentration in leachate from the 10cm gypsum column and the 10cm zeolite column may be due to the improved soil structure in the two columns. The initial Cl^- concentration was 1522.7mmol/L, 1606.4mmol/L, 1321.0mmol/L and 1225mmol/L from the 10cm gypsum, zeolite, sand and control column, respectively. Similar to Na^+, the Cl^- concentration in the initial leachate collection decreased sharply and then tended to stabilize at less than 1mmol/L, 2mmol/L, 4mmol/L, 3mmol/L for the 10cm gypsum, zeolite, sand and control columns, respectively.

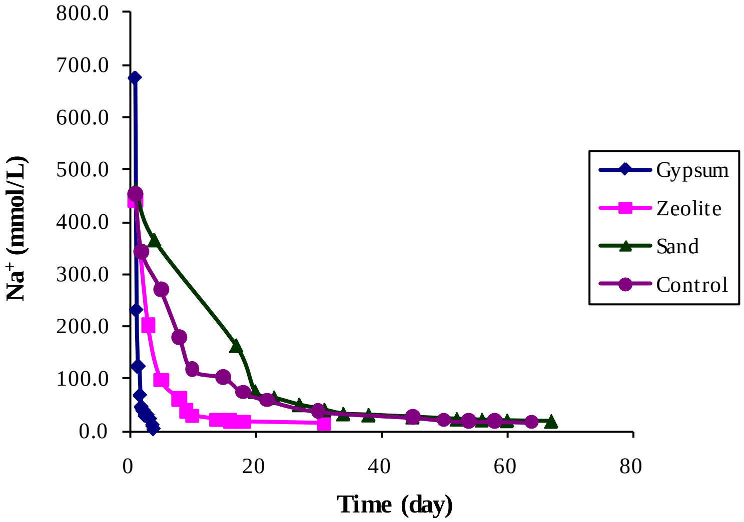


Figure 29: **Sodium concentration in the collected leachate from the 10cm soil columns as a function of time**

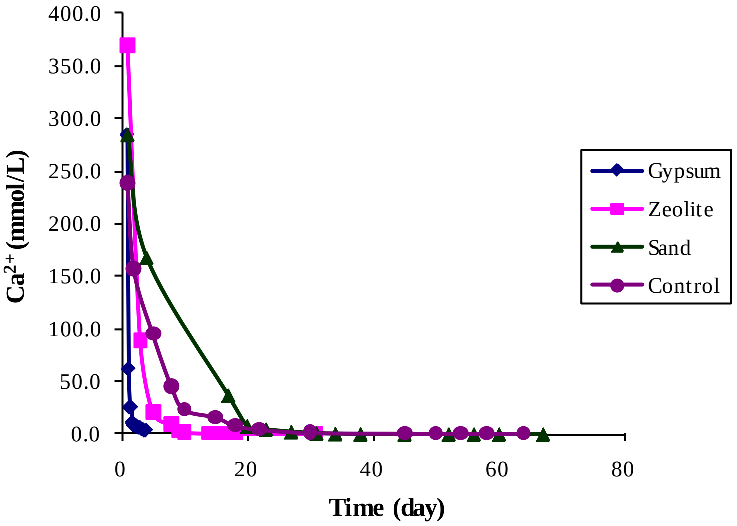


Figure 30: Calcium concentration in the collected leachate from the 10cm soil columns as a function of time

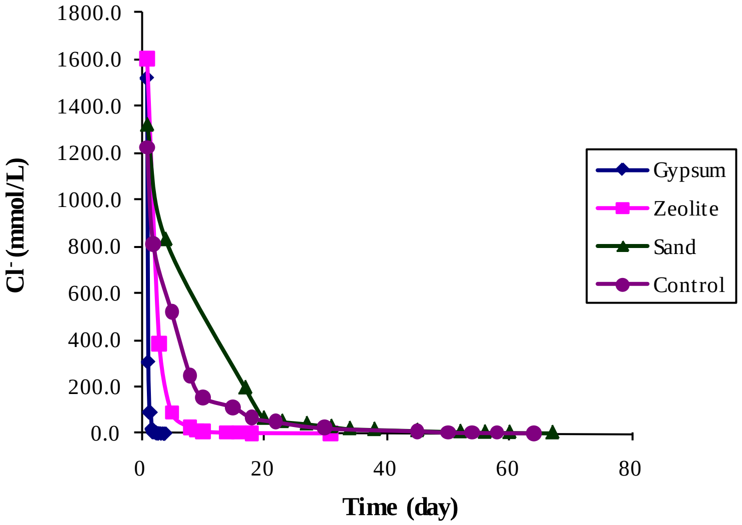


Figure 31: Chloride concentration in the collected leachate from the 10cm soil columns as a function of time

Figure 32 shows the variation of SO_4^{2-} concentration in the leachate of the 10cm soil columns. The concentration of SO_4^{2-} in the leachate from all 10cm columns increased during the first few collection days and then decreased. It is known that inorganic S exists in soils primarily as SO_4^{2-} in a dissolved, adsorbed, and/or solid state. When soils contain Al and Fe, the Al and Fe hydrous oxides are capable of adsorbing SO_4^{2-} and preventing losses due to leaching (Pierzynaki *et al.*, 2005). At first, only dissolved SO_4^{2-} was leached out of soil profile. With increased leaching, the adsorbed SO_4^{2-} was released slowly into the soil solution and then washed out of soil, which caused an increase of SO_4^{2-} concentration in the leachate. When most of the adsorbed SO_4^{2-} was leached out, the SO_4^{2-} concentration in leachate decreased.

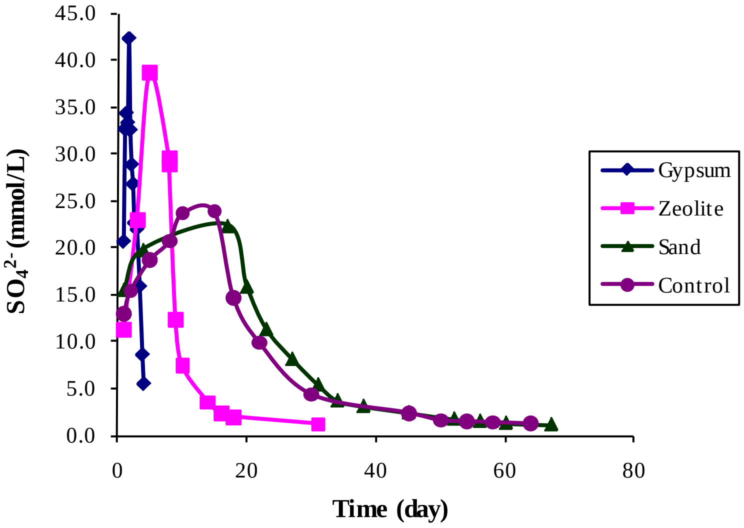


Figure 32: Sulfate concentration in the collected leachate from the 10cm soil columns as a function of time

4.3.5.2 Major ions removal from 10cm soil columns

Table 14 summarizes the percent removals of different ions by the four treatments with leaching: allu+gypsum (gypsum column), allu+zeolite (zeolite column), allu+sand (sand column), and allu (control column). Figure 33 presents the removal of ions after 1.2PVs of leaching and Figure 34 shows the Na^+ removal curve in each column. Under the leaching conditions, the cumulative sodium removal efficiency of the treatments was in the order: allu+gypsum> allu+sand>allu>allu+zeolite. The cumulative chloride removal efficiency of the treatments was in the order: allu+gypsum> allu+zeolite> allu+sand> allu.

It is observed that more than 100% sulfate was leached out of soil during the period of water ponding. The saturated paste extract method could not reflect calcium and sulfate concentration precisely (U.S. Salinity Laboratory Staff, 1954) because a large part of sulfate salt deposit in soils and could not dissolve into solution during saturation. Sulfate from gypsum can reach the lower soil layer and react with free aluminum ions in the soil solution to generate $Al_2(SO_4)_3$ which is non-toxic to plants and can be leached out with water due to its high solubility.

The cumulative amount of Na^+ removed from the 10cm gypsum, zeolite, sand and control soil column was found to be 74.62meq, 45.22meq, 57.18meq and 56.05meq, respectively when 1.2PVs water was applied. The cumulative amount of Cl^- removed from the 10cm gypsum, zeolite, sand and allu soil column was 100meq, 95.898meq, 92.12meq and 96.671meq, respectively when 1.2PVs water was applied.

Table 12: Salt removal (in %) from the 10cm soil columns after 1.2PVs of leaching

Columns	Na^+	Ca^{2+}	K^+	Mg^{2+}	Cl^-	SO_4^{2-}	Br^-
Gypsum	83.0%	18.8%	74.6%	35.5%	93.3%	328.1%	67.1%
Zeolite	52.2%	19.6%	137.0%	39.2%	92.8%	119.0%	71.1%
Sand	66.2%	15.7%	79.3%	31.3%	89.5%	102.1%	72.9%
Control	55.1%	12.9%	64.6%	29.8%	79.8%	84.8%	58.0%

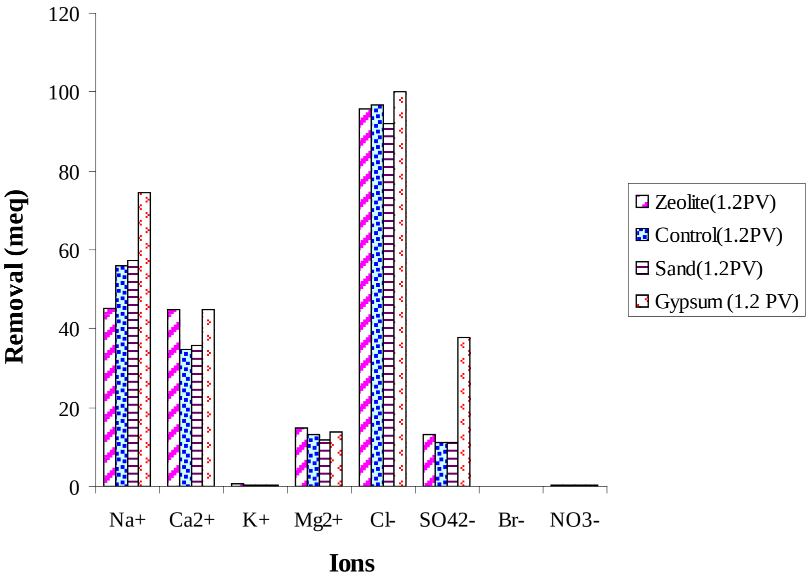


Figure 33: Salt removal after 1.2PVs of leaching from the 10cm soil columns

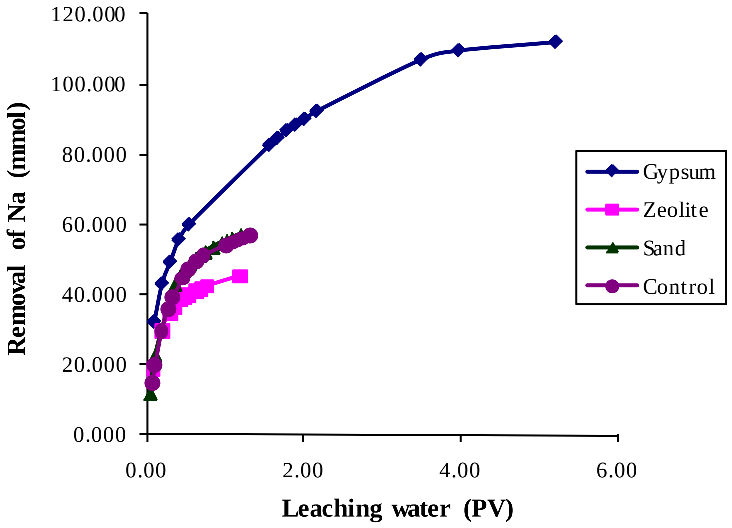


Figure 34: Removal of Na (mmol) in the 10cm soil columns as a function of PV

4.3.5.3 Sodium and chloride removal from the 10cm soil columns

Sodium and chloride are the two ions of concern with respect to salt removal in this project. The results indicate that gypsum treatment removed the largest amount of sodium and chloride with the same amount of irrigation water, 1.2PVs (Table 12 and Figure 33). Gypsum application provided a readily available source of calcium in the soil solution so sodium could be replaced by calcium on the soil's exchange sites. This exchange led to an increase in the soluble salt concentration in the leaching solution. Later in the leaching cycle, the concentration of sodium in the leachate of the gypsum column decreased slowly because the gypsum was depleted, and most amount of sodium has been washed out (Qadir *et al.,* 2003).

Sand addition increased sodium and chloride removal by approximately 10% as compared to the control column. This result indicates that 10% sand addition improved the leaching efficiency although it was not enough to change the soil texture significantly. Later in leaching, the concentration of soluble salts in the leachate from the 10cm sand column decreased slowly because of clay dispersion. Without cation replacement, sodium remained on the clay particles. Moreover, high clay content resulted in lower permeability that impeded sodium leaching.

With respect to sodium removal, zeolite application was the least effective method. Zeolites have a large surface area for trapping and exchanging positive cations because of its open framework and network of pores (Kazemian *et al.*, 2003; Noori *et al*., 2007). Zeolites adsorbed sodium and chloride that entered into their cavities. Zeolite sorption tests demonstrated that more than 60% of the sodium from 393.6mg/L and 787.1mg/L sodium solutions was trapped in zeolite. Zeolite also adsorbs Cl^- into its cavities and improves the soil properties. However, the sorption of Cl^- is very low, only about 2% under the same conditions as for Na^+. It should be noted that zeolite would release sodium which was trapped in it when it is put into a low Na^+ concentration solution. Desorption tests found that 15-16% sorbed Na^+ was released back into solution when the zeolite was placed into a solution containing no Na^+ (Data are listed in Appendix E.).

Chloride is another ion of concern for remediation of salt-contaminated soils because it is toxic to plants and readily taken up by plants. Cl^- is considered as an important diagnostic parameter to assess salt contamination due to oil production because chloride dominates as the anion in produced waters (Evans and Barck, 1995). Since chloride salts tend to be very soluble, Cl^- is very mobile in soil. All the treatments achieved a good removal rate. The chloride removal efficiency of the treatments was in the order: allu+gypsum> allu+zeolite> allu+sand> allu.

4.3.6 Comparison of treatments in the 10cm soil columns

This study used a guideline-based approach to determine the remediation objectives. Soil Quality Guidelines for Unrestricted Land Use (see Table 1) was adapted to compare the various treatments, that is an EC< 2dS/m and a SAR < 4 are the remediation objectives for this study.

At the end of the experiment, when the leachate from the 10cm soil columns reached an EC below 2dS/m, only the gypsum application achieved the soil remediation objective, EC< 1dS/m and SAR=1.27. The leached soil EC and SAR of top soil were 0.8dS/m and 15.9 in the 10cm zeolite column, 1.25dS/m and 19.4 in the 10cm sand column, and 1dS/m and 18.9 in the 10cm control column. These results indicate that leaching could significantly decrease the soluble salt concentration in the soil solution independent of whether chemical is applied or not as long as water can percolate the soil layer. However, without chemical application, the SAR could not be decreased to below the remediation objective in a practical period.

The typical steady infiltration rate for sodic clay soils is reported less than 1mm/hr (Alberta Environment, 2001). As discussed above, without Ca^{2+} introduction, the soil permeability decreased over time due to clay dispersion. Although it takes long time, it is possible to decrease soil salinity to a reasonable level. However, it is impractical to reduce the SAR to a reasonable value for plant growth in sodic clay soils.

When the EC< 2dS/m, the SAR is still high, more than 15 in most cases. The soil becomes a sodic soil. Under this situation, most cation exchange sites in the soil are occupied by sodium. The reduced amount of leachate generated indicated that the clay was dispersing, which resulted in lower and lower water infiltration.

The SAR of the leachate from the 10cm gypsum column decreased dramatically in the first two days (Figure 35). The SAR in the 10cm zeolite column declined slowly over the entire leaching period. In the 10cm sand and control columns, the leachate SAR did not show an obvious trend. The result indicates that the ratio of Na^+ to the square foot of Ca^{2+} and Mg^{2+} remained relatively constant during leaching. This result demonstrates again that leaching without chemical application could remove total salt, but could not readily reduce sodium adsorption ratio in soils.

Comparing all treatments and considering salt removal, the results reveal that gypsum treatment with leaching may be the best method to reclaim a saline-sodic soil containing a high percentage of clay.

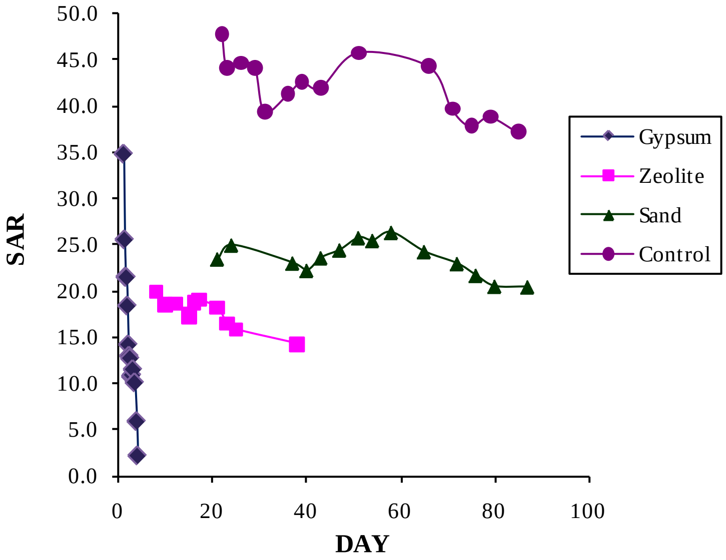


Figure 35: SAR variation of the leachate from the 10cm soil columns as a function of time

4.3.7 Soil properties after treatments

At the end of the experiment when the leachate from 10cm soil columns reached EC<2dS/m, the 10cm soil columns were taken apart in three segments for ion analysis. Table 13 gives the sodium, calcium and magnesium concentrations in each soil segment. The value of saturated paste extract EC and calculated SAR are also provided in Table 13. It was found that under leaching condition, allu treating (control), allu+gypsum addition, allu+zeolite addition and allu+sand decreased the EC to the expected value (below 2dS/m), but only gypsum application achieved the SAR objective (SAR<4). When soil permeability allows, leaching alone (the 10cm control column) could remove most soluble salts from the soil.

Table 13: Soil EC and SAR after treatments in the 10cm soil columns

Columns		Na^+	Ca^{2+}	Mg^{2+}	SAR	EC(dS/m)
		Concentration: mmol/L				
	Untreated Soil	141.40	32.24	12.42	29.924	23.43
Gypsum	Top soil	0.233	0.696	0.112	0.3663	182.3μS/cm
	Middle soil	0.872	0.737	0.129	1.3244	0.25
	Bottom soil	2.294	1.961	0.354	2.133	0.68
Zeolite	Top soil	4.637	0.242	0.062	11.888	0.80
	Middle soil	8.062	0.326	0.070	18.115	
	Bottom soil	10.681	0.588	0.129	17.827	
Control	Top soil	6.062	0.23	0.06	15.959	0.63
	Middle soil	9.837	0.41	0.09	19.666	0.99
	Bottom soil	12.129	0.54	0.12	21.031	1.20
Sand	Top soil	6.03	0.20	0.05	16.818	1.25
	Middle soil	9.866	0.39	0.09	20.261	
	Bottom soil	12.63	0.58	0.13	21.258	

4.3.8 Ion balance analysis for the leachate from the 10cm soil columns

The analyzed cations in the group of 10cm soil columns included Na^+, Ca^{2+}, Mg^{2+} and K^+ and the analyzed anions were SO_4^{2-}, Cl^-, Br^-, NO_3^-, HCO_3^- and CO_3^{2-}. The data is provided in Appendix B.

In the beginning of the experiment, the sum of cations in the leachate was less than the sum of anions. This result may be due to Al^{3+} not included in the sum of cations. CO_3^{2-} and HCO_3^- were measured after storing the leachate for a certain time, which may have caused lower measured values than the actual values. As leaching continued, the concentration of ions became smaller and smaller and the possible errors in CO_3^{2-} and HCO_3^- became more important and led to increased error. The amount of CO_3^{2-} and HCO_3^- showed their importance in the later leaching time.

The accuracy of analysis for major ions was estimated from the electrical balance since the sum of positive and negative charges in the water should be equal (Appelo *et al.,* 2005). The percent error in the electrical balance was calculated as follows:

$$\text{Electrical Balance (E.B., \%)} = \frac{(\text{Sum cations} - \text{Sum anions})}{(\text{Sum cations} + \text{Sum anions})} \times 100$$

where cations and anions are expressed as meq/L and inserted with their charge sign. The sums of cations are for Na^+, K^+, Mg^{2+} and Ca^{2+}, and the sum of anions are for Cl^-, HCO_3^-, SO_4^{2-} and NO_3^-. The differences in E.B. of up to 2% are inevitable in almost all laboratories (Appelo *et al.,* 2005). As long as the difference of ion balance is less than 10%, the balance is considered acceptable in commercial lab (personal communication, ALS Environmental Group, Edmonton, Alberta, Canada). The result of error% (Figure 36) suggests that the major ions in the soil have been accounted for and the ion balance was acceptable.

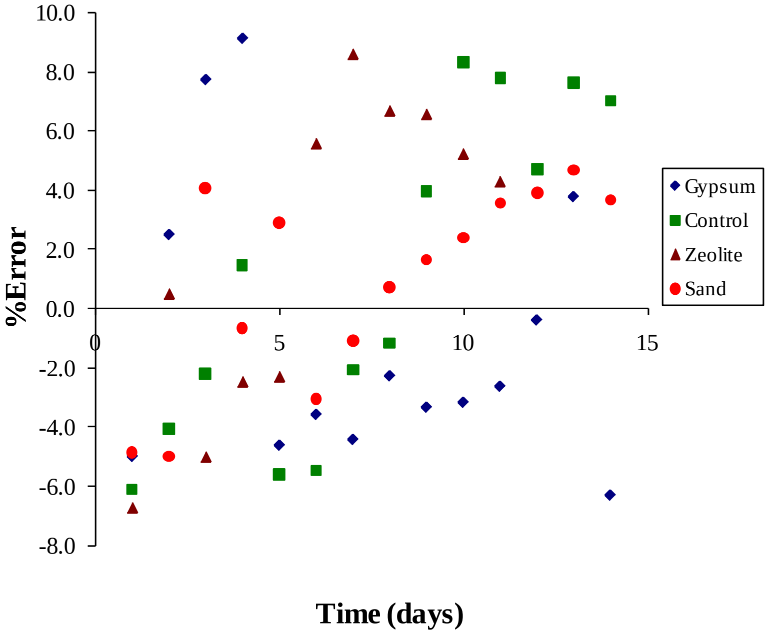


Figure 36: **%Error of electrical balance for the 10cm soil columns**

4.4 Irrigation

As described in Section 4.3.1, irrigation decreased the salinity of the soil in most field plots, but had no appreciable effect in control plots. Figure 16, 17, 18 19 and 20 indicated that irrigation did not decrease the sodicity (for which SAR is the indicator) in most plots, but have an inhibition on SAR increase by counteracting the capillary rise.

On site, irrigation and precipitation can both leach salts down into drainage system if the soil permeability allows, and thus remove them from the studied soil profile. Under this situation, EC at all depths decreases. When the soil is dispersed and becomes impermeable (for example, in the control plots), the surface soil salinity may be reduced during leaching. However, salt will enter the subsurface soil and may be stopped by an impermeable layer and may not enter the drainage system. The salts will deposit at a lower soil layer and increase the salinity of the subsurface soil. Evaporation and capillary rise may enhance the capability of soil to retain salt in the subsurface soil and even bring salt back up to the surface soil if the driving force from leaching is smaller than the driving force from capillary rise. These competing processes may explain why EC increased in some sampling locations after three months' treatment (for example 15-2, 18-2, 24-2 and 36-2). Large quantities of water and high water pressures would be required to counteract the capillary rise and evaporation if remediation time is a consideration.

The amount of water needed for irrigation depends on the initial salt content of the soil, the desired level of soil salinity after leaching, the required reclamation depth and the soil texture (Abrol *et al.*, 1988; Finlayson, 1993). It could be estimated from the leaching fraction. In this project, the field-scale experiments used tap water as irrigation water. The tap water EC is approximately 0.4dS/m, and the EC of drainage water is required to be less than 2dS/m. The leaching fraction can therefore be calculated as:

$$LF=EC_{iw}/EC_{dw}= (0.4\text{dS m}^{-1}) / (2\text{dS m}^{-1}) =0.2$$

This fraction is the fraction of water needed to pass through the soil profile. For the field-scale experiment, the total water required to decrease the drainage water to 2dS/m is

$$2.3\text{m} + (0.2)*(2.3)=2.76\text{m}$$

or a volume of $69m^3$ for each 5m*5m plot. For the field study, the actual amount of water applied to the field plots was not available and therefore can not be compared to the calculated leaching fraction.

For the 35cm soil columns, no leachate was collected from the columns except for the columns with gypsum addition (i.e. allu+gypsum and ripping+gypsum). The column with ripping+gypsum was discarded since the leachate was likely from leakage in the column. Therefore, the leaching fraction could only be verified for the 35cm allu+gypsum soil column. For this column, 3652mL tap water was applied as irrigation water and the EC of the leachate decreased to only 7.43dS/m (Appendix D). To achieve an EC of 2dS/m, the total amount of water required could be theoretically calculated as:

$$35cm + (0.2)*(35cm)=42.0cm$$

or a volume of 3430mL. The actual applied water volume is greater that the calculated leaching fraction required and therefore should have been sufficient to reduce the EC to the desired value of 2dS/m. However, evaporation losses and other factors may have resulted in a less water than the actual applied water moving through the column.

For the 10cm soil columns, deionized water with EC<0.018dS/m was used as the leaching water to decrease the leachate EC below 2dS/m and therefore the leaching fraction is calculated as

$$LF=EC_{iw}/EC_{dw}=(0.018dS\ m^{-1}) / (2dS\ m^{-1})=0.009$$

The total water required to decrease the leachate EC to 2dS/m is

$$10\text{cm} + (0.009)*(10\text{cm})=10.1\text{cm}$$

or a volume of 816mL. The amount of leaching water applied to the 10 cm columns is 1206mL, 1206 mL, 1121mL and 2300mL for the zeolite, sand, control and gypsum columns, respectively. In all cases, the amount of applied water is greater that the calculated leaching fraction and therefore the EC of the leachate should be less than the desired EC value of 2dS/m. The observed EC values of the leachate were 1.4, 1.9, 1.7 and 1.8dS/m for the zeolite, sand, control and gypsum columns, respectively, therefore the desired EC of 2dS/m was achieved in all cases.

It is usually believed that the depth of water equal to the depth of the soil could remove 80% of the salt out of a well permeable soil (Abrol *et al.,* 1988). This amount of water in terms of volume is equivalent to two times the soil pore volume given the soil/solution ratio to be about 15 grams of soil per 10mL of leaching water (Miyamoto *et al.*, 1975). Meyer (1952) also stated that for a high clay content soil, the leaching requirement may be as great as 1.5 to 2.0 pore volumes, or higher. In the 10cm soil columns of laboratory experiments, 1.2PVs water decreased the EC of leachate from all columns to less than 2dS/m and removed 52.2% sodium and 92.8% chloride from the zeolite column, 55.9% sodium and 79.9% chloride from the control column, 66.2% sodium and 89.5% chloride from the sand column, and 83.0% sodium and 93.3% chloride from the gypsum column (Table 12).

The need of irrigation could be decided by comparing the difference of precipitation and evapotranspiration with the leaching requirement. However, the concept of leaching requirement is based on assumptions of steady-state and of absolutely uniform conditions of irrigation, leaching, infiltration and evapotranspiration which often are not achieved under field conditions (Qadir *et al.*, 2000). American Petroleum Institute (1997) suggested keeping a record of the amount of precipitation and the amount of supplemental water used for previous remediation will help in calibrating irrigation to local conditions for future remediation activities. Carty *et al.* (1997) generalized from previous field experiments that irrigation may be required for salt leaching when annual evaporation exceeds annual precipitation by 30-70cm/yr, and will almost certainly be required when the difference is greater than 70cm/yr.

Alberta Environment (2007) states that the average annual precipitation in Edmonton (1883-2003) is, on average, 460mm, the highest being 745mm and the lowest being 210mm. The average annual evaporation in the Edmonton area is of the order of 650mm (Alberta Environment, 2007). The mean annual evaporation exceeds annual precipitation by 19cm/yr that is less than 30cm/yr, which means rainfall might provide sufficient water to remediate salt spills (Carty *et al.*, 1997). In the Edmonton area, rainfall may be sufficient to leach salts below the root zone if the contaminated soil is considered permeable.

However, irrigation can speed up the salt leaching process. The required leaching period is more critical when contaminated sites are farmlands. Therefore, irrigation is strongly recommended as a part of salt-affected soil remediation scenario for a soil that must be remediated quickly.

As found in this thesis, salt leaching was restricted by the low permeability of the soil, which was a result of insufficient pore size and continuity (Carty *et al.*, 1997). If salt leaching is part of the remediation scenario, then enhancement and maintenance of soil macropores with chemical amendments and mulch is critical.

5 Conclusions and Recommendations

The purpose of this research is to investigate treatment options for a highly salt-contaminated soil at both the lab-scale and field-scale. Emphasis is on how much sodium and chloride can be removed from the soil and in what time frame, and how the salts migrate during leaching of the soil. EC and SAR were used to assess the salinity and sodicity of soil in this thesis.

According to the classification proposed by regulatory agencies which uses EC and SAR to assess salt-affected soils, the soil at the studied field site can be classified as heavily affected saline-sodic silty clay loam soil. Large amounts of sodium and chloride were introduced into the soil by past activities related to the oil and gas industry.

Both lab-scale and field-scale tests were conducted to investigate the effect of the following physical and/or chemical treatments on leaching as a method to reduce the EC and SAR of the salt-contaminated soil: alluing, alluing with sanding, alluing with gypsum addition, alluing with zeolite addition, and ripping with gypsum. Field-scale tests also investigated the effect of irrigation in combination with these treatments.

Field-scale tests showed that, over the treatment period:

- irrigation appeared to lower the EC slightly in all treatments plots except for the control plots

- irrigation did not appear to decrease the SAR in most treatment plots
- without irrigation, the SAR appeared to increase in some plots of all treatments, likely due to capillary action and evaporation that brought sodium into the upper soil profile
- ripping with gypsum addition under irrigation was the most effective of the studied treatments at lowering the EC of soil and SAR of top soil. After the given period treatment, the EC and SAR of top soil in some plots met the “fair” category as defined by Alberta regulatory guidelines.

Therefore, leaching after ripping and gypsum addition is suggested to be the most suitable remediation option for the studied site based on the results of three months of treatment.

Lab-scale tests using salt-contaminated soil collected from the field showed that:

- without chemical addition, the soil became dispersed and swelled during leaching
- physical amendments or leaching alone could not remove salt from the studied soil profile due to the change in soil permeability during leaching
- the soil permeability was maintained or even improved with gypsum or zeolite addition but the addition of sand did not lead to a noticeable improvement in soil permeability

- due to its ability to sorb ions, zeolite addition did not result in a high removal of Na^+ from the soil column. The sodium was likely “trapped” in the zeolite and was not leached from the soil column
- with gypsum addition, the EC and SAR decreased along the entire length of the soil column since large amounts of Na^+ and Cl^- were removed from the soil layer
- gypsum addition need the shortest time to achieve the acceptable remediation objective (in terms of EC and SAR) by leaching.

Therefore, based on the lab tests, leaching with physical amendment (either alluing or ripping) and gypsum addition is suggested to be the most suitable remediation option for the studied site.

With respect to the field data, there were only three months of data for analysis. More data from the field site would be beneficial to lead to more conclusive trends. Moreover, background samples should be taken from uncontaminated soil at the field site. These samples would be useful in establishing remediation goals consistent with local surroundings. It may also be valuable to identify the type and health of the vegetation currently growing in and around the salt-impacted soil of the field site in order to identify potential salt tolerant species. Finally, additional follow-up observations and monitoring should be continued to follow the effectiveness of remediation.

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Appendices

Appendix A. Soil properties

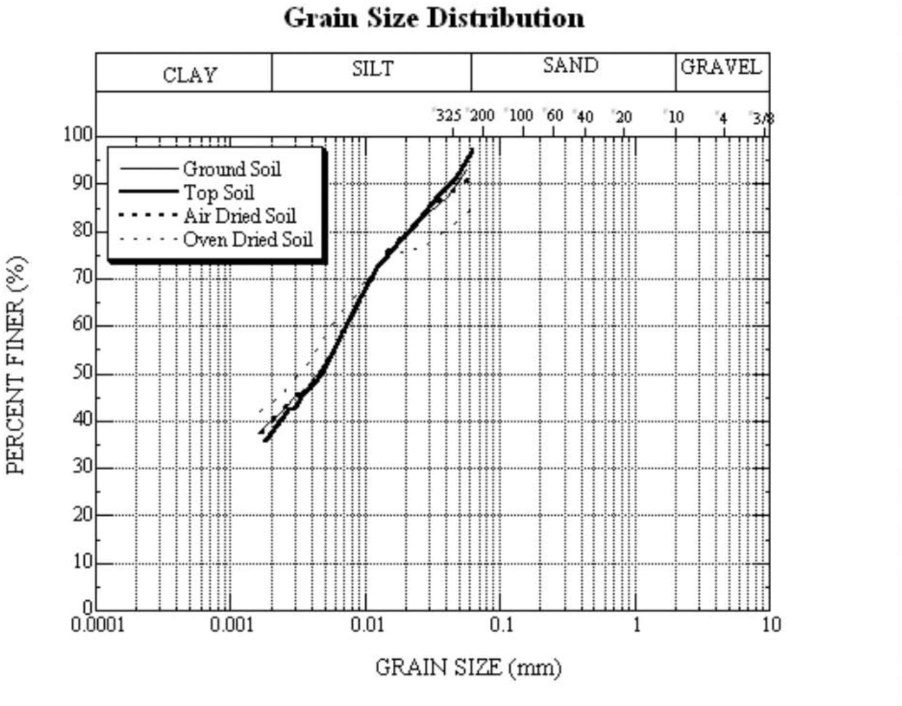

Figure A-1. Soil particle size distribution

Table A-1. Data for cation exchange capacity (CEC) calculation

Sample ID	**Cation concentration (mg/L)**					
	Li$^+$	**Na$^+$**	**NH$_4^+$ as N**	**K$^+$**	**Mg^{2+}**	**Ca^{2+}**
CEC-1	0.11	356.85	huge-added	26.01	90.20	766.90
CEC-2	0.13	286.81	huge-added	21.89	75.71	660.21
CEC-3	0.10	305.00	huge-added	19.10	77.29	666.17
CEC-4	0.08	293.37	huge-added	20.75	69.11	634.83
Average	0.11	310.51		21.94	78.08	682.03
Exchangeable cations in meq/100g	0.02	13.50		0.56	3.21	17.05
CEC	34.33					

Table A-2. Untreated soil data

Sample	EC (dS/m)	pH	Concentration: mg/L							
			Br^-	Cl^-	NO_3^-	SO_4^{2-}	Ca^{2+}	Na^+	Mg^{2+}	K^+
Untreated soil 1	20.40	7.25	18.33	6457.38	0.00	1023.30	1368.09	3078.38	234.82	23.26
Untreated soil 2	20.50	7.35	17.28	6466.29	0.00	1026.58	1362.92	3104.67	234.57	23.24
Untreated soil 3	19.46	7.74	18.47	5924.85	0.00	937.13	1254.83	2908.96	216.94	22.00
Untreated soil 4	19.99	7.65	17.43	6304.70	0.00	941.93	1314.31	3031.46	228.39	25.60
Untreated soil 5	19.88	7.39	17.45	6190.70	31.90	821.66	1366.61	2975.80	231.22	23.05

Appendix B. Results of the 10cm columns

Table B-1. Data of the 10cm gypsum column

Mass of Soil: 852.65 g; Volume: 816.7 cm^3; Gypsum: 6.5 g; Bulk Density (g/cm^3): 1.044; Porosity: 0.586.

Date	**Add water (mL)**	**Leachate volume (mL)**	**EC (dS/m)**	**pH**	**Concentration: mmol**											
					Na^+	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Cl^-**	**$SO4^{2-}$**	**Br^-**	**NO_3^-**	**HCO_3^-**	**Total cation**	**Total anion**	**%Error of electrical balance**
Dec. 12	1250															
Dec. 12-1		48	102.2	6.95	32.34	0.14	13.68	4.24	73.09	0.99	0.07	0.31	0.05	68.33	75.50	-4.98
Dec. 12-2		47	35.6	7.05	10.85	0.04	2.90	0.93	14.41	1.53	0.02	0.07	0.08	18.55	17.64	2.50
Dec. 12-3		50	15.73	7.2	6.18	0.02	1.25	0.40	4.61	1.71	0.00	0.02	0.07	9.50	8.14	7.73
Dec. 12-3-2		52	15.75	7.04	6.39	0.03	1.29	0.41	4.63	1.73	0.00	0.03	0.07	9.83	8.18	9.12
Dec. 12-4		63	7.85	7.5	4.31	0.02	0.67	0.20	1.26	2.66	0.00	0.01	0.08	6.08	6.67	-4.61
Dec. 13-1		490	5.66	7.85	22.70	0.11	4.08	1.14	3.23	15.90	0.00	0.02	0.67	33.25	35.71	-3.57
Dec. 13-2	900	48	5.15	7.95	1.95	0.01	0.37	0.10	0.32	1.38	0.00	0.00	0.08	2.89	3.16	-4.41
Dec. 13-2-2	100	56	5.06	7.93	2.19	0.01	0.42	0.11	0.32	1.50	0.00	0.00	0.09	3.26	3.41	-2.26
Dec. 13-3		54	4.02	7.99	1.62	0.01	0.34	0.08	0.11	1.22	0.00	0.00	0.09	2.48	2.65	-3.32
Dec. 13-4		54	3.93	7.98	1.63	0.01	0.33	0.08	0.08	1.22	0.00	0.00	0.10	2.46	2.62	-3.16
Dec. 13-5		75	3.84	8.06	2.28	0.01	0.42	0.10	0.09	1.64	0.00	0.00	0.15	3.35	3.52	-2.62
Dec. 14-1	750	634	3	8.12	14.69	0.08	2.70	0.65	0.42	10.04	0.00	0.00	1.13	21.46	21.63	-0.38
Dec. 14-2		230	1.805	7.71	2.61	0.02	0.67	0.18	0.07	1.98	0.00	0.00		4.35	4.03	3.78
Dec. 15-1		590	1.048	8.28	2.43	0.03	1.75	0.40	0.09	3.25	0.00	0.00	1.06	6.76	7.66	-6.29
Sum	3000	2491			112.18	0.54	30.87	9.04	102.73	46.75	0.10	0.46		192.53	196.80	-1.10

Table B-2. Data of the 10cm zeolite column

Mass of Soil: 821.69 g; Volume: 816.7 cm^3; Zeolite: 82 mL; Bulk Density (g/cm^3): 1.006; Porosity: 0.601.

Date	Add water (mL)	Leacha-te volume (mL)	EC (dS/m)	pH	Concentration: mmol												
					Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	$SO4^{2-}$	Br^-	NO_3^-	HCO_3^-	CO_3^{2-}	Total cation	Total anion	%Error of electrical balance
Nov. 27	2550																
Nov. 28	150																
Nov. 29	74																
Dec. 1	90																
Dec. 4	100	42	105.5	6.18	18.60	0.19	15.53	5.16	67.47	0.48	0.07	0.29	0.05	0.00	60.17	68.83	-6.71
Dec. 6	60	55	37.0	7.37	11.07	0.14	4.91	1.58	21.18	1.26	0.03	0.11	0.10	0.00	24.18	23.94	0.49
Dec. 8	0	49	13.1	8.17	4.79	0.06	1.03	0.32	4.36	1.89	0.00	0.03	0.16	0.00	7.54	8.33	-5.00
Dec. 11	110	32	7.3	8.39	1.96	0.03	0.30	0.10	0.90	0.95	0.00	0.00	0.13	0.00	2.79	2.93	-2.47
Dec. 11		32	7.5	8.44	1.91	0.03	0.30	0.09	0.86	0.93	0.00	0.00	0.13	0.00	2.72	2.84	-2.29
Dec.12		27	4.2	8.45	1.01	0.02	0.08	0.03	0.34	0.33	0.00	0.00	0.11	0.00	1.24	1.11	5.56
Dec.13		22	3.2	8.66	0.64	0.01	0.04	0.01	0.18	0.16	0.00	0.00	0.13	0.00	0.75	0.63	8.57
Dec.17		50	2.3	8.88	1.07	0.02	0.05	0.02	0.19	0.18	0.00	0.00	0.48	0.03	1.23	1.07	6.66
Dec.19		35	1.8	8.99	0.63	0.01	0.03	0.01	0.11	0.08	0.00	0.00	0.36	0.00	0.72	0.63	6.55
Dec.21		38	1.7	8.91	0.64	0.01	0.03	0.01	0.09	0.07	0.00	0.00	0.40	0.02	0.74	0.67	5.21
Jan.3		208	1.4	8.93	2.91	0.05	0.16	0.04	0.22	0.25	0.00	0.00	2.14	0.11	3.36	3.08	4.28
Sum	3134	590			45.22	0.57	22.45	7.36	95.90	6.57	0.10	0.43			105.42	114.06	-3.94

Cap water: 1928mL

Table B-3. Data of the 10cm control column

Mass of Soil: 963.72 g; Volume: 816.7 cm^3; Bulk Density (g/cm^3): 1.18;   Porosity: 0.53;

Date	Add water (mL)	Leachate volume (mL)	EC (dS/m)	pH	Concentration: mmol									Total cation	Total anion	%Error of electrical balance
					Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	$SO4^{2-}$	Br^-	NO_3^-	HCO_3^-			
Oct. 30	970															
Oct. 31	100															
Nov. 1	25															
Nov. 2	25															
Nov. 6	71															
Nov. 7	450															
Nov. 9	1250															
Nov. 13	75															
Nov.17	75															
Nov. 20	25	33	85.4	7.05	14.95	0.08	7.90	2.96	40.42	0.43	0.04	0.19	0.03	36.76	41.53	-6.10
Nov. 21	0	14	62.5	7.39	4.80	0.03	2.19	0.84	11.31	0.22	0.01	0.06		10.90	11.81	-3.99
Nov.24	75	36	44.6	7.53	9.73	0.05	3.44	1.32	18.65	0.67	0.02	0.10	0.05	19.30	20.17	-2.21
Nov. 27	50	35	26.6	7.94	6.26	0.03	1.57	0.57	8.70	0.72	0.01	0.05	0.07	10.58	10.28	1.46
Nov. 29		29	16.39	8.09	3.39	0.02	0.68	0.26	4.51	0.69	0.01	0.02	0.00	5.28	5.90	-5.59
Dec. 4		54	13.42	8.1	5.52	0.03	0.88	0.33	6.13	1.29	0.01	0.01	0.19	7.98	8.90	-5.46
Dec. 7		33	9.23	8.34	2.45	0.01	0.27	0.10	2.26	0.48	0.00	0.00	0.13	3.21	3.35	-2.07

Table B-3 (continued)

Date	Add water (mL)	Leachate volume (mL)	EC (dS/m)	pH	Concentration: mmol											
					Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	$SO4^{2-}$	Br^-	NO_3^-	HCO_3^-	Total cation	Total anion	%Error of electrical balance
Dec. 11		39	6.96	8.43	2.30	0.01	0.18	0.08	1.95	0.38	0.00	0.00	0.18	2.82	2.89	-1.16
Dec. 19		43	4.16	8.69	1.61	0.01	0.07	0.03	1.00	0.19	0.00	0.00	0.28	1.81	1.68	3.95
Jan. 3		122	2.78	8.92	3.21	0.02	0.13	0.04	1.33	0.29	0.00	0.00	0.98	3.57	3.02	8.31
Jan. 8		35	2.1	8.76	0.73	0.01	0.03	0.01	0.18	0.06	0.00	0.00	0.38	0.81	0.69	7.79
Jan. 12		31	1.964	8.92	0.57	0.00	0.02	0.01	0.13	0.05	0.00	0.00	0.34	0.64	0.58	4.70
Jan. 16		29	1.878	8.84	0.54	0.00	0.02	0.01	0.10	0.04	0.00	0.00	0.32	0.60	0.51	7.62
Jan. 22		42	1.742	8.85	0.72	0.01	0.03	0.01	0.11	0.05	0.00	0.00	0.46	0.80	0.70	7.02
Sum	3191	575			56.77	0.32	17.42	6.56	96.78	5.55	0.09	0.42		105.06	112.01	-3.20

Cap water: 2070mL

Table B-4. Data of the 10cm sand column

Mass of Soil: 818.73 g; Volume: 816.7 cm^3; Bulk Density (g/cm^3): 1.00; Porosity: 0.602.

Date	Add water (mL)	Leachate volume (mL)	EC (dS/m)	pH	Concentration: mmol												
					Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	$SO4^{2-}$	Br^-	NO_3^-	HCO_3^-	CO_3^{2-}	Total cation	Total anion	%Error of electrical balance
Nov. 27	2610																
Nov. 28	114																
Dec. 1	54																
Dec. 6	70																
Dec. 11	84																
Dec. 17		26	94.0	6.96	11.96	0.07	7.43	2.60	34.35	0.41	0.03	0.17			32.09	35.36	-4.84
Dec. 20		30	63.1	7.34	10.93	0.06	5.06	1.34	24.92	0.60	0.03	0.13	0.04	0.00	23.80	26.30	-4.99
Jan. 02		124	22.8	8.05	20.23	0.11	4.66	1.58	24.26	2.78	0.03	0.13	0.30	0.00	32.84	30.26	4.07
Jan. 05		30	9.1	8.41	2.27	0.01	0.25	0.10	1.96	0.48	0.00	0.00	0.10	0.00	2.98	3.02	-0.64
Jan. 08		27	7.5	8.46	1.72	0.01	0.14	0.06	1.39	0.31	0.00	0.00		0.00	2.13	2.01	2.89
Jan. 12		37	6.0	8.42	1.86	0.01	0.11	0.05	1.54	0.30	0.00	0.00	0.18	0.00	2.19	2.33	-3.06
Jan.16		35	4.7	8.57	1.42	0.01	0.06	0.03	1.03	0.19	0.00	0.00	0.21	0.01	1.60	1.64	-1.07
Jan. 19		29	3.8	8.81	0.96	0.01	0.03	0.02	0.60	0.11	0.00	0.00	0.21	0.01	1.06	1.04	0.72
Jan. 23		31	3.4	8.87	0.96	0.01	0.03	0.01	0.54	0.10	0.00	0.00	0.26	0.01	1.05	1.01	1.65
Jan. 29		49	3.0	8.83	1.32	0.01	0.04	0.02	0.62	0.12	0.00	0.00	0.47	0.03	1.45	1.38	2.41
Feb. 05		53	2.4	8.9	1.22	0.01	0.04	0.02	0.41	0.09	0.00	0.00	0.57	0.04	1.33	1.24	3.57
Feb.9		31	2.3	8.91	0.66	0.00	0.02	0.01	0.17	0.05	0.00	0.00	0.36	0.02	0.72	0.67	3.90
Feb.13		33	2.1	8.93	0.66	0.00	0.02	0.01	0.15	0.04	0.00	0.00	0.37	0.03	0.72	0.66	4.68
Feb.20		54	1.9	9.02	1.01	0.01	0.03	0.01	0.18	0.06	0.00	0.00	0.63	0.05	1.11	1.03	3.68
Sum	2932	589			57.18	0.33	17.93	5.85	92.12	5.62	0.10	0.43			105.06	107.94	-1.35

Cap water: 1726mL

Appendix C. Mass balance analysis for the 10cm soil columns

Table C-1. Mass balance analysis on the 10cm soil columns

Treatments		**Amount of ion: mmol**						
		Na^+	**Ca^{2+}**	**K^+**	**Mg^{2+}**	**Cl^-**	**SO_4^{2-}**	**Br^-**
Gypsum	Initial in soil	89.90	118.98	0.43	19.47	107.22	5.73	0.14
	Added	0.00	37.79	0.00	0.00	0.00	37.79	0.00
	leached out	112.78	30.87	0.54	9.04	102.73	46.75	0.10
	Left in soil	3.57	122.85	0.02	13.04	0.039	0.63	0.00
	Difference	-26.44	3.05	-0.13	-2.60	4.46	-3.86	0.05
	%	-29.41%	2.56%	-30.08%	-13.37%	4.16%	-67.39%	31.51%
Zeolite	Initial in soil	86.64	114.66	0.42	18.77	103.33	5.52	0.14
	Added	0.00	0.00	0.08	0.00	0.00	0.00	0.00
	Cap water	2.57	0.16	0.12	0.04	0.89	0.08	0.00
	leached out	45.22	22.45	0.570	7.36	95.90	6.57	0.10
	Left in soil	43.65	100.13	0.10	10.99	0.17	0.21	0.00
	Difference	-4.80	-8.08	-0.29	0.38	6.37	-1.34	0.04
	%	-5.54%	-7.05%	-68.78%	2.01%	6.17%	-24.25%	27.29%

Table C-1. (continued)

Treatments		Amount of ion: mmol						
		Na^+	Ca^{2+}	K^+	Mg^{2+}	Cl^-	SO_4^{2-}	Br^-
Control	Initial in soil	101.64	134.48	0.49	22.01	121.19	6.48	0.16
	Cap water	5.14	0.18	0.04	0.05	2.26	0.15	0.00
	leached out	56.77	17.42	0.32	6.56	96.78	5.55	0.09
	Left in soil	34.77	119.85	0.03	13.21	0.63	0.29	0.00
	Difference	4.95	-2.97	0.10	2.19	21.51	0.49	0.06
	%	4.87%	-2.21%	19.72%	9.97%	17.75%	7.54%	39.04%
Sand	Initial in soil	86.33	114.25	0.41	18.70	102.96	5.51	0.14
	Cap water	4.20	0.19	0.03	0.05	1.89	0.13	0.00
	leached out	57.178	17.93	0.33	5.85	92.12	5.62	0.10
	Left in soil	36.22	92.92	0.02	6.67	0.52	0.23	0.00
	Difference	-11.27	3.21	0.03	6.13	8.44	-0.48	0.03
	%	-13.06%	2.81%	8.13%	32.78%	8.20%	-8.68%	23.79%

Appendix D. Results of the 35cm soil columns

Table D-1. EC, pH and ion concentration of leachate from the 35cm allu+gypsum column

Date	**Day**	**EC (dS/m)**	**pH**	**Volume (mL)**	**SAR**	**Concentration: mmol/L**										
						Br$^-$	**Cl$^-$**	**NO$_3^-$**	**SO$_4^{2-}$**	**Ca^{2+}**	**Na$^+$**	**Mg^{2+}**	**K$^+$**	**Total anion**	**Total cation**	**%Error of electrical balance**
Tap water		0.376	7.78		2.25	0.00	1.38	0.03	6.22	11.21	4.72	6.46	0.26	13.84	40.31	
Rinse water		0.88	8.35		4.50	0.00	3.01	0.04	1.68	1.67	3.60	0.88	0.04	6.41	8.75	
Sept. 8(1)		5.88	8.29		35.11	0.00	1.34	0.02	36.92	6.81	53.26	2.40	0.25	75.21	71.93	
Sept. 8 (2)		5.88	8.4		34.94	0.01	1.42	0.01	36.25	6.75	52.82	2.39	0.26	73.93	71.36	
Aug. 8	1	189.20	6.31	50	78.79	3.74	3457.03	14.23	6.76	847.23	1301.51	244.10	6.95	3488.52	3491.13	0.04
Aug. 9	2	159.10	6.69	27	72.88	2.90	2327.87	12.42	8.48	598.22	1020.73	186.43	4.66	2360.15	2594.68	4.73
Aug. 10	3	129.00	6.96	19	68.09	1.89	1584.90	9.12	11.31	390.79	777.25	130.42	3.01	1618.53	1822.69	5.93
Aug. 11	4	105.50	7.2	20	66.36	1.36	1156.49	6.75	14.10	286.65	651.93	99.43	2.50	1192.80	1426.59	8.93
Aug. 12	5	84.30	7.38	20	64.92	1.08	825.18	4.44	17.70	203.24	538.82	72.32	2.00	866.10	1091.95	11.53
Aug. 13	6	62.90	7.54	16	61.50	0.80	560.71	2.37	19.62	131.20	411.86	48.18	1.49	603.11	772.12	12.29
Aug. 14	7	53.00	7.65	16.5	62.43	0.70	428.58	1.45	23.60	99.17	364.05	36.85	1.34	477.92	637.45	14.30
Aug. 15	8	42.20	7.77	17	64.12	0.56	446.35	0.69	28.16	74.35	325.52	28.75	1.23	503.93	532.96	2.80
Aug. 16	9	35.40	7.86	15	62.57	0.30	307.56	0.26	31.84	51.38	264.21	19.93	0.89	371.80	407.73	4.61
Aug. 17	10	29.50	7.79	16	63.43	0.15	177.92	0.06	46.25	32.20	212.10	12.52	0.75	270.64	302.29	5.52
Aug. 18	11	24.70	7.94	15	64.12	0.26	245.48	0.06	40.29	40.78	241.20	15.82	0.98	326.37	355.38	4.25
Aug. 19	12	23.10	8.11	15.5	65.45	0.22	140.97	0.04	55.57	28.24	206.26	11.48	0.88	252.38	286.58	6.35
Aug. 20	13	19.20	8.1	16	63.18	0.09	94.01	0.00	56.16	22.71	177.85	8.98	0.63	206.43	241.85	7.90
Aug. 21	14	17.76	8.11	14	66.22	0.13	71.80	0.00	62.32	20.86	179.07	8.39	0.54	196.57	238.11	9.56

Table D-1 (continued)

Date	Day	EC (dS/m)	pH	Volume (mL)	SAR	Concentration; mmol/L										
						Br$^-$	Cl$^-$	NO$_3^-$	SO$_4^{2-}$	Ca^{2+}	Na$^+$	Mg^{2+}	K$^+$	Total anion	Total cation	%Error of electrical balance
Aug. 22	15	16.83	8.27	14	64.34	0.07	56.93	0.07	64.93	18.65	165.14	7.70	0.47	186.94	218.31	7.74
Aug. 23	16	15.93	8.33	15	60.87	0.07	58.74	0.00	63.12	17.98	153.35	7.40	0.66	185.04	204.78	5.06
Aug. 24	17	15.25	8.3	14	62.09	0.06	47.89	0.00	65.56	17.40	154.05	7.22	0.69	179.07	203.98	6.50
Aug. 25	18	15.80	8.35	12.5	65.23	0.05	41.72	0.00	72.10	16.97	160.89	7.36	0.78	185.97	210.34	6.15
Aug. 26	19	14.31	8.28	15	62.56	0.04	31.37	0.00	68.10	15.52	147.37	6.68	0.65	167.62	192.41	6.89
Aug. 28	21	15.10	8.35	23	66.18	0.03	25.59	0.00	75.77	16.36	160.42	7.14	0.73	177.16	208.16	8.04
Aug. 29	22	13.30	8.2	15	62.93	0.02	16.01	0.01	68.36	13.60	140.00	6.19	0.62	152.75	180.20	8.24
Aug. 30	23	12.63	8.45	13.5	60.18	0.02	12.51	0.00	64.28	12.80	128.79	5.52	0.44	141.10	165.87	8.07
Aug. 31	24	12.38	8.38	13	59.96	0.02	10.14	0.01	64.46	12.12	125.48	5.40	0.57	139.08	161.09	7.33
Sept. 1	25	12.24	8.51	13.5	60.73	0.01	9.05	0.01	65.59	12.26	127.67	5.41	0.44	140.26	163.46	7.64
Sept. 2	26	11.80	8.49	14.2	59.39	0.01	6.85	0.01	63.35	11.67	122.00	5.21	0.53	133.57	156.29	7.84
Sept. 4	28	11.83	8.47	26	60.78	0.01	5.22	0.01	64.17	10.98	121.64	5.04	0.54	133.58	154.23	7.18
Sept. 5	29	11.64	8.48	15	60.33	0.01	4.35	0.01	63.75	10.94	120.50	5.02	0.54	131.88	152.96	7.40
Sept. 6	30	11.60	8.46	13	60.96	0.01	3.57	0.01	63.27	10.55	119.90	4.92	0.54	130.14	151.38	7.55
Sept. 7	31	11.56	8.44	13	61.55	0.01	3.44	0.03	63.77	10.66	121.82	5.01	0.57	131.00	153.72	7.98
Sept. 9	33	10.16	8.47	11.6	57.34	0.01	1.55	0.01	53.39	8.85	102.96	4.05	0.37	108.35	129.13	8.75
Sept. 10	34	10.82	8.45	12.8	59.01	0.01	1.66	0.00	58.63	9.81	111.72	4.53	0.51	118.93	140.91	8.46
Sept. 11	36	11.16	8.48	12.5	62.16	0.00	1.34	0.00	60.77	9.54	117.08	4.65	0.56	122.89	146.02	8.60
Sept. 12	37	10.86	8.41	12.8	61.38	0.00	1.25	0.00	58.85	9.41	114.50	4.51	0.52	118.96	142.86	9.13
Sept. 13	38	11.04	8.56	12.5	62.18	0.01	1.24	0.00	59.78	9.29	115.66	4.55	0.53	120.81	143.87	8.71
Sept. 14	39	11.61	8.57	10	64.59	0.01	1.34	0.00	64.23	9.76	123.40	4.84	0.57	129.81	153.16	8.25
Sept. 15	40	11.67	8.55	10.2	63.37	0.00	1.17	0.00	65.09	9.12	117.53	4.63	0.53	131.34	145.57	5.14
Sept. 16	41	10.92	8.46	11.2	61.91	0.01	1.13	0.00	59.60	9.10	113.80	4.41	0.49	120.33	141.31	8.02
Sept. 17	42	11.21	8.55	10.5	62.77	0.00	1.08	0.01	62.43	9.39	116.94	4.49	0.44	125.96	145.13	7.07
Sept. 18	43	11.50	8.54	11	62.00	0.01	1.02	0.00	63.69	9.98	118.63	4.66	0.55	128.42	148.48	7.24
Sept. 19	44	12.05	8.54	9.3	65.31	0.01	1.05	0.00	68.23	10.08	127.07	5.06	0.61	137.50	157.96	6.92
Sept. 20	45	11.63	8.5	10.6	63.18	0.00	0.93	0.00	65.86	9.83	120.88	4.81	0.57	132.64	150.73	6.38

Table D-1 (continued)

Date	Day	EC (dS/m)	pH	Volume (mL)	SAR	Concentration: mmol/L										
						Br^-	Cl^-	NO_3^-	SO_4^{2-}	Ca^{2+}	Na^+	Mg^{2+}	K^+	Total anion	Total cation	%Error of electrical balance
Sept. 21	46	12.67	8.45	11.2	70.46	0.00	0.98	0.00	71.34	9.51	135.84	5.35	0.64	143.67	166.22	7.28
Sept. 22	47	10.91	8.55	11.4	59.07	0.01	0.75	0.01	58.60	9.09	107.82	4.24	0.54	117.96	135.02	6.74
Sept. 23	48	10.54	8.37	11.8	58.54	0.01	0.69	0.00	56.34	8.98	106.13	4.17	0.50	113.38	132.93	7.94
Sept. 24	49	10.78	8.59	11.4	60.18	0.01	0.68	0.00	58.19	8.60	107.65	4.20	0.49	117.08	133.73	6.64
Sept. 25	50	11.00	8.58	11	62.09	0.01	0.68	0.01	59.75	8.53	111.21	4.30	0.51	120.18	137.39	6.68
Sept. 26	51	11.43	8.58	10	63.68	0.01	0.69	0.00	62.81	8.80	116.36	4.55	0.56	126.32	143.62	6.41
Sept. 27	52	12.17	8.59	9.4	66.93	0.01	0.68	0.00	64.58	8.21	119.16	4.47	0.44	129.85	144.96	5.50
Sept. 28	53	11.40	8.64	12.5	64.60	0.01	0.61	0.00	62.72	8.47	116.28	4.49	0.55	126.04	142.74	6.21
Sept. 29	54	11.38	8.6	9.5	64.49	0.01	0.59	0.00	62.63	8.45	115.64	4.41	0.54	125.87	141.90	5.99
Oct. 1	56	11.72	8.61	18.7	66.17	0.01	0.57	0.01	64.94	8.69	120.64	4.60	0.54	130.46	147.77	6.22
Oct. 2	57	13.01	8.64	10	74.71	0.01	0.65	0.00	74.53	8.54	139.43	5.39	0.66	149.72	167.96	5.74
Oct. 4	59	12.75	8.55	19	73.09	0.01	0.58	0.00	72.31	8.67	135.20	5.01	0.48	145.21	163.06	5.79
Oct. 5	60	10.75	8.48	11.2	62.98	0.01	0.48	0.00	58.40	7.92	109.95	4.28	0.50	117.30	134.83	6.95
Oct. 6	61	10.78	8.64	10.4	62.85	0.00	0.47	0.00	58.46	7.95	109.82	4.26	0.49	117.40	134.73	6.87
Oct. 9	64	10.91	8.49	32.5	61.16	0.00	0.42	0.00	59.30	8.44	108.67	4.19	0.48	119.03	134.41	6.07
Oct. 12	67	10.71	8.61	33.5	61.56	0.01	0.39	0.00	58.66	7.97	107.05	4.13	0.48	117.71	131.72	5.62
Oct. 15	70	10.64	8.59	32.7	62.66	0.01	0.39	0.00	57.97	7.68	107.67	4.13	0.47	116.34	131.77	6.22
Oct. 18	73	10.51	8.51	31.8	62.24	0.01	0.37	0.00	56.28	7.61	106.28	4.06	0.45	112.93	130.06	7.05
Oct. 20	75	10.63	8.44	20	63.84	0.01	0.37	0.00	57.81	7.56	109.19	4.14	0.38	116.01	132.98	6.81
Oct. 23	78	10.59	8.53	30	65.02	0.00	0.36	0.00	57.76	7.84	113.39	4.33	0.48	115.88	138.19	8.78
Oct. 26	81	10.65	8.52	28	64.91	0.01	0.35	0.00	58.32	7.27	109.50	4.11	0.36	117.00	132.63	6.26

Table D-2. The quantity of leaching water and leachate from the 35cm allu+gypsum column

Water* added						Leachate				
Date	Day	Water added to AG (mL)	Total added water (mL)	Pore Vol. (PV)	1 PV =1.3L	Date	Day	EC	pH	Volume (mL)
July 24/06	1	449	449	0.35	1300					
July 25	2	137	586	0.45						
July 26	3	50	636	0.49						
July 27	4	50	686	0.53						
July 28	5	50	736	0.57						
July 29	6	50	786	0.60						
July 31	8	110	896	0.69						
Aug 1	9	50	946	0.73						
Aug 2	10	20	966	0.74						
Aug 3	11	20	986	0.76						
Aug 4	12	0	986	0.76						
Aug8	16	56	1042	0.80		Aug. 8	1	189.20		50
Aug9	17	27	1069	0.82		Aug. 9	2	159.10		27
Aug10	18	20	1089	0.84		Aug. 10	3	129.00		19
Aug11	19	20	1109	0.85		Aug. 11	4	105.50		20
Aug12	20	0	1109	0.85		Aug. 12	5	84.30		20
Aug13	21	16	1125	0.87		Aug. 13	6	62.90		16
Aug14	22	17	1142	0.88		Aug. 14	7	53.00		16.5

Table D-2 (continued)

Water* added						Leachate				
Date	**Day**	**Water added to AG (mL)**	**Total added water (mL)**	**Pore Vol. (PV)**	**1 PV =1.3L**	**Date**	**Day**	**EC**	**pH**	**Volume (mL)**
Aug15	23	17	1159	0.89		Aug. 15	8	42.20		17
Aug16	24	15	1174	0.90		Aug. 16	9	35.40		15
Aug17	25	16	1190	0.92		Aug. 17	10	29.50		16
Aug19	27	50	1240	0.95		Aug. 19	12	23.10		15.5
Aug20	28	0	1240	0.95		Aug. 20	13	19.20		16
Aug21	29	25	1265	0.97		Aug. 21	14	17.76		14
Aug22	30	14	1279	0.98		Aug. 22	15	16.83		14
Aug23	31	11	1290	0.99		Aug. 23	16	15.93		15
Aug24	32	25	1315	1.01		Aug. 24	17	15.25		14
Aug25	33	16	1331	1.02		Aug. 25	18	15.80		12.5
Aug26	34	9	1340	1.03		Aug. 26	19	14.31		15
Aug28	36	44	1384	1.06		Aug. 28	21	15.10		23
Aug29	37	0	1384	1.06		Aug. 29	22	13.30		14.5
Aug30	38	25	1409	1.08		Aug. 30	23	12.63		13.5
Aug31	39	25	1434	1.10		Aug. 31	24	12.38		13
Sep.1	40	11	1445	1.11		Sept. 1	25	12.24		13.5
Sep.2	41	23	1468	1.13		Sept. 2	26	11.80		14.2
Sep.4	43	25	1493	1.15		Sept. 4	28	11.83		26
Sep.5	44	25	1518	1.17		Sept. 5	29	11.64		15
Sep.6	45	0	1518	1.17		Sept. 6	30	11.60		13
Sep.7	46	13	1531	1.18		Sept. 7	31	11.56		13
Sep.9	48	0	1531	1.18		Sept. 9	33	10.16		11.6

Table D-2 (continued)

Water* added						Leachate				
Date	Day	Water added to AG (mL)	Total added water (mL)	Pore Vol. (PV)	1 PV =1.3L	Date	Day	EC	pH	Volume (mL)
Sep.10	49	25	1556	1.20		Sept. 10	34	10.82		13
Sep.11	50	0	1556	1.20		Sept. 11	36	11.16		12.5
Sep.12	51	25	1581	1.22		Sept. 12	37	10.86		13.5
Sep.13	52	13	1594	1.23		Sept. 13	38	11.04		13
Sep.14	53	14	1608	1.24		Sept. 14	39	11.61		10
Sep.15	54	16	1624	1.25		Sept. 15	40	11.67		10.5
Sep.16	55	0	1624	1.25		Sept. 16	41	10.92		12.5
Sep.17	56	25	1649	1.27		Sept. 17	42	11.21		10.5
Sep.18	57	17	1666	1.28		Sept. 18	43	11.50		11
Sep.19	58	14	1680	1.29		Sept. 19	44	12.05		10
Sep.20	59	14	1694	1.30		Sept. 20	45	11.63		10.5
Sep.21	60	0	1694	1.30		Sept. 21	46	12.67		12
Sep.22	61	25	1719	1.32		Sept. 22	47	10.91		12
Sep.23	62	0	1719	1.32		Sept. 23	48	10.54		12.5
Sep.24	63	25	1744	1.34		Sept. 24	49	10.78		12
Sep.25	64	13	1757	1.35		Sept. 25	50	11.00		11
Sep.26	65	18	1775	1.37		Sept. 26	51	11.43		10
Sep.27	66	14	1789	1.38		Sept. 27	52	12.17		10
Sep.28	67	12	1801	1.39		Sept. 28	53	11.40		12.5
Sep.29	68	12	1813	1.39		Sept. 29	54	11.38		9.5
Oct.1	70	22	1835	1.41		Oct.1	56	11.72		18.5
Oct.2	71	25	1860	1.43		Oct. 2	57	13.01		10

Table D-2 (continued)

Water* added						Leachate				
Date	**Day**	**Water added to AG (mL)**	**Total added water (mL)**	**Pore Vol. (PV)**	**1 PV =1.3L**	**Date**	**Day**	**EC**	**pH**	**Volume (mL)**
Oct.4	73	31	1891	1.45		Oct.4	59	12.75		19
Oct.5	74	8	1899	1.46		Oct.5	60	10.75		12
Oct.6	75	12	1911	1.47		Oct.6	61	10.78		11
Oct.9	78	42	1953	1.50		Oct.9	64	10.91		32.5
Oct.12	81	33	1986	1.53		Oct.12	67	10.71		32.5
Oct.15	84	44	2030	1.56		Oct.15	70	10.64		32.5
Oct.18	87	38	2068	1.59		Oct.18	73	10.51		31.5
Oct. 20	89	20	2088	1.61		Oct. 20	75	10.63	8.44	20
Oct. 23	92	42	2130	1.64		Oct. 23	78	10.59	8.53	30
Oct. 26	95	34	2164	1.66		Oct. 26	81	10.65	8.52	28
Oct. 30	99	54	2218	1.71		Oct. 30	85	10.63	8.43	38
Nov.2	102	40	2258	1.74		Nov.2	88	10.63	8.5	27
Nov.6	106	25	2283	1.76		Nov.6	92	10.41	8.52	38
Nov.9	109	49	2332	1.79		Nov.9	95	11.18	8.54	29
Nov.13	113	48	2380	1.83		Nov.13	99	9.84	8.53	40
Nov.16	116	40	2420	1.86		Nov.16	102	10.42	8.55	29
Nov.20	120	33	2453	1.89		Nov.20	106	9.8	8.48	37
Nov.24	124	49	2502	1.92		Nov.24	110	9.42	8.5	39
Nov.27	127	40	2542	1.96		Nov.27	113	9.26	8.51	30
Nov.30	130	31	2573	1.98		Nov.30	116	9.39	8.53	28
Dec. 4	134	42	2615	2.01		Dec. 4	120	10.59	8.47	34
Dec.19	149	162	2777	2.14		Dec.19	135	10.62	8.45	106

Table D-2 (continued)

Water* added						Leachate				
Date	**Day**	**Water added to AG (mL)**	**Total added water (mL)**	**Pore Vol. (PV)**	**1 PV =1.3L**	**Date**	**Day**	**EC**	**pH**	**Volume (mL)**
Jan. 3/07	164	125	2902	2.23		Jan. 3	150	9.12	8.41	120
Jan.12	173	125	3027	2.33		Jan.12	159	8.89	8.35	56
Jan.16	177	25	3052	2.35		Jan.16	163	8.73	8.42	49
Jan.23	184	75	3127	2.41		Jan.23	170	8.82	8.45	54
Jan.29	190	50	3177	2.44		Jan.29	176	8.56	8.38	47
Feb.07	199	75	3252	2.50		Feb.07	185	8.52	8.41	72
Feb.13	205	50	3302	2.54		Feb.13	191	8.41	8.34	48
Mar. 7	227	225	3527	2.71		Mar. 7		7.99	8.42	170
Mar. 23	243	125	3652	2.81		Mar. 21		7.43	8.35	106

* Added water is tap water with EC=0.376 (dS/m) and pH=7.78

Table D-3. Infiltration depth in the 35cm soil columns

Unit:cm

Day	Control	Sand	Allu+ Gypsum	Allu	Zeolite	Ripping+ Gypsum
1	11.4	12.3	6	13.3	12.3	2.5
2	11.5	12.3	17	14	13.7	14
3	12.2	12.8	21.8	14	14.2	16.8
4	12.7	13.4	25	15	14.5	18
5	13.1	14	27	15.2	15.2	19.5
6	13.5	14.5	29.3	15.3	15.3	20.7
8	14.4	15.3	33.6	16.2	16.6	23.5
9	14.5	15.6	35.4	16.4	16.6	24.5
10	15	15.8		16.5	17	25.6
11	15.5	16.3		16.8	17.8	26.5
12	15.6	16.7		16.8	17.8	27.4
16	16.7	17.5		17.8	19.2	30.8
17	17.2	17.8		18.5	19.8	31.5
18	17.2	18.2		18.9	20	32.5
19	17.5	18.6		18.9	20.5	33.5
21	18	18.7		19	21.4	
22	18	19.3		19.5	21.7	
23	18.3	19.5		20	21.8	
24	18.7	19.6		20.5	22	
25	18.7	19.8		20.9	22.1	
27	19	20.3		21	22.3	
28	19.4	20.5		21.1	22.8	
29	19.7	20.7		21.4	23	
30	19.8	21.2		21.7	23.1	
31	20	21.3		21.9	24	
32	20.2	21.4		22	24.1	
33	20.5	21.6		22.3	24.4	
34	21	21.8		22.4	24.6	
36	21.4	22.3		22.7	24.9	
37	21.6	22.5		23	25.2	
38	21.7	22.7		23.3	25.4	
39	21.8	22.9		23.6	25.7	
40	21.9	23		23.9	26.1	
41	22	23.2		23.9	26.4	
43	22.2	23.5		24.2	26.6	
44	22.5	24		24.5	26.7	
45	23	24.1		24.9	26.9	
46	23.4	24.3		25.2	27.2	
47	23.6	24.7		25.6	27.6	

Table D-3 (continued)

Day	Control	Sand	Allu+ Gypsum	Allu	Zeolite	Ripping+ Gypsum
49	23.7	25		25.7	28	
50	24.1	25.2		25.7	28.7	
51	24.4	25.3		25.8	28.9	
52	24.5	25.5		25.8	29	
53	24.6	25.7		25.9	29.1	
54	24.7	25.9		25.9	29.2	
56	25.1	26.4		25.9	29.5	
57	25.3	26.4		26	29.8	
58	25.4	26.6		26.3	30	
59	25.4	26.8		26.4	30.1	
61	25.6	27.1		26.5	30.3	
63	26.1	27.5		27.3	30.7	
64	26.4	27.6		27.3	31.1	
65	26.7	27.7		27.3	31.3	
66	27	27.8		27.5	31.7	
67	27	27.9		27.6	31.8	
68	27.3	28.1		27.8	31.9	

Appendix E. Data of zeolite sorption and desorption tests

Table E-1. Zeolite Na^+ and Cl^- sorption results

Tube No.	Added Zeolite (g)	Concentration: mg/L				%Sorption	
		Added Na^+	Added Cl^-	Na^+ after 24h Shaking	Cl^- after 24h shaking	Na^+ after 24h Shaking	Cl^- after 24h shaking
Zeo 1	8	393.6	606.4	141.4	601.8	64.1	0.8
Zeo 2	8	393.6	606.4	142.6	601.0	63.8	0.9
Zeo 3	8	787.1	1212.9	320.2	1383.8	59.3	-14.1
Zeo 4	8	787.1	1212.9	328.4	1424.8	58.3	-17.5
Zeo 5	8	0.0	0.0	19.2	5.0		
Zeo 6	8	0.0	0.0	19.1	5.3		
Zeo 7	14	393.6	606.4	121.2	626.4	69.2	-3.3
Zeo 8	14	393.6	606.4	129.6	634.9	67.1	-4.7
Zeo 9	14	787.1	1212.9	235.2	1418.7	70.1	-17.0
Zeo 10	14	787.1	1212.9	236.2	1433.0	70.0	-18.1
Zeo 11	14	0.0	0.0	23.0	4.4		
Zeo 12	14	0.0	0.0	22.7	5.2		

Table E-2. Zeolite Na^+ desorption results

Vial No.	Added zeolite (g)	Na^+ in zeolite (mg/L)	Na^+ in solution after 72 h shaking (mg/L)	%Desorption
Zeo 1	8	259.8	39.2	15.1
Zeo 2	8	258.8	39.4	15.2
Zeo 3	8	470.6	76.3	16.2
Zeo 4	8	477.8	77.3	16.2
Zeo 7	14	278.8	45.1	16.2
Zeo 8	14	278.5	45.2	16.2
Zeo 9	14	551.9	82.9	15.0
Zeo 10	14	555.1	83.9	15.1

Appendix F. Field data

Table F-1. Ion concentration of field samples in June, 2005

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration:mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
1-1 (1,2.5)	0.2	5.59	3.98	1.28	353.51	754.96	2.12	54.30	428.10	2.97	699.73
	0.6	9.16	7.02	6.78	479.03	2035.00	3.68	82.70	826.34	1.32	242.35
	1.3	13.45	11.80	11.48	695.06	3757.57	45.27	141.95	1490.79	0.69	177.08
	2.0	18.12	7.53	11.52	242.17	2232.41	10.54	55.88	1204.32	2.96	96.41
1-2 (3,5)	0.2	7.39	3.85	1.91	240.46	886.91	1.63	38.54	468.47	3.93	239.23
	0.6	9.49	5.80	4.38	340.83	1613.86	3.21	58.80	722.09	1.07	186.71
	1.3	16.80	13.77	14.89	741.19	4518.77	12.37	156.89	1930.91	1.24	206.25
	2.0	20.70	8.51	9.24	243.73	2542.11	11.53	59.07	1390.11	1.70	105.51
1-3 (5,1)	0.2	7.07	4.70	1.99	327.32	1177.00	1.60	54.03	524.38	1.93	245.46
	0.6	7.99	6.15	3.17	417.01	1686.81	1.57	72.98	673.75	0.76	193.12
	1.3	11.34	14.77	16.86	1121.23	4979.72	10.75	236.97	1602.70	1.23	250.48
	2.0	10.24	10.27	12.41	694.18	3240.19	12.83	167.26	1158.98	2.86	164.45
2-1 (2,4)	0.2	5.48	6.23	1.29	613.00	1391.51	29.55	106.16	559.63	1.36	971.77
	0.6	7.10	6.60	3.00	498.23	1840.31	5.65	104.77	668.33	0.27	257.72
	1.3	12.30	9.88	6.93	567.60	3049.99	11.07	131.92	1253.37	0.83	171.16
	1.3	12.32	9.89	9.75	566.92	3060.94	11.03	131.69	1254.66	1.16	171.05
	2.0	17.17	11.70	13.59	544.66	3901.39	15.01	129.27	1718.57	4.35	134.45
2-2 (2.5, 3)	0.2	5.90	5.60	2.14	484.81	1360.72	2.41	84.73	536.03	5.11	492.07
	0.6	8.16	8.29	4.85	629.85	2552.45	6.65	128.77	860.62	2.96	226.11
	1.3	14.37	10.62	10.43	573.59	3492.93	13.75	129.34	1465.99	1.74	171.96
	2.0	18.86	10.78	12.20	392.49	3292.77	16.37	93.72	1603.70	3.50	109.80

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br$^-$	Ca^{2+}	Cl$^-$	K$^+$	Mg^{2+}	Na$^+$	NO$_3^-$	SO$_4^{2-}$
2-3 (5,2.5)	0.2	8.15	5.99	5.05	454.52	1384.55	3.59	67.08	704.65	7.08	707.53
	0.6	12.12	6.21	3.53	309.89	1664.79	4.61	55.69	883.21	2.67	354.86
	1.2	23.67	15.51	16.35	622.56	5069.32	15.92	133.37	2497.83	3.57	336.81
	1.3	23.71	13.99	16.48	518.42	4498.15	14.42	111.11	2283.48	4.10	292.46
	2.0	28.75	9.18	11.37	176.25	2741.25	12.89	40.04	1627.19	3.82	101.08
3-1 (2,1.5)	0.2	5.59	3.44	0.87	277.80	715.52	3.01	38.47	375.78	31.51	289.78
	0.6	7.44	4.93	1.20	358.92	1101.31	23.14	60.62	579.12	0.54	550.63
	1.3	25.37	12.13	16.90	363.96	3817.79	15.09	75.02	2037.31	10.13	112.94
	2.0	40.60	18.64	25.15	410.07	6278.86	25.72	94.16	3510.00	26.87	164.07
3-2 (4, 4)	0.2	12.04	3.30	1.73	120.63	574.47	1.11	18.76	538.76	18.85	422.04
	0.6	15.93	5.01	1.83	154.28	1245.42	4.84	27.65	818.88	2.16	296.03
	1.3	31.10	7.98	9.00	127.54	2335.45	8.95	24.22	1463.12	4.16	132.37
	2.0	51.88	14.03	17.18	154.48	4555.50	19.41	38.12	2780.64	21.44	123.02
3-3 (1.5,3.8)	0.2	4.93	5.42	1.06	668.39	789.70	2.96	99.30	517.49	5.27	1762.30
	0.6	7.28	4.67	1.67	316.80	1110.98	1.79	58.37	538.20	1.00	349.55
	1.3	21.49	12.04	14.62	451.89	3703.57	13.29	98.58	1937.12	6.00	142.97
	2.0	28.65	11.99	13.95	306.85	3638.67	14.66	68.48	2134.22	9.19	112.31
4-1 (0.5,2.5)	0.2	12.93	4.85	1.47	241.06	708.34	4.94	34.23	810.68	18.95	962.81
	0.6	20.19	7.95	4.91	273.62	2238.22	24.96	52.97	1394.86	2.61	327.06
	1.3	41.70	12.17	13.16	192.87	3875.79	17.06	39.44	2435.10	18.13	138.26
	2.0	54.21	13.00	14.56	136.75	4185.72	18.79	34.03	2737.06	23.83	89.31
4-2 (2,2)	0.2	13.53	5.51	0.46	313.87	768.24	6.18	43.78	966.95	13.00	1483.22
	0.6	27.53	5.03	2.42	69.74	1215.77	5.17	12.50	951.59	0.83	204.34
	1.3	50.68	9.04	9.57	74.04	2675.98	10.55	17.41	1867.63	10.85	106.04
	2.0	53.47	11.76	12.27	111.35	3655.20	16.76	27.67	2435.77	18.10	129.19

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration:mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
4-3 (4.5,1.5)	0.2	16.50	3.76	2.28	104.38	720.96	3.20	13.96	677.33	44.51	271.58
	0.6	27.71	4.02	1.68	45.02	859.42	4.41	8.94	778.78	1.70	222.63
	1.3	49.27	12.40	16.66	134.40	3767.13	36.58	33.02	2461.58	10.71	137.88
	2.0	57.33	18.90	24.09	231.61	6260.21	29.03	59.52	3784.96	28.02	140.19
5-1 (2,3)	0.2	10.51	1.72	0.41	55.75	140.97	1.83	6.68	312.15	9.04	354.67
	0.6	26.03	1.37	n/a	6.69	74.35	1.72	1.28	280.71	2.44	196.23
	1.3	56.08	13.04	15.20	124.97	3949.65	17.89	32.44	2723.56	8.40	378.37
	2.0	56.44	16.08	18.19	177.62	5123.85	24.31	48.57	3294.02	32.53	211.25
5-2 (3,0.5)	0.2	10.45	4.47	0.87	288.75	410.45	3.73	36.59	710.06	12.11	1469.47
	0.6	25.37	3.71	1.16	48.97	567.32	3.47	8.89	735.76	0.52	563.82
	1.3	24.48	6.28	5.89	146.27	1435.42	5.73	25.31	1220.51	8.81	600.69
	2.0	45.91	11.95	14.07	154.72	3640.72	18.58	36.80	2449.64	18.35	232.49
5-3 (5,2)	0.2	13.58	1.19	0.66	34.54	173.99	1.57	6.01	329.14	7.96	236.50
	0.6	32.88	6.52	3.43	89.10	1466.33	6.79	15.79	1282.64	0.88	573.62
	1.3	48.19	17.34	23.24	281.06	5679.99	35.81	69.74	3486.61	20.22	371.59
	2.0	46.67	17.20	21.36	278.12	5625.92	26.85	69.40	3361.74	35.33	222.25
6-1(0.5,3.5)	0.2	11.67	2.95	1.35	111.57	459.74	3.27	17.10	501.55	22.34	390.55
	0.6	35.44	4.86	4.58	48.01	971.99	4.43	8.48	1014.58	3.51	541.82
	1.3	47.13	15.41	19.03	232.12	4778.59	21.32	59.08	3110.51	22.05	348.79
	2.0	47.73	11.29	9.27	115.44	3453.62	17.76	30.12	2229.51	22.44	159.25
6-2 (2,5)	0.2	16.27	2.27	1.10	38.97	355.47	3.07	7.69	425.04	6.54	172.88
	0.6	24.18	6.23	3.87	129.09	1418.07	5.36	25.64	1151.07	1.77	560.28
	1.3	46.01	19.47	30.12	371.70	6582.29	27.94	95.33	3847.36	30.88	285.79
	2.0	48.05	7.66	14.38	106.39	3231.83	15.14	27.70	2154.35	23.14	77.57

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
6-3 (3,1.5)	0.2	2.18	0.74	0.50	62.66	56.22	0.87	9.98	70.50	6.84	102.08
	0.6	13.21	1.47	0.00	26.68	31.77	9.38	5.41	286.48	0.75	420.83
	1.3	34.70	5.17	7.17	47.33	1206.68	6.77	10.53	1014.63	3.43	300.29
	2.0	44.99	/	5.95	59.38	1991.14	9.20	12.79	1467.34	8.55	206.67
7-1(5,1.5)	0.2	17.43	3.12	0.92	63.54	570.69	10.87	13.13	584.78	6.74	304.13
	0.6	29.47	7.95	5.88	141.85	2144.42	7.50	32.45	1497.77	0.81	372.40
	1.3	51.66	20.40	27.86	331.52	6900.76	27.65	94.71	4147.56	47.00	105.19
	2.0	52.80	10.74	12.90	84.17	3304.56	13.77	21.91	2105.56	27.84	46.34
7-2 (4,1)	0.2	18.54	2.68	0.81	43.55	465.66	2.84	8.32	510.01	10.71	219.69
	0.6	28.35	6.39	4.32	111.81	1644.47	8.22	22.08	1254.97	1.08	375.47
	1.3	49.90	22.50	36.74	420.71	7809.48	34.50	114.00	4476.11	56.70	176.45
	2.0	48.00	17.08	22.13	255.94	5680.73	23.92	66.61	3337.91	45.23	75.34
7-3 (1.5, 0.5)	0.2	16.90	2.44	1.21	46.11	412.28	3.08	9.16	480.60	22.63	147.86
	0.6	33.77	6.14	2.75	75.64	1505.05	4.87	15.99	1240.19	2.09	432.32
	1.3	51.10	20.90	24.77	339.95	7049.71	30.05	92.71	4124.62	43.65	265.96
	2.0	49.35	17.70	21.79	278.60	6009.92	28.94	71.67	3573.65	50.31	103.61
8-1 (5,0.5)	0.2	12.62	1.50	0.95	28.65	207.45	1.69	5.54	281.98	10.70	83.99
	0.6	31.98	3.99	1.06	36.21	547.80	5.18	7.50	810.38	1.14	729.68
	1.3	53.72	20.10	25.95	292.56	6741.59	38.49	78.46	4012.08	38.46	293.32
	2.0	50.32	20.80	23.74	342.47	7081.39	31.82	92.82	4072.71	52.60	162.05
8-2 (3.5, 2.5)	0.2	15.54	1.85	0.00	32.99	109.94	2.23	5.93	369.48	2.71	457.38
	0.6	34.16	4.36	2.90	39.74	782.81	13.29	7.84	901.44	1.21	562.44
	1.3	53.18	15.97	17.28	191.32	5119.83	22.71	49.60	3195.42	41.14	268.87
	2.0	58.29	20.90	32.11	280.75	7141.59	33.24	76.25	4272.43	88.92	136.37

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br$^-$	Ca^{2+}	Cl$^-$	K$^+$	Mg^{2+}	Na$^+$	NO$_3^-$	SO$_4^{2-}$
8-3 (0.5,4.5)	0.2	22.52	2.30	1.24	24.58	397.73	2.80	4.41	462.23	9.92	165.45
	0.6	36.99	5.66	2.97	55.57	1376.36	6.47	11.23	1157.71	2.36	334.19
	1.3	49.38	13.58	15.65	155.47	4294.81	17.83	39.96	2671.21	7.44	156.48
	2.0	59.15	18.86	23.62	224.88	6303.90	27.21	65.01	3918.52	26.43	37.83
9-1 (2, 5)	0.2	33.04	2.76	1.63	24.42	598.65	0.98	3.38	658.06	11.70	153.45
	0.6	55.13	2.71	0.00	6.51	530.65	3.00	1.00	572.38	0.00	123.23
	1.3	73.63	8.98	9.41	34.93	2626.26	11.24	8.10	1860.10	3.58	141.71
	2.0	65.76	15.22	17.63	119.42	4947.98	19.56	30.63	3116.56	6.51	109.48
9-2 (1.5, 1.5)	0.2	23.94	2.27	1.41	25.86	387.82	2.37	3.76	492.83	38.71	133.18
	0.6	34.11	1.77	0.53	6.44	252.07	2.48	1.12	357.05	1.70	112.05
	1.3	56.63	6.72	5.04	32.91	1835.77	8.92	6.92	1370.80	3.15	158.33
	2.0	62.18	8.38	10.12	35.68	2475.59	9.31	9.24	1612.94	7.63	99.24
9-3 (0.5, 2)	0.2	18.73	3.18	1.64	66.89	568.77	4.40	9.79	620.56	60.41	215.71
	0.6	34.68	3.02	1.16	17.14	602.92	2.98	3.13	595.51	2.33	134.27
	1.3	62.72	6.74	4.54	23.95	1825.94	7.70	5.89	1323.17	4.52	89.91
	2.0	62.23	10.44	12.18	57.11	3284.46	13.68	15.17	2050.29	11.12	102.24
10-1 (3,5)	0.2	22.29	3.32	1.42	56.43	654.87	9.72	7.69	673.70	18.59	174.66
	0.6	28.61	1.95	0.47	10.44	358.02	2.44	1.95	384.22	1.08	98.44
	1.3	56.73	7.08	6.98	35.51	1973.55	7.90	7.60	1429.70	2.19	114.87
	2.0	61.15	9.38	6.65	54.14	2809.81	12.55	12.27	1917.26	5.69	113.57
10-2 (1, 3)	0.2	17.23	3.42	1.95	74.77	802.20	3.47	12.70	612.92	2.92	106.22
	0.6	22.15	6.65	2.69	167.50	1924.20	6.98	31.48	1193.18	1.28	115.88
	1.3	43.40	11.67	18.30	138.87	3707.04	14.11	31.69	2181.51	11.92	73.13
	2.0	49.47	11.53	16.00	117.49	3593.05	15.34	26.59	2284.66	11.29	71.34

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
10-3 (0.5, 1.5)	0.2	10.07	3.05	1.65	124.94	560.73	3.23	20.92	462.24	2.53	300.44
	0.6	13.94	5.02	1.95	183.15	1251.60	18.24	34.76	785.82	1.17	225.19
	1.3	16.65	5.53	3.00	159.31	1497.31	6.03	30.38	876.23	9.32	133.56
	2.0	38.35	12.44	14.80	206.00	3967.17	14.64	46.43	2343.92	9.77	102.76
11-1 (1,4)	0.2	16.15	5.04	1.96	153.46	1247.75	4.76	27.90	829.32	3.27	204.18
	1.3	22.39	7.13	4.66	171.36	1974.83	7.56	37.56	1243.24	6.76	153.88
	2.0	31.47	8.08	11.39	122.66	2337.96	10.26	32.33	1517.71	4.63	101.94
11-2 (2,4.5)	0.2	12.74	7.67	7.72	419.51	2177.25	5.53	81.86	1090.39	7.36	347.49
	0.6	21.60	6.81	5.85	163.59	1873.37	6.01	36.29	1173.84	0.74	162.23
	1.3	24.72	14.93	22.85	546.06	5047.76	15.63	122.66	2458.11	3.81	178.05
	2.0	30.52	9.15	8.93	165.48	2843.90	13.36	37.28	1671.55	3.49	85.11
11-3 (4,5)	0.2	11.10	5.80	2.98	315.25	1483.16	3.62	53.09	810.33	8.54	347.33
	0.6	14.95	5.13	2.26	164.49	1377.96	5.21	35.77	812.71	1.29	135.19
	1.3	23.00	13.25	18.20	463.13	4473.20	13.68	116.70	2140.77	2.93	142.33
	2.0	30.21	9.83	12.13	184.48	2970.70	14.07	48.17	1784.11	2.12	81.18
12-1 (5,1)	0.2	8.08	3.58	1.48	239.09	476.77	2.82	29.45	498.48	1.67	860.67
	0.6	14.05	6.56	4.34	259.11	1784.57	6.77	49.15	942.17	0.61	233.21
	1.3	22.67	7.35	5.53	167.25	2156.64	9.40	39.06	1254.67	2.37	128.97
	2.0	29.03	6.50	8.87	89.47	1937.02	9.83	23.10	1192.04	3.39	79.97
12-2 (1,2)	0.2	7.26	3.62	4.91	220.01	795.97	2.57	36.43	441.76	2.33	205.91
	0.6	8.84	5.65	4.10	356.76	1557.13	22.83	55.93	681.26	1.16	215.11
	1.3	15.06	11.14	15.92	583.57	3632.55	10.68	124.13	1536.94	2.69	186.58
	2.0	17.62	8.29	11.22	284.76	2628.68	36.31	67.52	1275.27	3.90	114.93

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
12-3 (0.5,0.5)	0.2	6.93	3.50	2.52	203.54	781.68	25.22	33.42	405.06	14.93	231.01
	0.6	8.44	5.59	2.98	348.28	1525.63	3.29	62.35	651.88	2.80	257.79
	1.3	12.70	10.50	9.39	597.87	3284.13	9.00	122.91	1306.96	1.60	209.82
	2.0	11.72	9.61	11.23	564.75	2905.44	6.74	112.54	1167.58	4.26	295.97
13-1 (1,3)	0.2	9.41	4.06	1.48	207.83	985.78	2.34	29.42	548.03	10.36	202.87
	0.6	13.11	7.36	3.77	366.41	2153.44	5.53	60.34	1028.59	2.11	226.78
	1.3	21.05	7.32	4.21	194.16	2142.73	9.22	38.10	1226.76	5.86	138.86
	2.0	31.14	5.21	3.82	65.69	1639.04	8.31	14.89	1075.64	5.84	79.19
13-2 (5,4)	0.2	15.15	3.58	0.97	91.64	838.98	1.82	15.06	594.50	2.86	159.92
	0.6	19.11	6.07	2.64	165.55	1685.07	4.80	30.31	1019.94	0.64	204.30
	1.3	36.00	4.62	6.79	66.26	1928.89	7.68	15.82	1257.64	3.61	98.40
	2.0	38.86	5.09	3.80	49.85	1760.61	7.36	12.73	1189.08	4.24	69.61
13-3 (5,2.5)	0.2	16.49	4.11	1.42	103.12	981.22	3.50	17.30	687.83	1.33	201.54
	0.6	20.84	5.46	2.55	124.92	1488.79	4.98	19.93	951.63	n.a	176.41
	1.3	33.22	6.47	4.12	74.46	1881.82	7.40	16.92	1221.97	3.68	121.33
	2.0	39.76	9.20	9.92	106.63	2806.17	11.08	23.98	1747.56	4.80	118.20
14-1 (2.5, 1)	0.2	16.94	4.86	1.91	127.68	1289.34	4.26	24.10	796.97	2.57	127.44
	0.6	21.67	5.29	2.33	103.51	1463.84	4.71	21.18	926.93	1.00	121.38
	1.3	36.47	13.99	11.68	272.49	4642.35	18.00	66.12	2590.08	1.67	116.04
	2.0	40.16	8.53	7.25	89.67	2669.31	10.47	22.59	1645.06	3.16	64.91
14-2 (2.5,3)	0.2	20.45	4.91	1.56	100.40	1328.56	3.33	18.87	852.80	1.59	115.42
	0.6	27.00	5.93	5.39	87.69	1691.99	23.16	18.27	1065.64	0.57	108.58
	1.3	36.43	11.13	12.19	170.51	3544.05	14.27	44.49	2068.60	1.50	111.02
	2.0	41.38	8.91	9.73	86.18	2698.27	10.66	23.18	1678.04	2.22	78.87

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
14-3 (4.5,4.5)	0.2	31.48	3.37	1.47	23.53	804.24	1.98	4.71	640.17	1.56	123.75
	0.6	41.47	3.55	2.90	29.17	1333.50	3.86	6.94	960.83	1.22	126.03
	1.3	33.46	1.88	0.92	5.28	251.09	1.91	0.92	316.96	1.93	112.87
	2.0	65.80	5.42	5.51	17.29	1812.42	7.89	5.70	1235.88	2.19	58.61
15-1 (3.5,1.5)	0.6	39.76	1.80	1.38	5.70	271.68	0.87	0.80	383.15	1.81	134.35
	1.3	63.25	4.15	5.45	13.71	1281.76	5.82	3.37	1009.26	1.71	134.03
	2.0	67.95	6.20	10.48	39.93	2745.19	10.25	10.16	1860.12	2.47	123.31
15-2 (4.5,0.5)	0.2	28.77	/	0.52	12.38	257.40	2.30	1.32	399.00	4.31	96.98
	0.6	47.71	1.58	n.a	3.16	319.07	1.57	0.61	354.10	1.79	95.22
	1.3	70.50	3.91	2.24	6.88	937.03	4.30	1.52	785.14	0.48	90.90
	2.0	70.86	8.16	7.78	28.16	2454.88	10.71	7.79	1649.53	2.09	90.67
15-3 (4.5,5)	0.2	50.42	/	0.83	6.68	426.93	3.80	1.13	535.64	2.61	61.43
	1.3	111.74	7.58	6.68	9.96	2220.48	8.96	2.86	1556.15	n.a	23.76
	2.0	67.26	9.38	12.28	38.72	2988.48	13.64	12.15	1874.41	1.37	26.69
16-1 (0.5,1.5)	0.2	34.38	1.87	0.38	13.09	396.28	2.99	1.62	496.40	4.16	104.12
	0.6	42.90	2.17	0.95	4.94	336.57	2.10	0.78	389.35	1.18	96.50
	2.0	71.83	12.50	13.16	65.57	4022.87	17.19	18.71	2564.41	2.66	105.10
16-2 (4.5,1)	1.3	76.24	9.79	15.99	37.86	2953.17	14.09	9.39	2024.58	5.56	52.62
	2.0	67.58	17.14	23.64	140.29	5721.74	30.70	39.60	3522.74	7.78	34.74
16-3 (2.5,5)	1.3	68.92	10.34	11.58	50.53	3222.94	21.78	13.68	2142.15	2.32	24.95
	2.0	58.56	6.81	8.52	46.13	2726.78	15.25	12.82	1746.20	1.54	30.73

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
17-1 (1,2.5)	0.2	21.31	2.06	0.54	20.45	355.23	2.30	3.50	396.69	5.26	110.37
	0.6	27.62	2.79	1.02	20.05	629.94	3.08	4.59	527.77	1.30	105.64
	1.3	60.49	7.09	5.78	30.55	2336.43	7.86	7.11	1430.03	3.60	40.61
	2.0	57.56	11.50	14.76	77.89	3683.80	17.04	22.54	2244.55	12.49	15.00
17-2 (3,1)	0.2	18.24	2.11	1.36	24.99	422.94	2.01	5.45	386.52	4.54	59.56
	0.6	25.93	5.06	2.95	74.42	1289.76	5.29	13.47	926.71	2.14	154.45
	1.3	48.02	10.99	10.27	110.64	3405.26	15.03	26.78	2172.13	13.10	90.97
	2.0	60.25	16.01	31.01	245.28	8138.96	28.72	67.65	4137.56	52.47	23.29
17-3 (0.5,0.5)	0.2	19.17	2.60	0.74	38.44	482.39	2.94	7.10	493.64	16.01	127.71
	0.6	26.07	3.32	1.26	34.76	722.66	3.99	7.14	646.67	1.28	151.75
	1.3	39.21	10.44	10.89	150.05	3199.50	13.64	33.21	2040.25	10.29	115.34
	2.0	54.96	10.84	16.11	78.18	3490.86	15.08	21.35	2127.66	15.59	24.03
18-1 (1.5,2)	0.2	25.39	5.66	2.02	106.16	1419.42	6.13	21.03	1095.45	10.88	284.91
	0.6	29.18	4.58	1.43	46.08	1146.57	60.85	9.25	830.93	1.33	166.73
	1.3	64.23	8.91	6.28	39.40	2708.29	8.60	10.29	1753.46	1.78	44.80
	2.0	66.37	14.38	12.28	101.06	4746.37	20.46	26.57	2904.40	26.05	15.13
18-2 (3,0.5)	0.2	24.19	2.96	1.30	35.87	562.01	4.99	7.08	606.47	4.88	211.40
	1.3	53.19	8.76	6.78	58.79	2625.01	8.87	13.42	1739.56	5.35	124.58
	2.0	63.67	13.12	18.09	90.34	4256.59	18.44	23.63	2632.46	34.23	29.84
18-3 (4.5, 5)	0.2	33.78		0.58	7.34	228.45	2.26	1.09	371.30	6.37	63.82
	1.3	95.62	6.69	15.45	33.52	3485.92	15.30	8.68	2404.40	8.38	13.78
	2.0	75.67	12.51	12.36	54.22	3992.23	71.76	15.82	2465.50	26.18	8.87

Table F-1 (continued)

Sampling Location	**Depth (m)**	**SAR**	**EC (dS/m)**	**Concentration: mg/L**							
				Br^-	**Ca^{2+}**	**Cl^-**	**K^+**	**Mg^{2+}**	**Na^+**	**NO_3^-**	**SO_4^{2-}**
19-1 (4,0.5)	0.2	31.18	1.74	0.00	7.15	144.96	2.23	1.31	345.97	6.05	113.40
	0.6	68.32	2.67	0.90	3.25	486.73	6.62	0.84	534.98	1.12	119.28
	1.3	53.33	6.40	14.19	96.71	3645.28	22.45	27.09	2305.17	3.78	84.69
	2.0	38.00	5.80	8.94	61.52	1962.88	11.70	15.64	1290.89	4.12	67.92
19-2 (5,4.5)	0.2	22.35	1.60	0.00	11.34	223.34	2.75	2.11	312.89	8.68	82.03
	0.6	35.06	2.17	1.02	8.19	377.19	4.74	2.00	431.96	5.51	98.73
	1.3	62.65	4.68	6.37	28.69	2097.66	13.52	7.71	1465.70	5.18	51.83
	2.0	88.06	10.74	12.97	30.73	3308.71	23.84	9.69	2188.11	6.12	30.15
19-3 (5,1.5)	0.2	75.27	2.74	2.02	3.42	527.23	2.67	0.69	584.10	4.15	66.20
	0.6	109.70	6.04	5.01	6.50	1968.05	43.18	2.12	1260.14	0.95	30.85
	1.3	82.88	9.71	27.21	98.05	6092.35	31.38	30.89	3677.93	5.65	11.16
	2.0	62.46	17.22	25.80	155.43	5849.25	35.52	46.09	3454.31	17.31	11.14
20-1 (1,3.5)	0.2	17.06	5.18	0.87	146.50	1290.01	4.23	25.88	853.24	38.55	166.65
	0.6	22.53	6.93	2.06	165.28	1900.23	10.11	31.35	1206.86	15.52	168.90
	1.3	53.64	17.99	21.81	205.75	6048.78	31.14	69.11	3486.77	17.14	16.10
	2.0	53.86	19.69	29.50	274.07	7915.78	34.71	77.63	3926.04	16.60	31.79
20-2 (2.5,1)	0.2	14.37	1.69	0.77	40.94	400.13	1.32	8.75	388.89	10.66	103.77
	0.6	22.16	3.51	0.58	48.73	904.04	3.97	10.69	656.22	6.11	138.30
	1.3	47.29	6.08	9.37	112.92	3945.51	18.46	30.33	2194.67	0.66	115.81
	2.0	46.11	12.51	13.93	151.96	4690.66	20.32	39.82	2472.87	0.87	96.17
20-3 (0.5,0.5)	0.2	11.34	1.87	1.110	47.063	300.524	1.780	7.861	319.508	2.752	83.193
	0.6	27.46	2.37	1.35	27.34	671.05	4.43	5.05	596.23	6.28	98.25
	1.3	42.05	7.61	8.95	65.75	2173.55	15.76	16.59	1475.31	2.14	109.59
	2.0	37.87	6.89	15.87	261.80	4674.11	25.19	65.21	2646.02	1.43	145.72

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br$^-$	Ca^{2+}	Cl$^-$	K$^+$	Mg^{2+}	Na$^+$	NO$_3^-$	SO$_4^{2-}$
21-1 (3,4)	0.2	23.62	3.78	2.01	143.45	1800.15	7.01	25.34	1168.62	13.71	129.54
	0.6	35.15	7.22	4.72	87.02	2104.41	10.28	16.33	1364.15	8.91	85.30
	1.3	43.53	15.89	24.99	248.61	5483.83	27.98	70.92	3025.62	9.46	14.46
	2.0	37.37	14.60	20.44	283.09	4962.53	19.84	69.24	2708.21	n.a	24.49
21-2 (2,2)	0.6	32.31	6.88	4.80	90.39	2016.88	51.40	17.30	1281.02	4.35	92.74
	1.3	53.53	12.98	18.36	115.84	4285.76	18.86	33.13	2540.86	5.02	50.28
	2.0	45.63	17.09	24.60	310.95	5785.68	27.33	79.97	3490.89	9.58	50.17
21-3 (1,1.5)	0.2	11.30	2.05	0.54	53.06	398.23	1.69	10.16	343.32	14.27	67.76
	0.6	33.95	5.84	1.66	59.77	1581.93	11.34	11.86	1099.51	2.16	108.15
	1.3	36.97	10.33	11.63	144.10	3277.68	17.14	37.20	1926.40	3.23	106.49
	2.0	38.18	9.66	10.42	119.62	3064.06	13.28	30.96	1813.27	1.57	78.49
22-1 (1,1.5)	0.2	18.80	4.79	2.60	122.73	1372.00	4.51	21.01	857.35	25.01	164.53
	0.6	41.29	5.45	2.45	36.67	1475.05	9.41	8.05	1060.83	3.34	101.54
	1.3	78.59	11.77	10.63	50.05	4366.30	19.50	14.24	2450.24	1.92	14.96
	2.0	52.87	18.64	28.31	258.45	6451.36	30.03	66.17	3685.39	3.59	56.64
22-2 (2.5,2)	0.2	17.31	2.32	1.51	35.43	477.52	2.94	5.89	422.83	7.79	59.28
	0.6	36.13	3.85	2.34	52.51	1596.48	23.59	11.41	1109.32	13.14	100.85
	2.0	45.65	11.05	17.28	181.95	5032.12	19.05	42.77	2636.94	5.93	80.86
22-3 (2.5,4)	0.2	16.91	2.45	1.15	35.03	489.17	25.05	6.82	418.19	10.74	60.63
	0.6	27.34	4.31	2.21	48.89	1075.01	7.58	9.98	803.52	4.38	124.00
	1.3	52.95	17.89	22.70	236.39	7133.12	33.67	67.20	3586.69	14.34	31.68
	2.0	48.43	12.34	15.71	137.77	4708.40	19.26	35.03	2461.97	10.83	36.08
23-1 (3.5,1.5)	0.6	67.07	4.28	3.36	8.42	1120.68	5.30	2.56	866.67	2.33	68.31
	1.3	66.30	5.16	8.04	32.84	2229.45	9.69	5.96	1574.57	5.02	133.06

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
23-1 (3.5,1.5)	2.0	83.46	11.20	13.96	41.69	3502.98	14.43	9.14	2286.31	7.26	87.48
23-2 (1,2)	0.6	40.50	3.24	1.80	17.97	858.32	3.89	3.22	710.39	1.52	115.99
	1.3	59.06	10.38	14.93	68.86	3326.64	11.27	14.94	2076.16	13.07	85.68
23-3 (1.5,3)	0.2	37.46	3.42	0.71	18.65	735.61	3.23	3.01	661.84	7.66	142.13
	0.6	40.68	2.76	2.23	13.14	706.17	1.83	2.43	612.42	3.01	98.99
	1.3	66.28	8.90	6.65	42.64	2681.56	10.94	8.09	1803.15	7.65	74.45
	2.0	67.13	6.71	5.59	32.54	2398.73	9.47	6.84	1615.56	13.47	47.80
24-1 (3,3.5)	0.2	34.72	3.53	1.64	49.11	1247.13	1.95	6.36	974.48	5.53	144.77
	0.6	35.73	3.26	1.25	18.82	745.41	3.02	2.95	632.20	1.49	87.87
	1.3	53.51	12.83	11.14	125.37	4077.07	17.14	26.01	2523.75	10.88	88.57
	2.0	52.82	12.25	12.20	115.46	3899.30	16.97	28.19	2443.61	19.83	86.54
24-2 (0.5,3)	0.2	34.03	3.50	0.96	23.29	808.60	3.99	3.81	672.94	6.62	100.56
	0.6	39.81	3.28	1.48	15.42	710.27	2.23	2.48	639.42	9.90	109.36
	1.3	49.76	8.61	7.37	66.24	2557.41	9.97	12.51	1686.28	5.60	94.26
	2.0	51.01	17.85	23.43	265.48	6184.58	25.22	62.29	3558.72	33.03	178.34
24-3 (4,1.5)	0.2	27.02	3.90	2.06	45.63	926.34	5.45	6.12	733.21	2.11	127.17
	0.6	26.12	5.33	4.13	87.73	1458.22	25.02	9.84	968.25	2.24	102.19
	1.3	38.86	11.60	11.75	180.17	3616.17	13.86	35.53	2183.31	7.00	115.23
	2.0	47.79	6.50	10.97	81.52	3008.57	13.65	19.21	1848.49	18.05	80.20
25-1 (1,3)	0.2	29.71	2.26	0.64	15.24	359.36	2.74	1.75	459.80	9.34	96.68
	0.6	47.59	2.67	2.17	11.62	758.55	2.85	2.15	673.77	2.90	102.82
	1.3	54.89	14.10	13.51	144.00	4558.51	18.22	32.94	2810.18	10.18	133.30
	2.0	51.29	12.64	13.15	131.58	4076.89	16.81	28.47	2491.76	27.74	93.10

Table F-1 (continued)

Sampling Location	**Depth (m)**	**SAR**	**EC (dS/m)**	**Concentration: mg/L**							
				Br^-	**Ca^{2+}**	**Cl^-**	**K^+**	**Mg^{2+}**	**Na^+**	**NO_3^-**	**SO_4^{2-}**
25-2 (2,2.5)	0.6	56.64	3.13	3.28	14.81	1258.05	2.80	2.88	910.50	1.61	108.51
	1.3	54.78	14.32	16.75	138.65	4619.32	47.53	35.91	2801.77	10.59	123.83
	2.0	53.80	12.47	16.20	116.38	4111.74	16.46	27.86	2492.05	21.45	102.68
25-3 (3.5,2)	0.2	48.76	2.79	0.47	8.15	548.60	3.56	1.50	577.99	1.60	78.68
	0.6	67.64	4.43	2.66	9.97	1100.37	2.95	2.05	898.49	0.00	84.42
	1.3	65.62	7.07	4.99	25.83	1981.13	8.06	5.10	1395.95	6.94	71.79
	2.0	58.11	5.15	5.79	33.60	2163.00	9.01	8.14	1448.78	12.43	74.61
26-1 (2.5,1)	0.2	54.65	3.83	1.67	12.68	863.91	4.93	2.35	808.64	2.05	115.13
	0.6	64.34	3.91	2.01	9.97	1069.28	5.00	2.43	874.37	0.58	72.31
	1.3	67.65	11.68	11.30	110.85	5698.64	21.60	27.54	3074.52	8.03	45.81
	2.0	58.13	14.69	17.52	134.76	4941.59	22.11	36.73	2953.96	15.97	36.57
26-2 (0.5,2.5)	0.6	59.07	3.68	2.47	10.41	999.68	3.63	2.28	808.19	1.12	62.14
paste EC	2.0	54.50	7.96	11.75	63.12	2941.66	12.18	15.47	1865.41	7.75	51.78
26-3 (3,3.5)	0.6	58.99	3.53	2.15	8.24	780.84	2.14	1.60	707.18	2.83	54.22
	1.3	72.40	9.00	9.81	37.40	3280.40	12.35	8.10	1875.35	7.19	26.71
	2.0	59.10	5.94	12.05	42.67	2848.18	23.14	9.33	1637.02	7.84	34.16
27-1 (0.5,1)	0.2	11.20	3.01	0.80	88.61	630.35	4.42	15.34	434.65	16.01	55.67
	0.6	28.72	6.31	4.86	90.84	1779.73	13.46	19.23	1155.96	4.34	86.73
	1.3	49.68	16.95	22.68	235.55	6497.90	31.20	62.88	3326.53	14.74	20.25
	2.0	47.59	11.98	20.59	196.71	5693.11	22.00	48.82	2880.96	16.07	42.93
27-2 (0.5,3.5)	0.2	17.80	6.14	5.25	199.95	1987.65	6.08	36.94	1045.28	12.70	164.91
	0.6	21.65	9.35	6.52	289.54	3253.23	16.71	59.03	1548.55	8.75	148.80
	1.3	39.89	12.22	22.54	435.51	7733.64	41.35	110.70	3605.32	16.37	17.12
	2.0	51.77	14.41	19.17	163.48	5614.69	38.72	45.43	2906.08	12.04	23.01

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
27-3 (5,2.5)	0.2	17.83	6.21	3.53	243.67	2275.48	4.94	44.82	1155.45	13.42	206.80
	0.6	28.96	7.94	3.96	139.53	2317.28	11.70	28.00	1434.80	3.93	113.48
	1.3	49.43	17.91	18.20	287.32	7289.28	27.89	73.99	3636.09	15.51	63.21
	2.0	56.11	12.44	22.26	194.39	6563.33	20.22	48.58	3379.99	19.80	42.29
28-1 (0.5,0.5)	0.2	14.48	3.65	0.26	93.51	923.64	2.58	15.71	575.50	6.99	85.18
	0.6	29.46	8.16	7.81	146.38	2455.51	11.74	31.85	1510.51	8.35	119.40
	1.3	40.58	24.80	35.43	693.16	10000.00	33.41	165.31	4585.34	19.25	77.00
	2.0	37.74	21.10	31.24	574.66	8561.29	28.59	137.62	3885.06	9.58	63.99
28-2 (2,5)	0.6	22.30	9.62	5.42	321.13	3478.72	10.89	62.33	1669.26	18.62	222.03
	1.3	31.04	23.40	32.26	959.10	10000.00	32.31	207.04	4070.18	17.48	210.93
	2.0	31.73	24.70	35.36	945.58	10000.00	30.97	216.66	4164.03	8.35	118.03
28-3 (3.5,2)	0.6	29.43	11.81	8.40	310.16	4326.69	15.25	60.61	2167.01	7.00	205.91
	1.3	43.48	23.40	32.02	517.90	9287.64	30.94	126.93	4263.15	5.05	58.39
	2.0	44.19	27.20	40.69	707.41	10000.00	35.88	168.91	5044.76	2.44	54.57
29-1 (2,3.5)	0.6	29.18	7.20	3.90	131.27	2042.04	6.87	25.68	1397.89	36.73	164.51
	1.3	41.72	11.17	12.11	160.72	3560.30	17.71	37.07	2259.17	26.61	118.62
	2.0	61.26	14.98	15.15	131.92	4933.27	31.42	40.56	3140.39	35.30	100.97
29-2 (1,4.5)	0.6	32.34	9.04	7.42	166.16	2925.35	9.56	36.26	1767.19	22.01	136.64
	1.3	55.15	22.60	26.64	369.67	8079.93	38.06	110.65	4711.40	43.33	109.21
	2.0	53.70	19.38	25.30	274.32	6776.74	28.39	86.60	3986.84	35.37	51.46
29-3 (4.5,2)	0.2	21.09	5.74	1.37	142.50	1538.72	7.47	30.78	1065.86	17.54	181.25
	0.6	29.33	6.75	2.03	106.44	1896.32	10.22	26.06	1303.46	8.97	107.64
	1.3	52.92	16.54	15.08	210.36	5530.72	32.65	60.92	3391.74	24.62	68.25

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
29-3 (4.5,2)	2.0	51.28	11.42	8.36	103.87	3703.78	20.50	31.68	2329.43	19.21	33.79
30-1 (1.5,1.5)	0.2	24.39	3.84	2.08	51.38	961.75	5.73	11.30	741.98	3.30	107.94
	0.6	34.44	5.32	6.15	54.55	1522.96	7.64	12.63	1087.11	4.36	85.11
	1.3	81.41	16.25	18.68	92.21	5556.60	34.56	29.09	3504.10	6.15	17.47
	2.0	70.23	13.99	17.44	89.88	4660.45	18.16	27.00	2959.91	7.59	19.70
30-2 (2.5,1)	0.2	18.14	3.32	1.90	62.38	818.87	5.91	14.49	612.42	4.12	69.17
	0.6	32.49	7.16	3.49	99.43	2161.32	22.71	25.01	1400.81	3.01	58.27
	1.3	68.37	10.86	13.03	58.20	3508.59	25.00	16.55	2298.14	6.78	6.81
	2.0	76.39	11.16	13.98	52.50	3593.26	18.52	13.12	2391.40	0.91	20.58
30-3 (3.5,3)	0.2	16.69	4.01	1.54	96.55	1016.89	5.55	23.44	705.60	6.83	106.34
	0.6	31.64	7.34	3.39	105.58	2184.75	11.73	27.24	1411.16	3.44	60.91
	1.3	62.69	14.88	20.98	129.20	5111.30	38.10	38.17	3159.21	4.07	8.92
	2.0	57.19	14.92	18.26	147.58	5127.37	28.40	47.69	3126.89	5.04	13.31
31-1 (3,0.5)	0.2	16.01	2.87	0.78	59.70	622.91	4.55	13.91	529.06	5.74	114.83
	0.6	34.19	7.56	5.31	93.49	2210.08	13.71	26.09	1452.16	6.58	94.70
	1.3	57.75	13.48	13.92	112.07	4451.75	31.90	36.54	2755.91	31.28	9.84
	2.0	50.39	17.57	21.55	251.71	6002.78	41.06	75.88	3556.34	11.18	24.06
31-2 (2,3)	0.2	21.23	5.14	2.11	100.76	1379.45	11.80	26.48	927.50	5.07	104.97
	0.6	38.61	8.09	8.51	91.02	2406.29	11.36	23.71	1601.16	2.87	96.63
	1.3	54.11	14.39	14.55	143.79	4755.51	18.03	43.14	2884.04	10.58	37.04
	2.0	37.75	15.56	20.06	289.35	5255.60	21.00	97.87	2913.92	5.90	39.34
31-3 (0.5,2.5)	0.2	18.68	4.42	1.80	97.52	1113.65	8.05	24.56	797.80	2.38	122.86
	0.6	39.72	8.47	6.32	91.40	2527.22	14.80	25.19	1665.00	2.89	105.45
	1.3	51.25	14.36	17.96	163.40	4888.99	31.77	52.48	2945.44	3.36	83.77

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
31-3 (0.5,2.5)	2.0	39.71	14.99	18.61	257.01	5020.68	29.38	81.29	2855.10	14.08	57.40
32-1 (5,2)	0.2	17.52	3.31	0.39	70.13	723.92	3.51	13.42	611.95	9.85	155.29
	0.6	23.49	7.24	2.24	170.45	2091.62	11.03	42.25	1323.62	12.56	191.35
	1.3	29.53	11.05	7.79	244.52	3466.32	20.99	67.90	2027.10	5.23	205.10
	2.0	46.51	11.48	11.16	117.19	3771.62	20.18	39.18	2279.59	6.52	106.77
32-2 (1.5,1.5)	0.2	20.53	7.62	6.20	221.16	2200.61	8.31	52.06	1307.85	22.11	148.80
	0.6	25.43	12.42	9.32	380.58	4040.02	17.50	102.76	2168.72	3.22	159.73
	1.3	24.45	17.81	21.23	716.24	6172.65	21.94	200.64	2876.82	9.68	158.42
	2.0	20.04	16.40	21.47	794.76	5730.19	20.49	217.86	2474.41	1.84	109.53
32-3 (0.5,3.5)	0.2	15.36	6.05	3.68	219.33	1673.85	8.00	52.53	976.69	12.88	139.59
	0.6	16.04	9.56	9.46	430.56	2987.69	11.27	112.83	1448.33	10.93	136.36
	1.3	17.24	23.50	31.58	1573.92	8571.72	21.01	411.42	2974.98	2.90	164.98
	2.0	17.36	25.30	39.07	1736.00	9346.29	24.80	447.23	3139.29	0.32	121.71
33-1 (4,3.5)	0.2	15.93	2.52	1.55	48.58	503.60	2.15	9.94	466.98	5.15	109.10
	0.6	22.02	7.46	4.08	203.16	2140.44	8.88	43.79	1328.37	14.05	210.11
	1.3	28.61	17.92	18.90	614.95	6153.62	19.36	159.63	3082.58	13.24	187.41
	2.0	33.63	26.10	32.80	947.20	9522.50	35.68	257.65	4528.54	0.44	106.30
33-2 (0.5,3.5)	0.2	14.83	3.20	1.25	81.05	707.44	3.05	16.42	560.77	10.60	124.69
	0.6	21.90	8.81	1.97	264.38	2566.64	8.15	60.88	1520.91	21.29	254.43
	1.3	38.74	22.30	28.43	598.42	7933.70	32.34	163.99	4151.36	21.78	111.78
	2.0	40.20	23.70	30.36	634.39	8537.17	34.22	172.58	4430.18	21.45	61.73
33-3 (2.5,0.5)	0.2	20.73	3.90	1.51	76.62	913.76	3.39	12.92	745.99	22.56	129.64
	0.6	29.58	10.85	8.84	265.00	3272.38	13.13	53.61	2022.04	15.40	240.71
	1.3	42.93	22.50	27.80	511.33	7957.88	32.49	145.60	4278.73	21.45	106.72

Table F-1 (continued)

Sampling Location	Depth (m)	SAR	EC (dS/m)	Concentration: mg/L							
				Br^-	Ca^{2+}	Cl^-	K^+	Mg^{2+}	Na^+	NO_3^-	SO_4^{2-}
33-3 (2.5,0.5)	2.0	43.97	23.20	31.75	535.09	8254.75	34.59	147.88	4461.79	1.05	83.52
34-1 (5,1.5)	0.2	16.46	4.95	1.68	157.32	1254.91	4.92	28.06	854.05	18.71	159.46
	0.6	25.57	8.46	1.80	205.54	2488.10	9.23	42.19	1542.21	5.01	185.42
	1.3	44.64	22.00	22.81	501.05	7697.97	32.91	125.95	4320.38	13.34	120.00
	2.0	42.71	19.85	23.29	413.14	6999.68	28.41	118.31	3829.61	13.53	68.55
34-2 (1,4.5)	0.2	13.54	2.44	1.65	56.23	521.58	2.30	11.84	428.54	10.25	40.57
	0.6	23.30	5.28	2.72	103.77	1340.57	5.50	21.12	997.34	23.28	168.36
	1.3	37.75	15.97	18.48	335.87	5306.11	38.02	93.89	3040.15	2.49	193.25
	2.0	65.66	9.22	11.74	39.08	2845.33	18.64	14.09	1884.26	11.92	11.15
34-3 (1.5,0.5)	0.2	21.15	3.18	0.69	52.95	659.87	2.20	8.08	625.92	24.36	91.85
	0.6	39.79	8.71	3.59	110.92	2573.14	9.97	21.68	1752.06	16.98	132.59
	1.3	60.57	22.50	29.44	318.50	8230.04	43.24	83.66	4704.77	26.70	46.24
	2.0	44.26	16.90	21.06	300.37	5713.05	25.90	76.08	3320.81	32.87	98.01
35-1 (5,3)	0.2	55.69	2.55	1.16	8.36	613.37	3.56	1.39	661.01	5.30	102.33
	0.6	79.73	5.83	4.08	11.84	1579.98	6.79	3.22	1200.49	1.53	30.84
	1.3	70.66	3.82	3.90	13.16	1413.55	5.78	3.07	1096.82	6.64	49.97
	2.0	53.08	16.34	21.79	196.77	5302.40	18.38	50.51	3229.55	11.25	46.56
35-2 (4.5,4)	0.2	57.15	2.56	1.57	10.40	776.00	3.07	1.62	751.31	5.39	71.17
	0.6	71.49	2.98	1.83	8.60	1003.07	4.95	1.86	887.37	2.49	75.33
	1.3	71.34	7.88	8.21	29.92	2344.38	9.11	6.32	1647.40	4.22	21.92
	2.0	52.97	10.42	14.48	84.86	3235.45	13.31	21.10	2106.63	13.65	29.49
35-3 (0.5,1)	0.2	32.27	2.90	1.88	21.92	590.21	2.95	2.70	602.56	23.48	51.30
	0.6	57.05	3.45	1.53	8.89	739.58	2.79	1.65	707.00	2.62	94.35
	1.3	72.18	10.76	12.36	52.63	3251.90	12.24	10.66	2198.93	5.61	50.29

Table F-1 (continued)

Sampling Location	**Depth (m)**	**SAR**	**EC (dS/m)**	**Concentration: mg/L**							
				Br^-	**Ca^{2+}**	**Cl^-**	**K^+**	**Mg^{2+}**	**Na^+**	**NO_3^-**	**SO_4^{2-}**
35-3 (0.5,1)	2.0	63.43	6.92	5.80	26.96	1950.31	8.10	5.45	1382.84	7.38	34.44
36-1 (1.5,1.5)	0.2	20.93	1.68	n.a.	15.42	167.79	1.55	1.34	319.47	6.95	59.53
	0.6	47.59	2.31	0.80	6.34	429.40	3.09	1.06	492.01	0.91	103.68
36-1	1.3	52.26	7.40	12.60	51.55	2226.92	8.25	9.84	1564.30	4.99	104.52
	2.0	49.31	12.78	17.18	160.63	4198.10	17.30	35.42	2653.45	19.64	106.42
36-2 (1,4)	0.2	13.18	1.18	n.a.	11.07	70.60	1.39	1.36	174.84	16.58	27.53
	0.6	30.09	1.84	1.30	9.02	247.80	2.15	1.31	365.82	3.58	85.47
	1.3	49.98	12.74	17.80	156.80	4203.71	16.81	34.12	2652.50	6.15	113.20
	2.0	48.91	11.96	15.00	141.61	3914.71	13.62	29.44	2452.36	16.42	83.62
36-3 (3.5,3.5)	0.6	46.13	2.27	1.23	5.28	354.41	2.09	0.96	439.36	0.83	87.46
	1.3	58.44	16.06	22.80	176.67	5399.47	36.83	44.42	3359.16	19.07	89.76
	2.0	56.16	14.90	18.27	167.32	5061.06	20.36	41.63	3136.26	29.82	70.65

Table F-2. Ion concentration of field samples in August, 2005

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
1-2 (3,5)	0.2	50.1	16.8	49.3	0.39	24	79.1
ripping+gypsum	1.0	67.7	35.4	82.9	0.89	9.96	135
	2.0	55.9	34.9	97.5	1.05	6.91	137
2-2 (2.5, 3)	0.2	86.3	36.8	80.1	0.85	29.9	133
allu+gypsum	1.0	83.1	36.9	77.4	0.97	31.9	123
	2.0	84.9	36.3	82.4	0.95	32.5	128
3-2 (4, 4)	0.2	37.9	14.2	59.5	0.59	12.8	84.2
allu+zeolite	1.0	57.8	33.7	91	1.17	12.4	119
	2.0	64.3	35.7	101	1.03	14	142
4-2 (2,2)	0.2	15.6	14.3	68.1	0.26	8.3	66.7
allu+sand	1.0	17.2	13.8	65.5	0.3	9.13	66.5
	2.0	32.4	34.1	107	0.75	8.53	109
5-2 (3,0.5)	0.2	35.9	33.8	107	0.72	20.8	105
allu	1.0	22.5	14.3	74.1	0.24	20	72.6
	2.0	20.1	14.3	61.9	0.25	22.2	53.2
6-2 (2,5)	0.2	52.3	16.8	58.5	0.17	68.4	28.1
Control	1.0	38.8	34.9	114	0.57	17.2	110
	2.0	29.8	35.9	122	6.88	6.51	130
7-2 (4,1)	0.2	22.4	15.3	76.7	0.37	5.82	90.7
allu+zeolite	1.0	22.8	15.3	68.4	0.38	4.77	84.3
	2.0	39	36.2	93.3	0.82	6.77	106
8-2 (3.5, 2.5)	0.2	38.5	35.9	89.3	0.52	13.6	86
allu+sand	1.0	39.6	36.1	109	0.48	13.7	106
	2.0	12.1	14.6	52.5	0.27	5.19	52
9-2 (1.5, 1.5)	0.2	48.7	35.2	96.5	0.82	56.3	72.5
ripping+gypsum	1.0	55.5	34.6	134	0.66	94.6	85.3
	2.0	26	35.3	144	0.69	13.4	143
10-2 (1, 3)	0.2	45.3	35.3	113	0.76	54.4	95.4
aluu+gypsum	1.0	47.5	38.4	113	0.71	58.5	90.6
	2.0	41.5	35.7	116	0.67	40.3	107
11-2 (2,4.5)	0.2	54.8	38.6	92.3	0.71	15.7	131
allu	1.0	43.8	37.6	87.6	0.7	9.37	116
	2.0	47.6	38.2	78.5	0.69	11.6	109

Table F-2 (continued)

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
12-2 (1,2)	0.2	30.1	16.4	51.6	0.33	14.4	67.2
control	1.0	23.5	16.5	78	0.24	8.62	96.9
	2.0	16.8	16	79	0.29	4.07	93.5
13-2 (5,4)	0.2	30.9	16.8	56.7	0.4	8.57	84.4
aluu+zeolite	1.0	30.3	17.2	53.7	0.35	7.1	82.1
	2.0	36.9	18	60.8	0.64	6.9	101
14-2 (2.5,3)	0.2	20.6	16.2	80.9	0.2	5.98	95.2
allu+sand	1.0	16.4	15.9	85.6	0.24	4.6	96.3
	2.0	16.7	16.2	79.9	0.23	4.32	92.7
15-2 (4.5,0.5)	0.2	10.1	15.6	47	0.24	3.98	44.3
allu	1.0	10.3	15.2	60.9	0.22	4.96	58.9
	2.0	26.2	36.3	114	0.64	4.36	116
16-2 (4.5,1)	0.2	15	8.1	47.4	0.05	9.68	30.5
control	1.0	10.4	14.8	75	0.21	3.07	73.6
	2.0	24.5	36.5	119	0.65	1.03	124
17-2 (3,1)	0.2	35.1	17.9	62	1.49	43.8	50.5
ripping+gypsum	1.0	36.9	35.4	106	0.67	51.6	83.2
	2.0	36.5	36.1	149	0.56	35	146
18-2 (3,0.5)	0.2	16.6	14.6	74.9	0.2	23	66.7
allu+gypsum	1.0	41	35.1	99.2	0.61	56.1	74.8
	2.0	24.9	14.8	93.6	0.19	48.3	74.7
19-2 (5,4.5)	0.2	30.6	16.6	55	0.45	48.8	40.7
ripping+gypsum	1.0	16.7	14.7	78.9	0.3	16.8	81.2
	2.0	10.1	14.1	59	0.23	3.61	62.7
20-2 (2.5,1)	0.2	36.9	36.1	95.5	0.65	32	88.3
allu+gypsum	1.0	52	37.4	95.5	0.59	52.6	86.3
	2.0	47.7	36.7	118	0.59	51.2	112
21-2 (2,2)	0.2	37.1	37.6	131	0.54	2.05	158
allu	1.0	19.7	15.7	69.1	0.19	2.32	87.4
	2.0	24.7	16.3	66.9	0.15	3.56	87.6
22-2 (2.5,2)	0.2	23.1	16.4	39.3	0.2	4.12	46.6
control	1.0	36.2	37.7	97.9	0.79	6.18	113
	2.0	31.2	38.3	112	0.64	3.35	129

Table F-2 (continued)

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
23-2 (1,2)	0.2	15.2	15.8	60.9	0.23	3.73	68.4
allu+zeolite	1.0	14.6	15.6	63.2	0.26	3.34	70.8
	2.0	11	15.1	82.1	0.21	2.49	87.8
24-2 (0.5,3)	0.2	15.2	14.7	78.6	0.21	4.16	88.2
allu+sand	1.0	14.9	14.8	70.9	0.19	5	80.9
	2.0	16.9	14.7	80.9	0.2	4.25	94.3
25-2 (2,2.5)	0.2	30.1	10.1	88.5	0.3	63.9	51.2
ripping+gypsum	1.0	16.2	12	105	0.28	19.9	94.4
	2.0	15.7	13.4	103	0.3	6.74	105
26-2 (0.5,2.5)	0.2	35.4	12.8	105	0.27	65.3	73
allu+gypsum	1.0	22.1	11.6	98.2	0.14	54.1	62.7
	2.0	12.2	8.69	91.3	0.19	13.7	87.4
27-2 (0.5,3.5)	0.2	34.7	22.2	116	0.67	1.82	138
allu+zeolite	1.0	32.2	20.2	120	0.64	2.3	142
	2.0	32.7	18.9	155	0.48	2.22	184
28-2 (2,5)	0.2	41	20	126	0.51	4.44	158
allu+sand	1.0	40.6	18.9	133	0.37	4.13	168
	2.0	35.4	18	124	0.3	3.8	157
29-2 (1,4.5)	0.2	21.2	11.2	78.5	0.25	4.11	99.3
allu	1.0	16.9	10.4	101	0.21	4.12	121
	2.0	16.5	11	102	0.11	3.82	119
30-2 (2.5,1)	0.2	10	4.37	36.3	0.05	4.96	41.8
control	1.0	12.4	9.83	101	0.25	0.56	114
	2.0	11.6	9.53	103	0.24	0.39	117
31-2 (2,3)	0.2	17.1	7.52	73.1	0.29	2.1	101
allu+zeolite	1.0	19.8	11.3	72.7	0.32	2.15	102
	2.0						
		12.9	7	65.6	0.18	2.08	94.4
32-2 (1.5,1.5)	0.2	21	9.5	86.1	0.14	4.45	126
allu+sand	1.0	20.9	11.3	79.7	0.13	4.7	119
	2.0	22.6	12.7	85.9	0.05	5.01	134
33-2 (0.5,3.5)	0.2	17.8	5	31.1	0.08	38.3	21.6
ripping+gypsum	1.0	35.2	19.5	96.7	0.34	9.62	146
	2.0	39.5	21	131	0.48	7.46	204

Table F-2 (continued)

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
34-2 (1,4.5)	0.2	28.9	11.8	72.4	0.14	51.8	75.2
allu+gypsum	1.0	32.3	18.4	106	0.42	59.3	112
	2.0	39.1	18.7	95.8	0.36	68.9	97.3
35-2 (4.5,4)	0.2	5.07	6.98	50.8	0.11	1.6	61.2
allu	1.0	3.54	2.96	48	0.07	2.04	54.8
	2.0	2.32	3.14	33.3	0.07	1.77	37.6
36-2 (1,4)	0.2	1.43	0.58	5.61	< 0.05	1.53	2.42
control	1.0	2.9	3.71	21.1	0.08	2.86	20.9
	2.0	5.59	6.27	71.5	0.19	3.31	84.6

Table F-3. Ion concentration of field samples in November 2005

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
1-2 (3,5)	0.2	64.2	11.1	42.1	0.14	42.4	72.6
ripping+gypsum	0.6	31.3	6.14	41.2	< 0.05	10.4	68.8
	1.0	63.8	12.5	87.7	0.2	11.9	153
	2.0	46	10.9	92.8	0.42	5.67	143
2-2 (2.5, 3)	0.2	89.2	16.9	65.0	0.32	42.6	126
allu+gypsum	0.6	76.3	13.9	58.5	0.14	47.8	96.1
	1.0	86.5	16.7	69.8	0.32	35.7	134
	2.0	51.8	11.2	57.4	0.50	29.0	98.7
3-2 (4, 4)	0.2	24.8	4.27	40.6	0.39	13.3	54.8
allu+zeolite	0.6	40.3	7.28	60.7	0.63	15.6	99.6
	1.0	59.3	9.94	73.5	0.79	12.7	127
	2.0	54.6	9.88	98.5	0.57	11.4	152
4-2 (2,2)	0.2	12.6	2.67	59.4	0.07	8.14	58.9
allu+sand	0.6	12.7	2.53	57.7	0.05	7.88	60.6
	1.0	6.43	1.35	44.7	0.13	6.16	45.3
	2.0	17.0	3.86	121	0.16	3.84	132
5-2 (3,0.5)	0.2	32.4	5.37	86.7	0.12	31.0	99.3
allu	0.6	18.1	3.22	78.4	0.09	19.0	83.2
	1.0	21.1	3.65	71.8	0.07	27.2	70.2
	2.0	29.1	4.93	67.0	< 0.05	36.6	63.7
6-2 (2,5)	0.2	18.0	3.22	57.0	0.06	15.3	59.1
Control	0.6	26.4	4.04	45.7	< 0.05	50.7	20.7
	1.0	18.1	3.32	106	< 0.05	13.8	108
	2.0	9.80	2.40	73.1	0.11	5.56	82.0
7-2 (4,1)	0.2	24.3	5.42	61.8	0.35	4.60	87.5
allu+zeolite	0.6	18.4	4.34	56.0	0.17	5.21	72.1
	1.0	25.7	5.72	67.2	0.26	4.91	99.2
	2.0	35.6	7.45	103	0.17	4.60	137
8-2 (3.5, 2.5)	0.2	15.6	3.59	72.8	0.10	8.64	85.8
allu+sand	0.6	13.4	3.08	69.0	0.06	8.33	76.8
	1.0	18.1	3.95	84.7	0.11	8.93	105
	2.0	21.4	5.10	136	0.10	2.50	159
9-2 (1.5, 1.5)	0.2	12.5	2.05	25.7	0.07	12.3	16.3
ripping+gypsum	0.6	4.32	1.09	24.2	< 0.05	3.90	17.9
	1.0	6.39	1.25	71.5	0.10	3.62	73.9

Table F-3 (continued)

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
9-2 (1.5, 1.5)	2.0	13.4	2.50	120	0.10	1.94	129
10-2 (1, 3)	0.2	31.7	4.53	81.8	0.17	49.9	59.9
aluu+gypsum	0.6	20.5	2.81	61.1	0.17	46.0	32.0
	1.0	31.9	4.92	95.5	0.24	46.6	84.6
	2.0	23.1	3.99	88.1	0.21	30.2	91.4
11-2 (2,4.5)	0.2	35.0	7.74	71.6	0.19	9.77	108
allu	0.6	41.2	8.23	80.8	0.10	8.36	110
	1.0	42.4	9.14	86.3	0.16	7.57	126
	2.0	48.1	9.06	61.4	0.09	22.3	105
12-2 (1,2)	0.2	16.7	3.04	29.7	< 0.05	10.8	32.8
control	0.6	8.94	1.89	28.0	< 0.05	8.48	27.9
	1.0	31.3	6.99	91.0	0.15	5.99	114
	2.0	14.2	3.53	68.8	0.27	3.47	82.2
13-2 (5,4)	0.2	30.5	5.18	57.8	0.34	7.61	88.6
aluu+zeolite	0.6	29.5	4.93	55.1	0.53	6.64	85.5
	1.0	37.8	6.31	53.3	0.88	6.05	96.4
	2.0	31.0	5.69	69.8	0.75	4.96	108
14-2 (2.5,3)	0.2	17.9	3.57	67.9	0.19	4.86	84.8
allu+sand	0.6	16.6	3.41	77.2	0.10	4.20	96.0
	1.0	17.2	3.69	88.3	0.19	4.12	112
	2.0	16.6	3.25	74.2	0.27	4.58	90.1
15-2 (4.5,0.5)	0.2	5.21	1.02	43.4	< 0.05	3.73	42.9
allu	0.6	11.4	2.32	69.3	< 0.05	4.61	76.8
	1.0	11.4	2.69	80.6	0.09	2.66	95.9
	2.0	8.51	1.84	88.3	0.13	3.42	102
16-2 (4.5,1)	0.2	10.7	1.88	50.3	0.08	3.49	53.5
control	0.6	4.59	1.28	28.8	< 0.05	3.31	26.8
	1.0	5.43	1.11	73.6	0.08	2.24	78.0
	2.0	13.5	2.89	105	0.07	0.98	114
17-2 (3,1)	0.2	11.8	2.90	42.3	0.07	8.97	39.2
ripping+gypsum	0.6	4.29	1.38	34.7	0.07	3.94	32.9
	1.0	7.49	2.04	98.4	0.25	2.89	99.1
	2.0	15.2	4.32	169	0.40	0.83	173
18-2 (3,0.5)	0.2	20.8	4.42	103	0.29	26.9	94.4
allu+gypsum	0.6	27.5	5.52	101	0.27	53.6	69.4

Table F-3 (continued)

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
18-2 (3,0.5)	1.0	51.3	8.69	125	0.43	89.8	82.4
	2.0	24.4	5.45	190	0.46	24.6	183
19-2 (5,4.5)	0.2	10.8	3.26	23.1	0.35	18.0	14.3
ripping+gypsum	0.6	5.65	1.93	34.2	0.18	8.57	28.2
	1.0	4.66	1.44	27.7	0.14	21.5	7.98
	2.0	1.83	0.68	22.4	0.08	4.06	14.8
20-2 (2.5,1)	0.2	24.8	6.08	60.0	0.42	35.9	47.9
allu+gypsum	0.6	22.3	4.94	46.5	0.33	42.6	24.0
	1.0	38.0	8.77	76.5	0.62	42.7	70.6
	2.0	29.3	7.09	102	0.54	35.0	89.0
21-2 (2,2)	0.2	22.0	5.85	146	0.47	1.50	163
allu	0.6	15.0	3.94	111	0.31	0.85	119
	1.0	19.4	4.86	72.8	0.25	1.52	90.0
	2.0	15.1	3.93	67.4	0.23	1.73	75.8
22-2 (2.5,2)	0.2	9.90	2.38	41.0	0.09	4.02	44.3
control	0.6	6.65	1.75	53.9	0.20	3.63	53.1
	1.0	11.6	3.20	91.2	0.26	3.24	102
	2.0	10.7	3.39	90.3	0.28	2.73	99.8
23-2 (1,2)	0.2	7.21	1.59	56.1	0.30	4.12	51.7
allu+zeolite	0.6	6.23	1.32	48.9	0.53	3.35	48.2
	1.0	4.62	1.56	69.5	0.13	2.25	67.3
	2.0	7.32	1.56	58.5	0.15	3.24	55.3
24-2 (0.5,3)	0.2						
allu+sand	0.6	9.47	2.13	80.2	0.20	3.39	80.9
	1.0	13.0	2.80	97.7	0.22	3.72	107
	2.0	12.5	2.92	115	0.29	3.42	115
25-2 (2,2.5)	0.2	28.1	3.91	66.4	0.06	56.9	35.1
ripping+gypsum	0.6	3.11	0.74	35.2	< 0.05	5.24	30.4
	1.0	9.54	2.02	89.3	0.14	8.36	93.2
	2.0	9.90	2.41	90.4	0.17	2.94	104
26-2 (0.5,2.5)	0.2	17.8	2.83	71.9	0.09	47.9	40.7
allu+gypsum	0.6	27.9	3.52	67.1	0.17	71.1	20.8
	1.0	29.5	4.26	101	0.21	69.7	64.7
paste EC	2.0	32.5	4.71	109	0.06	66.8	73.1

Table F-3 (continued)

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO$_4^{2-}$	Cl^{-}
27-2 (0.5,3.5)	0.2	30.9	6.35	98.5	0.38	2.07	129
allu+zeolite	0.6	30.3	6.16	104	0.37	1.83	136
	1.0	31.2	6.55	128	0.22	1.68	163
	2.0	26.7	6.53	157	0.11	1.37	194
28-2 (2,5)	0.2	30.6	6.37	102	0.06	2.93	133
allu+sand	0.6	24.6	5.38	98.3	< 0.05	2.18	121
	1.0	27.4	6.10	104	0.09	2.51	131
	2.0	34.6	7.71	114	0.05	2.84	150
29-2 (1,4.5)	0.2	13.7	3.37	67.7	0.13	3.30	82.1
allu	0.6	13.6	3.25	63.7	0.12	2.70	78.3
	1.0	18.9	4.52	79.6	0.20	3.54	106
	2.0	18.3	4.34	81.1	0.10	3.71	100
30-2 (2.5,1)	0.2	8.09	2.42	37.1	0.14	3.14	42.1
control	0.6	10.1	2.66	79.4	0.15	2.01	94.1
	1.0	10.6	2.41	115	0.13	< 0.05	124
	2.0	14.1	4.05	118	0.11	0.20	129
31-2 (2,3)	0.2	10.8	2.66	56.4	0.37	1.72	66.0
allu+zeolite	0.6	15.1	3.74	72.3	0.54	1.48	92.0
	1.0	17.9	4.60	69.1	0.51	1.89	93.1
	2.0	21.4	5.17	84.6	0.61	2.07	113
32-2 (1.5,1.5)	0.2	10.4	2.38	38.9	0.15	3.83	36.8
allu+sand	0.6	12.6	3.12	47.5	0.11	3.56	49.8
	1.0	22.1	5.57	73.3	0.22	3.78	101
	2.0	31.8	8.29	96.2	0.25	4.22	124
33-2 (0.5,3.5)	0.2	23.5	4.71	34.4	< 0.05	17.1	41.7
ripping+gypsum	0.6	23.2	5.36	60.4	< 0.05	8.52	79.4
	1.0	50.5	11.1	113	0.21	12.1	165
	2.0	50.6	12.6	135	0.27	6.46	188
34-2 (1,4.5)	0.2	42.6	7.84	87.3	0.12	44.9	83.7
allu+gypsum	0.6	54.5	9.25	92.5	0.17	66.3	83.6
	1.0	42.3	7.98	88.7	0.23	45.2	84.3
	2.0	44.1	7.98	91.9	0.16	49.9	88.4
35-2 (4.5,4)	0.2	4.82	0.95	42.7	< 0.05	2.44	41.4
allu	0.6	5.72	1.34	49.9	< 0.05	1.98	49.9
	1.0	7.47	1.72	83.0	0.07	1.33	94.3

Table F-3 (continued)

Sampling Location	Depth (m)	Concentration: meq/L					
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
35-2 (4.5,4)	2.0	6.16	1.23	68.5	< 0.05	1.20	72.0
36-2 (1,4)	0.2	5.73	1.03	25.6	< 0.05	1.49	25.7
control	0.6	2.33	0.75	18.8	< 0.05	2.68	19.7
	1.0	9.17	1.99	94.0	0.10	2.04	110
	2.0	10.7	2.22	91.7	0.13	1.77	109

Table F-4. EC, pH and SAR of field samples in June, August and November

Note: The origin is the northeast corner of each plot. **Unit: m**											
Sampling Location	**Depth (m)**	**EC (Jun.,05)**	**EC (Aug.8,05)**	**EC (Nov.,05)**	**Decreased EC(%)**	**pH (Jun.,05)**	**pH (Aug.,05)**	**pH (Nov.,05)**	**SAR (Jun.,05)**	**SAR (Aug.,05)**	**SAR (Nov.,05)**
1-2 (3,5)	0.2	3.85	8.74	8.92	-0.02	7.43	6.80	6.8	7.39	8.50	6.9
ripping+gypsum	0.6	5.80		7.05		7.31		6.9	9.49		9.5
	1.3	13.77	12.70	13.9	-0.09	7.19	7.20	7.1	16.80	11.50	14.2
	2.0	8.51	12.80	13.3	-0.04	7.28	7.10	7.0	20.70	14.50	17.4
2-2 (2.5, 3)	0.2	5.60	13.20	13.2	0.00	7.31	7.20	7.0	5.90	10.20	8.9
allu+gypsum	0.6	8.29		11.1		7.23		7.1	8.16		8.7
	1.3	10.62	12.50	13.4	-0.07	7.34	7.20	7.2	14.37	10.00	9.7
	2.0	10.78	12.90	10.2	0.21	7.10	7.10	7.2	18.86	10.60	10.2
3-2 (4, 4)	0.2	3.30	8.78	6.04	0.31	7.62	7.30	7.3	12.04	11.70	10.6
allu+zeolite	0.6	5.01		9.57		7.30		7.2	15.93		12.4
	1.3	7.98	11.60	12.1	-0.04	7.63	7.20	7.1	31.10	11.50	12.5
	2.0	14.03	13.60	14.1	-0.04	7.32	7.30	7.2	51.88	14.50	17.3
4-2 (2,2)	0.2	5.51	7.84	6.80	0.13	7.64	7.80	7.7	13.53	17.60	21.5
allu+sand	0.6	5.03		6.74		7.82		7.6	27.53		20.9
	1.3	9.04	7.51	4.97	0.34	7.89	7.70	7.8	50.68	16.60	22.7
	2.0	11.76	10.70	12.5	-0.17	7.57	7.70	7.5	53.47	18.50	37.4
5-2 (3,0.5)	0.2	4.47	11.30	11.0	0.03	7.89	7.90	7.5	10.45	18.10	20.0
allu	0.6	3.71		9.10		8.04		7.7	25.37		24.0
	1.3	6.28	8.63	8.58	0.01	7.75	7.80	7.7	24.48	17.30	20.4
	2.0	11.95	7.12	8.40	-0.18	7.77	7.90	7.6	45.91	14.90	16.2
6-2 (2,5)	0.2	2.27	8.00	7.04	0.12	8.12	7.00	7.6	16.27	10.00	17.5

Table F-4 (continued)

Sampling Location	Depth (m)	EC (Jun.,05)	EC (Aug.8,05)	EC (Nov.,05)	Decreased EC(%)	pH (Jun.,05)	pH (Aug.,05)	pH (Nov.,05)	SAR (Jun.,05)	SAR (Aug.,05)	SAR (Nov.,05)
6-2 (2,5)	0.6	6.23		5.89		7.86		7.7	24.18		11.7
control	1.3	19.47	11.90	11.4	0.04	7.55	7.20	7.8	46.01	18.80	32.3
	2.0	7.66	12.40	8.25	0.33	7.78	7.50	7.7	48.05	21.40	29.6
7-2 (4,1)	0.2	2.68	9.51	8.75	0.08	7.98	7.50	7.4	18.54	17.70	16.0
allu+zeolite	0.6	6.39		7.36		7.80		7.5	28.35		16.6
	1.3	22.50	8.97	9.34	-0.04	7.67	7.50	7.4	49.90	15.70	16.9
	2.0	17.08	11.00	13.2	-0.20	7.61	7.30	7.4	48.00	15.20	22.3
8-2 (3.5, 2.5)	0.2	1.85	10.30	8.87	0.14	8.13	7.10	7.7	15.54	14.60	23.5
allu+sand	0.6	4.36		8.13		8.02		7.7	34.16		24.0
	1.3	15.97	11.90	10.2	0.14	7.74	7.10	7.6	53.18	17.70	25.5
	2.0	20.90	5.84	15.1	-1.59	7.58	8.00	7.6	58.29	14.40	37.3
9-2 (1.5, 1.5)	0.2	2.27	10.40	3.26	0.69	8.06	7.30	7.3	23.94	14.90	9.5
ripping+gypsum	0.6	1.77		2.61		8.54		8.2	34.11		14.7
	1.3	6.72	13.20	7.60	0.42	8.16	7.60	8.1	56.63	20.00	36.6
	2.0	8.38	13.80	12.4	0.10	7.93	7.80	7.9	62.18	25.90	42.5
10-2 (1, 3)	0.2	3.42	11.80	9.62	0.18	7.70	7.50	7.4	17.23	17.90	19.2
aluu+gypsum	0.6	6.65		6.87		7.55		7.5	22.15		17.9
	1.3	11.67	11.60	10.7	0.08	7.61	7.60	7.3	43.40	17.20	22.3
	2.0	11.53	12.10	10.1	0.17	7.82	7.50	7.3	49.47	18.60	23.9
11-2 (2,4.5)	0.2	7.67	12.60	10.5	0.17	7.40	7.30	7.2	12.74	13.50	15.5
allu	0.6	6.81		11.2		7.24		7.2	21.60		16.3
	1.3	14.93	11.10	12.1	-0.09	7.08	7.30	7.3	24.72	13.70	17.0
	2.0	9.15	10.40	10.2	0.02	7.54	7.30	7.2	30.52	12.00	11.5

Table F-4 (continued)

Sampling Location	Depth (m)	EC (Jun.,05)	EC (Aug.8,05)	EC (Nov.,05)	Decreased EC(%)	pH (Jun.,05)	pH (Aug.,05)	pH (Nov.,05)	SAR (Jun.,05)	SAR (Aug.,05)	SAR (Nov.,05)
12-2 (1,2)	0.2	3.62	7.36	4.36	0.41	7.36	7.20	7.1	7.26	10.70	9.4
control	0.6	5.65		3.69		6.75		7.1	8.84		12.0
	1.3	11.14	9.69	11.4	-0.18	7.07	7.20	7.0	15.06	17.40	20.8
	2.0	8.29	9.26	8.11	0.12	7.15	7.20	7.3	17.62	19.50	23.1
3-2 (5,4)	0.2	3.58	8.69	8.38	0.04	7.51	7.20	7.1	15.15	11.60	13.7
aluu+zeolite	0.6	6.07		8.41		7.14		7.1	19.11		13.3
	1.3	4.62	8.28	9.09	-0.10	7.45	7.20	7.1	36.00	11.00	11.4
	2.0	5.09	9.72	9.80	-0.01	7.74	7.20	7.1	38.86	11.60	16.3
14-2 (2.5,3)	0.2	4.91	9.76	8.37	0.14	7.30	7.10	7.2	20.45	18.90	20.7
allu+sand	0.6	5.93		9.09		6.96		7.2	27.00		24.4
	1.3	11.13	9.89	10.2	-0.03	7.17	7.20	7.2	36.43	21.30	27.3
	2.0	8.91	9.33	8.58	0.08	7.32	7.30	7.2	41.38	19.70	23.6
15-2 (4.5,0.5)	0.2	4.08	4.90	4.66	0.05	7.85	8.10	7.8	28.77	13.10	24.6
allu	0.6	1.58		7.78		8.26		7.5	47.71		26.5
	1.3	3.91	6.29	8.93	-0.42	8.47	7.90	7.6	70.50	17.00	30.4
	2.0	8.16	11.50	9.57	0.17	7.78	7.60	7.8	70.86	20.30	38.8
16-2 (4.5,1)	0.2	5.79	5.19	5.92	-0.14	7.86	7.20	7.3		14.00	20.1
control	0.6	4.41		3.24		7.93		8.2			16.8
	1.3	9.79	7.76	7.86	-0.01	8.10	7.90	8.3	76.24	21.10	40.7
	2.0	17.14	11.70	11.0	0.06	7.93	8.00	7.9	67.58	21.60	36.6
17-2 (3,1)	0.2	2.11	8.69	4.97	0.43	7.90	7.2	7.5	18.24	12.1	15.6
ripping+gypsum	0.6	5.06		3.81		7.86		7.7	25.93		20.6
	1.3	10.99	10.8	9.74	0.10	7.87	7.9	7.7	48.02	17.7	45.1
	2.0	16.01	15.8	16.2	-0.03	7.57	7.8	7.6	60.25	24.7	53.9

Table F-4 (continued)

Sampling Location	Depth (m)	EC (Jun.,05)	EC (Aug.8,05)	EC (Nov.,05)	Decreased EC(%)	pH (Jun.,05)	pH (Aug.,05)	pH (Nov.,05)	SAR (Jun.,05)	SAR (Aug.,05)	SAR (Nov.,05)
18-2 (3,0.5)	0.2	2.96	8.22	10.6	-0.29	8.12	7.7	7.5	24.19	19.0	29.0
allu+gypsum	0.6	2.25		10.3		8.00		7.4			24.9
	1.3	8.76	10.2	13.6	-0.33	7.58	7.6	7.4	53.19	16.1	22.8
	2.0	13.12	10.6	17.9	-0.69	7.76	7.6	7.6	63.67	21.0	49.3
19-2 (5,4.5)	0.2	1.60	7.47	3.27	-1.05	8.19	7.4	7.4	22.35	11.3	8.7
ripping+gypsum	0.6	2.17		3.86	-0.78	8.08		7.8	35.06		17.6
	1.3	4.68	9.02	2.95	0.37	8.05	8.0	8.1	62.65	19.9	15.8
	2.0	10.74	6.64	2.39	0.78	8.01	8.2	8.2	88.06	16.9	20.0
20-2 (2.5,1)	0.2	1.69	10.4	7.48	-3.42	7.71	7.5	7.4	14.37	15.8	15.3
allu+gypsum	0.6	3.51		5.77	-0.64	7.87		7.5	22.16		12.6
	1.3	6.08	11.2	9.52	-0.57	7.81	7.4	7.3	47.29	14.3	15.8
	2.0	12.51	13.3	11.4	0.09	7.65	7.5	7.5	46.11	18.1	24.0
21-2 (2,2)	0.2		14.7	14.9			7.6	7.5		21.5	39.2
allu	0.6	6.88		11.8	-0.72	7.54		7.5	32.31		36.2
	1.3	12.98	8.78	8.79	0.32	7.69	7.3	7.4	53.53	16.4	20.9
	2.0	17.09	9.00	7.68	0.55	7.48	7.2	7.5	45.63	14.8	21.9
22-2 (2.5,2)	0.2	2.32	5.62	4.98	-1.15	7.98	7.1	7.6	17.31	8.8	16.6
control	0.6	3.85		5.98	-0.55	7.84		7.8	36.13		26.3
	1.3	8.37	11.0	9.83	-0.17	7.73	7.6	7.7		16.1	33.6
	2.0	11.05	12.5	9.53	0.14	7.59	7.7	7.6	45.65	18.9	34.0
23-2 (1,2)	0.2	6.76	7.30	5.97		7.56	7.5	7.6		15.5	26.7
allu+zeolite	0.6	3.24		5.45	-0.68	8.00		7.7	40.50		25.2
	1.3	10.38	7.50	7.13	0.31	7.79	7.9	7.9	59.06	16.3	39.6
	2.0	8.96	9.11	6.22		7.74	8.1	7.6		22.7	27.8

Table F-4 (continued)

Sampling Location	Depth (m)	EC (Jun.,05)	EC (Aug.8,05)	EC (Nov.,05)	Decreased EC(%)	pH (Jun.,05)	pH (Aug.,05)	pH (Nov.,05)	SAR (Jun.,05)	SAR (Aug.,05)	SAR (Nov.,05)
24-2 (0.5,3)	0.2	3.50	9.32		1.00	7.90	7.9		34.03	20.3	
allu+sand	0.6	3.28		8.39	-1.56	8.16		7.6	39.81		33.3
	1.3	8.61	8.59	10.3	-0.20	7.81	7.9	7.6	49.76	18.4	34.7
	2.0	17.85	9.72	11.8	0.34	7.45	7.8	7.5	51.01	20.4	41.4
25-2 (2,2.5)	0.2	2.64	9.86	7.48	-1.83	8.10	7.40	7.7		19.70	16.6
ripping+gypsum	0.6	3.13		3.61	-0.15	8.39		8.4	56.64		25.4
	1.3	14.32	11.00	8.97	0.37	7.65	8.00	8.0	54.78	27.90	37.1
25-2	2.0	12.47	10.80	9.40	0.25	7.60	7.80	7.8	53.80	27.10	36.4
	0.6			10.5	-1.85			7.8			24.7
26-2 (0.5,2.5)	0.2	7.12	11.60	7.43		7.80	7.40	7.8		21.40	22.4
allu+gypsum	1.3	3.68	10.10	7.19		8.38	7.80	7.8	59.07	23.90	16.9
paste EC	2.0	7.96	9.75	11.3	-0.42	7.74	7.80	7.8	54.50	28.30	25.2
27-2 (0.5,3.5)	0.2	6.14	13.30	12.1	-0.97	7.60	7.60	7.5	17.80	21.80	22.8
allu+zeolite	0.6	9.35		12.6	-0.35	7.53		7.5	21.65		24.4
	1.3	12.22	13.70	14.5	-0.19	7.56	7.60	7.6	39.89	23.30	29.5
	2.0	14.41	17.20	16.7	-0.16	7.65	7.40	7.6	51.77	30.50	38.4
28-2 (2,5)	0.2		15.20	12.3			7.20	7.5		22.90	23.8
allu+sand	0.6	9.62		11.5	-0.20	7.54		7.6	22.30		25.4
	1.3	23.40	16.30	12.3	0.47	7.21	7.20	7.5	31.04	24.50	25.4
	2.0	24.70	14.90	13.6	0.45	7.36	7.20	7.5	31.73	23.90	24.8
29-2 (1,4.5)	0.2		10.10	7.88			7.20	7.6		19.50	23.2
allu	0.6	9.04		7.59	0.16	7.61		7.6	32.34		22.0
	1.3	22.60	11.80	9.56	0.58	7.31	7.20	7.4	55.15	27.40	23.2
	2.0	19.38	11.60	9.59	0.51	7.22	7.60	7.4	53.70	27.50	24.1

Table F-4 (continued)

Sampling Location	Depth (m)	EC (Jun.,05)	EC (Aug.8,05)	EC (Nov.,05)	Decreased EC(%)	pH (Jun.,05)	pH (Aug.,05)	pH (Nov.,05)	SAR (Jun.,05)	SAR (Aug.,05)	SAR (Nov.,05)
30-2 (2.5,1)	0.2	3.32	4.87	4.44	-0.34	7.89	7.30	7.6	18.14	13.50	16.2
control	0.6	7.16		8.71	-0.22	7.77		7.7	32.49		31.5
	1.3	10.86	11.10	11.8	-0.09	8.04	7.50	8.0	68.37	30.30	45.1
	2.0	11.16	11.30	11.8	-0.06	8.39	7.60	7.7	76.39	31.70	39.2
31-2 (2,3)	0.2	5.14	9.90	6.60	-0.28	7.67	7.20	7.6	21.23	20.80	21.8
allu+zeolite	0.6	8.09		8.61	-0.06	7.73		7.5	38.61		23.5
	1.3	14.39	10.30	8.75	0.39	7.69	7.20	7.4	54.11	18.40	20.6
	2.0	15.56	9.56	10.3	0.34	7.48	7.20	7.3	37.75	20.80	23.2
32-2 (1.5,1.5)	0.2	7.62	12.60	4.55	0.40	7.66	7.10	7.5	20.53	22.00	15.4
allu+sand	0.6	12.42		5.71	0.54	7.61		7.3	25.43		16.9
	1.3	17.81	11.60	9.28	0.48	7.62	7.20	7.3	24.45	19.90	19.7
	2.0	16.40	13.00	11.8	0.28	7.24	7.20	7.3	20.04	20.50	21.5
33-2 (0.5,3.5)	0.2	3.20	5.12	5.63	-0.76	7.94	7.40	7.4	14.83	9.20	9.2
ripping+gypsum	0.6	8.81		8.31	0.06	7.78		7.2	21.90		16.0
	1.3	22.30	14.00	15.2	0.32	7.70	7.40	7.5	38.74	18.50	20.4
	2.0	23.70	18.50	17.6	0.26	7.53	7.50	7.3	40.20	23.80	24.0
34-2 (1,4.5)	0.2	2.44	10.40	11.2	-3.59	8.04	7.30	7.5	13.54	16.00	17.4
allu+gypsum	0.6	5.28		12.3	-1.33	7.83		7.4	23.30		16.4
	1.3	15.97	14.10	11.5	0.28	7.80	7.60	7.5	37.75	21.10	17.7
	2.0	9.22	13.40	11.4	-0.24	8.17	7.30	7.5	65.66	17.80	18.0
35-2 (4.5,4)	0.2	2.56	6.51	4.60	-0.80	8.30	8.00	8.1	57.15	20.70	25.1
allu	0.6	2.98		5.38	-0.81	8.28		8.2	71.49		26.6
	1.3	7.88	5.83	8.80	-0.12	8.06	8.00	8.0	71.34	26.60	38.7
	2.0	10.42	4.17	7.27	0.30	7.77	8.30	8.0	52.97	20.20	35.6

Table F-4 (continued)

Sampling Location	Depth (m)	EC (Jun.,05)	EC (Aug.8,05)	EC (Nov.,05)	Decreased EC(%)	pH (Jun.,05)	pH (Aug.,05)	pH (Nov.,05)	SAR (Jun.,05)	SAR (Aug.,05)	SAR (Nov.,05)
36-2 (1,4)	0.2	1.18	0.78	3.07	-1.60	8.13	8.00	7.9	13.18	5.60	13.9
control	0.6	1.84		2.17	-0.18	8.53		8.2	30.09		15.2
	1.3	12.74	2.71	10.0	0.22	7.93	8.60	7.9	49.98	11.60	39.8
	2.0	11.96	8.52	10.1	0.16	7.89	8.00	7.8	48.91	29.40	36.0