Remediation of brine-contaminated soil using calcium nitrate, gypsum, and straw

by

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Abstract

Salt-affected soils from point source brine contamination are common in the active oil field in SE Saskatchewan. A remediation process that included dewatering by sub-surface tile drains, application of surface amendments (calcium nitrate and straw), and growing forages has been successful but not previously examined. In a field study of two remediation sites, the changes in vegetation, soil salinity, and groundwater were assessed using geo-referenced electromagnetic (EM) maps (EM38h, EM38v, and EM31v), piezometers, and soil sampling. A laboratory soil core leaching experiment studied the effect of gypsum, calcium nitrate, and straw at various rates on the remediation of a brine-contaminated soil. All treatments including the control reduced the electrical conductivity (EC) to non-saline values (<4 dS m^{-1}). The sodium adsorption ratio (SAR) was reduced to <13 with the high rates of gypsum and calcium nitrate. The fastest and most effective treatments were comprised of all rates of gypsum and the highest rate of calcium nitrate.

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I also thank my parents for their tremendous support. My mom helped take care of Mila when she was born while I finished my school term in Winnipeg. Without her help this thesis would not have been possible. Finally I thank my husband for his support. He took care of our eldest daughter alone in Vancouver while I went to school in Winnipeg. He also patiently listened to my frustrations as I juggled work, writing a thesis, and being a mom.

AND life would not be complete without my two amazing daughters Katarina and Mila Bee. They make life worthwhile.

Dedication

I dedicate my thesis to my husband and to my two beautiful daughters Katarina and Mila Bee.

1.0 INTRODUCTION

Salt-affected agricultural land is ubiquitous. Whether the result of poor irrigation practices, saline parent material or contamination from a salt source, the remediation goal is the same. This thesis investigated the remediation strategies and progress of two brine-contaminated sites in an oil field in southeast Saskatchewan. The progress of these remediation practices was evaluated through in-field analysis as well as in a laboratory experiment.

1.1 Background: oil production in southeastern Saskatchewan from the 1950s to the present

In southeastern Saskatchewan, in an oil field that has been producing since the 1950's, contamination from oil field activities as a result of historic management practices and / or recent spills (pipeline ruptures) is creating salt-affected land.

In the 1950s, drilling rigs were advanced into the ground in search of a geological formation with oil. When oil was found, a pumpjack was placed on the borehole and the oil was pumped from the ground. In southeast Saskatchewan most of the oil pumped from the ground is called emulsion and it is a mixture of oil and brine (salt water).

A single well Battery was constructed around the pumpjack that included a treater building to separate the oil and brine, a tank farm with storage tanks to hold emulsion, oil, and brine, and an unlined flare pit to flare off (burn) any unwanted natural gas, and to store unwanted oil, emulsion, and brine. Pipelines were constructed to transport the oil to larger Battery sites for further refinement, sale and distribution and to transport the brine to water disposal facilities. The brine was subsequently injected back into the geological formation (Schlumberger 2012). Brine from the oil formation in southeast Saskatchewan has very high salt concentrations (dominated by chloride and sodium ions) (Millar and Trudell 2002). Table 1.1 shows the relative salt concentrations of brine from Saskatchewan and Alberta, compared to seawater and Canadian Council of Minister of the Environment (CCME) drinking water criteria. Any time this brine comes in contact with the soil there are devastating consequences to plant growth.

Table 1.1 Selected ion concentrations

Parameter ($mg\ L^{-1}$)	Hastings, Saskatchewan Brine ($mg\ L^{-1}$)	Alberta Brine * ($mg\ L^{-1}$)	Seawater * ($mg\ L^{-1}$)	CCME Drinking water criteria ** ($mg\ L^{-1}$)
Cl^-	160,000	125,000	19,500	≤250
Na^+	98,000	47,250	10,800	≤200
Ca^{2+}	5,500	20,434	413	NS
Mg^{2+}	1,500	3,687	1,300	NS
$SO4^{2-}$	1,200	<3	2,700	≤500
HCO^{3-}	230	394	ND	NS

NS – No Standards
ND – Not Detectable
* (Alberta Environment 2001)
** (Canadian Council of Minister of the Environment 2010)

Three common ways by which brine contaminates the soil are: (1) a pipeline break, (2) an equipment malfunction, or (3) a flare pit. A pipeline carrying emulsion or brine can break causing a release. Equipment can malfunction causing a release at the oil facilities. On Batteries and Water Plants that have been operational since the 1950s there have been many pipeline breaks and equipment malfunctions and most of these older Batteries have unlined flare pits where unwanted oil, brine, and emulsion were stored (James G. Nielsen, personal communication).

Over time, some unlined flare pits were buried without removing any oil or brine and others remained open and in use until 2004 when the Saskatchewan government regulated that all open flare pits be decommissioned. These buried pit areas have often been returned to the landowner without removing any of the brine or hydrocarbon impacted soil (James G. Nielsen, personal communication). Most of these areas are still evident today, usually indicated by a barren area in the farmer's field or an area of poor crop growth which developed and became visible some time after the flare pit was buried.

Once an area is barren or has poor crop or excessive weed growth it usually will only increase in size if not remediated.

The contamination from the buried pit causes different growth problems compared to pipeline breaks or spills on facilities. In the case of buried flare pits, the contamination typically occurs from the bottom up, that is, the buried brines gradually migrate upward into the root zone and gradually reduce the growth and vigor of vegetation (James G. Nielsen, personal communication). When a pipeline breaks or equipment malfunctions and a spill is detected the fluid is commonly deposited on the soil surface, which will affect growing vegetation almost immediately. First response to spill remediation activities usually involves recovering the surface fluid by vacuum as quickly as possible, and excavating the bulk of contaminated soil including all the oil (hydrocarbon) impacted soil and transporting to a landfill.

While the hydrocarbons in the pits are relatively immobile in the surrounding soils, the salts in the brine are mobile. The salt concentrations in the brine are extremely high and when the brine water is not removed the salts gradually migrate out from the pit area and contaminate the adjacent soils. Once the rooting zone is contaminated by this brine, most agricultural crops and sensitive vegetation cease to grow.

Salts in these buried pits will move away from the pit area during periods of high water tables such as after snowmelt or a heavy rain. The flow path the salts take depends on the soil's physical characteristics. Soils with high hydraulic conductivity (buried sand and gravel seams, and lighter textured sands and silt loams) will facilitate the spread of salts faster than soils with higher clay content (Freeze and Cherry 1979).

1.2 Geology, climate, and soils

1.2.1 Geology

Saskatchewan Soil Survey (1997) describes the area in southeast Saskatchewan as the Weyburn/Virden Area (62E/F). Surface geological deposits in this area are formed from drift sediments that range in thickness between 0 m and 175 m and underlain by bedrock (Simpson 1993). Glaciers advancing and retreating deposited an unsorted mix of sand, silt, clay, pebbles, and boulders. When the glaciers melted the melt water also deposited stratified layers of sediments and eroded other sediments. This mix of drift sediments is called glacial till and it is the parent material from which the soils are formed.

As glaciers advanced, retreated, and melted, the topography was left hummocky with small potholes and sloughs; this area is often referred to as the prairie pothole region (van der Valk 2005). The melt water in these sloughs and between sloughs deposited layers of sediments around and between sloughs. As a result, sand, silts, and gravels are often found around potholes and range in thickness from 0-1.5 m. Deeper sand and gravel seams are also found in various areas throughout the landscape. The seams tend to be smaller areas surrounded by clay loam till (Lissey 1968).

1.2.2 Climate

The study area has a temperate continental climate with relatively low humidity throughout the year (Saskatchewan Soil Survey 1997). The summers are warm and the winters, cold. Snowfall is moderate with extremes more common than averages. On average, 65-70% of the rain falls from May to September during the growing season. Mean daily temperature and precipitation are presented in Table 1.2.

Table 1.2 Climatic Data (Saskatchewan Soil Survey 1997)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp. Daily Mean (C)	-17	-13	-6	4	11	16	19	18	11	5	-5	-13
Precipitation (mm)	18	19	18	31	49	59	64	53	45	23	15	17

1.2.3 Soils

The soils are Black Chernozems formed under grassland vegetation. The dominant soil type on upper slopes and knolls are agricultural soils of capability classes 2 and 3 (Saskatchewan Soil Survey 1997). These soils are limited by a slight moisture deficit imparted by a moderate water-holding capacity and sub humid regional climate. The soil profile consists of a loam to clay loam black Ap horizon (10-16 cm), underlain by a brownish B horizon. These are neutral to moderately alkaline soils.

Lower areas are often fair to poor agricultural soils of capability classes 3 and 4, respectively, depending mainly on the degree of solonetzic development and depth to saline subsoil (Saskatchewan Soil Survey 1997).

1.3 Thesis objectives and goals

This study was undertaken to examine field remediation strategies for soils contaminated with brine as a result of the oil field activities in southeastern Saskatchewan. Remediation approaches which have been underway for about 10 years have been successful but their mechanisms have not been examined. The goal of this thesis was to assess the effect of common amendments and treatments and evaluate the remediation progress.

1.3 Thesis hypotheses

1. Sub-surface tile drainage systems combined with Ca-sourced amendments and forage growth can remediate brine-contaminated soils.
2. Calcium nitrate is a better calcium sourced amendment than gypsum (better at reducing SAR).

1.4 Thesis format

Following this chapter, is a chapter reviewing the literature. The literature review focuses on the chemical and physical properties of salt-affected soils, the hydrology of soils with an emphasis on landscape processes in southeast Saskatchewan, and remediation strategies of salt-affected soils.

The third chapter describes the general field remediation activities that have been occurring in the oil field in southeast Saskatchewan. These activities are similar to the remediation activities that have occurred at the two field sites selected for this thesis.

The fourth chapter is a characterization of the salinity status of the two field sites, an assessment of the effect of the remediation practices, an evaluation of the progress to meeting remediation target end points, and a recommendation of additional remediation necessary to meet target end points.

The fifth chapter describes methodology, results, and discussion of the laboratory experiment to evaluate the various amendments applied to the contaminated sites.

An evaluation of the field study and laboratory experiment is presented in chapter six followed by a synthesis of the results of both studies in chapter seven.

Finally, the recommendations of the thesis are presented in chapter eight.

2.0 LITERATURE REVIEW

About 10% of the total arable lands in the world are salt-affected (Tanji 1996). Dissolved mineral salts present in the waters and soil cause salt-affected land when the concentration of the salts reaches levels which adversely affect plant growth. The major solutes which cause salt-affected land are the cations Na^+, Ca^{2+}, Mg^{2+} and K^+ and the anions Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-} and NO_3^- (Tanji 1996; Sparks 1995). The sources of salts include saline irrigation and drainage water, saline and sodic soils, saline groundwater, seawater intrusion, brines from natural salt deposits or geological formations and brines from oil and gas fields and mining (Tanji 1996). This literature review will focus on the chemical and physical effects of salt-affected soil, the chemical and biological amendments used as methods of remediation, and the hydrology of semi-arid soils.

2.1 Measuring salt-affected soils

Three measurements are used to measure and describe salt-affected soil: the electrical conductivity (EC), the sodium adsorption ratio (SAR) and the exchangeable sodium percentage (ESP).

2.1.1 Electrical conductivity

The electrical conductivity (EC) of a soil is a measure of the soil's ability to conduct electricity (Bresler et al. 1982). Pure water is an insulator (will not conduct electricity). As the salt content rises, more current flows and the EC increases. The amount of electrical current measured is directly proportional to the amount of soluble salts in the soil. The EC can be measured either directly by soil sampling or indirectly by using an EM survey (McNeill 1980; Rhoades et al. 1999). How the EC is measured will affect the EC value and therefore the EC measure should have subscript that indicates what method was used to measure EC.

ECe – If the EC is measured from a saturation paste extract of a soil sample then it is ECe. Most literature uses ECe and it is often abbreviated to simply EC to characterize plant tolerance to soluble salts. ECe is measured in desiSiemens per meter (dS m^{-1}). To determine the ECe, the saturation paste of the soil sample is placed on a vacuum extractor in a soil laboratory (U.S. Salinity Laboratory Staff 1954).

ECp – An ECp is the EC of the saturation paste (before vacuum extraction). This measurement can be completed in the field by making a saturation paste and using a soil probe to read the EC (U.S. Salinity Laboratory Staff 1954).

ECa - The ECa is the EC measured by an EM - Electromagnetic induction instrument (McNeill 1980). The EM conductivity values reflect the weighted average electrical conductance of the bulk soil depth which is proportional to the distance between the sending and receiving sensors at either end of the EM instrument. An EM has both a transmitter coil and a receiver coil (McNeill 1980). The transmitter sets up an electric current, this induces a second current that is received and read by the receiver coil. The EM reads the speed at which the current flows through the soil or the conductivity of the soil. Conductivity increases in the soil with increased salts.

The EM is a non-contacting, non-destructive method of measuring insitu electrical conductivity of the soil. The EM measures the apparent EC or ECa in units of milliSiemens per meter (mS m^{-1}) for the bulk soil and is an indirect EC measurement. The EM equipment is commonly used to map the extent of salinity by passing it over the surface of the soil and continuously recording measurements.

The limitations of the EM are that it is also affected by the soil texture (amount of clay), the soil water content, the soil temperature, buried metal (i.e. buried pipe), and edge effects (i.e. the edge of the road) (Corwin 2009).

Two types of EMs, the EM31 and EM38 have been used in the remediation program. Each EM can makes two types of readings, a reading in vertical mode (v) and one in horizontal mode (h). The EM31 measures the average conductivity to 6 m in the vertical mode and 3 m in the horizontal mode. An EM38 measures the average conductivity to 0.75 m in the horizontal mode (h) and 1.5 m in the vertical mode (v).

2.1.2 Sodium adsorption ratio (SAR) & exchangeable sodium percentage (ESP)

The SAR is the measure of the concentration of Na^{+} ions in relation to the concentration of Ca^{2+} and Mg^{2+} ions in the soil solution. The formula for SAR is calculated in meq/l.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{1}{2}\left(Ca^{2+} + Mg^{2+}\right)}} \quad [1]$$

The ESP is the percentage of Na^{+} occupying the exchange sites on the soil.

2.2 Salt-affected soils

There are three types of salt-affected soils: saline, sodic, and saline-sodic.

2.2.1 Saline

A saline soil has a high concentration of soluble salts, an EC >4 dS m^{-1}, a SAR <13 or an ESP <15, and a pH<8.5 (Brady and Weil 2002). The excess salts increase the EC of the soil and lower the osmotic potential of the soil water. When the osmotic potential is lower in the soil than plant roots, plants cannot extract water from the soil. Water moves from high potential (the plant roots) to low potential (the soil) and the plants desiccate. A saline soil can also cause specific ion toxicity. This occurs when the concentration of a specific ion is at a level which is toxic to the plant.

Leaching is used to remediate a saline soil. Leaching water should have a low EC (be low in soluble salts). As the water moves down through the soil the salts are dissolved in the leaching water and moved further down into the soil. If there are sub-surface drains to collect the leached water, these salts will be removed from the soil. If there are no sub-surface drains, the leaching will move the salts lower into the soil. When the salts are low enough, they will not affect plant growth. The depth to which the salts need to leach is dependent on the root depth of the plant and depth of the groundwater. Further discussion is provided in Section 2.5.

Most soluble salts can be removed quickly if the soil is saturated and water is able to leach through. Frenkel et al. (1989) found that most Cl^- could be removed in one pore volume (Figure 2.1). A pore volume is the amount of water that is needed to completely saturate the soil. Therefore remediating a saline soil can happen quickly if one pore volume is able to leach through the soil.

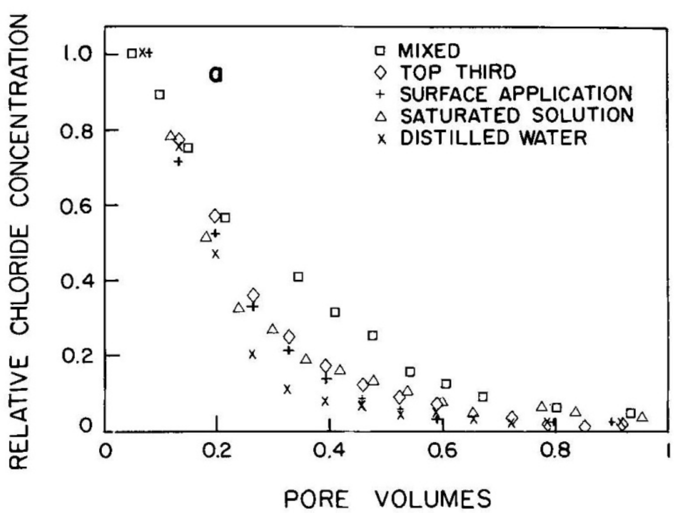


Figure 2.1 Scaled ion concentration as a function of leachate pore volume: (a) chloride (chloride per increment/chloride in initial increment). (Frenkel et al. 1989)

2.2.2 Sodic

A sodic soil has a high concentration of exchangeable Na^+. The EC is <4 dS m^{-1}, the SAR is >13 or the ESP is >15, and the pH is >8.5 (Brady and Weil 2002). The high percentage of Na^+ on the soil exchange sites affects the structure of the soil. Of all the physical properties, most important is soil structure. Soil used for cropping depends greatly on the degrees to which the soil conducts water and air (permeability) and on physical properties (Rhoades and Loveday 1990). When the clay particles are close enough, van der Waals forces cause them to be weakly attracted, and they flocculate. Good soil structure occurs when flocculated particles form secondary aggregates in the presence of a cementing agent like organic matter or carbonates (Brady and Weil 2002). An aggregated soil has better drainage, space for roots to penetrate, and air movement.

Water infiltrates through the macro pores that are between the aggregates (Freeze and Cherry 1979). As the water leaches down through the soil the macro pores dry out (aerate). The aggregated soil provides both water and air to roots. When percentage of Na^{+} on the exchange sites rises above 15% (ESP >15), the soil aggregates start to disperse (Tanji 1996). Due to the large hydrated size of the Na^{+} ion the clay particles are not close enough to flocculate. Instead the soil particles repel, the soil disperses, and the macro pores collapse (Keren and Miyamoto 1996). With no macro pores, water infiltrates very slowly through micro pores. The hydraulic conductivity is reduced and the permeability decreased (Hanay et al. 2004). Water ponds on the surface and the soils do not aerate.

Remediation of a sodic soil usually includes a Ca^{2+} amendment to replace the Na^{+} on the exchange sites. When the soil is flooded with a large concentration of Ca^{2+} ions, these ions displace the Na^{+} ions on the exchange sites and the Na^{+} ions leach through the soil. The result is that Ca^{2+} now dominates the exchange sites. Calcium does not have a large hydrated size and therefore the soil will re-flocculate and re-form aggregates.

2.2.3 Saline-sodic

The saline-sodic soil has both an EC >4 dS m^{-1}, a SAR >13 or an ESP >15, and a pH <8.5 (Brady and Weil 2002). Brine contamination causes saline-sodic soils. The brine consists of high concentrations of Na^+ and Cl^-. The Na^+ causes the soil to become sodic and the Cl^- is a soluble salt that causes the soil to become saline.

Remediation must include leaching the soluble salts (primarily the Cl^-) and exchanging Na^+ through the application of an amendment (usually calcium sourced) (Bresler et al. 1982). Calcium sourced amendments are added to the soil and the soil is leached until the Na^+ and soluble salts are removed to below the rooting zone. Due to the potential for poor permeability of this soil as a result of high Na^+ concentrations, leaching can be slow if the soil is dispersed (Keren and Miyamoto 1996). When the chemical amendment is combined with a biological amendment such as organic matter and/or cropping the permeability of the soil is increased and greater infiltration occurs (Qadir et al. 1996b). This combination of chemical and biological amendments is the most effective method of remediation (Ilyas et al. 1997).

2.3 Genesis of salt-affected soils

Salt-affected soils occur through both natural and anthropogenic sources. Natural causes of salinization are found in many forms throughout the world. Anthropogenic causes of salinization are: (1) land use practices that, over time cause secondary salinization and (2) sudden and catastrophic events (Brady and Weil 2002).

2.3.1 Natural salinization

The parent material from which soils form may contain salts. These salts are generally chloride and sulphates of calcium, magnesium, sodium, and potassium (Brady and Weil 2002). If the parent material does have salts, the soils can become salt-affected. For example, in southeast Saskatchewan, some of the soil is characterized by high concentrations of gypsum ($CaSO_4 \cdot 2H_20$) (Saskatchewan Soil Survey 1997). Weathering of gypsum releases the ions Ca^{2+} and SO_4^{2-} which increases the soluble salt content of the soil and increases the potential for these soils to become salt-affected.

Natural salinization may also occur from atmospheric deposits of salts on lands near sea water, seawater intrusions, and rising saline groundwater (Tanji 1996).

2.3.2 Secondary salinization

Secondary salinization occurs as a result of land uses practices that unintentionally cause salinization. These practices can include improper application of irrigation water, amendments, manures, fertilizer, and sewage (Tanji 1996). Secondary salinization happens over time and is often due to poor management practices. This type of salinization may be curbed with appropriate knowledge and changes to management practices.

On the Western Canadian prairies one of the more visible signs of secondary salinization are the areas of salt-affected soil next to roads. Roads were built higher than the surrounding land. They were built this way to minimize snow on the road in winter and to facilitate drainage in the summer so that the road is usable all year long. By changing the topography and natural drainage of the landscape an unintended consequence is road side salinity (Figure 2.2) (Skarie et al. 1986). Water drains off the road and collects in the ditch alongside the road. The water is pushed down and out of the ditch and rises further into the field. When the water moves it dissolves salts along its path and becomes more saline. When the saline water surfaces, the water evaporates and leaves the salts behind. Over time the salts accumulate and a saline area forms (Richardson 2009).

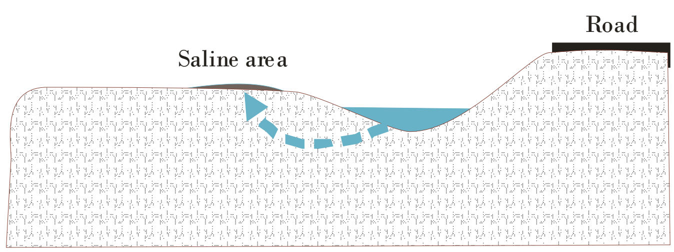


Figure 2.2 Ditch effect (adapted from Richardson 2009)

2.3.3 *Sudden salinization*

Sudden salinization occurs as a onetime event (Liang et al. 1995). Usually the impact is finite (a known volume and concentration), localized and documented. From the source of the release there will be a migration of salts. The concentration will be highest at the source and decrease away from the source (Alberta Environment 2001). Brine contamination is an example of sudden salinization. As the salt concentrations can be extremely high it is important to consider how the salts will migrate in order to intercept the migration as soon as possible.

2.4 Hydrology of semi-arid saline-sodic soils

Understanding the hydrology of semi-arid saline-sodic soils is important. It is with an understanding of how water moves overland and subsurface that remediation techniques are implemented. Ca sourced amendments are effective as long as water is able to penetrate and flush the sodium ion below the rooting zone or to tile drains. Likewise removing the chloride ion is based on moving it below the rooting zone or to tile drains. Both of these remediation strategies take for granted that water will be passing through the contaminated zone.

2.4.1 *Hydrologic cycle*

The hydrologic cycle describes the movement of water on earth (figure 2.3) (Freeze and Cherry 1979). Precipitation falls on the soil surface. Some water infiltrates the soil and the rest flows over the surface as overland flow. Water that infiltrates into the soil can percolate down through the soil, be retained in the soil, evaporate from the soil surface, or be taken up by plants. Water that percolates down into the soil may flow directly down into the water table (the zone where pore water pressure equals atmospheric pressure i.e. zone of permanent saturation) or it may move laterally as through flow into a local low area or slough.

Interception refers to water used by plants (Freeze and Cherry 1979). Plants return water to the atmosphere through transpiration. Evaporation from soil and water surfaces returns water to the atmosphere. Evapotranspiration is a term used to describe the water that evaporates to the atmosphere from soil, water, and plants.

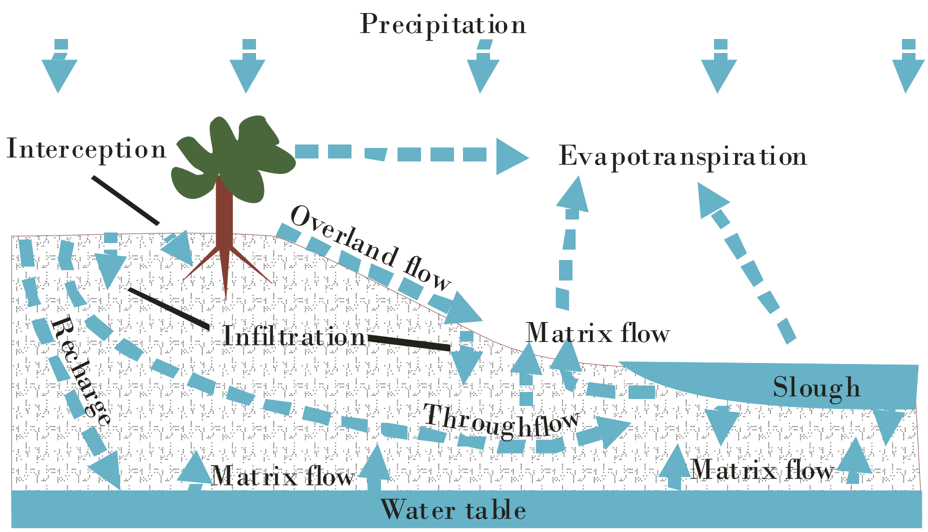


Figure 2.3 Hydrologic cycle (adapted from Freeze and Cherry 1979; Richardson 2009)

Water moving downward in the unsaturated soil zone toward the water table is called infiltration. Water moving downward in the saturated zone below the water table is called groundwater recharge. In combination these flow processes are commonly referred to simply as recharge. The term discharge is commonly used to describe the process of water flowing upward from depth to the water table in the saturated zone, and upward from the water table in the unsaturated zone via matrix and capillary flow.

2.4.2 Landscape hydrology

Southeastern Saskatchewan is in the prairie pothole region of North America (figure 2.4) (van der Valk 2005). This hummocky topography is characterized by numerous small enclosed depressions (potholes, sloughs, ponds, wetlands, lakes, etc.) and water ways (rivers, creeks, or intermittent streams). This landscape affects how overland flow moves over the soil surface and consequently sloughs are important to the local hydrology. There are three kinds of sloughs recharge, discharge, and flowthrough sloughs (Arndt and Richardson 1989).

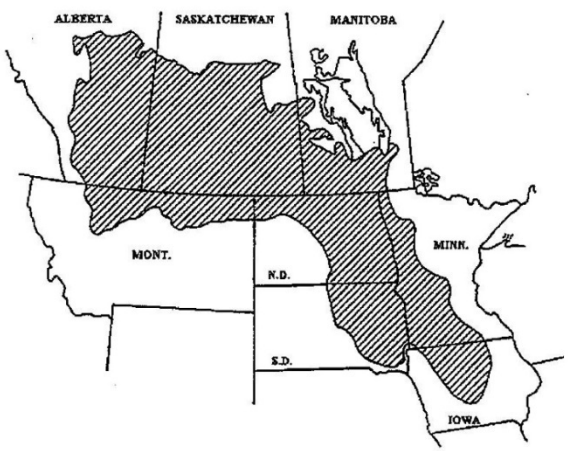


Figure 2.4 The prairie pothole region of North America (van der Valk 2005)

Figure 2.5 is a simplified flownet diagram of the three slough types (Richardson et al. 1992). Water flows from areas of high potential to areas of low potential. The dotted (equipotential) lines represent equal potential. Flow will be perpendicular to the equipotential lines; water flows down in the recharge slough, laterally through the flowthrough slough, and upward in the discharge slough.

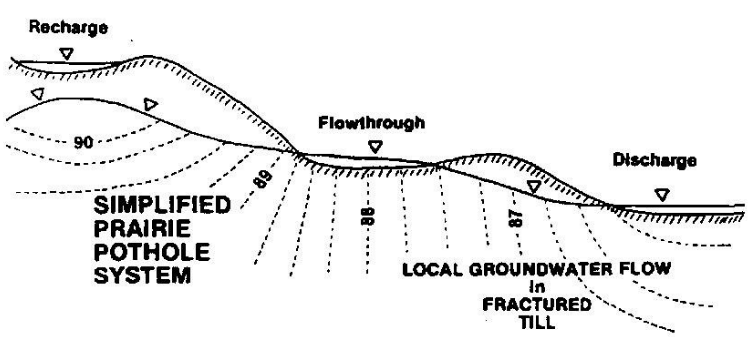


Figure 2.5 Generalized and simplified flownet of a local groundwater system in fractured till that lacks integrated drainage. The equipotential lines (dashed) represent head (m). Note that in recharge areas the lines are parallel to the surface and decrease in value downward. In discharge areas the lines are parallel but increase in value downward. In flow-through conditions the lines are perpendicular to the surface (Richardson et al. 1992).

Recharge sloughs are sloughs that recharge the water table (Richardson et al. 1992). Water moving downward in the unsaturated soil zone toward the water table is called recharge. Fast recharge slough typically do not hold water for long period during the year. Slow recharge sloughs may have an area of open water that shrinks during the course of the year. During recharge water dissolves and removes the salts from the flow zone moving them to lower depths. The soils under these sloughs are well leached; all soluble salts have been removed (Miller et al. 1985).

Slow recharge slough have a shallow marsh zone (sedges and slough grass) in the centre with hydrophytic vegetation (cattails and bulrushes) when the water table is high (Lissey 1968, Stewart and Kantrud 1969, Van der Valk 2005). Surrounding the shallow marsh zone is a wet meadow zone of mesophytes like grasses (Ross 2009). Willows and trees are commonly found around these sloughs. Fast recharge slough have a wet meadow zone. They are in filled with grasses and surrounded by trees and willows (Lissey 1968).

Flow-through sloughs both receive water and yield water (Arndt and Richardson 1989). These sloughs behave as intermediaries between recharge and discharge sloughs; they connect the water movement between the sloughs.

Discharge sloughs are sloughs where groundwater movement is towards the soil surface (Arndt and Richardson 1989). The water level in discharge sloughs usually represents the groundwater level at that point in the landscape. These sloughs usually hold water most of the year and therefore they generally do not have vegetation in the centre of the slough. The centre of the discharge slough is an open water zone, surrounded by a deep marsh zone (cattails and bulrushes), and a shallow marsh zone (sedges and slough grass) (Lissey 1968, Stewart and Kantrud 1969, Van der Valk 2005). There are no wet-meadow mesophytes surrounding a discharge slough. If the discharge is saline then the vegetation surrounding it will only be halophytic.

Discharge, the process of water flowing upward from depth via matrix and capillary flow, moves water toward the soil surface and typically carries higher concentrations of salts leached from other areas (Miller et al. 1985). When discharge water evaporates into the atmosphere, the salts are left behind in the soil (Steinwand and Richardson 1989). Over time this can cause salinity around the edge of the slough if there are salts in the soil (figure 2.6). In the Prairie pothole region rings of salinity around sloughs is very common.

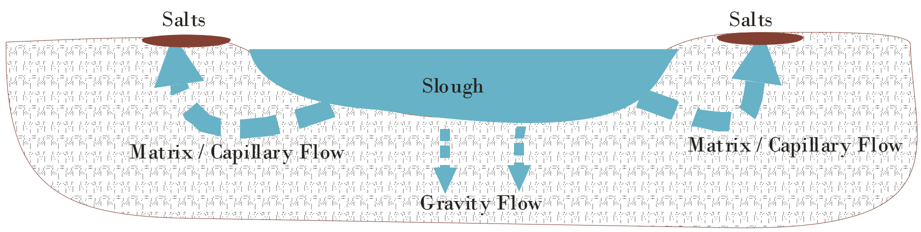


Figure 2.6 Landscape salinity (adapted from Richardson 2009)

2.4.3 Soil hydrology

Soil hydrology describes the water flow in the soil (Freeze and Cherry 1979). The rate at which water flows through a uniform medium is constant and is described as the hydraulic conductivity (Freeze and Cherry 1979). The higher the hydraulic conductivity of the medium the faster water flows through it. More porous mediums have higher hydraulic conductivity. Sands and gravels are more porous than clays. Therefore water will move faster through sand and gravel and slower through clay.

Gravity, matrix and osmotic are three mechanisms of flow in the soil (Richardson 2009).

Gravity – When precipitation falls on the soil it either infiltrates into the soil surface or it runs off. Gravity acts on overland flow to move the water on the soil surface down topographic gradients to the lowest position in the landscape. Water that infiltrates the soil and percolates downward toward the water table is being pulled by gravity. Water in excess of field capacity (water holding capacity) percolates downward through the root zone and eventually some of this water reaches the water table. The result of this additional water is a decrease in the depth to the water table and a change in the quality of the groundwater (Hayashi and van der Kamp 2009).

Matrix – Water moves from a saturated zone (water table) to an unsaturated zone through matrix flow. This flow is usually upward; water moves up from the water table. Matrix and capillary flow are both terms used to describe this water movement in the unsaturated soil zone. The soil zone affected by upward matrix flow is called the capillary fringe. The depth of the capillary fringe is dependent on the soil texture. Clayey textured soils with smaller size pores have a thicker capillary fringe than sandy textured soils with larger pores (Brady and Weil 2002).

Osmotic – Osmotic flow is the flow of water across a semi permeable membrane separating solutions with different partial pressures due to solute contents (Bresler et al. 1982). Osmotic flow is how plants receive the water they need to survive. Water moves into the root cells of plants when the soil water has a lower salt content than the plant. If the soil is saline, the soil water has a high salt content. This reverses the water flow and the water moves from the plant to the soil. Therefore the plant loses all its water, dries up and dies.

2.4.4 Remediation of saline-sodic soil

Understanding hydrology is important to remediation strategies of saline-sodic soils. A saline-sodic soil needs water to pass through the soil in order to flush out the salts. Referring to the hydrology cycle (Section 2.4.1) it is infiltration water that flushes salts down. In some cases the salts may be flushed into the groundwater or tile drains or in other cases the salts will be flushed well below the zone where plant roots are not affected. Some hydrogeologic processes may move salts into the rooting zone from depth such as matrix flow above the water table and matrix flow on the edge of sloughs (Richardson 2009). Whether the salts are flushed into the groundwater, to tile drains, or below the rooting zone it is important to understand how the groundwater table fluctuates, how the chemistry of the groundwater changes, and to what depth do the salts need to be flushed to prevent resalinization of the soil.

When the contaminant is dissolved in the groundwater (as is the case with soluble salts) it will move with the groundwater flow. In order to remediate a site where the groundwater is contaminated, it is important to monitor the groundwater flow, the depth to groundwater, and the groundwater chemistry. For instance, if soluble salts have caused saline groundwater there is a chance that the groundwater will continue to salinize the soil or resalinize a remediated area. The local groundwater flow path is the direction the salts will move. By understanding the flow path and the chemistry of the groundwater it is possible to predict if the groundwater will salinize or resalinize the soil.

2.4.4.1 Groundwater flow

Groundwater is a zone of subsurface water below the water table that is fully and permanently saturated (Freeze and Cherry 1979). On regional scale water flow is from the highest topographical point in the regional landscape to the closest large river or lake. Local groundwater flow in the hummocky landscape of the Canadian prairies is depression-focused (Lissey 1968). The water table recharges under sloughs creating a groundwater mound and subsequently groundwater flows laterally toward depressions in the water table (figure 2.7). Overland flow is from slough to slough through local and intermittent rivers and streams. Flow amounts are dependent on the amount of snowmelt and precipitation. Water levels in streams, rivers and sloughs will fluctuate throughout the year.

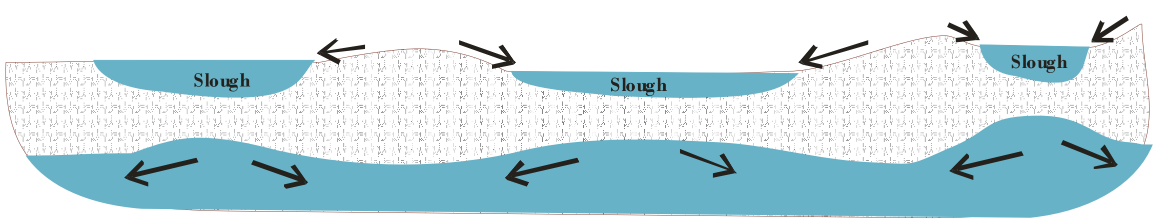


Figure 2.7 Depression-based groundwater recharge (adapted from Lissey 1968)

Monitoring Groundwater Flow - To measure the groundwater level and determine the local groundwater flow piezometers are installed to monitor the changes in the groundwater level during the year. A water level tape is used to measure the depth to groundwater. The water level changes during the year and therefore the water level must be measured regularly. The groundwater flow is towards lowest groundwater level or toward the well with the lowest water level. Local groundwater flow is dependent on (1) the soil characteristics of the area and (2) the local topography. For example, (1) soils with courser texture such as sand and gravels will have faster groundwater flow and (2) sloughs will create mounds in the groundwater and subsequent lateral flow away from the slough (Lissey 1968).

2.4.4.2 Depth to groundwater

There is an interaction between groundwater and surface water (Hayashi and van der Kamp 2009). Downward percolation of excess soil water from spring melt and heavy summer rains induces a rise in the water table. As the year progresses and through the winter, the water table usually declines. The local groundwater slowly moves downward into the regional water table and flows to the nearby large river/lake. If there is no excess soil water to recharge the water table the local water table lowers. Capillary rise from the water table can also move water from the water table into the soil above the water and subsequently lower the water table.

Groundwater levels fluctuate depending on the season and on the amount of precipitation (Eilers 1982; Conly et al. 2004; Mills and Zwarich 1986). Figure (2.8) shows the levels of groundwater (stages 1, 2, and 3) during the year in a cross sectional landscape from southeast Saskatchewan (Eilers 1982). Stage 1 is after spring snowmelt and runoff, stage 2 is during late summer, and stage 3 is in the winter. The groundwater table is the highest in the spring and it continues to fall throughout the year. It may rise occasionally during the year only if there is a large rainfall. There may be a groundwater rise of up to 2 m in the spring followed by a 0-1 m drop in the summer (Conly et al. 2004).

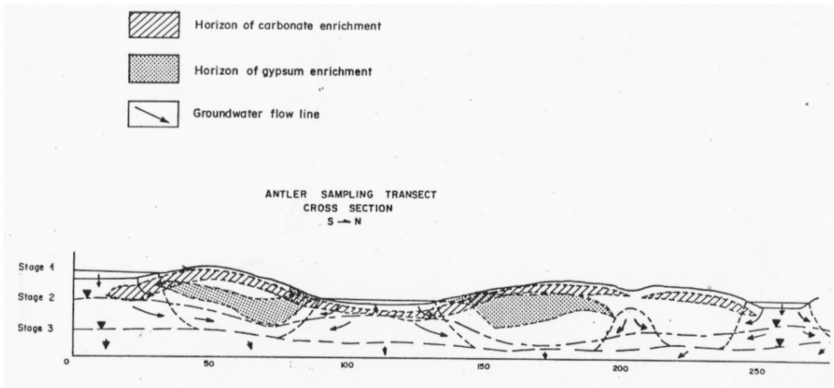


Figure 2.8 Groundwater depth and flow during the year. Stage 1 is after spring runoff, stage 2 is during late summer and stage 3 is during the winter. (Eilers 1982)

2.4.4.3 Groundwater chemistry

The chemistry of the groundwater changes during the year. A rise in the water table induces a subsequent dilution of the soluble salt contained in the groundwater (Hayashi and van der Kamp 2009). When the water table is the highest (often in late spring or after heavy rains) the soluble salt concentration will be the lowest. As the year progresses and through the winter, the water table normally declines. The lower water table concentrates the soluble salts. The salts, however, are not lost from the soil system (Armstrong et al. 1996).

2.4.4.4 Contaminant flow

When there is a soluble contaminant in the soil the behavior of the contaminant will vary (Freeze and Cherry 1979). Typically the contaminant will follow the flow of infiltration in the unsaturated zone and the flow of groundwater in the saturated zone.

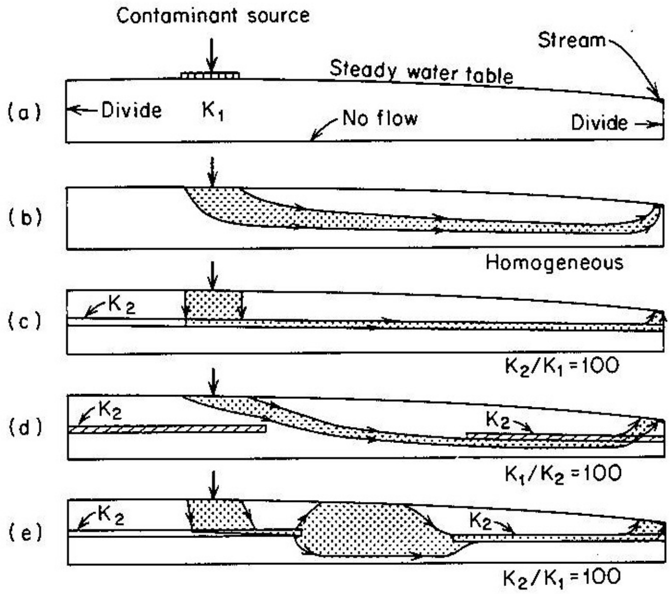


Figure 2.9 Effect of layers and lenses on flow paths in shallow steady-state groundwater flow systems. (a) Boundary conditions; (b) homogeneous case; (c) single higher-conductivity layer; (d) two lower-conductivity lenses; (e) two higher-conductivity lenses (Freeze and Cherry 1979).

Figure 2.9 shows the movement of a contaminant through different soils. If there is no flow the contaminant will not move (a). If the soil is heterogeneous the flow path will move steadily through the soil (b). If the contaminant finds a zone where the hydraulic conductivity is greater than the surrounding soil (i.e. a sand or gravel seam), the flow path is concentrated and the travel time would be faster (c). If the contaminant encounters an area of lower hydraulic conductivity (i.e. a compact layer like clay), the contaminant is confined to a flow path that outside of the zone of lower hydraulic conductivity (d). If the contaminant finds a zone of higher hydraulic conductivity but that zone is discontinuous the contaminant spreads out when the zone ends and then follows the higher hydraulic conductivity when the zone continues again (e).

To be able to predict the path of the contaminant is therefore extremely difficult if the stratigraphy of the soil is unknown. Glacial tills soils have formed with layers of different soil types all of which have different hydraulic conductivities (Lissey 1968). These different layers would further complicate the flow paths in figure 2.9. To map out the soil stratigraphy sufficient deep soil sampling is necessary.

2.4.4.5 Leaching requirement

The leaching requirement is a term used often when determining how much irrigation water is necessary to satisfy the crop and to leach away soluble salts (U.S. Salinity Laboratory Staff 1954). The leaching requirement is usually determined based on a steady state model (U.S. Salinity Laboratory Staff 1954). In this thesis study, leaching is dependent on precipitation and not irrigation therefore the traditional definition of leaching requirement under steady state conditions is ineffective. Instead the leaching requirement for this study is defined as how much precipitation is needed to flush the salts down the soil profile. This type of leaching is transient and not steady state. Leaching under steady state conditions is thought to be more effective than transient leaching because of the variability of transient conditions (Shainberg and Letey 1984). Completely removing the salts requires the soil to be fully saturated and these conditions may not occur in transient flow and therefore transient leaching has traditionally been thought to be less effective. However, in a study by Corwin et al. (2007) the leaching requirement using a transient model required less water than using a steady state model and yet the effectiveness of the leaching was equal.

2.4.4.6 By-pass flow and episodic leaching

Leaching in the field rarely occurs in saturated conditions because the soil is rarely completely saturated. Therefore some leaching of salts must occur in unsaturated conditions. In a leaching study, Corwin et al. (2007) found that salts will be removed even with transient flow. Another term for transient flow is episodic leaching. There are episodes of leaching between which the soil drains.

Soil drains first in the largest pores and progresses towards smaller pores (Freeze and Cherry 1979). The water held in the smallest pores is held tightly. The soil acts like a sponge filling up the pores (Phillips 2010). Most models of water flow assume that new water infiltrating the soil displaces the old water (Brooks et al. 2010). New research by Brooks et al. (2010) suggests that there are two pools of water in the soil. One pool is held tightly in the soil and is not easily moved within the soil profile. This water is used by plants especially during drier conditions. The second pool of water is mobile and new infiltration will displace it. The second pool of water is the water which reaches the water table. The study site for this research was in a wetter climate than southeast Saskatchewan; however, the concepts presented here could apply in semi-arid conditions. Further research in this area of hydrology is necessary to understand if this type of by-pass flow occurs in all climatic conditions.

2.4.4.7 Risk of resalinization

If the risk of salts rising into the rooting zone from a rise in the groundwater table is low then the site has a low potential of resalinization. Throughout the year the groundwater table changes. The risk of salts rising is determined by measuring the changes in the groundwater depth and the changes in the chemistry of the groundwater.

The measured height of the water table affects the risk of resalinization. It is not just the height of the water table that is important but also the height of the capillary fringe.

Upward movement of salts occurs during dry periods. When the water evaporates, the salts are left in the soil and subsequently increase the salinity of the soil. In a field study in Texas, the ECe decreased due to rainfall from May to July (Figure 2.10). After July 3, there is a sharp increase in the surface ECe when very little rain fell (Carter and Fanning 1964).

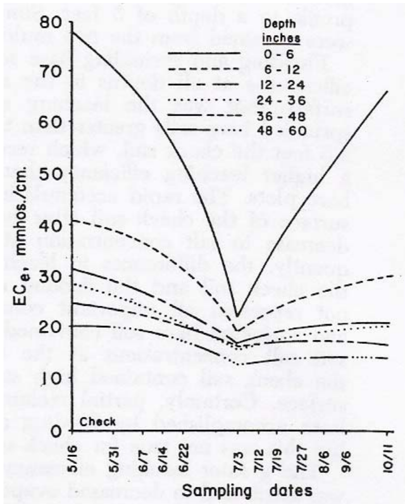


Figure 2.10 The soluble salt concentration expressed as ECe in mmhos/cm. for various depths of check soil in relation to sampling dates (Carter and Fanning 1964).

The rise of the water table is, of course, dependant on the amount of rainfall. Average yearly rainfall is flawed because it is average. It only takes one abnormal year and the water table rises unusually high and the salts are brought into the rooting zone. Fortunately, when the water table is high, the salts become diluted and therefore the salts have less effect (Hayashi and van der Kamp 2009).

Factors that influence the depth at which a saline water table will resalinize the root zones are the concentration and composition of solutes, the frequency and amount of rainfall and irrigation, the soil physical properties, the crop characteristics and the weather (Peck 1978). The critical depth to water is often referred to as between 1-2 m (Rhoades 1974; Nulsen 1981). However, Peck (1978) suggests that this depth is much greater for dryland agricultural conditions, as deep as 3-6 m.

Southeast Saskatchewan would be considered dryland agricultural conditions. The depth at which the groundwater presents a low risk of resalinization is site specific. The depth will be determined by considering the soil type, the chemistry of the groundwater, and the topography.

2.5 Remediation strategies - amendments

Chemical amendments are used to treat sodic and saline-sodic soils (Bresler et al. 1982). A sodic soil has a high percentage of Na^+ on the exchange sites. If the exchange sites are flooded with another ion, the Na^+ on the exchange sites will be replaced by this ion. The Ca^{2+} ion is often used to replace the Na^+ (Keren and Miyamoto 1996). When Ca^{2+} is used to treat sodic and saline-sodic soil, the Na^+ is replaced by Ca^{2+} and the Na^+ is leached out of the soil.

Any salt with Ca^{2+} can be used as an amendment. Gypsum ($CaSO_4 \cdot 2H_20$) is the most common amendment but other salts such as $CaCl_2$ and calcium nitrate [$Ca(NO_3)_2 \cdot 2H_20$] also supply Ca^{2+} and are used to treat sodic soils (Keren and Miyamoto 1996; SPIGEC 1999b).

2.5.1 Gypsum

Gypsum, because it is readily available and is relatively inexpensive, is often used as a chemical amendment to treat sodic and saline-sodic soils (Keren and Miyamoto 1996). Many studies have found gypsum decreases EC and SAR and helps remediate sodic and saline-sodic soils (Karamanos 1996, Carter et al. 1978, Qadir et al. 1996a).

2.5.1.1 Gypsum lowers SAR and EC

Liang et al. (1995) studied the effect of phosphogypsum (PG) on brine contaminated soil properties. Phosphogypsum is a by-product of the production of phosphate fertilizer and is made up of primarily gypsum plus some impurities. 400 Mg ha^{-1} PG was added to the top 15 cm of a 60 cm soil column. The saturation paste of the loamy soil had an ECp of 118 dS m^{-1} and a SAR of 135 before PG was incorporated. Barley was planted on the soil column and the column was watered with deionised water to simulate precipitation of 24 cm and 42 cm per year. At the end of the experiment the saturation paste EC was 35.5 dS m^{-1} and the SAR was 41.5 in the 0-15 cm depth of the PG amended treatment compared to EC and SAR of 48.2 dS m^{-1} and 62.9, respectively when no PG was applied.

This study showed that Ca^{2+} from the gypsum exchanged the Na^{+} and the exchanged Na^{+} leached down the soil profile. Figure 2.11 shows an increase in exchangeable Na^{+} at 35 cm depth of the PG amended treatment compared to the brine contaminated check because the Na^{+} has leached to this depth. Leaching of extractable K^{+}, Ca^{2+}, and Mg^{2+} also occurred in the PG applied treatment compared to the treatment without PG.

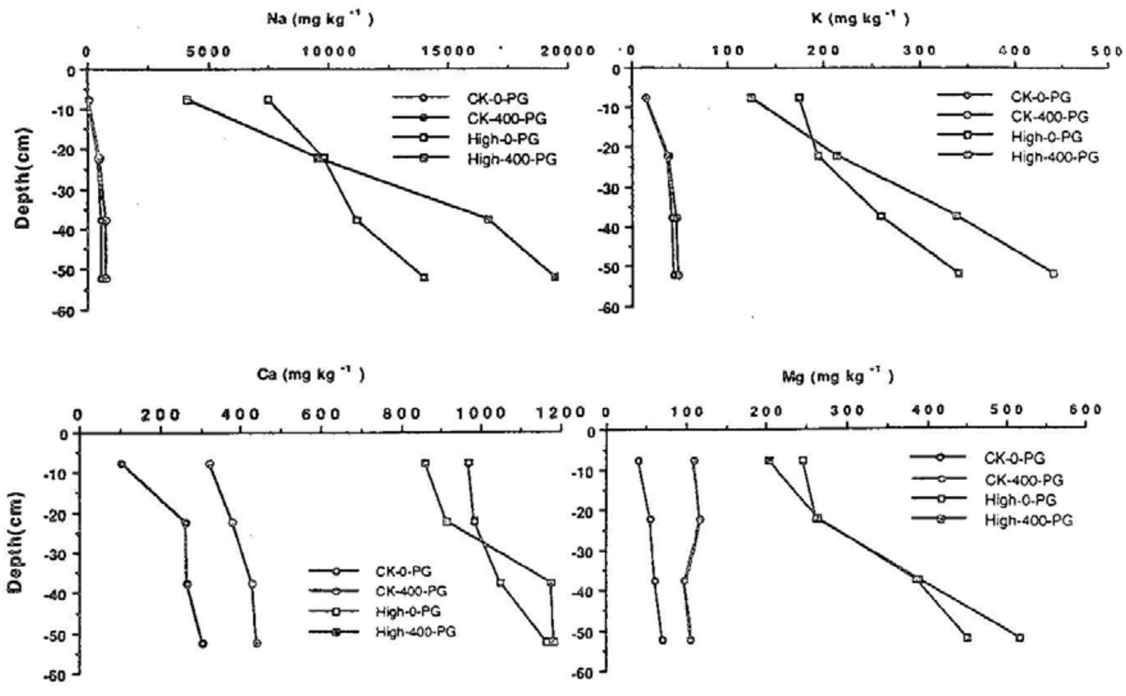


Figure 2.11 Distribution of exchangeable cations in the control and HB loamy soil profiles. (Liang et al.1995)

In a field study of a brown solodized solonetz soil in Alberta, Carter et al. (1977) found that the SAR decreased with surface application of 4.48 t ha^{-1} gypsum applied annually with 449 kg ha^{-1} ammonium nitrate. After five years, the SAR of the Ap horizon treated with gypsum and ammonium nitrate was 2.7 compared to 15.47 with ammonium nitrate alone. The ammonium nitrate and gypsum treatment also had a significant decrease of soluble and extractable Na^{+} and a significant increase in soluble and extractable Ca^{2+} compared to ammonium nitrate alone. A follow up study by Carter et al. in 1978 looked at gypsum alone compared to ammonium nitrate alone and a combination of ammonium nitrate and gypsum. The field study with a black solonetz soil was seven years long and yearly application rates of gypsum and ammonium nitrate were 11.2 t ha^{-1} and 896 kg ha^{-1}, respectively. Water penetration was significantly higher in the ammonium nitrate and gypsum treatment and the gypsum treatment compared to ammonium nitrate alone and the control. The treatments with gypsum had significantly lower extractable Na^{+} and significantly higher extractable Ca^{2+} concentrations in both the A and B horizons. With the combined ammonium nitrate and gypsum treatment there was some loss of Ca^{2+} to the C horizon compared to gypsum alone or the control. The authors concluded that this loss of Ca^{2+} was due to leaching of the Ca^{2+} before it was able to exchange the Na^{+}.

Qadir et al. (1996a) found a significant decrease of EC and SAR in a leaching experiment with gypsum. The soil was calcareous saline-sodic with an EC of 98 dS m^{-1} and a SAR of 103 and it was packed in 30 cm diameter columns to a depth of 35 cm. Four treatments were prepared: a control, 50% (7.8 Mg ha^{-1}) gypsum requirement (GR), 100% (15.6 Mg ha^{-1}) GR, and kallar grass. The gypsum was incorporated 8-10 cm into the soil column. Four leaching cycles were completed by ponding a 5 cm water head on the surface of the column. The length of each the four cycles was 24, 41, 46, and 21 days. Leaching cycles 1 and 4 were completed in winter and 2 and 3 during the summer growing period. The 100% GR decreased the EC and SAR significantly more than the 50% GR, kallar grass or control in all depths (table 2.1). Of note was that the kallar grass and 50% GR were equally successful at decreasing EC and SAR. One of the goals of this experiment was to study the effectiveness of cropping to supply Ca^{2+} through $CaCO_3$ dissolution (see section 1.4 for further discussion of $CaCO_3$ dissolution).

Table 2.1 Effect of reclamation treatments on EC, SAR and pH of the soil (Qadir et al. 1996a)

Treatment	Soil depth		
	0–15 cm	15–30 cm	0–30 cm
EC_e ($dS\ m^{-1}$)			
Control	4.3 a	7.0 a	5.7 a
50% GR	3.3 b	4.4 b	3.9 b
100% GR	1.3 c	2.1 c	1.7 c
Kallar grass	2.9 b	3.6 b	3.3 b
SAR ($mmol\ L^{-1})^{1/2}$			
Control	42.3 a	56.6 a	49.5 a
50% GR	19.4 b	28.6 b	24.0 b
100% GR	12.1 c	16.9 c	14.5 c
Kallar grass	20.0 b	29.8 b	24.9 b
pH_s			
Control	9.0 a	9.2 ^{NS}	9.1 a
50% GR	8.8 b	9.0	8.9 b
100% GR	8.8 b	8.8	8.8 b
Kallar grass	8.2 c	8.6	8.4 c

Means with different letters (a, b, c or d) in a column for each soil characteristic and soil depth differ significantly according to Duncan's Multiple Range Test at $P = 0.05$.
^{NS} = Non-significant.

Gypsum is effective at reducing the SAR and EC of sodic and saline-sodic soils (Carter et al. 1977; Liang et al. 1995; Qadir et al. 1996a). Gypsum supplies Ca^{2+} to replace the Na^+ on the soil exchange sites to reduce the SAR. Leaching removes the Na^+ and all other soluble ions from the soil thereby reducing the EC. Effective leaching is important for reducing both the SAR and EC. The hydraulic conductivity is a measure of how well a soil will leach and soils with high SAR can have reduced hydraulic conductivity. Therefore understanding and maintaining the soil's hydraulic conductivity is important to the remediation of salt-affected soils.

2.5.1.2 Gypsum maintains hydraulic conductivity (electrolyte effect)

Hydraulic conductivity is often reduced in sodic and saline-sodic conditions (Bresler et al. 1982). A soil with a high SAR may be dispersed and have a low hydraulic conductivity. For remediation to be successful the Na+ must be exchanged by Ca^{2+} and the hydraulic conductivity of the soil must be high enough to leach the Na^+ below the rooting zone. If the soil is dispersed, the macro pores are collapsed and there are only micro pores between the soil particles. Water flows much slower though small pores (Freeze and

Cherry 1979). By preventing dispersion and the decrease of the hydraulic conductivity there is remediation potential.

One unique characteristic of a saline-sodic soil is that the soils may not be dispersed. Soils do not disperse if the EC of the soil is high (Shainberg et al. 1982; Armstrong and Tanton 1992; Gupta and Singh 1988). Therefore if the EC is kept high during leaching, the hydraulic conductivity will not decrease; this is called the electrolyte effect (Shainberg et al. 1982). Gypsum supplies the Ca^{2+} but it also increases or maintains the EC of the soil. When the EC is high enough, the hydraulic conductivity remains high even if the SAR is high. Therefore hydraulic conductivity will be maintained because gypsum is a slightly soluble salt and it will release soluble salts slowly (Shainberg et al. 1982).

Other highly soluble salts such as $CaCl_2$ and calcium nitrate also supply Ca^{2+} and keep the EC high enough to prevent dispersion. The difficulty of keeping a high EC with highly soluble salts is that the salts will leach through the soil too quickly. Calcium chloride was found to leach though the soil before exchanging Na^+ due to its high solubility (Gupta and Singh 1988). Once the salts have leached, the EC will be low. If the SAR is still high because not enough Ca^{2+} exchanged the Na^+ there is a potential the soil will now disperse (Shainberg et al. 1982).

In a soil column leaching experiment comparing gypsum and calcium chloride, it was concluded that calcium chloride did not replace as much Na^+ as gypsum or gypsum with calcium chloride (Gupta and Singh 1988). This was due to the highly soluble calcium chloride being leached from the soil before an exchange with Na^+ could take place.

Hydraulic conductivity can also be increased or maintained with cropping. Roots of plants create macro pores and increase infiltration and hydraulic conductivity. Ilyas et al. (1993) found that hydraulic conductivity increased with gypsum, cropping, and gypsum and cropping compared to fallow control. In his field experiment, Ilyas et al. (1993) found a significant increase of K_{fs} (field saturated hydraulic conductivity) with gypsum after six months but no significant increase in K_{fs} with cropping after six months. After one year a significant increase in K_{fs} was found with gypsum, cropping, and an interaction between gypsum and cropping. That hydraulic conductivity significantly increased in gypsum only after six months is probably due to the increased electrolyte concentration from the gypsum. Ilyas et al. (1993) concluded that for an effect from cropping sufficient time must pass for roots to develop. Six month was not sufficient time however; after one year some effect of the cropping was evident.

2.5.1.3 Gypsum is not mobile

Gypsum application can prevent dispersion and maintain the EC (Shainberg et al. 1989). The exchange of Na^+ for Ca^{2+} occurs in the layer of soil where the gypsum is applied. Gypsum is a slightly soluble salt and it is not leached quickly. Therefore, the maximum amount of exchange occurs in the layer of soil where the gypsum is applied. Frenkel et al. (1989) found that gypsum applied to the entire soil column exchanged more Na^+ than treatments that mixed the gypsum to 3 cm, surface applied the gypsum, added the gypsum in a saturated solution, or added no gypsum. Gupta and Singh (1988) also found that gypsum incorporated had a higher infiltration rate than surface applied gypsum and therefore surface applied gypsum was not as effective.

Therefore, when the gypsum is close to the exchange sites it exchanges quickly (Frenkel et al. 1989). More Ca^{2+} exchanged for Na^+ when the gypsum was mixed in the whole soil column since the amount of Na^+ leached out of the soil was the greatest with this treatment (figure 2.12). Gypsum mixed in the top 1/3 of the column leached the next most Na^+. Gypsum placed on the surface or applied in a saturated solution leached less Na^+. Distilled water leached the least amount of Na^+ which would be expected since no Ca^{2+} was added to exchange the Na^+.

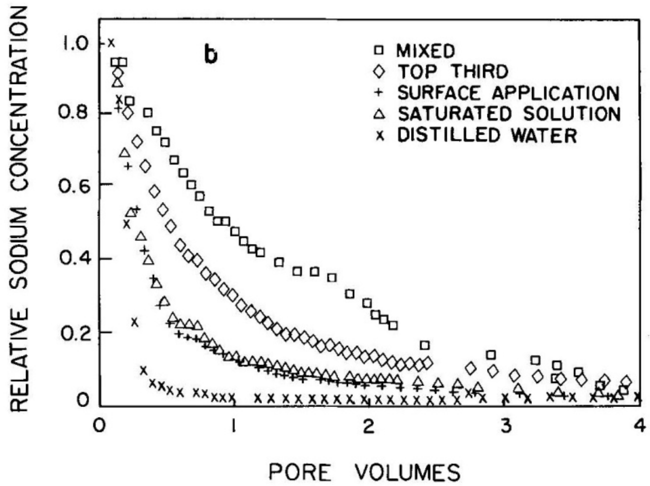


Figure 2.12 Scaled ion concentration as a function of leachate pore volume: (b) sodium (sodium per increment/sodium in initial increment) (Frenkel et al. 1989)

The leaching experiment (Frenkel et al. 1989) also found that most of the chloride was leached within one pore volume (figure 2.1 – in section 2.1.1). This occurred in all treatments. This is not surprising since soluble ions should leach quickly regardless of treatment as long as the hydraulic conductivity of the soil remains high.

Qadir et al. (2001) also found that gypsum was not mobile in the soil profile. When gypsum was applied to soil to a depth of 0.2 m it lowered the ESP and EC at that depth (Figure 2.13). When 0.87 m of water was applied the ESP and EC were lower in the 0-0.2 m depth compared to only 0.17 m of applied water. Below 0.2 m there was an increase in ESP and EC and this was more pronounced when more water had been applied.

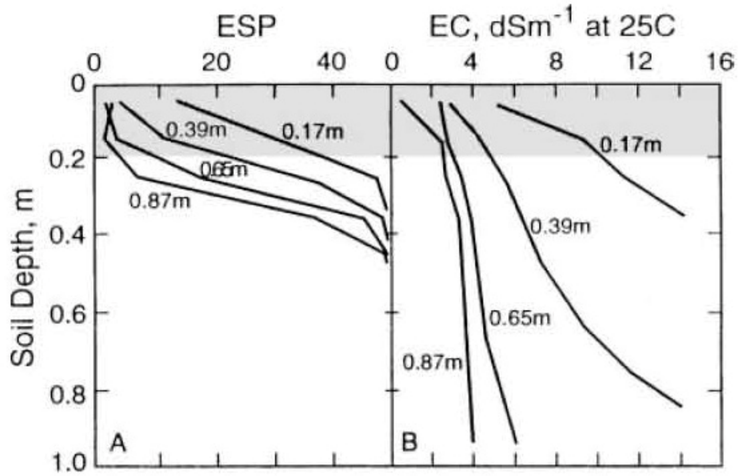


Figure 2.13 Computer model results (ESP and EC) for amelioration of a soil (initial ESP=50, CEC=200 mmolc kg-1) with gypsum and water (EC=0). Numbers next to lines are depths of applied water. (Qadir et al. 2001)

Gypsum's lack of mobility is due to it being a slightly soluble salt (U.S. Salinity Laboratory Staff 1954). This is sometimes viewed as a disadvantage in remediation as the Ca^{2+} will not be immediately available to replace the Na^{+} and remediation may take longer. However, gypsum solubility does increase in the presence of Na^{+} and Cl^{-} (Oster 1982) This increases the efficiency of remediation with gypsum. How much the solubility increases depends on the ions in the soil solution. Oster (1982) suggests there is a threefold increase in solubility. The USDA Handbook 60 (U.S. Salinity Laboratory Staff 1954) suggests that the solubility increases from 30 meq/l in water to 50 meq/l in a saline solution.

Another advantage of this lack of mobility is that gypsum will maintain the EC. Shainberg et al. (1982) found that the gypsum treatment maintained a higher hydraulic conductivity and higher EC compared to the $CaCl_2$ treatment. This effect was observed in a non calcareous soil. No difference between treatments was observed in a calcareous soil. The reason the EC and hydraulic conductivity were maintained was because not all the gypsum dissolved and consequently it did not all leach out. The gypsum slowly dissolved and kept the EC high and prevented dispersion. The calcareous soil in the Shainberg et al. (1982) study released enough electrolytes to prevent dispersion.

2.5.1.4 Theoretical gypsum requirement

The amount of gypsum needed to exchange the Na^+ in the soil is called the theoretical gypsum requirement (TGR) (Karamanos 1996). Calcium in the gypsum will replace the Na^+ on the exchange sites. TGR calculates how much Ca^{2+} is needed to replace the Na^+ on the exchange sites. The formula is

$$TGR = \frac{ESP_i - ESP_f}{100} \times CEC \times \rho_b \times D_{soil} \times A$$

where ESP_i is the initial ESP, ESP_f is the final ESP, CEC is the cation exchange capacity in cmol+ kg $^{-1}$, ρ_b is the bulk density in kg $m^{3\ -1}$, D_{soil} is the depth of soil to be reclaimed in m, and A is the area in m^2.

2.5.2 Calcium nitrate

Calcium nitrate can also be used as a Ca^{2+} amendment to treat sodic and saline-sodic soils (SPIGEC 1999b). Like gypsum it supplies Ca^{2+} ions to exchange the Na^+. No research on the use of calcium nitrate to treat salt-affected soil was available for review. In the past ten years calcium nitrate has become popular in Saskatchewan and Alberta to treat brine contaminated soil (Alberta Environment. 2001; SPIGEC 1999b). Both the Saskatchewan and Alberta governments recommend using both calcium nitrate and gypsum (Alberta Environment. 2001; SPIGEC 1999b).

The Alberta government (Alberta Environment 2001) recommends calcium nitrate be applied in combination with gypsum since the calcium nitrate will act fast compared to gypsum due to its higher solubility. Gypsum is recommended at 45 t ha^{-1} to treat brine contaminated soil while there is no specific recommendation for calcium nitrate. If gypsum and calcium nitrate are applied together, the rate should not exceed the gypsum rate

(SPIGEC 1999b). Since excess nitrates in groundwater can be hazardous to human and animal health, the amount of calcium nitrate should be limited in areas where potential for contamination is high.

SPIGEC (1999) recommends calcium nitrate is applied at 1.135 t ha^{-1}, gypsum at 45 t ha^{-1} and straw incorporated to treat brine contaminated soil. The combination of calcium nitrate and gypsum should not exceed 45 t ha^{-1}. If there is open water or a shallow water table the amount of nitrates added must be minimized.

One advantage of calcium nitrate is the nitrogen fertilizer that it is providing to the soil. Saline-sodic soils are usually nitrogen deficient (Abrol et al. 1988, Qadir et al. 1997). Nitrogen applied to the soil will increase plant growth since nitrogen is a macronutrient needed by plants (Grattan and Grieve 1999, Irshad et al. 2002). The nitrogen application rate for saline-sodic soils recommends 25% extra nitrogen is applied compared to non saline-sodic soil (Abrol et al. 1988).

2.5.2.1 Nitrate leaching

The concentration of calcium nitrate that is applied to have enough Ca^{2+} amendment to exchange the Na^{+} will mean the concentration of applied nitrate will be high. Excess nitrate in the soil does not create a problem if it does not leach to the water table (SPIGEC 1999b). Spring time presents the greatest risk of nitrates reaching the water table due to downward flow to the water table (see Section 1.5). Even though nitrate may be reaching the water table, this is not necessarily a zone of water used for drinking. Most drinking water wells are >25 m below ground surface in Saskatchewan (Simpson 1993).

2.5.3 Organic matter

Organic matter, added to soil in the form of straw, manure, and plant residues, improves the overall health of the soil. Saline-sodic soils are usually low in organic matter and nitrogen (Qadir et al. 1997). Organic matter from plant residues increases soil aggregation, aggregate stability and consequently infiltration (Chaney and Swift 1984, Boyle et al. 1989).

Wahid et al. (1998) found that increases in water holding capacity (WHC) and water stable aggregates (WSA) decreased ECe. More leaching of salts occurred with increased WSA and more water was available to plants with increased WHC. If WHC and WSA are increased in the soil through organic matter then the EC will decrease. A negative correlation was also found with wheat growth and ECe and a positive correlation with WHC and growth in saline-sodic soil (Wahid et al. 1998).

Organic amendments are recommended by the Alberta and Saskatchewan Governments (Alberta Environment. 2001; SPIGEC 1999b). If the organic amendment is low in nitrogen (i.e. straw), an application of a nitrogen source is recommended (ammonium nitrate, ammonium sulphate or calcium nitrate) with the organic matter.

2.6 Remediation strategies - forage

Biological amendments using forage have become popular due to the expense of chemical amendments. Sometimes it is used alone or with chemical amendments to remediate salt-affected soils. While the use of forages can be very effective, when a soil is highly salt-affected, plant growth will be severely impacted or nonexistent and chemical amendments may be the only alternative (Qadir et al. 2006).

Plant roots physically break up soil and increase permeability (Qadir et al. 1996b). Roots increase dissolution of Ca^{2+} from $CaCO_3$ by increasing the CO_2 pressure, decreasing the pH of the rhizosphere and releasing organic compounds. Lime content decreased in a calcareous soil with kallar grass without gypsum amendment due to root affects (Ilyas et al. 1997).

Plant cover decreases evaporation from the soil surface and reduces capillary rise (Qadir et al. 2000). Water evaporation from capillary rise to the ground surface leaves salts in the soil. If evaporation is decreased and capillary rise is minimized, fewer salts accumulate on the soil surface.

Plants also increase infiltration, especially in frozen soil (van der Kamp et al. 2003). A study in the prairie pothole region of Manitoba converted 1.2 km^2 from annual crops into brome grass. The conversion resulted in a significant increase in infiltration under forage. Depressions which were filled with water under annual crops dried out with the conversion to forage. The drying out of the wetland was partially due to the increased infiltration but also due to more snow trapping on upper and mid-slope landscapes. The trapped snow was found to infiltrate more effectively in the higher landscapes and therefore run off into depressions was minimized. Steppuhn (2005) also found that snow trapping was increased when grass wind breaks were established on a saline area resulted in a decreased ECe

In a study comparing forage and two gypsum rates for one year, forage removed more Na^+ compared to 50% gypsum requirement (GR) during its peak growing season (Qadir et al. 1996a). Table 2.2 shows the Na^+ removal during leaching cycles 2 & 3 (LC2 and LC3, respectively) during summer months for the kallar grass. Na^+ removal rates with the forage growth were substantially lower in LC1 and LC4, however, the total removal rate for the year was still higher than the 50% TGR.

Table 2.2 (Qadir et al. 1996a)

Sodium removal efficiency of the reclamation treatments during different leaching cycles

Treatment	Na^+ leached ($mmol_c$)				
	LC_1	LC_2	LC_3	LC_4	Total
Control	113.4 b	176.8 b	82.7 d	19.9 c	392.8 d
50% GR	391.4 a	231.5 b	343.4 c	56.4 b	1022.7 c
100% GR	485.4 a	792.0 a	543.9 a	62.9 b	1884.2 a
Kallar grass	80.0 b	663.9 a	460.9 b	95.9 a	1300.7 b

Means with different letters (a, b, c or d) in a column differ significantly according to Duncan's Multiple Range Test at $P = 0.05$.

LC – Leaching Cycle

Cropping also helps the removal of soluble salts since plants will extract water from small pores that may be by-passed during leaching. This water use by the crop increases the leaching efficiency. When the soil is unsaturated the water flow to plant roots is from smaller pores. During leaching events these smaller pores may not be active as a result of by-pass flow (Qadir et al. 2000).

The cropping choice must be a saline tolerant plant. Alfalfa is moderately sensitive and is often used since it is deep rooted and leguminous; however, it will not germinate in highly saline-sodic soils (SPIGEC 1999b). Alfalfa increases hydraulic conductivity and in combination with gypsum, alfalfa roots penetrated 1.2 m in a gypsum amended plot and only 0.8 m in a non-amended plot after one year (Ilyas et al. 1993). Other research from Pakistan has used more saline tolerant crops like *leptochloa fusca* (kallar grass - tolerant) and sesbania (moderately tolerant) (Qadir et al. 1996b). In Western Canada, barley is a tolerant crop and grasses such as wheatgrass and ryegrass are moderately tolerant (SPIGEC 1999b).

Qadir et al. (1997) found a decrease in SAR and ECe as a result of cropping and this decrease was dependant on the type of crop (Table 2.3). Sesbania and kallar grass had a greater decrease in EC than gypsum (without crop). Sesbania has a deep root system and kallar grass has a dense fibrous root system. The SAR decreased the most with gypsum.

Table 2.3 (Qadir et al. 1997)

Effect of reclamation treatments on EC_e and SAR of the 0–30 cm soil depth

Treatment	Original soil (before start of experiment)	After first harvest season	After second harvest season
		EC_e(dS m^{-1})	
Control	8.8^{NS}	8.0 a	7.8 a
Gypsum	9.0	7.2 ab	6.8 b
Sesbania	7.5	5.5 c	4.4 c
Sordan	7.8	6.4 bc	6.0 b
Kallar grass	7.4	5.3 c	4.9 c
		SAR	
Control	66.1^{NS}	62.8 a	57.2 a
Gypsum	73.0	53.3 ab	24.7 b
Sesbania	55.6	43.5 b	30.1 c
Sordan	62.3	55.1 ab	40.0 b
Kallar grass	57.9	44.7 b	32.5 bc

Means with different letters in the same column differ significantly at $P = 0.05$. ^{NS}, non-significant; EC_e, saturation paste extract electrical conductivity; SAR, sodium absorption ratio.

2.6.1 Forage and amendments

The combination of biological and chemical amendments is the most effective remediation for saline-sodic soils. While gypsum improves permeability at shallow depths, roots will penetrate deeper to improve permeability to a deeper depth (Ilyas et al. 1993).

Increased infiltration from increased permeability leaches the soluble salts from the soil. The chemical amendment must infiltrate the soil to reach the exchange sites to displace the Na^+. Ilyas et al. (1997) found that gypsum application in conjunction with cropping was more successful at reducing EC and SAR than gypsum application without cropping. His field experiment on a saline-sodic soil with an ECe of 5.6 dS m^{-1} (0-20 cm) and a SAR of 49 (0-20 cm) had four treatments: alfalfa, sesbania-wheat-sesbania (crop rotation), wheat straw, and fallow. The four treatments were prepared as whole plots and then the plots were split and 25 Mg/ha gypsum applied to ½ the plots and the other ½ left without gypsum. The plots were irrigated with 20 mm of well water every 14 days. After 1 year the treatments with gypsum and crop (either alfalfa or crop rotation) were more effective at reducing soluble Na^+, soluble Cl^-, EC and SAR in the top 20 cm than the treatments without gypsum and the treatment without crops. The most significant reduction was in the crop rotation with gypsum where the SAR decreased to 11.

Figure 2.14 shows the concentration of soluble Na^+ in the four treatments after 6 months and one year with and without gypsum (Ilyas et al.1997). After one year the cropped treatments with gypsum had the lowest concentration of soluble Na^+ in the top 20 cm (Figure 2.14 Graph D). Both of the cropped treatments have an increase in soluble Na^+ at lower depths as the Na^+ has leached down the profile. At six months the soluble Na^+ concentration in all of the gypsum applied treatments is similar (Figure 2.14, Graph B). There appears to be no effect of cropping. The effect of cropping is only evident after one year and sufficient time for roots to establish and leaching to be effective.

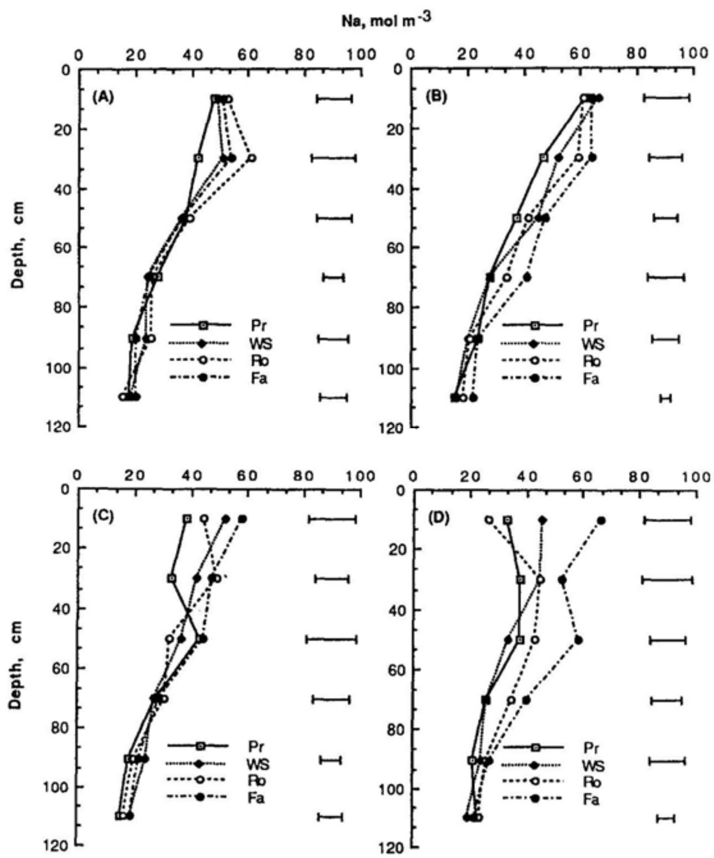


Figure 2.14 Effect of crops and straw on water-soluble sodium. (A) Without gypsum after 6 months, (B) with gypsum after 6 months, (C) without gypsum after 1 year and (D) with gypsum after 1 yr. Horizontal lines indicate LSD (0.05). Pr = perennial alfalfa, WS = wheat straw, Ro = rotation of sesbania-wheat-sesbania, Fa = fallow. (Ilyas et al. 1997)

The most successful remediation of saline-sodic soil is to apply enough Ca^{2+} amendment to exchange for the Na^{+} in the soil and to leach the Na^{+} and the other soluble salts to either tile drains or well below the rooting zone (Keren and Miyamoto 1996). The Ca^{2+} source most often used and researched is gypsum. Advantages of gypsum include its costs and availability. Another advantage includes its solubility, which causes it to be most effective at exchanging Na^{+} in the layer it is applied. The other two most common Ca^{2+} amendments are $CaCl_2$ and calcium nitrate, two salts that are more soluble and more expensive.

Effective remediation of saline-sodic soil includes not only using a Ca^{2+} source but adding organic matter and/or plant growth. Plant roots improve deep permeability of the soil and maintain hydraulic conductivity. Plants also increase soil health by increasing organic matter, aggregation, and soil nutrients (Qadir et al. 1996b).

3.0 FIELD REMEDIATION ACTIVITIES FROM 1998 TO PRESENT

Field remediation activities in southeastern Saskatchewan were initiated in 1998. The approach taken involved the following steps:

1. Identification of the flare pit from historic air photographs;
2. Delineation of the salt impacted areas using electromagnetic (EM) induction equipment to map the extent of the problem;
3. Deep soil sampling to verify the type and severity of contamination;
4. Excavation of the hydrocarbon impacted materials in the flare pits and back filling with clean subsoil and topsoil;
5. Installation of sub-surface tile drains in the salt contaminated area around the excavated flare pits;
6. Installation of sump pumps to remove the brine water collected in the tile drainage systems;
7. Initiation of an agronomic surface remediation program; and
8. A follow up monitoring program was adopted to evaluate the success of the remediation activities.

The following is a brief description of each of the above steps:

1. The air photographs from 1958 and 1962 showed many flare pits around single well batteries. In the 1979 aerial photograph, generally these flare pits were not visible. Rarely had the flare pit been removed; more often the flare pit had been buried without removing any oily or brine material.

2. The extent of the contaminated area was delineated using EM mapping as the first step. The EM instrument was very useful for identifying the extent of brine

contaminated soil since the soil has very high salt concentrations. For flare pit delineation all EM31 readings were measured with the instrument in the vertical mode (EM31v) since flare pits were deeper than 1.5 m.

3. The field soil sampling was done with a solid stem auger to a depth of 6 m. The soil profile was recorded and soil samples from each horizon were tested in a mobile field lab for chlorides and electrical conductivity. Select soil samples were sent to a commercial soil laboratory for analysis of major ions, electrical conductivity (EC), sodium adsorption ratio (SAR), and pH.

   The soil profile inspections in combination with the chemical analysis of the soils indicated how deep the salts were and where they were likely moving. This information was used to design a remediation plan.

4. With flare pits, the approach was to remove the hydrocarbon impacted soil to comply with Saskatchewan Government guidelines (SPIGEC 1999b). Once the hydrocarbon impacted soil was excavated, soil samples from the floor and walls of the excavation were sent to a laboratory for analysis. If the samples did not meet the hydrocarbon guidelines, additional soil was excavated until the guidelines were met. The material was typically excavated with a track hoe and the soil hauled by truck to a nearby landfill. Non-saline subsoil and topsoil were used to fill in the excavation.

5. Oftentimes the salts had contaminated the soil outside of the hydrocarbon impacted zone. It was not cost effective to remove all of the salt impacted soil. The borehole logs often intersected coarse textured saturated sand and gravel

seams through which the salts had migrated. To remove these salts in situ, the soil/ground water was collected and removed from the soil.

To remove the salts in situ, sub-surface tile drains were installed. The design of the sub-surface tiles was based on the EM31v map and intercepted any lighter textured soil found in the borehole logs. Where possible the topography of the area was utilized to ensure the tiles sloped into the pump-out culvert.

After stripping off the topsoil, a chain trencher was used to install tiles into the sand and gravel seams if possible. These coarse textured layers were usually 1.5-2 m deep. The lateral tiles were connected to a deeper and larger header trench installed with a track hoe. A sock tile was placed in the bottom of the lateral and header trenches. The sock tile was a 13.2 cm diameter PVC pipe with perforations enclosed in a nylon sock. The perforations in the pipe allowed water to collect in the pipe and the nylon sock prevented smaller grained soils like clays from clogging the perforations. Crushed rock (2 cm in diameter) to a depth of 0.5 m was placed on the top of the tile in the bottom of the trench. The crushed rock was used to augment drainage and the effectiveness of the tiles. Subsoil was used to back fill the trench. The lateral tiles were sloped to ensure drainage toward the header trench and the header trench was sloped toward a discharge or pump-out culvert.

The pump-out culvert consisted of a PVC pipe 100 cm in diameter. Perforations were made in the culvert at the time of installation at the depth of the lateral tiles and crushed rock. When the soil above the tiles was saturated, water could preferentially flow into the crush rock and sock tile because the hydraulic conductivity of this medium was much higher than the surrounding soil. The water collected in the sock tile drained into the header trench and into the culvert.

6. A submersible pump and flow meter were installed in the culvert with an automatic control switch. The pump operated when the water level reached a predetermined level. The discharged brine water was pipelined to a nearby disposal well and re-injected into the deep geologic formation with other brine.

   Once the tile system was installed the culvert pump was inspected regularly to ensure the tile system was working. The meter recorded the volume of water removed from the system. Bi-annual water samples from the culvert were obtained and analyzed for routine salinity parameters (EC, Cl^-, SO_4^{-2}, Na^+, NO_3^-, pH, Ca^{+2}, SAR). Since Cl^- is the main indicator of contamination from the flare pit, it was the concentration of this ion that was tracked during the remediation process. There should be decreases in the Cl^- concentration throughout the life of the tile system.

7. A surface remediation program was initiated once the topsoil had been replaced on the tiled area. The surface remediation activities included straw and calcium nitrate incorporation to 25 cm and seeding of saline tolerant barley. After two to three years of this remediation program the site was seeded to permanent forage consisting of a mixture of saline tolerant grass and alfalfa. Once some permanent vegetation was established, over seeding with an alfalfa and barley mixture was done in the spring and/or fall when needed. Calcium nitrate was also broadcast on the site with the seed mixture.

The forage growth was important to build soil health, including soil structure and nutrients. But most importantly, the forages used available water in the topsoil and allowed more effective leaching as rain water infiltrated the soil instead of running off. The forage was maintained by mowing at 30 cm height. This height optimized plant growth and snow trapping in the winter. Growing forage on the tiled areas was very important to the success of the remediation.

8. Routine monitoring of each site included observations of depth to water tables in the wells and culverts, measurements of water chemistry (salinity), checking of pump operations, applying agronomic amendments as required, and noting changes in the type, growth, vigor and extent of vegetation cover on the site.

To briefly summarize, the complete remediation program which included careful delineation of the contamination, removal of the salt source, dewatering of the soil through tile drains, and forage growth all contributed to the success of the remediation. All parts of the program were integrated and interconnected. Delineation of the soil stratigraphy including the sand, silt and gravel seams facilitated the location of the tiles. The layout and installation of the tile was designed to ensure drainage to the culvert from which saline ground water was pumped out of the tile system. Finally the establishment of permanent forage on the site was integral to the remediation process and an indicator of the rejuvenated productivity of the soil.

4.0 FIELD STUDY

4.1 Field study objectives and hypothesis

The overall objective of the field study was to evaluate the remediation practices of point-source brine-contaminated soils which have been successful since 1998. Two typical sites were selected and specific remediation practices were examined with the following objectives:

- Characterize the current salinity status of the soil and water
- Assess the change in soil and water quality since installation of the sub-surface tile drainage system
- Discuss the effect of the remediation practices on vegetation, soil salinity, and groundwater depth.
- Compare the current salinity status relative to target endpoints (SPIGEC criteria and/or productivity equivalent to off-site)
- Recommend additional remediation practices

The hypothesis of the field study was:

Sub-surface tile drainage systems combined with calcium sourced amendments and forage growth can remediate brine-contaminated soils.

4.2 Background information

4.2.1 Goals of remediation program

The goals of the remediation were to restore the productivity of brine-contaminated soil and to return it to the agricultural use similar to the background area.

4.2.2 Site selection

The two field sites were selected because they were both good representatives of the normal field remediation activities as outlined in Chapter 3. The remediation work began at Hastings and Willmar in 2001 with the installation of monitoring wells, the removal of the contamination point-source, the flare pit, and the installation of sub-surface tiles in the contaminated area. These two sites had successful ongoing remediation activities since 2002 and growth had improved on both sites.

4.2.3 Site characterization and monitoring

The previous remediation activities which occurred at both sites were similar to those described in Chapter 3. Specific background information, including borehole locations, borehole logs, and sub-surface tile system locations for both sites can be found in Phase II & III reports by J&V Nielsen and Associates Ltd. (2002; 2003). Monitoring of groundwater quality and depths has continued to the present for both sites since installation and this information can be found in groundwater monitoring reports (Wiebe Environmental Services (WES) 2004; J&V Nielsen and Associates Ltd. (Nielsen) 2004; WES 2005; Nielsen 2005; WES 2006; Nielsen 2006; SLR Consulting Ltd. 2008a; SLR Consulting Ltd. 2008b; SLR Consulting Ltd. 2009; SLR Consulting Ltd. 2010).

4.3 Field methods

4.3.1 EM38

The EM38v and EM38h surveys were completed from May 12-17, 2010. A Geonics EM38RT recorded the EM38h and EM38v ECa. Eight soil samples locations were selected based on the EM38h and EM38v surveys. Spot EM38h and EM38v readings of these sample points were recorded.

The ECe, EM38v, EM38h, and soil temperature for all samples and depths were entered in a calibration spreadsheet. The calibrated EM values temperature corrected (soil at 50 cm estimated to be 12°C) were calculated using a weighted formula for sampling to 120 cm (Fitzgerald and Eilers 1997). The formula for the EM38v calibration was:

$$0.23[(0\text{-}15cm+15\text{-}30cm)/2] + 0.35(30\text{-}60cm) + 0.24(60\text{-}90cm) + 0.18(90\text{-}120cm)$$

The formula for EM38h calibration was:

$$0.54[(0\text{-}15cm+15\text{-}30cm)/2] + 0.26(30\text{-}60cm) + 0.13(60\text{-}90cm) + 0.08(90\text{-}120cm)$$

Where 0-15cm, 15-30cm, 30-60cm, 60-90cm and 90-120cm are the ECe at the described depth.

4.3.2 *Soil sampling*

Soil samples were collected using a dutch auger from 0-15 cm, 15-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm. Saturated pastes were made in the field using deionised water and left to equilibrate for one hour (U.S. Salinity Laboratory Staff 1954). The ECp was measured using a Field Scout EC Probe. Soil samples were sent to Maxxam Laboratories in Calgary, Alberta for complete chemical analysis (using saturated paste extracts) of major ions, ECe, and pH. Sulphate (SO_4^{2-}) and chloride (Cl^-) concentrations were analyzed by automated colorimetry and calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+) concentration were analyzed by inductively coupled plasma (ICP)(Varian Vista Pro manufactured in Australia by Varian).

4.3.3 *EM31*

The EM31v was completed from May 12-17, 2010 using a Geonics EM31. GPS coordinates were used to ensure the area mapped was the same as the area mapped in 2001.

4.3.4 *Topographical analysis*

The elevation contours were measured using a Trimble Geo XH from May 12-17, 2010. Only elevation points with <30 cm vertical accuracy were used to create the topographical map.

4.3.5 GPS mapping of poor growth areas

Poor growth areas were mapped using a Trimble Geo XT. The poor growth areas were overlaid on the EM maps to see if there was a correlation between high ECa and poor growth.

4.3.6 Pedological inspections

A pedology field inspection was completed on September 14 and 15, 2010. The field inspection included soil classification of selected boreholes and classification of vegetation types and growth on the tiled area.

Six borehole locations were selected at Hastings and four borehole locations were selected at Willmar for the pedology field inspection. Spot EM38v and EM38h values were recorded at each borehole and the boreholes were dug into the C horizon (0.5-0.8 mbgs). Soil horizons were delineated, measured, and characterized based on the Canadian system of soil classification (1998). The focus of characterization was to describe the pedology in terms of understanding hydrological processes which are reflected in leached and non-leached profiles. Soil chemistry of the borehole locations from 0-15cm, 15-30cm, 30-60cm, 60-90 cm, and 90-120 cm was previously completed in May, 2010 at all locations except three locations at Hastings.

4.3.7 Groundwater sampling of monitoring wells

A Dipper-T water level tape was lowered into the wells and culverts to measure the depth to water on a regular basis from June, 2009 to March, 2011. A water sample was collected using the baler at each well/culvert. From August, 2009 to January, 2010, Cl^- levels in the wells were measured using Hach Quantabs®. Quantabs® are individual titrators that are inserted in the solution. Once the titrator is completely saturated the white peak on the Quantabs® scale is measured. The value on the scale is converted into the concentration of chlorides in the solution. From March, 2010 to March, 2011 EC was measured using a WTW Conductivity 340i meter.

4.4 Characterization of current salinity status of soil and water

4.4.1 Hastings

The current salinity status at Hastings was determined by examining EM surveys, soil sample results, topography, soil profiles, and groundwater. Photos from 2002 (Figures 4.1 and 4.2) show the areas of poor growth. Photos from 2008 and 2009 (Figures 4.3 and 4.4) show the same areas now vegetated.

Figure 4.1 Looking northeast at poor growth (2002)

Figure 4.2 Looking south at poor growth (2002)

Figure 4.3 Looking northeast at growth (2008)

Figure 4.4 Looking south at growth (2009)

4.4.1.1 Soil sampling

Soil samples were obtained from 0-120 cm at eight different locations for the EM38 calibrations (Figure 4.5).

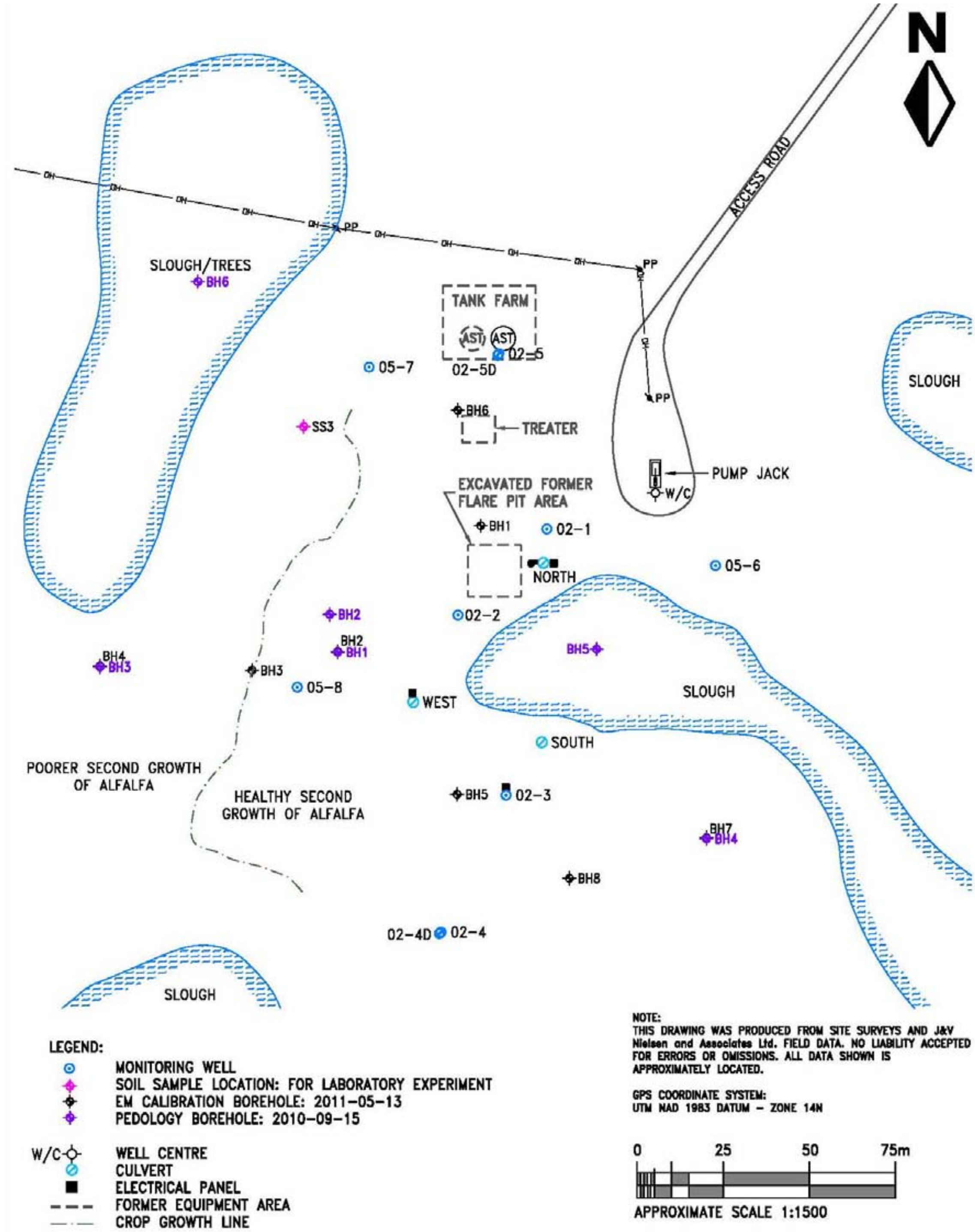


Figure 4.5 Locations of EM38h/EM38v calibration boreholes and pedological inspection boreholes (© Canadian Natural Resources Ltd. used with permission)

4.4.1.2 EM38

The EM38h was used to map the salinity within the upper rooting zone (0-60 cm) or the plant fertility zone. The scale on the EM38h at Hastings distinguished the change between weakly saline (ECe <4 dS m^{-1}) to moderately saline (ECe 4-8 dS m^{-1}) at about 50 mS m^{-1} and from moderately saline to moderately strong salinity (ECe 8-16 dS m^{-1}) at 110 mS m^{-1} (Figure 4.6). The majority of the tiled area fell within the moderately strong salinity class (ECe 8-16 dS m^{-1}). An area of strong salinity (ECe >16 dS m^{-1}) or >220 mS m^{-1} on the EM38h was mapped on the east site of the slough.

Field Legend - values for soil Temp @ 50 cm est. ~ 12 oC	Calculated ECe values equivalent to T corrected EM38h	Salinity classification for agricultural crop production
	0-60 cm	
500	33.8	Strong >16 dS/m
400	27.3	
390	26.6	
380	25.9	
370	25.3	
360	24.6	
350	22.8	
340	22.2	
330	22.7	
320	22.0	
310	21.3	
300	20.7	
290	20.0	
280	19.4	
270	18.7	
260	18.1	
250	17.4	
240	16.7	
230	16.1	
220	15.4	Moderately strong 8-16 dS/m
210	14.8	
200	14.1	
190	13.5	
180	12.8	
170	12.1	
160	11.5	
150	10.8	
140	10.2	
130	9.5	
120	8.9	
110	8.2	
100	7.5	Moderate 4-8 dS/m
90	6.9	
80	6.2	
70	5.6	
60	4.9	
50	4.3	
40	3.6	weak-nil <4 dS/m
30	2.9	
20	2.3	
10	1.6	

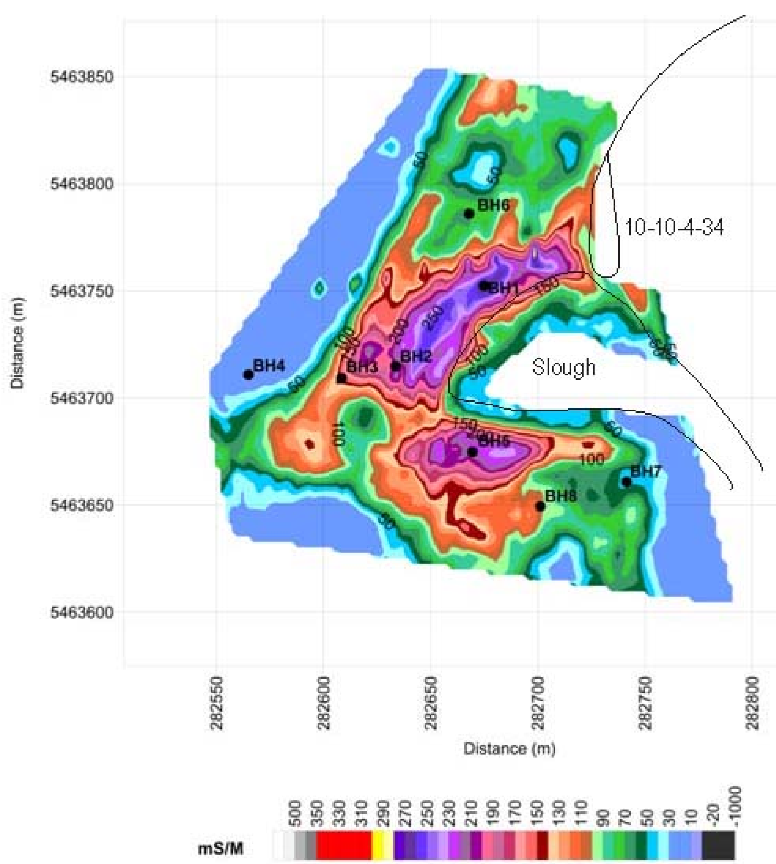


Figure 4.6 EM38h, May, 2010 (© Canadian Natural Resources Ltd. used with permission)

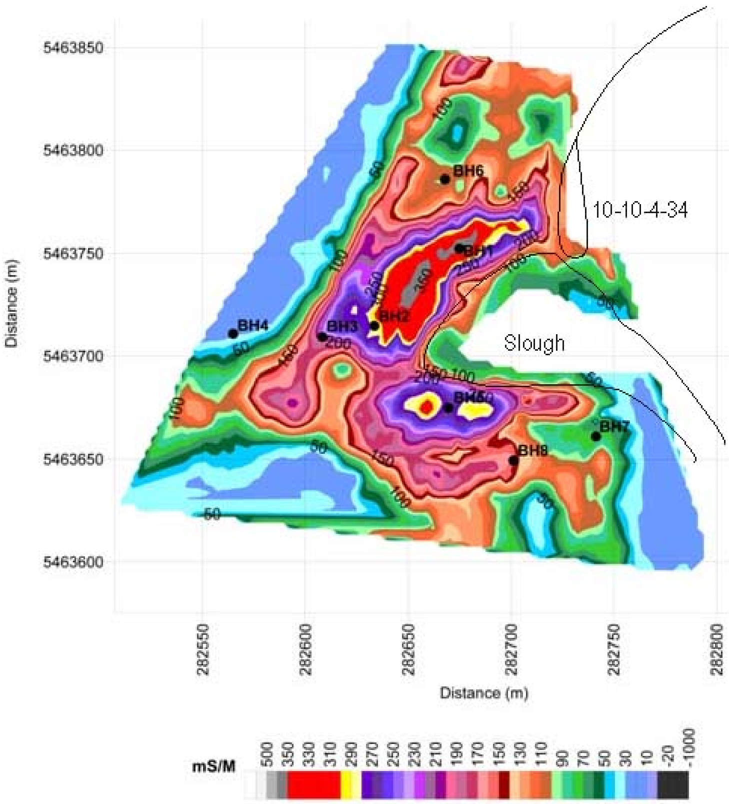


Figure 4.7 EM38v, May, 2010 (© Canadian Natural Resources Ltd. used with permission)

Field Legend - values for soil Temp @ 50 cm est. ~ 12 oC	Calculated ECe values equivalent to T corrected EM38v	Salinity classification for agricultural crop production
	0-120 cm	
500	33.9	Strong >16 dS/m
400	27.4	
390	26.8	
380	26.1	
370	25.5	
360	24.8	
350	23.1	
340	22.5	
330	22.9	
320	22.2	
310	21.6	
300	20.9	
290	20.3	
280	19.6	
270	19.0	
260	18.3	
250	17.7	
240	17.0	
230	16.4	
220	15.7	Moderately strong 8-16 dS/m
210	15.1	
200	14.4	
190	13.8	
180	13.1	
170	12.5	
160	11.8	
150	11.2	
140	10.5	
130	9.9	
120	9.2	
110	8.6	
100	7.9	Moderate 4-8 dS/m
90	7.3	
80	6.6	
70	6.0	
60	5.3	
50	4.7	
40	4.0	weak-nil <4 dS/m
30	3.4	
20	2.7	
10	2.1	

The EM38v mapped the salinity to 120 cm or the soil moisture zone. The calibrated Hastings EM38v scale was similar to the EM38h scale (Figure 4.7). Areas that were moderately saline on the EM38h were classified as moderately strong on the EM38v. The size of the strongly saline area on the east side of the slough increased and a second area of strong salinity was mapped south of the slough.

4.4.1.3 EM31

There was a notable reduction in conductivity values between the EM31 maps from 2001 and 2010 (Figures 4.8 and 4.9). The EM31 survey from 2010 had a pattern of conductivity very similar to the EM38 (Fig. 4.9).

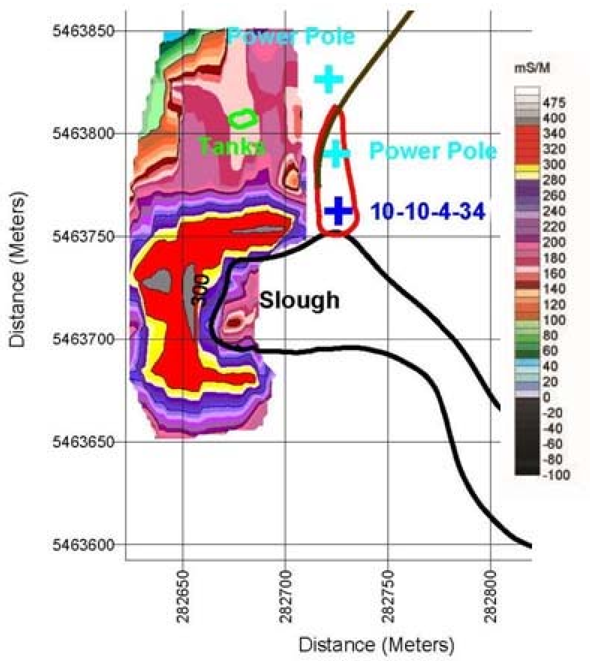


Figure 4.8 Hastings EM31 survey, 2001 (© Canadian Natural Resources Ltd. used with permission)

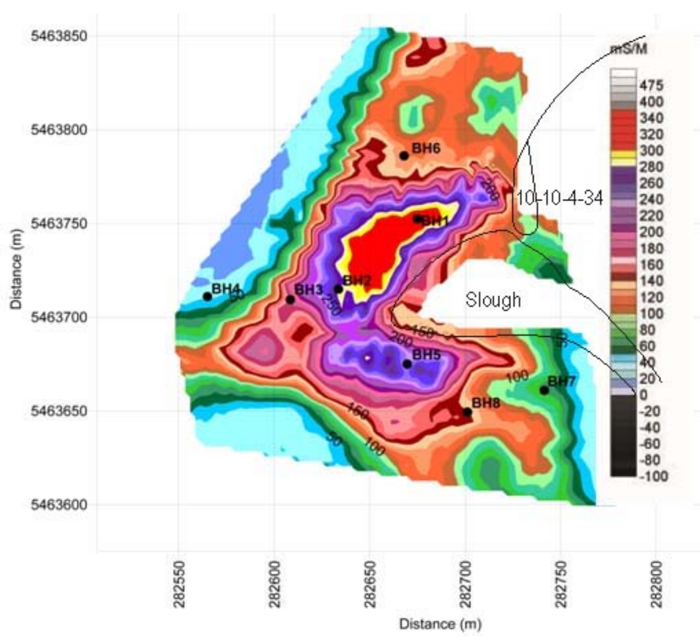


Figure 4.9 EM31, May, 2010 (© Canadian Natural Resources Ltd. used with permission)

4.4.1.4 Topographic analysis

The elevation contour plot showed that the three sloughs in the area are nearly equal in depth (Figure 4.10). The bottom surface of each slough was also nearly level. Excess surface water from snowmelt or very heavy rains that did not infiltrate directly in the soil likely moved into the sloughs.

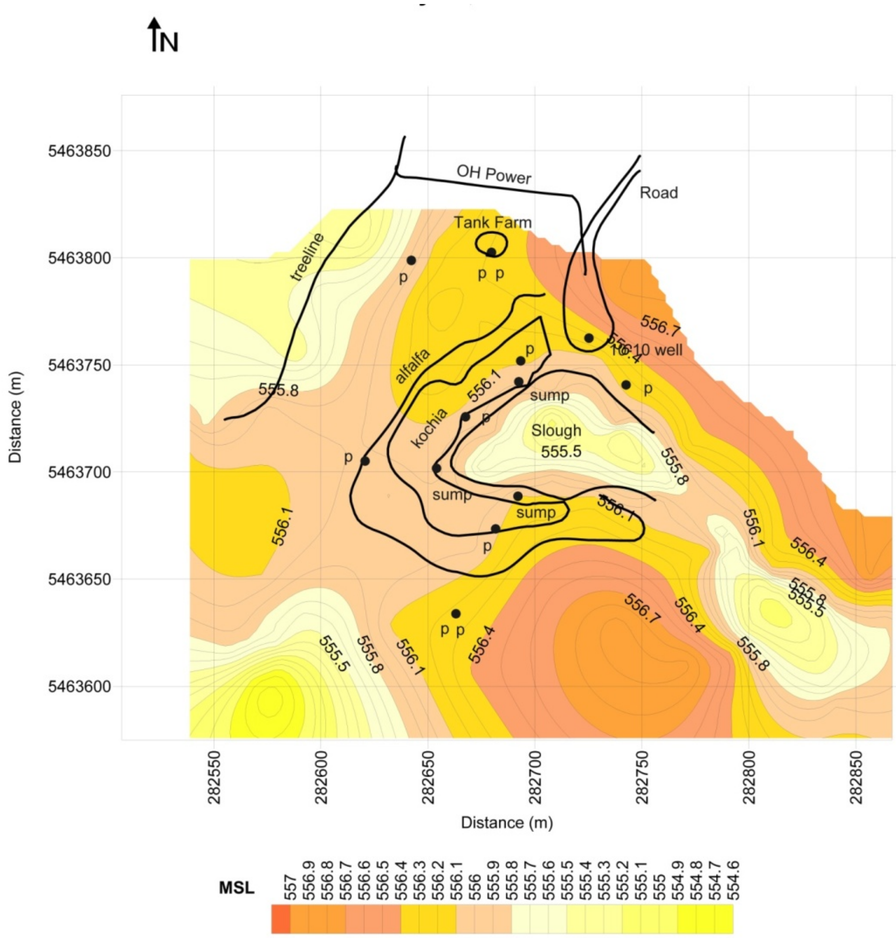


Figure 4.10 Topographical contours, May, 2010 (© Canadian Natural Resources Ltd. used with permission)

4.4.1.5 GPS mapping of poor growth areas

An area of new alfalfa growth was mapped September 19, 2010 (Figure 4.5). The alfalfa was flowering after having been cut and baled. South of the east slough there was a consistent bloom of alfalfa. West of the east slough, a strip of alfalfa was in bloom closest to the grasses. The alfalfa further west and close to the northwest and southwest sloughs was not in as full bloom and did not have as full growth.

4.4.1.6 Pedological inspections

The long term and ongoing ecological and hydrological processes in the landscape are typically reflected in the type and distribution of pedological soil properties. Thickness, sequences and degree of development of soil horizons, are indicative of hydrological conditions such as infiltration, exfiltration, recharge and discharge. Pedological investigations and observations of vegetation were conducted at strategic landscape locations at Hastings to help define and understand the functioning landscape processes, and to determine possible impacts that may be attributed to the remediation and land use practices.

There were three sloughs: east, northwest, and southwest. Poplar trees were growing around the northwest and southwest sloughs and a few willows were growing around the east side of the east slough. Vegetation between the sloughs was grasses around east slough progressing toward alfalfa midway between the east slough and west sloughs and alfalfa around the northwest and southwest sloughs.

The oilfield salinity source was on the north edge of the east slough. The salts affected growth on the north, west and south sides of the slough. The area around the slough was bare in 2001 however; it was now growing grasses and some foxtail and kochia. The foxtail and kochia areas occurred where the EC was higher.

Apk - loam, black, moist, loose friable

Ck - silt loam, olive, moist, loose friable, gypsum and carbonate concretions (pseudo-mycelia) structure is not dispersed

Ckgj - silt loam, olive with grey streaks, wet, friable, no observable roots

Figure 4.11 BH1

Vegetation type can be an indication of the salinity status of the soil. Foxtail and kochia are the most salt tolerant plants followed by grass and then alfalfa (SPIGEC 1999b). Generally, foxtail and kochia are the first plants to grow in a salt affected area followed by grasses. When alfalfa is established the area is considered to be non-saline or very weakly saline since alfalfa is moderately sensitive to salt.

The grass around the east slough that progressed toward alfalfa around the northwest and southwest slough indicated that there were some salt impacts around the east slough and no salt impacts around the other two sloughs.

Four borehole (BH) profiles dug around the sloughs were described and classified as Rego Black Chernozems. For exact borehole location refer to Figure 4.5. The Apk horizon was between 12-20 cm think and loam textured. Below the Apk horizon was a silt loam and calcareous Ck horizon.

The EM38h and EM38v values at BH1 (figures 4.11) were 393 mS m^{-1} and 487 mS m^{-1}, respectively and indicated a moderately strong to strongly saline area. BH1 was located in grass; however, in the fall of 2009 this area was in kochia (Figure 4.5). Sufficient moisture during 2010 had allowed grass to compete very well however no roots were visible below 20 cm. The site was probably too saline for alfalfa. Pseudo-mycelia (gypsum and carbonate concretions), visible in the C horizon, were an indication of salinity. No evidence of dispersed structure was found. This is likely due to naturally high calcium carbonate in the soil.

Apk - loam, black, moist, loose friable

AC - silt loam, dark brown, moderately dry, loose friable, no observable roots below 20 cm

Ck - silt loam, olive, moist, gypsum and carbonate concretions, structure is not dispersed, very friable

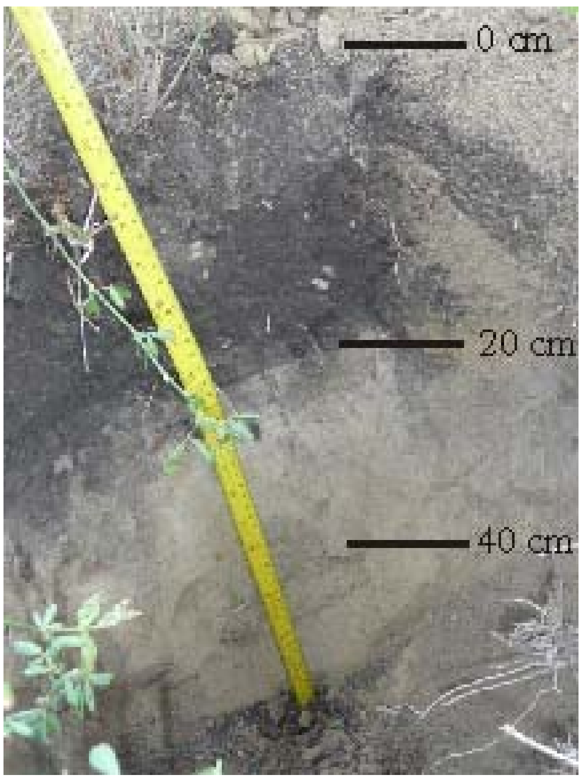
Ckg - silt loam, olive with grey and yellowish mottles, wet

Figure 4.12 BH2

BH2 (Figure 4.12) was located in good alfalfa growth about 12 m northwest of BH1 (Figure 4.5). The EM38h and EM38v readings were 267 mS m^{-1} and 372 mS m^{-1}, respectively, and indicated that this was a saline area. The roots of the alfalfa in BH2 did not extent into the C horizon; they were concentrated in the top 15 cm of the profile, probably a result of high salinity at the low depth which would not support alfalfa growth. This shallow root had taken advantage of recent rains and had a very good second growth. There was no indication of a dispersed structure at BH2 and like BH1 this was likely due to the high calcium carbonate content of the soil.

Both BH1 and BH2 had yellow and grey mottles at 75 cm. This was due to periodic reducing conditions from the influence of the water table.

BH3 (Figure 4.13) was located near the northwest slough (Figure 4.5) and had very low salinity. The EM38h and EM38v readings were 29 mS m^{-1} and 36 mS m^{-1}, respectively. The alfalfa roots were well established and deep, running well into the C horizon. The C horizon was powder dry at 40 cm, even though there had been 63 mm of precipitation in the three weeks prior to inspection. The alfalfa growth was fair to moderate, likely due to moisture deficit.



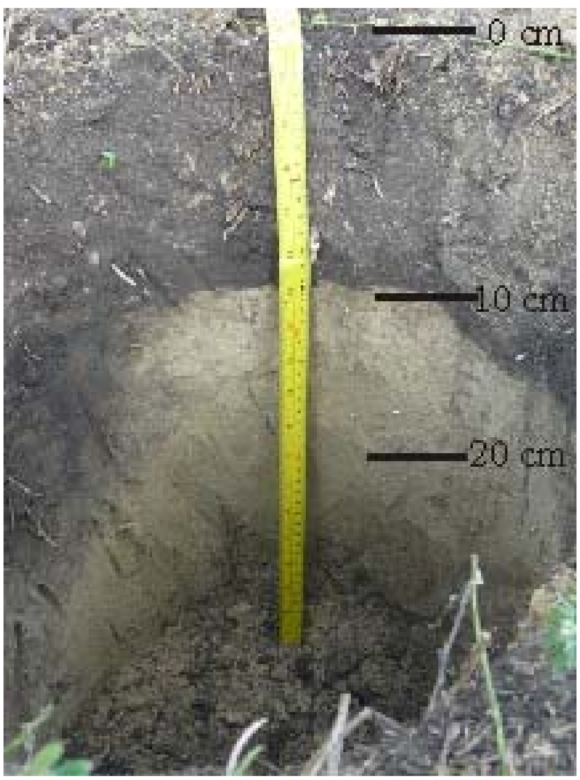
Apk - loam, black, moist, loose friable

Ck1 - silt loam, olive, moist, loose friable, very calcareous

Ck2 - silt loam, olive, very dry, friable, very calcareous, loose structure

Figure 4.13 BH3

At BH4 (Figure 4.14) there was slight salinity (ECe 9.2 dS m^{-1} from 60-90 cm) even though the EM38h and EM38v readings of 64 mS m^{-1} and 44 mS m^{-1}, respectively, indicated that it was non-saline. The low EM38 readings were from the dry soil conditions particularly because of the second growth of alfalfa. The alfalfa was lush and blooming with roots that extended >80 cm. These roots quickly dried out the soil. The C horizon was moist and biopores were visible. No biopores were visible at BH1, BH2 and BH3. The soil was too saturated at BH1 and BH2 and too dry at BH3 to have developed biopores. BH4 had no evidence of deep leaching. Precipitation infiltrated quickly and was likely retained by the soil storage capacity.

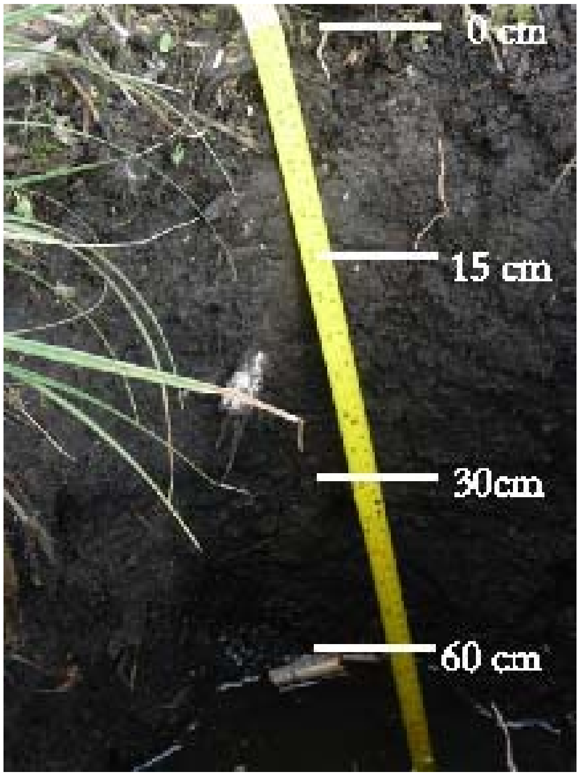


Apk - loam, black, moist, loose friable

Cca - silt loam, olive, moist, loose friable, very calcareous

Ck - silt loam, olive, moist, loose friable, very calcareous, gypsum and lime concretions, small tubular biopores, loose structure

Figure 4.14 BH4



Ah1 - loam, black, wet, no cattail growth on surface

Ah2 - loam , black, very wet, EC (soil - field scout) = 1.27 dS m^{-1}, stiff

Ah3 - loam, black, very wet, EC (soil - field scout) = 0.99 dS m^{-1},

Water table at 30 m - EC = 4 dS m^{-1}, 200 mg L^{-1} Cl

Ah4 - loam, black, very compact, very low permeability, no carbonates

Figure 4.15 East slough (BH5)

The east slough is described and classified as a Rego Humic Gleysol typical of a slow local recharge slough (Richardson 1992). BH5 (Figure 4.15) was dug to a depth of 60 cm, the maximum depth of inspection due to infilling with free water). Groundwater was found near the surface, ~15 cm after 24 hours. A very compact clay layer was found in the slough at 60 cm. When the water encounters a compact and less permeable layer the flow moves laterally through more permeable soil. The slough was surrounded by a more permeable silt loam which would provide an easy conduit for water to move outward from the slough. All salt precipitates and carbonates were leached out of the soil in the bottom of the slough.

The slough vegetation was mostly cattails growing on the east side and little to no vegetation growing on the west side. Cattails are hydrophytes; they like to have their roots in water and are found in sloughs characterized by slow recharge (Lissey 1968) and a water table close to the soil surface. Cattails are not salt tolerant (Stewart and Kantrud 1969).

The east center of the slough had a lower EC (1.2 dS m^{-1} in the free water and 2 dS m^{-1} in the soil) and there was a good growth of cattails. The EC was 1.99 dS m^{-1} in the free water under the reeds. There was no vegetation in the west centre of the slough; the EC of the free water was 4 dS m^{-1} and chlorides were 200 mg L^{-1}. This was likely too saline for cattails. The EM38h and EC38v readings in the no growth were 126 mS m^{-1} and 179 mS m^{-1}, respectively. On the edge of the slough in slough grass the EM38 h and v readings were 94 mS m^{-1} and 138 mS m^{-1}, respectively.

Slough grass was growing surrounding the cattails towards the edge of the slough and willows were observed on the east side of the slough near the edge of the cultivated field. Willows typically grow along the outer edge of slough as they are mesophytes and like to be near water but not in water (Ross 2009). Slough grass is also a mesophyte (Ross 2009).

The northwest slough was classified as a Humic Luvic Gleysol typical of a rapid local recharge slough (Lissey 1968). BH6 was augured to 1 m, the water table was not found to this depth, and all carbonates had been leached. Vegetation in the slough included slough grasses and ladies thumb. Ladies thumb is a disturbance species and a species susceptible to salinity. Poplar trees surrounded the north, east and south sides of the slough (Hayashi et al. 1998).

The vegetation, soil development and lower water table indicated that the northwest slough is a rapid local recharge (Miller et al. 1985). Water temporarily ponded here in the spring, infiltrated quickly into the soil, and was used by the surrounding trees, willows and grass. No compact layer was found in this borehole (unlike the east slough); therefore, water was probably moving down toward the water table and contributed to the local water table in a recharge environment.

The southwest slough had similar vegetation to the northwest slough and therefore appeared to be a rapid recharge slough as well.

<u>Summary of observations</u>

- The soils had not developed a B horizon. They still had a lot of primary carbonates and were imperfectly drained. The east slough had a very compact layer at 60 cm which promoted lateral water flow.
- The water movement in the east slough was likely lateral. Besides BH5 and BH6 (in the sloughs) none of the BH's showed evidence of deep leaching. The high salinity of the soil around the east slough was preventing roots from penetrating below 20 cm. However, since the tile system was installed a lot of salts have been removed as evident by the change in EM31 maps from 2001 to 2010 (Figures 4.8 & 4.9).
- Soil profiles around the slough were silt loam. The boreholes characterized close to the edge of the east slough were moderately to strongly saline, the profile was saturated, and the boreholes had evidence of water table effects. The C horizon was also friable and loose except the Gleysolic soils in the sloughs. No structural deterioration from high sodium brines was evident. High lime content and low clay content likely made these soils more resilient to the effect of high sodium concentrations.
- Nearly level topography minimized surface runoff and contributed to local retention of precipitation in the landscape.
- Plant growth on saline soil during years with consistent rains was better than during a dry year. The growth did not represent the true salinity status of the soil. Plants in saline soils did not develop deep roots if the subsoil was too saline. The shallow roots of these plants took advantage of timely and consistent rains. These rains also diluted the salts at the surface of the soils and allowed for better plant growth.

4.4.1.7 Groundwater sampling of monitoring wells

Depth to water table

The depth to water table was measured for nearly two years, from the summer of 2009 to the spring of 2011. There was a difference in water table depth between these two years. The main contributor to the difference in the depth to the water table in the summer and fall of 2009 compared to the summer and fall of 2010 was above average precipitation in 2010. The above average precipitation started in August, 2010 and stopped in June, 2011. Normal yearly precipitation (1971-2000) for Estevan is 433.3 mm (Environment Canada 2012). In 2010 and 2011, the yearly precipitation was 620 and 600 mm, respectively (Environment Canada 2012). The yearly precipitation from July, 2010 to June, 2011 was 772 mm (Environment Canada 2012). The increased precipitation recharged the sloughs and low areas. Water in the sloughs percolated downward into the water table and the water table rose. The soil was completely saturated.

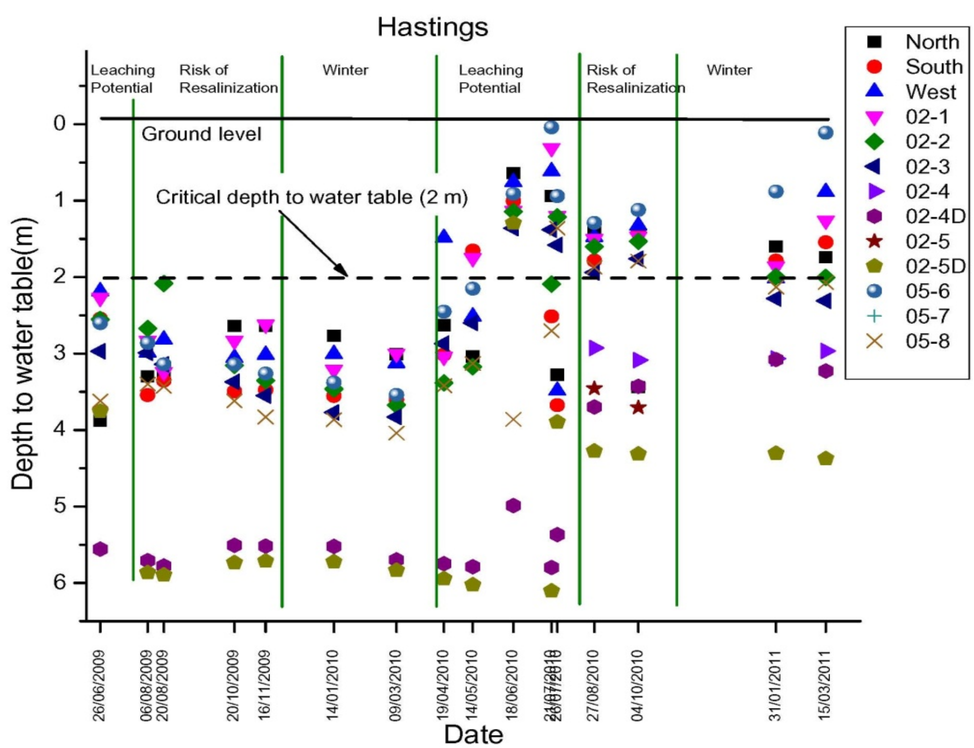


Figure 4.16 Depth to water at Hastings

The higher water table as a result of above average precipitation was observed in the wells at Hastings. The depth to the water table was 1-2 m higher in 2010 compared to 2009. The depth to water table from June, 2009 to March, 2010 ranged from 2-5.5 meters below ground surface (mbgs) (Figure 4.16). From April, 2010 to March 2011 the depth to water table ranged from 0 to 4.5 mbgs (Figure 4.16). The risk of resalinization of the surface soils is higher if the water table is within 2 m of the ground surface (Rhoades 1974; Nulsen 1981).

The high water table in 2010 was also a result of inconsistent removal of tile drainage water. If the tile drainage system was functioning properly in 2010, the water table in the tiled area would have been maintained at approximately 2-3 mbgs through the removal of the tile drainage water. However, in 2010, the culverts pumps were not working consistently and therefore water was being removed sporadically.

Year to year variation in precipitation amounts is normal and therefore changes in the average yearly depth to water table will change (Eilers 1982). However, the increased precipitation in the summer and fall of 2010 and the spring of 2011 was above average and cannot be considered normal variation. The saturated soil resulted in most fields in this area not being seeded in 2011, something that farmers had not seen in their lifetime.

Seasonal variation in the depth to the water table is normal (Eilers 1982). Downward percolation of excess soil water from spring melt and heavy summer rains induces a rise in the water table (Eilers 1982). As the year progresses and through the winter, the water table usually declines as there is no new infiltration to contribute to the water table (Eilers 1982).

Throughout the winter of 2009 (October, 2009 to March, 2010) the depth to the water table declined (Figure 4.16). Likewise in 2010, the water table depth declined between October, 2010 and February, 2011 in most wells (Figure 4.16).

There was a sharp rise of the water table during 2010 spring melt between March, 2010 and April, 2010 (Figure 4.16). In 2011, the rise in the water table had begun in some of the wells by March, 2011 (Figure 4.16).

<u>Groundwater flow</u>

Groundwater flow was mapped from June, 2009 to March, 2011. Examples of groundwater flow diagrams for October, 2009 and 2010 are presented in Figure 4.17 and 4.18. Groundwater flowed away from the centre of the slough generally to the west and remained the same for all months of the year. This was consistent with Lissey's research (1968). Fluctuations in groundwater table depth occurred relatively uniformly in all the wells and did not cause a change in the groundwater flow pattern.

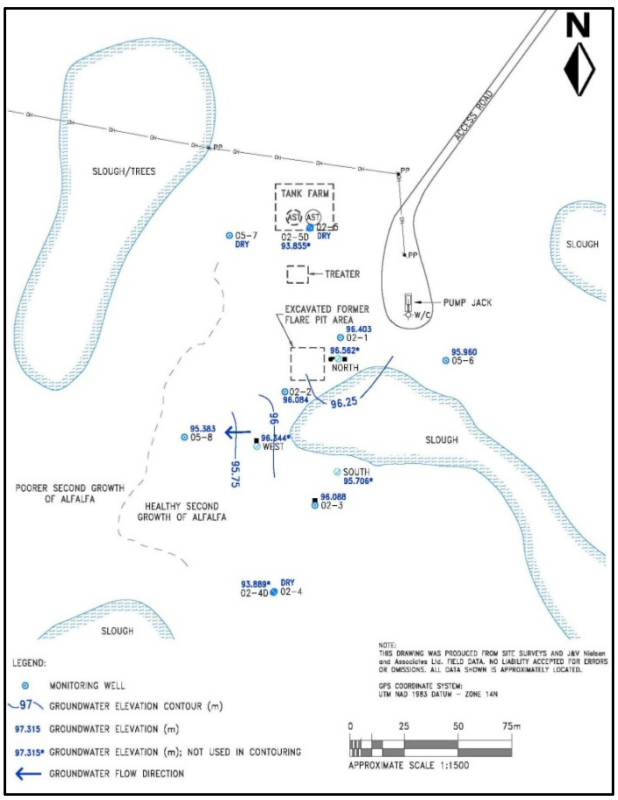


Figure 4.17 Groundwater flow from Oct, 2009 (© Canadian Natural Resources Ltd. used with permission)

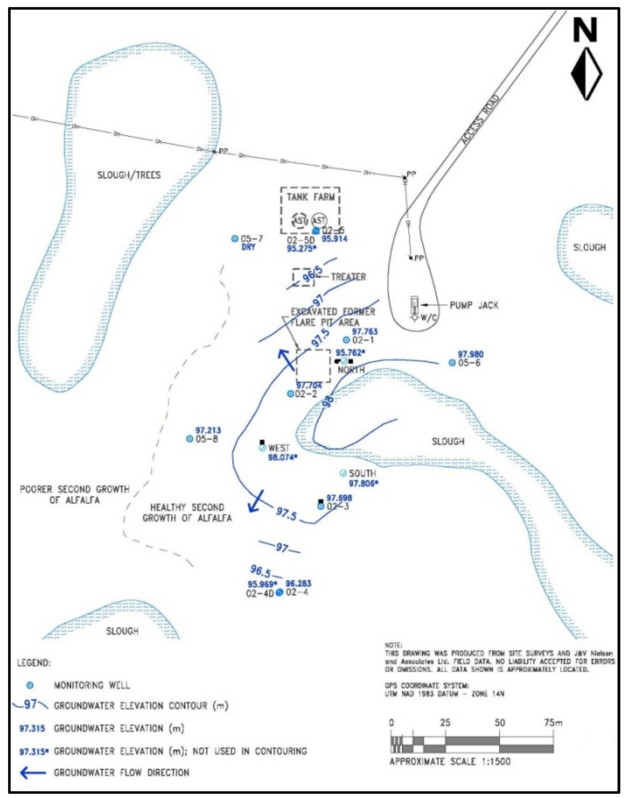


Figure 4.18 Groundwater flow from Oct, 2010 (© Canadian Natural Resources Ltd. used with permission)

Groundwater chemistry

Monitoring wells were installed both in and outside of the contaminated area by J & V Nielsen and Associates in 2002 and 2005. The wells 02-4, 02-4D, 05-7, 02-5, and 02-5D were outside the tiled area and were used to identify background groundwater conditions (Figure 4.7). Wells 02-1, 02-2, 02-3, 05-8, and the culverts were within the tile drains and the groundwater at these wells had elevated levels of chlorides. Well 05-6 was not within the tile drains but the groundwater has some chlorides. The groundwater in this well had been affected by brine.

Some of the background wells were dry for most of the sampling dates. Wells 02-4 and 02-5 only had groundwater in the fall of 2010 and 05-7 never had groundwater. These wells were approximately 4 m deep. Therefore when the well was dry, the groundwater was deeper than 4 m.

The previous section looked at the changes in the depth to water table. The groundwater chemistry changed in tandem with water table depth (Hayashi and van der Kamp 2009). The principal was that salts were not lost from the system. When the water table rose, there was more water and the salts were diluted. Likewise, when the water table fell there was less water and the salts were more concentrated. Therefore, the salts were the highest when the groundwater was the lowest, just before spring melt. After spring melt the water table rose and the salts were diluted.

The water chemistry was measured regularly in the wells and culvert from June, 2009 to March, 2011. The data from June, 2009 to March, 2011 was used to look at changes in the water chemistry in relation to the groundwater table depths.

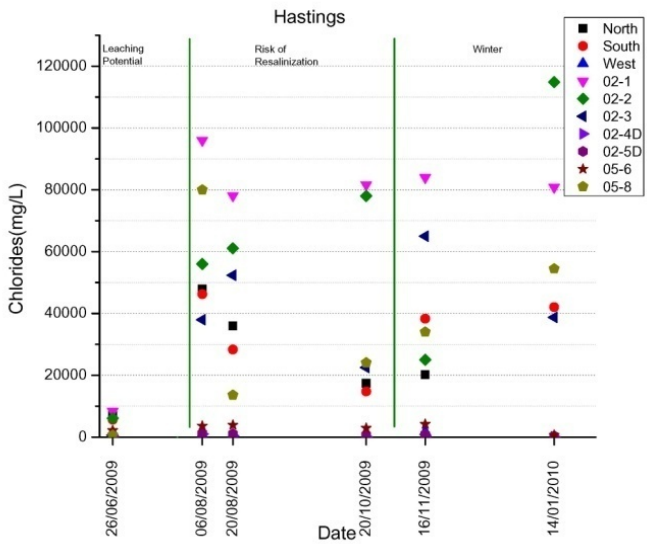


Figure 4.19 Chloride concentrations (Jun., 2009 to Jan., 2010)

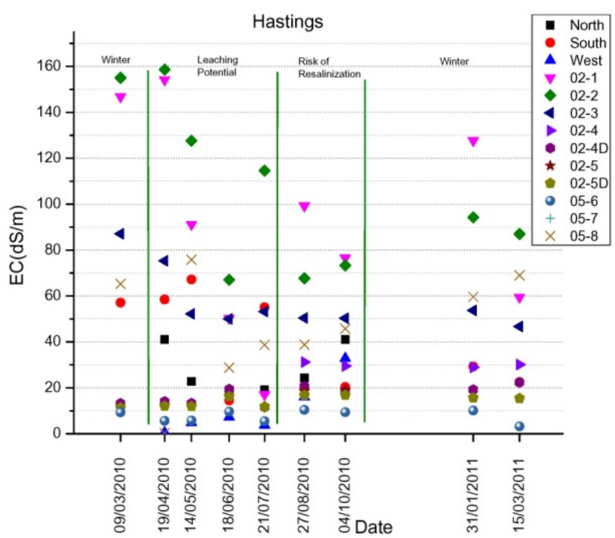


Figure 4.20 EC values (Mar., 2010 to Mar., 2011)

The effect of dilution after spring melt was observed in the water chemistry of the wells in June, 2009 (Figure 4.19). Chlorides concentrations at this time were much lower than the next sampling date in August, 2009 (Figure 4.19). Concentration of salts was observed from the sampling in November, 2009 and January, 2010. The concentration of chlorides increased in all the wells between November and January (Figure 4.19).

In 2010, between March and June, the water table trended higher (Figure 4.16). During these months the EC trended lower (Figure 4.20). This is an example of a dilution effect. As the water table depth rose, the salts were more diluted and the EC was lower.

<u>Summary of observations</u>

- The water table depth decreased during the winter, rose sharply during spring snowmelt, and declined through the summer and fall unless there was excess precipitation.
- The water table depth in 2010 was 1.5-2 m higher than 2009 due to inconsistent pumping of the culverts and excess precipitation.
- The depth to water table was approximately 3 mbgs in 2009 and 1.5 mbgs in 2010.
- Groundwater flow was perpendicular to the edge of the slough. The flow direction remained constant and was not affected by changes in the water table depth.
- Background water chemistry was determined through background wells. The background wells were classified as naturally saline.
- All wells and culverts within the tile drained area had EC above background levels. Elevated concentrations of chlorides and sodium were the main contributors to salinity.
- Changes in water chemistry (dilution and concentration) were observed in tandem with changes to the water table depth. When the water table depth lowered the salts were more concentrated and vice versa.

4.4.2 Willmar

The current salinity status at Willmar was determined by examining EM surveys, soil sample results, topography, soil profiles, and groundwater. Photos from 2002 (Figures 4.21 and 4.22) show the areas of poor growth on the west and east sides while Figure 4.23 and 4.24 show the same areas in 2008 and 2009 with good alfalfa growth.

Figure 4.21 Looking northwest at bare area on west side (2002)

Figure 4.22 Looking east at bare area on east side (2002)

Figure 4.23 Looking north at good alfalfa growth on west side (2008)

Figure 4.24 Looking east at good alfalfa growth on east side (2009)

4.4.2.2 Soil sampling

Soil samples were obtained from 0-120 cm at eight different locations for the EM38 calibrations (Figure 4.25).

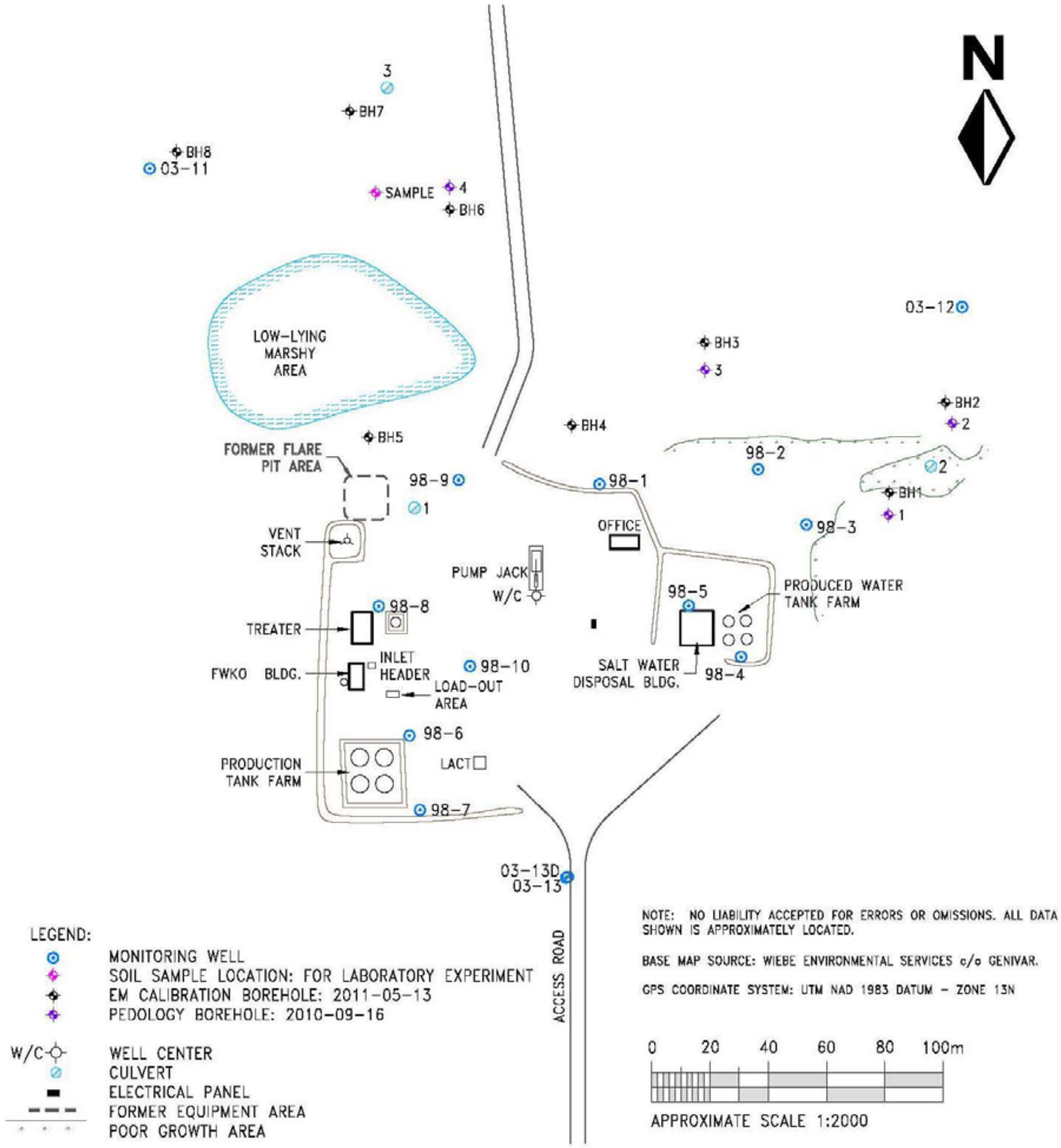


Figure 4.25 Locations of EM38h/EM38v calibration boreholes and pedological inspection boreholes (© Canadian Natural Resources Ltd. used with permission)

4.4.2.1 EM38

On the EM38h the moderate salinity class (4-8 dS m^{-1}) started at 40 mS m^{-1} and the moderately strong salinity class (ECe 8-16 dS m^{-1}) at 120 mS m^{-1} (Figure 4.26). On the east side, most of the tiled area (94%) was classified as moderately saline (ECe 4-8 dS m^{-1}); the area of moderately strong salinity (ECe 8-16 dS m^{-1}) was small (6% - just north of the battery). On the west side, most of the area was classified as weakly to moderately saline and there were no areas which were classified as moderately strong or strongly saline.

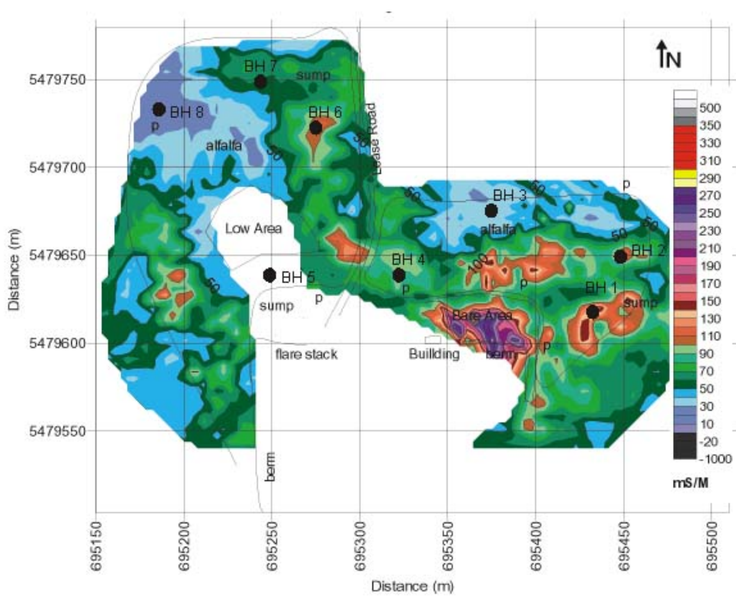


Figure 4.26 EM38h, May, 2010 (© Canadian Natural Resources Ltd. used with permission)

Field Legend - values for soil Temp @ 50 cm est. ~ 12 oC	Calculated ECe values equivalent to T corrected EM38h	Salinity classification for agricultural crop production
	0-60 cm	
500	35.3	Strong >16 dS/m
400	28.4	
390	27.7	
380	27.0	
370	26.3	
360	25.6	
350	24.9	
340	24.2	
330	23.5	
320	22.8	
310	22.1	
300	21.4	
290	20.7	
280	20.0	
270	19.3	
260	18.6	
250	17.9	
240	17.2	
230	16.5	
220	15.8	Moderately strong 8-16 dS/m
210	15.1	
200	14.4	
190	13.7	
180	13.0	
170	12.3	
160	11.6	
150	10.9	
140	10.3	
130	9.6	
120	8.9	
110	8.2	
100	7.5	Moderate 4-8 dS/m
90	6.8	
80	6.1	
70	5.4	
60	4.7	
50	4.0	weak-nil <4 dS/m
40	3.3	
30	2.6	
20	1.9	
10	1.2	

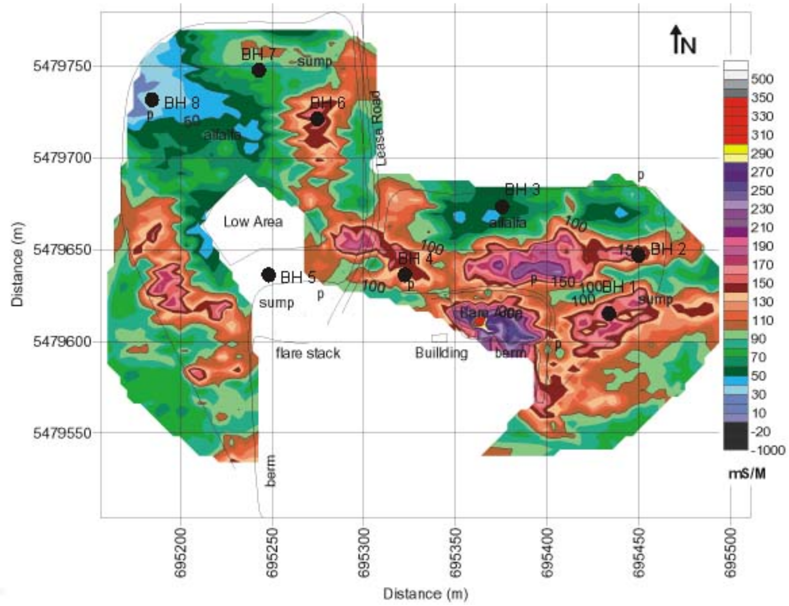


Figure 4.27 EM38v, May, 2010 (© Canadian Natural Resources Ltd. used with permission)

Field Legend - values for soil Temp @ 50 cm est. ~ 12 oC	Calculated ECe values equivalent to T corrected EM38v	Salinity classification for agricultural crop production
	0-120 cm	
500	37.0	Strong >16 dS/m
400	29.8	
390	29.1	
380	28.4	
370	27.6	
360	26.9	
350	26.2	
340	25.5	
330	24.8	
320	24.0	
310	23.3	
300	22.6	
290	21.9	
280	21.2	
270	20.4	
260	19.7	
250	19.0	
240	18.3	
230	17.6	
220	16.8	
210	16.1	
200	15.4	Moderately strong 8-16 dS/m
190	14.7	
180	14.0	
170	13.2	
160	12.5	
150	11.8	
140	11.1	
130	10.3	
120	9.6	
110	8.9	
100	8.2	
90	7.5	Moderate 4-8 dS/m
80	6.7	
70	6.0	
60	5.3	
50	4.6	
40	3.9	weak-nil <4 dS/m
30	3.1	
20	2.4	
10	1.7	

The EM38v map had a similar pattern of conductivity as the EM38h except all the areas of moderate salinity on the EM38h were areas of moderately strong salinity (Figure 4.27). The area of weak/moderate salinity decreased from 94% of total area on the EM38h to 55% on the EM38v whereas the area of moderately strong salinity increased from 6% to 43%. On the east side, the large area that was classified as moderately saline on the EM38h was classified as moderately strong salinity on the EM38v. The area on the east side that was moderately strong salinity on the EM38h was classified as strongly saline on the EM38v and was about the same size. The area of moderate salinity from the EM38h on the west side was classified as moderately strong salinity on the EM38v and there were still no areas of strong salinity.

4.4.2.3 EM31

On the east side the EM31 survey had the same pattern of conductivity as the EM38 surveys (Figure 4.29). On the west side the EM31 mapped an area of high conductivity in the same area as on the EM38 surveys but also mapped a higher conductivity area on the edge of the battery compared to the EM38 surveys. When the EM31 map from 2010 was compared to the 2001 EM31 there was a 79% decrease in the conductivity in the strongly saline areas (200-260 mS m^{-1}) (Figures 4.28 and 4.29).

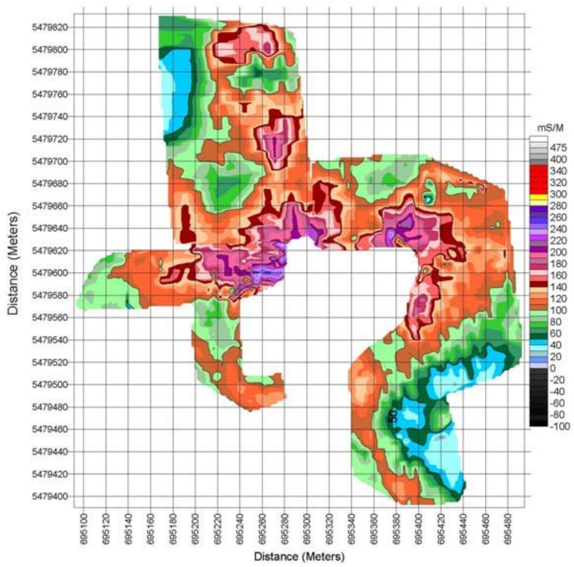


Figure 4.28 2001 EM31 (© Canadian Natural Resources Ltd. used with permission)

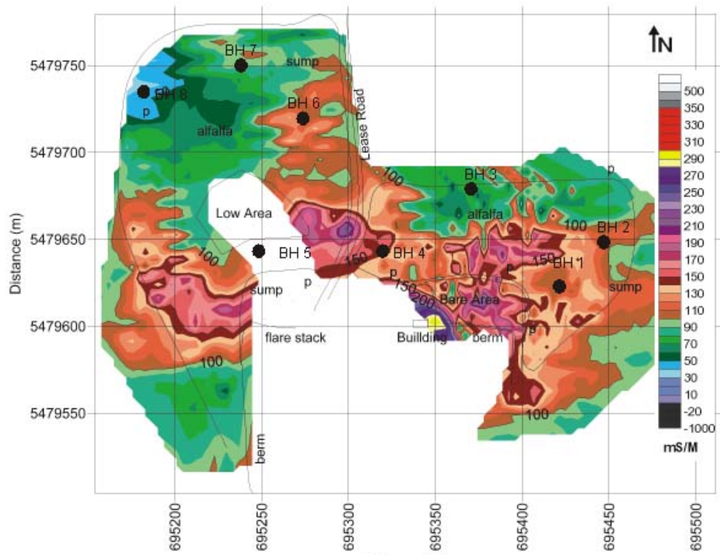


Figure 4.29 2010 EM31 (© Canadian Natural Resources Ltd. used with permission)

4.4.2.4 Topographic analysis

The site was located on a 3-5% slope (Figure 4.30). The east side sloped north and east and the west side sloped north.

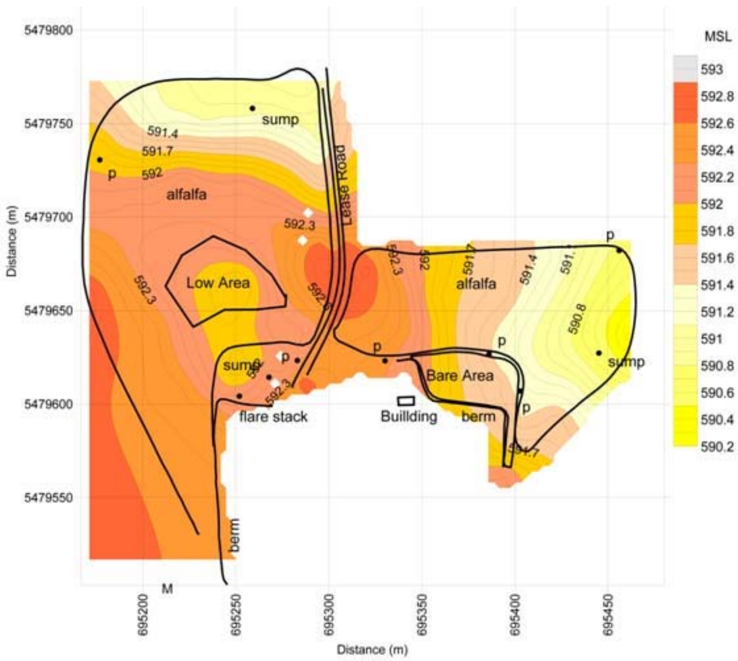


Figure 4.30 Topographical contours, May, 2010 (© Canadian Natural Resources Ltd. used with permission)

4.4.2.5 GPS mapping of poor growth areas.

The poor growth area on the east side was mapped with the GPS on Sept. 19, 2010 (Figure 4.25). Poorer growth was observed on the east side around the east culvert. The pattern of poor growth coincides with higher conductivity mapped on the EM38v.

4.4.2.6 Pedological inspections

The soils were Black Chernozem and the vegetation was alfalfa. The alfalfa growth on the west side was very good. On the east side the alfalfa growth was good except for a bare / poor growth area just north of the battery.

BH1 (figures 4.25 and 4.31) was a disturbed profile with 8 cm of buried parent material (Ckb) between the A and B horizons. This was a well-drained mid slope profile with 3-5% slope to the east / northeast. Alfalfa growth was good even though the EM38h and EM38v readings were 143 mS m^{-1} and 180 mS m^{-1}, respectively.

Ap - clay loam, black, moist, friable, weakly carbonated (in-situ ECfs = 1.9 dS m^{-1})

Ckb - clay loam, carbonated, disturbed layer (from backfilling C horizon after construction)

Bm1 - clay loam, dark brown (10YR3/3), weak medium angular blocky structure, (in-situ ECfs - 3.5 dS m^{-1}), salinity dominated by chlorides therefore
no crystalline precipitate visible
Bm2 - clay loam, slight change in colour to brown (10YR5/3)
BC - clay loam, gradual transition, streaks of carbonates
Cca - clay loam, highly carbonated, (in-situ ECfs - 5.3 dS m^{-1}), many stones

Figure 4.31 BH1

The soil texture was clay loam throughout the profile. The surface of this soil had been disturbed and modified likely during the oil exploration. The original soil surface was likely removed by construction activities and subsequently replaced with calcareous spoil materials placed on the exposed underlying B horizon. The resulting profile had been salinized as indicated by the white salt precipitates throughout as well as the high EC values. The salinity analysis from May, 2010 showed high concentrations of chlorides of

3,100 mg L^{-1} (60-90 cm) to 6,400 mg L^{-1} (90-120 cm) and sulphates ranging from 3,400-3,800 mg L^{-1} (30-120 cm).

BH2 (figures 4.25 and 4.32) was not a disturbed profile. Gypsum visible as white specks of salts had accumulated in the A and B horizons, indicating that this site had been re-salinized. The EM38h and EM38v readings were 138 mS m^{-1} and 193 mS m^{-1}, respectively. Salinity analysis from May 2010 showed sulphate concentrations of 2,900 mg L^{-1} (0-15 cm), 5,900 mg L^{-1} (15-30 cm), 11,000 mg L^{-1} (30-90 cm), and 6,400 mg L^{-1} (90-120 cm). The chloride concentrations were somewhat less at 100 mg L^{-1} (0-15 cm), 220 mg L^{-1} (15-30 cm), 1,100 mg L^{-1} (30-60 cm), 2,400 mg L^{-1} (60-90 cm) and 4,000 mg L^{-1} (90-120 cm). The high sulphate levels were interpreted as likely from natural sources, although the presence of chlorides at depth indicate some contamination may have occurred in the past.

Ap - loam, black, moist, friable, cloddy (in-situ EC fs = 0.75 dS m^{-1}), grey-white salt precipitates (gypsum)

Ah - loam, moist, friable, weak angular blocky, (in-situ EC fs = 4.4 dS m^{-1})

Bm - clay loam, dark brown to brown, weak blocky structure, (in-situ EC fs = 3.7 dS m^{-1})

Cca - silty clay loam, (in-situ EC fs = 6.85 dS m^{-1})

Ck - silt loam, highly carbonated, (in-situ EC fs = 4.8 dS m^{-1})

Figure 4.32 BH2

The presence of salt precipitates in the B horizons was indicative that secondary salinization had occurred at BH1 and BH2. The chemistry of the salts indicated that it could be from a spill on the surface that had not completely leached out or from upward migration from a high saline water table. The chemistry of the groundwater at culvert 2 indicated that the chloride concentration was 11,000 mg L^{-1} and the sulphates were 3,700 mg L^{-1}. If the secondary salinization was from a brine spill or from the water table it does not explain the higher proportion of sulphates in the soil. Anecdotally some landowners have said that brine spills were treated in the past with inches of gypsum broadcast on the surface.

BH3 (Figure 4.33) was an upper mid slope profile that was well drained and vegetated with second growth alfalfa. Compared to BH2, BH3 was higher in the landscape (Figure 4.30) and therefore the A horizon was thinner. It had also developed a stronger structure in the B horizon compared to BH2. Like BH1 and BH2, BH3 had an accumulation of gypsum in the B horizon. This salinity was not reflected in the EM38h and EM38v readings of 31 mS m^{-1} and 46 mS m^{-1}, respectively, which indicated, incorrectly, that there was no salinity in the profile. Soil sample analysis from May, 2010 had sulphate concentrations of 5,200 mg L^{-1} (30-60 cm), 6,500 mg L^{-1} (60-90 cm), and 5,300 mg L^{-1} (90-120 cm). Unlike BH1 and BH2 there were very low levels of chlorides (<160 mg L^{-1}) in the profile. If the secondary salinization at BH3 was from a brine spill one would expect to find higher concentrations of chlorides. If the explanation for the secondary salinization at BH 1 and BH2 was correct (a brine spill treated with excess gypsum) perhaps some gypsum was put not only on the brine spill but also on adjacent soil that was not brine contaminated.

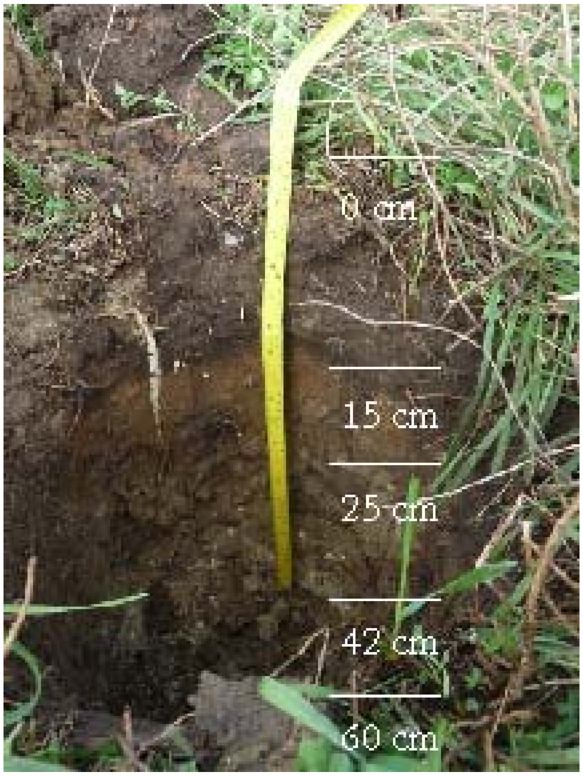
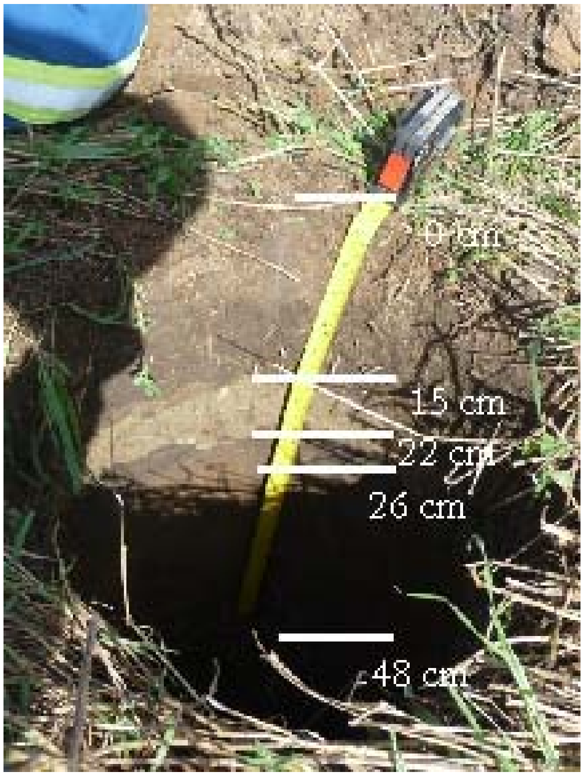


Figure 4.33 BH3

BH4 (Figure 4.34) was a disturbed profile with a buried Ck horizon from 15-22 cm. The vegetation was second growth alfalfa and growth was good. This was an upper mid slope profile with drainage to the north and good moisture throughout the profile. The EM38h and EM38v readings were 123 mS m^{-1} and 173 mS m^{-1}, respectively and indicated some salinity. Laboratory results indicated that there were still oilfield impacts in the subsoil. Chlorides were 4,300 mg L^{-1} (30-60 cm), 7,300 mg L^{-1} (60-90 cm), and 6,400 mg L^{-1} (90-120 cm). Sulphates ranged from 1,400-2,600 mg L^{-1} (0-120 cm). This profile was in the process of being reclaimed. Salts were leaching into the subsoil and no visible surface salts remained. Water drained north off the west forage area and east off the east forage area (Figure 4.30). There was a small depression on the west side which may hold some water but this was not affecting the general drainage of the west forage area. On the east side the movement of salts underground from the battery appeared to be following the above ground topography (Figure 4.30).



Ap - loam, black, friable

bCk - clay loam, buried C horizon (evidence of prior soil disturbance)
Ah - loam, very dark brown, friable
Bm - silt loam, dark brown (10YR4/3), moist, friable, weak fine sub angular blocky structure

Ck - sandy loam, brown to dark brown (10YR5/3)

Figure 4.34 BH4

Summary of observations

- The soils had a weak sub-angular blocky B horizon, were well drained with a loam texture, and primary salts and carbonates had leached into the C horizon. Soil parent material was strongly calcareous. The soils were developed under a regime of wetting, drying, and leaching of primary salts and carbonates.
- The salinity on the east side was classified as moderately and moderately strong according to the calibrated EM38. Some of the growth on this side was poor; however not all the growth in the moderately strong saline area was poor. No structural deterioration from high sodium brines was evident. High lime content and low clay content make these soils resilient to the effect of high sodium concentrations.

- The well-drained soil at Willmar was contributing to the flushing of salts and allowing root penetration through areas of higher salinity. It was expected that leaching at Willmar should continue to flush salts more quickly than Hastings because it has a more developed soil structure.
- Results of the EM38 may be inaccurate due to powdery dry soil when the crop was mature alfalfa. Care should be taken to take the reading in the spring when the soil is still moist.

4.4.2.7 Groundwater sampling of monitoring wells

Depth to water table

Wells were installed at Willmar in 1998 and 2003 (Figure 4.25) (WES 1998; Nielsen 2003). Some of the wells installed in 1998 were on the battery and therefore were not within the tile system (98-4, 98-5, 98-6, 98-7, 98-8, and 98-10). Wells 98-1, 98-2, 98-3, 98-9, and the culverts were wells within the tile drainage area (contaminated zone). Wells 03-11, 03-12, 03-13, and 03-13D represented background groundwater depths and quality.

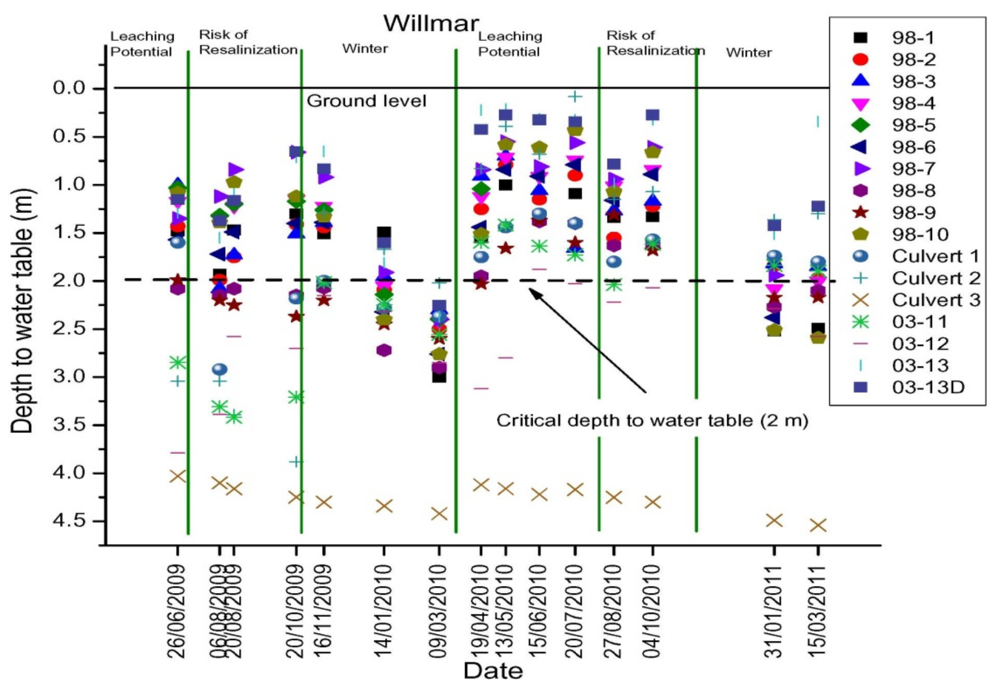


Figure 4.35 Depth to water at Willmar

Many of the conclusions made at the Hastings were echoed at Willmar. The above average amount of precipitation in the summer and fall of 2010 had affected the depth to the water table in 2010. The depth to water table was approximately 1-1.5 m higher in 2010 compared to 2009 (Figure 4.35). Like Hastings, the pumps were not consistent working during 2010 which also contributed to the high water table. A higher water table (within 2 m of the ground surface) poses a greater risk of resalinization of the surface soils (Rhoades 1974; Nulsen 1981).

Unlike Hastings where the tile system was located around a slough, this tile system was located mid-slope just north of the battery which is in the upper slope landscape position. Upper and mid-slope landscape positions would typically have lower depths to water table compared to lower positions (Richardson et al. 1992). The data from all of the wells (including the ones on the active lease) confirmed that the depth to the water table was typically 1-2 mbgs under the active lease. Wells 03-11 and 03-12 which were located in background areas, mid-slope, have a depth to the water table that was consistently lower than the wells on the active lease (Figure 4.35). This leads to the conclusion that the water table at Willmar was mounded under the active lease.

Two factors had created the groundwater mound: (1) berms throughout the battery did not allow runoff of rain water and (2) no vegetation was allowed to grow on the battery. The berms ponded precipitation until either the water infiltrated or evaporated. As a result these bermed areas behaved similar to a recharge slough; water ponding in the berms was connected to the water table and thus raised the water table. The depth to water table was also higher because there was no vegetation to consume water and promote infiltration.

The wells on the active lease were removed from the data analysis and discussion of the depth to water table in the tile drained area. During the summer of 2009 the depth to the water table remained fairly constant (Figure 4.35). During the winter, from November, 2009 to March, 2010 the depth to the water table lowered as expected based on Eilers' (1982) research of seasonal changes in the groundwater table observed in southeast Saskatchewan (Figure 4.35). From March, 2010 to April, 2010 there was a dramatic rise in the water table depth during spring melt (Figure 4.35).

In 2010, the depth to the water table was consistently higher than 2009. At the August, 2010 reading the depth to the water table had fallen but then it had raised again at the next measurement data in October, 2010 (Figure 4.35). This was the summer and fall of above average rainfall. This was the reason the water table rose between August and October; the rains recharged all the low areas and caused the water table to rise.

Groundwater flow

As was discussed in the previous section on the depth to the water table, the groundwater under the active facility was mounded. Therefore the groundwater movement was similar to the groundwater movement under a slough where the groundwater is also mounded (Lissey 1968). The movement was perpendicular to the edge of the groundwater mound. A sample of two months of groundwater flow diagrams (Figures 4.36 and 4.37) shows that the groundwater flowed to the north off of the active lease.

Like Hastings the groundwater flow direction remained the same even when the groundwater table rose and fell. Figure 4.36 when the water table was low and Figure 4.37 when it was high both had the same flow direction.

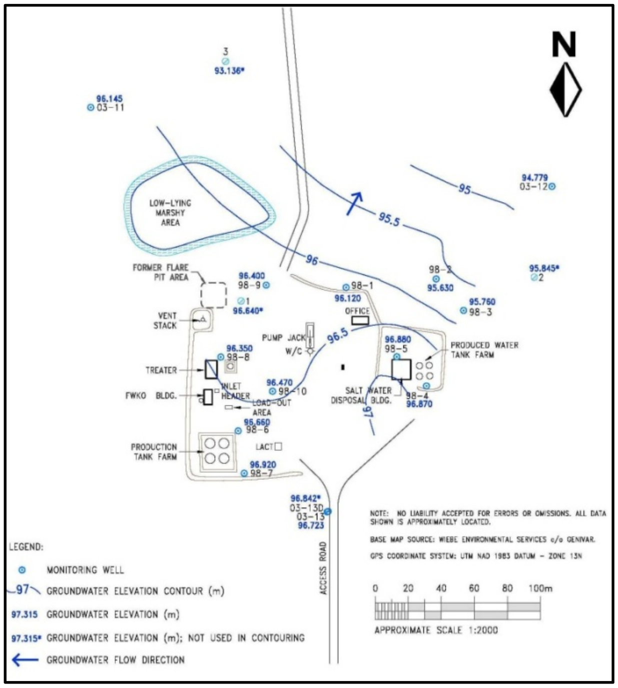


Figure 4.36 Groundwater flow from March, 2010 (© Canadian Natural Resources Ltd. used with permission)

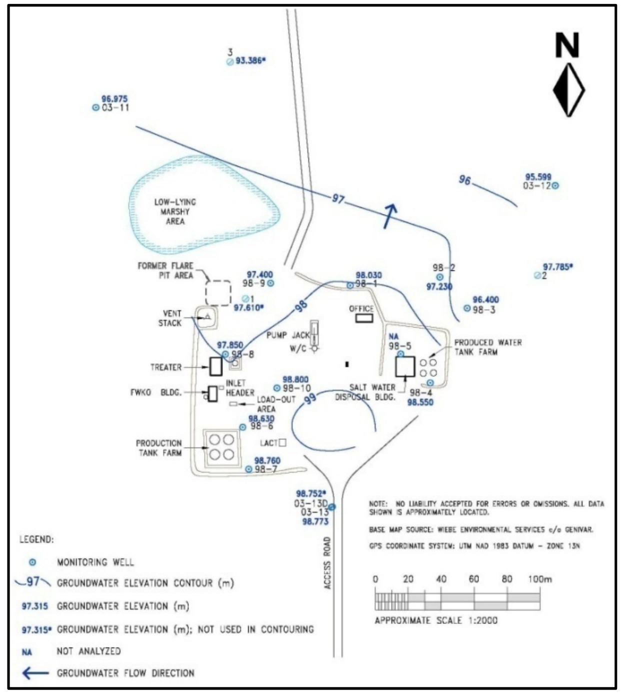


Figure 4.37 Groundwater flow from July, 2010 (© Canadian Natural Resources Ltd. used with permission)

<u>Groundwater chemistry</u>

For the purpose of examining the progression of the tile drainage system, the groundwater chemistry of the background wells, the wells within the tiled area, and the wells on the battery will be discussed as separate groups.

The background wells were saline and non-saline. Well 03-11 had non-saline groundwater, 03-12 had saline groundwater, and 03-13 and 03-13D had slightly saline groundwater (Figure 4.38). The salts found in the saline groundwater were mainly sulphates. Since each of these wells was a different direction from the battery the well used to represent background conditions may depend on which background well was closest to the area being compared.

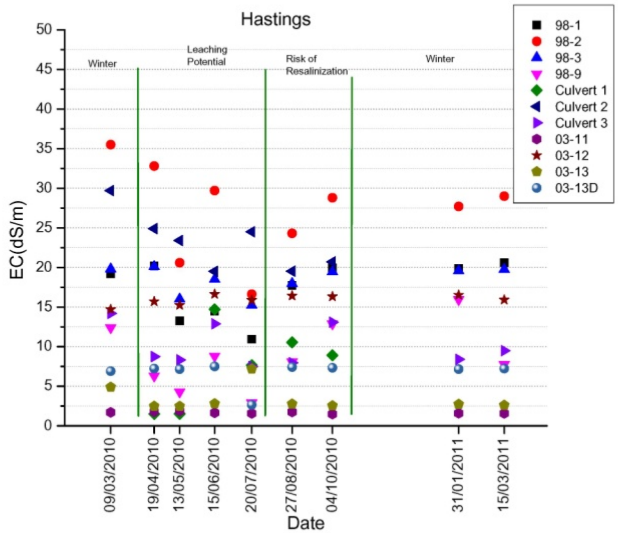


Figure 4.38 EC values within tiled area

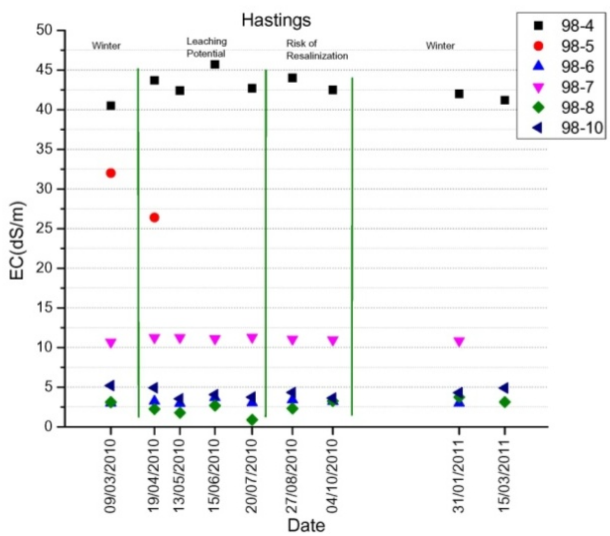


Figure 4.39 EC values on battery

The wells within the tile drained area were still affected by chloride salts. The EC was above background (above the background level of the most saline background well) (Figure 4.38). The wells on the battery had also been contaminated by brine. The wells on the southwest and west side of the battery (98-6, 98-7, 98-8, and 98-10) were near background salinity levels (Figure 4.39). The wells on the north side of the battery (98-4 and 98-5) had chloride concentrations equal to or greater than the most saline wells within the tile drainage system (Figure 4.39).

The chloride and EC results of the wells within the tile drainage area behaved similarly to the Hastings site and changed with the changing depth to water table. From March, 2010 to May, 2010 the EC fell as the water table rose during spring melt; this was the dilution of the salts as the water table rose (figures 4.38 and 4.39). In July, 2010 when the water table was the highest, the EC was the lowest (figures 4.38 and 4.39). From July to August, 2010 the EC rose in most wells and the water table declined (figures 4.38 and 4.39). This was an example of concentration of the salts from a decreasing water table. From August, 2010 into the winter and spring of 2011, there was little change in the EC.

<u>Summary of observations</u>

- The water table depth in 2010 was 1-1.5 m higher in 2010 compared to 2009. The depth to groundwater was approximately 1.5 mbgs in 2009 and approximately 0.75 mbgs in 2010.
- The water table depth decreased during the winter, rose during spring melt, and declined gradually during the summer and fall except for the fall of 2010 when there was above average precipitation.
- The groundwater table was mounded underneath the battery.
- The groundwater flow was perpendicular to the groundwater mound or north from the battery into the tiled area.
- The background water chemistry was determined through three background wells. These wells were located in different directions from the tiled area and these wells varied from having non-saline to naturally saline groundwater.

- Changes in the water chemistry (dilution and concentration) were observed in tandem with changes to the water table depth. When the water table depth lowered the salts were more concentrated and vice versa.

4.4.3 Discussion of current salinity status – Hastings and Willmar

The current salinity status was determined through the EM data, soil and water results, and pedological inspections. Both Hastings and Willmar had some areas which were not saline and other areas which were strongly saline.

The varying degrees of salinity were mapped by the EM's and confirmed from the observed types of salt-tolerant vegetation and from the soil test results. Areas with salt-tolerant grasses, foxtail, and kochia or poor alfalfa growth were areas where the higher conductivity was mapped.

EM38 readings were low on mature alfalfa because of the low water content of the soil. Alfalfa roots were deep, they consumed the moisture in the soil, and therefore the soil was too dry for an accurate EM38 reading.

The quality of the groundwater in the tiled area had salinity above background levels. The groundwater quality changed as the depth to the water table changed. A high water table diluted the salts in the groundwater and a low water table concentrated the salts.

The landscape contour map showed that the topography at Hastings was fairly level and therefore the precipitation was retained in the landscape while at Willmar the topography was more sloping and precipitation ran off.

The pedology inspection at Hastings indicated that the soils in the forage area were Rego Black Chernozems and were imperfectly drained. The water movement from the east slough was lateral as confirmed by the groundwater flow diagrams. Lighter textured silt loams have high hydraulic conductivity and were found around the east slough. These soils both increased the water flow out of the slough and increased the water flow into the tiles. There were still high levels of primary carbonates in the soil which likely had minimized the deleterious structure effects of high Na^+ concentrations.

At Willmar, the soils were Orthic Black Chernozems. The soils had a weak sub angular B horizon formed under a regime of wetting and drying and were well drained. The good structure of these soils had contributed to their remediation as the salts flushed more quickly in a well drained soil.

4.5 Discussion of the change in soil and water quality due to remediation practices

The soil and water quality has changed as a result of the remediation practices. Salts were leached down the soil profile and pumped out via the tile drains (see 10.0 Appendix for pump out water quality results and volumes from 2003 to 2011). Changes in soil salinity were mapped in the EM maps and verified by soil tests. The remediation has occurred through natural leaching processes and has been dependent on the amount and distribution of precipitation. The effectiveness of the leaching was dependent on the site topography and on the amount of infiltration. Changes to the quality of the groundwater were a result of both removals of salts through the dewatering of the tiles and from seasonal variation in the depth to the water table.

4.5.1 Characterization of local weather/climate and leaching potential

Leaching occurred in the spring and early summer when available snowmelt and precipitation exceeded the water holding capacity of the soil profile. Also at this time, water tables had receded during the winter months to their lowest levels. As precipitation infiltrated it carried soluble salts and induced a rise in the water table (recharge). By late summer and fall (Aug-October), the soil became dry since most of the soil water had been used by plants, and most rains would not have sufficient volume to create a leaching event. The high spring water tables had receded due to upward capillary flow for plant uptake and evaporation (evapotranspiration). Therefore this period was considered to have the highest risk for soil re-salinization. The winter season (November-March) was characterized by an accumulation of snow, minimal infiltration, and a declining water table.

Precipitation records from 2001-2009, the years during which remediation has occurred, was obtained for seven weather stations surrounding Hasting and Willmar (table 4.1). For comparison, the 30 year (1971-2000) normalized precipitation records were also obtained from Environment Canada (2012). During this thesis study, rainfall from April to October was collected in rain gauges at Willmar and Hastings for 2009 and 2010 (table 4.2). Mineral oil was put in the rain gauges to prevent evaporation and the gauges were measured at the end of every month. The mean rainfall from 2001-2009 from the seven weather stations was compared to the rainfall collected at Hastings and Willmar (table 4.2).

Table 4.1 Long-term normal precipitation & 2001-2009 mean precipitation (Environment Canada 2012)

Summary of rainfall	Leaching Potential					Soil Re-Salinization				Snow Accumulation						
Month	A	M	J	J	Total	A	S	O	Total	N	D	J	F	M	Total	**Annual**
Long term normal precipitation	30	58	82	63	233	54	43	26	123	18	22	21	17	26	104	**461**
2001-2009 mean precipitation	31	66	87	56	240	51	23	29	103	14	25	21	14	20	94	**438**

Table 4.2 Mean rainfall for Hastings, Willmar, and surrounding weather stations (Environment Canada 2012)

Summary of rainfall	Leaching Potential					Soil Re-Salinization				Snow Accumulation						
	A	M	J	J	Total	A	S	O	Total	N	D	J	F	M	Total	**Annual**
Hastings 2010	0	59	11	0	169	70	77	0	147						0	**316**
Willmar 2009	0	55	22	53	130	110	0	0	110						0	**240**
Willmar 2010	35	125	0	57	217	77	0	0	77						0	**294**
Mean of nearby stations	20	63	87	51	221	50	19	17	86	2	0.3	0.9	0	7	10.3	**317.3**

The goal of examining the precipitation data was to determine how many potential leaching events occurred on average during a year. Leaching occurred when there was more precipitation than was necessary to saturate the soil. Any precipitation above saturation would leach through the soil. To effectively leach salts from the upper part of the rooting zone, there should be sufficient precipitation which was sufficient to leach the salts below the upper root zone (25 cm).

The water holding capacity (WHC) of the soil is the amount of water the soil can hold before reaching saturation and is expressed in mm/cm (Haluschak et al. 2004). Any precipitation which is greater than the WHC is a potential leaching event.

The WHC is determined by the texture of the soil; Hastings was a silt loam and Willmar was a loam. Based on the texture of the soil, the WHC of Hastings is 2.4 mm/cm and Willmar, 2.0 mm/cm, respectively (Haluschak et al. 2004). Therefore the total WHC to 25 cm for Hastings was 60 mm and for Willmar, 50 mm and any precipitation greater than these amounts would be classified as a leaching event.

The normal annual precipitation is 461 mm (table 4.1) (Environment Canada 2012). The normal snowmelt is approximately 100 mm. Only 30% of the snow cover melts into the ground (Ross 2009). Assuming 30% of snow accumulation infiltrated the soil it does not represent one leaching event. However, it was assumed that one leaching event occurs in the spring because the combination of late fall rains, snowmelt, and early spring rains when evapotranspiration and plant growth was minimal would be enough precipitation to cause a leaching event.

Precipitation during the late spring, summer, and early fall would be sufficient for a leaching event if more than 60 mm fell at Hastings or 50 mm fell at Willmar within a few days. This would result in episodic transient flow but was still an effective method of leaching (Corwin et al. 2007).

To determine the average number of leaching events from precipitation that occurred during the summer and fall, one weather station was selected (Estevan) and daily precipitation was reviewed for 10 years (2001-2010) (Environment Canada 2012). Any precipitation event that exceeded 60 mm in one or more days between May and October with no more than 3 consecutive days between precipitation was considered a leaching event. During the period 2001 to 2010, there was an average of 1.6 leaching events per year.

In conclusion, there are, on average, two to three leaching events per year; one leaching event in the early spring and one or two more in the summer and fall. Thus remediation under natural leaching events is a long term process.

4.5.2 Local topographic influences on distribution of surface waters and groundwater flow

At Hastings, the three sloughs had the same depth. Therefore because of the lack of gradients, the local groundwater flow was likely not moving toward any of these sloughs. Surface run off will be retained in the landscape and this should allow for increased leaching.

At Willmar, the tile system was located mid-slope and groundwater flow was down slope to the north. Surface water will not be retained in the landscape and therefore there will be less potential for leaching.

4.5.3 Change in quality of groundwater

Dewatering the tile systems removed salt and lowered the depth to the water table. Seasonal variation of the water table depth changed the water quality. Once salts were flushed from the upper rooting zone, the risk of re-salinization of the soil was dependent on the depth and quality of the groundwater.

4.5.3.1 Background water quality

Monitoring the groundwater chemistry over time was done to evaluate the effectiveness of the tile system. Background wells helped to determine the background water quality of the area. The goal of the remediation was to meet background water quality. Not all background groundwater was non-saline.

At Hastings the background wells (02-4, 02-4D, 05-7, 02-5, and 02-5D) had some natural salinity (elevated sulphates). Since EC was a measure of the total salinity and did not distinguish between sulphates or chlorides, the goal of the tile system was to meet equivalent EC of the background water. An example of meeting background water quality was well 05-6. This well had chlorides and has likely been influenced by brine but the EC was lower than the background wells. Therefore it meets background water chemistry (as per SPIGEC 1999b). No other wells in the tiled area met background water quality.

The three Willmar background wells were located northeast, northwest, and south of the tiled area and there were both saline and non-saline background water quality results. To meet background water quality would depend on which well was closest to the area being compared. The wells on the west side (both on the battery and in the tiled area) met background water quality while the east side wells are still very saline.

4.5.3.2 Dewatering the tile drainage system affected the depth to the water table

When the groundwater was saline it affected growth when it rose into the rooting zone. At Hastings and on the east side of Willmar the groundwater was saline and therefore when the pumps were not working there was a risk that the water table would raise into the rooting zone and affect the plants.

In the winter time when the pumps were removed or when they were not working, the water level in the culverts reflected the depth of the water table. In the spring, a submersible pump and a float were put in the culvert to dewater the tiles and the pump automatically shut off when the water level in the culvert moved below the float. Whenever the water table rose above the float, the pump started and dewatered to the level of the float again. Typically, most dewatering occurred in the spring when the water table was the highest. During the summer and fall, the pump worked only when there was enough precipitation to infiltrate the soil and reach the tiles.

If the pump was working, the water level measured in the culvert was the same depth every time it was measured. This was an artificial water level and was not the actual water table. Any wells within the tile drainage system may also have been affected by the dewatering of the tile system and may not have represented the true water table.

At Hastings water levels in the culverts remained fairly constant from July, 2009 to October, 2009 when the pumps were working (Figure 4.40). In October, 2009, the water levels in all the wells and culverts were trending lower and this trend continued until March, 2010 (spring melt) (Figure 4.16). When the pumps were removed in October, 2009, the tile system was completely dewatered. If it had not been completely dewatered, there would have been a spike in the water table in November, 2009 as the water table within the tile drainage system equilibrated with the water table outside the tile drainage area (Figure 4.16).

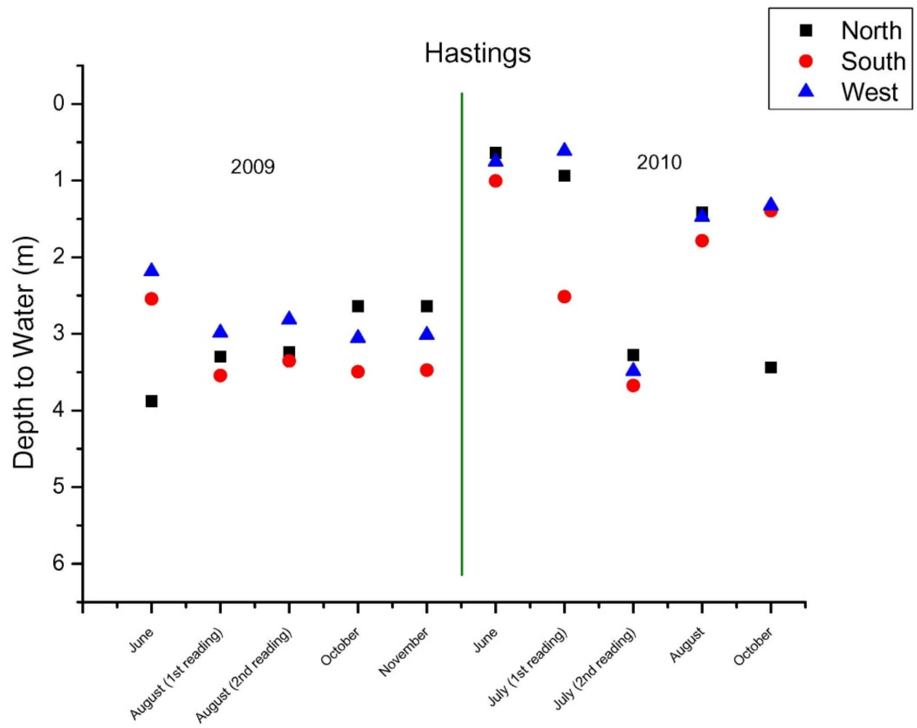


Figure 4.40 Comparison of water level in the culverts at Hastings between 2009 & 2010 (June to November)

Water levels in the culverts varied in the summer of 2010 depending on whether the pumps were working. June, July (1st reading), August, and October (S and W culverts) had high water levels because the pumps were off (Figure 4.40). These readings represented the true water table depth. July (2nd reading) and October (N culvert) had low water levels (Figure 4.42). The July reading (2nd) occurred when the tile system was working and the large variability between the two readings highlights the effectiveness of the tiles. The water level in October, 2010 in the north culvert was low because the pump in this culvert was working, while the pumps in the other two culverts were not.

By August, 2010, the water levels were trending lower in all the wells (compared to the July, 2010 readings) (Figure 4.16). This would be the expected trend if there are usually no large precipitation events that contribute to the water table (Eilers 1982). In the fall of 2010 there was more than average precipitation (table 4.1). This unusual trend was the reason the water table depths were equal to or higher in January, 2011 compared to October, 2010 (Figure 4.16).

4.5.3.3 The risk of re-salinization

The risk of re-salinization was high when there was a potential for the water table to rise into the rooting zone and its water quality was saline. The critical depth to water table cited in literature is often 1-2 m (Rhoades 1974; Nulsen 1981) although some research suggests that a lower critical water table depth is more appropriate in dryland conditions (Peck 1978).

At Hastings, average depths to groundwater were <2 m in 2010. Although the forage growth was good above the tile system, this depth to groundwater coupled with the very saline groundwater poses a risk of re-salinization if the tiles were not pumped. The groundwater will rise if the culverts are not pumped. The groundwater flow was perpendicular to the edge of the slough (Figure 4.17 and 4.18). The tiles around the edge of the slough were designed to intercept the water flow and stop salts from moving further away from the slough. Without the tile system and with the high salt concentrations in the groundwater, there was the potential the salt contaminated area will move further away from the slough.

At Willmar, the risk of re-salinization needs to be examined by dividing the site into the west side and the east side. The east side had a high risk of re-salinization. This was due to a number of factors: (1) high water table, (2) mounded water table under the battery with groundwater flow north toward the tiled area, (3) saline groundwater in the tiled area and under the battery.

The water table on the east side was <2 mbgs. The wells both on the battery and in the tiled area had salinity levels above background. Therefore, there was potential for the saline groundwater to be within the rooting zone and affect plant growth. Culvert 2 (on the east side) should eventually remove the salts in the soil and groundwater in the tiled area and reach background salinity levels. This will take time since the groundwater flow was north from the battery into the tiled area and the groundwater under the battery was saline. The groundwater flow was bringing more salts from the battery into the tile area and therefore the east tiles were intercepting the salt migration.

By dewatering the tile system, plant growth had been established on the east side of the battery. When the tiles were dewatered, the depth to saline groundwater was maintained below the root zone of the plants. If the tiles were not dewatered, the potential for poorer to no growth to result was very high.

Two factors decreased the risk of re-salinization on the west side from the groundwater. The groundwater depth was >2 m and the groundwater quality was non-saline or near background salinity concentrations. The depth to the water table at culvert 3 was >4 m and depth to water table at 03-11 was between 1.5-3.5 m (Figure 4.35). The quality of groundwater at 03-11 was non-saline and therefore does not pose a risk to the health of plants if it rises into the rooting zone. The quality of groundwater at culvert 3 is slightly saline but since the depth to water table was below 2 m there was little risk of the vegetation being affected by the slightly saline groundwater. The wells on the battery on the west side were also near background salinity concentrations and therefore salt migration from the groundwater flow from this side of the battery posed a low risk of re-salinizing the soil.

4.5.4 Change in extent and severity of soil salinity

The extent and severity of soil salinity has changed as a result of the remediation practices. Salts have leached down the soil profile and have been removed via the tile system.

4.5.4.1 Comparison of calibrated EM38 maps

The EM38h (upper rooting zone) was considered to be the more important indicator of the salinity status as it is most critical to the establishment of vegetation. The upper root zone was weak to moderately saline at Willmar and moderate to moderately strongly saline at Hastings.

The salinity class change between weakly, moderately, moderately strong, and strongly saline on the calibrated EM38 maps was consistent between sites and between horizontal and vertical EM38 maps with the exception of the Willmar EM38v. The change between moderate to moderately strong salinity class on the Willmar EM38v was a lower ECa value. This was due to the very dry conditions that existed at Willmar because of the mature crop of alfalfa; however alfalfa growth on the site in the areas of moderate salinity does not appear to be greatly affected by the salts. EM38 readings at Willmar on mature alfalfa were low even though there were salts in the soil.

4.5.4.2 Comparison of EM31 (old and new)

When the EM31 map from 2010 was compared to 2001 EM31 there was a decrease in the conductivity of the sites. At Hastings the extent of the strongly saline area around the edge of the slough had been reduced indicating that the tiles had been effective at removing the salts from the soil (Figures 4.8 and 4.9). At Willmar both the east and west sides had a reduction in conductivity but the east side had greater reduction (Figures 4.28 and 4.29). Between 200-260 mS m^{-1} (the highest conductivity class) the EM31 area decreased 79% from 2001 to 2010 at Willmar. The reduction in conductivity can be attributed to the removal of soluble salt via the tile drains and to the leaching of salts below 6 m. The change in conductivity between the EM31 in 2001 and 2010 was evidence that the remediation program has been functioning successfully.

4.5.4.3 Depth of Salinity

The conductivity pattern between the EM38h and the EM38v surveys was very similar (Figures 4.5, 4.6, 4.25 and 4.26). The areas with the highest conductivity on the EM38h were the areas with even higher conductivity on the EM38v. There was more salinity in the lower part of the rooting zone (60-120 cm) compared to the upper part of the rooting zone. This relationship was interpreted as meaning that the in-situ salts have been leached down.

4.5.4.4 Extent of salinity

The majority of the tiled area at Hastings still had moderately strong to strong salinity and therefore was in an intermediate stage of remediation. The salts had been leached down as EM38h was less saline compared to the EM38v (Figures 4.5 and 4.6). As the tile system continues to dewater the site, these salts should continue to move down into the tiles and the upper portion of the soil become less saline.

Most of the west side of Willmar was classified as weak or moderately saline (figures 4.25 and 4.26). Remediation is complete on this side. On the EM31, any of the salinity mapped was too deep to affect growth (Figure 4.29).

Most of the east side of Willmar was classified as moderate salinity. More salts were found in the lower parts of the soil profile (60-120 cm) therefore the salts are leaching down but the remediation is not complete. It is in an intermediate stage of remediation and the tile system must continue operating.

4.5.4.5 Severity of salinity

Hastings had a larger area of strong salinity compared to Willmar.

4.5.4.6 Area of poor crop growth

Areas of poor crop growth were observed at both Hastings and Willmar. These areas coincide with the areas of moderately strong and strong salinity on the EM maps. Forage growth was good on the weak and moderate salinity areas.

4.5.4.7 Classification of soil salinity relative to agronomic applications

Saline tolerant vegetation (wheat grass, foxtail barley, and kochia) was established on the most saline areas. Where alfalfa was established the soil was less saline (alfalfa is more salt sensitive). Even in areas classified as moderately saline (ECe 4-8 dS m^{-1}) the alfalfa growth was excellent and did not show signs of salt stress even though alfalfa salt tolerance is 2 dS m^{-1} (SPIGEC 1999b).

The severity of the salinity classified by the EM maps was not reflected in the observed health of the plants. Salt stress may occur in years with more moisture deficit than the years this study was under taken.

4.6 Evaluation of the effect of the remediation practices

The remediation practices included the operation of the tile drainage system, the growing of forages, and the addition of calcium sourced amendments. These practices have been effective. Natural leaching from precipitation flushed salts down the soil profile. The sub-surface tile drains removed the salts from the tiled area and maintained the groundwater below the rooting zone.

When the salts were flushed from upper rooting zone, forage plants germinated and established on the tiled area. No bare soil areas were present. Areas that were once bare now supported alfalfa or saline tolerant vegetation. The forage increased infiltration and leaching of salts.

The field study could not measure the effect of the calcium nitrate but its addition has not inhibited the remediation. A thorough evaluation of calcium nitrate was completed in the leaching experiment discussed in Chapter 5.

4.7 Compare the current salinity status relative to target endpoints

If a soil can support vegetation comparable to the surrounding area then it has reached a target end point, however, this is a subjective evaluation. Guidelines for EC, SAR, and pH from SPIGEC (1999b) provide concrete salinity endpoint goals. These criteria are the most stringent soil and water target endpoints and in order to meet SPIGEC criteria in the topsoil and subsoil, the soil must have very little salinity. A less stringent endpoint is meeting SPIGEC soil criteria in the upper rooting zone (0-60 cm), leaving salts in at depth, and mitigating the risk of the deep salts returning to surface. The SPIGEC criteria recognize that: (1) endpoints may not be achieved due to natural background salinity and (2) salts may be left in at depth if the risk of re-salinization of surface soils is low (SPIGEC 1999b).

Only the west side of the Willmar tile system has reached the target endpoint. Vegetation on this area is comparable to the surrounding vegetation, the soils in the upper rooting zone meet SPIGEC criteria, and the groundwater although saline is comparable to background water quality.

The tile systems at Hastings and on the east side of Willmar should continue to be operated. Currently the upper rooting zones of these sites do not meet SPIGEC criteria. When the upper rooting zone has no areas of moderately strong or strong salinity then the target endpoint for the rooting zone soil has been met. At this time the vegetation type and vigor on these areas should be consistent with the non-saline areas. There will still be salts in the soil at lower depths which do not meet SPIGEC criteria, but if the risk of these salts moving up into the rooting zone is low then vegetation growth will not be affected.

It may not be possible to reach SPIGEC water criteria in the groundwater under the tile systems. Salinity at Hastings and on the east side of Willmar is very high. In this case, salts can be left in-situ as long as the risk of the groundwater migrating into the rooting zone is low. Engineered controls may be necessary (i.e. filling in the slough at Hastings) to ensure the groundwater depth is maintained >2 mbgs.

4.8 Conclusions

The hypothesis was that sub-surface tile drainage systems combined with calcium amendments and forage will remediate brine-contaminated soil. The evaluation of the two tile drainage sites in this thesis showed that the hypothesis is true.

Hastings and the east side of Willmar are in an intermediate stage of remediation and the west side of Willmar has completed remediation. Prior to remediation, the ground surface was bare but now it is completely re-vegetated. The calibrated EM maps confirm that there are still saline soils at Hastings and on the east side of Willmar. The groundwater levels and chemistry confirm that the groundwater under the tile systems is still saline and is <2 mbgs at times during the year.

The tile systems have been effective at removing salts from the soil. This is evident in the change in EM31 between 2001 and 2010 and in the absence of bare areas. The tile systems have also been effective at maintaining a water level below the rooting zone and this is important especially since the groundwater is saline.

Therefore there is a high potential for re-salinization of the tiled area at Hastings and on the east side of Willmar if the culvert pumps are turned off. Even when leaching is complete in the rooting zone if the groundwater is still saline there is risk that the site will re-salinize. Additional remediation work and/or engineered controls may be necessary to minimize the risk for saline water to rise into the rooting zone.

On the west side of Willmar, the EM mapped very little saline soil areas and this was confirmed during soil sampling and through the forage inspection. Alfalfa growth on the west side was excellent. Groundwater salinity was at or near background salinity levels on the west side and the depth groundwater was >2 m. There is less chance of the west side to re-salinize if the pumps were turned off.

4.9 Recommendations

The remediation practices have been effective and should continue. The tile systems should be operated, the forage should be maintained, and more calcium nitrate should be added. To speed up the time to reach target endpoint, the moderately strong/strongly saline area at Hastings could be back-flooded. This would increase the number of leaching events and flush more salts from the soil. At Willmar there are salts migrating from the battery and the tiles on the east side are intercepting the salts. Until the source of the salts can be identified and removed, no additional remediation is recommended.

5.0 LEACHING EXPERIMENT

The goal of the leaching experiment was to examine the effect of various rates and combinations of calcium nitrate, gypsum, and straw on the remediation of a saline-sodic soil. The amendment types and rates were based on SPIGEC recommended remediation guidelines (SPIGEC 1999a), remediation strategies already in use in the field (see Chapter 3 of this thesis), and commonly accepted methods of calculating amendment rates (Karamanos 1996). The hypothesis was that calcium nitrate was a better calcium sourced amendment compared to gypsum due to its greater solubility and therefore the potential to infiltrate into the soil more effectively and replace more Na^+.

5.1 Materials and Methods

Soil samples from the 0 to 15 cm layer were taken from Hastings and Willmar in southeastern Saskatchewan, June, 2011 (see Chapter 4, Figures 4.5 and 4.25 for soil sample locations). The samples were taken from uncontaminated areas. Moisture content of the soil was measured by weighing a container of soil in the field (U.S. Salinity Laboratory Staff 1954) (Table 5.1). The soil was dried in an oven set at 104^0C for 24 hours, weighed, and the moisture content measured using the formula:

$$Ww\text{-}Wd/Wd$$

where Ww is the weight of the wet soil and Wd is the weight of the dry soil

The field bulk density was determined by collecting the soil from the soil auger to a known depth and weighing it in the field (Zwarich et al. 1969) (Table 5.1). The dry weight of the soil was calculated by adjusting the field weight for the moisture content of the sample depth. The volume of soil was calculated from the depth of the sample interval and the width of the soil auger (6.25 cm).

$$Db = Wd/Volume$$

Table 5.1 Physical properties of Hastings and Willmar soil samples

Site	Depth (cm)	H_2O Content	ρ_b (g cm^{-3})	% sand	% silt	% clay	Texture	CEC
Hastings	0-15	0.16	1.11	6	73	21	Silt loam	34
Willmar	0-15	0.07	1.24	61	20	19	Sandy loam	17

The soil was air-dried and ground to 2 mm. Percent sand, silt and clay were determined using the pipette method (Sheldrick and Wang 1993) (Table 5.1). Soil samples were sent to Exova, Edmonton, AB for CEC determination by ammonium acetate (Carter 2007) (Table 5.1).

Brine from the Hastings oil field was analyzed by Maxxam Analytics Inc., Calgary, AB. Sulphate (SO_4^{2-}) and chloride (Cl^-) concentrations were analyzed by automated colorimetry and calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+) concentrations were analyzed by inductively coupled plasma (ICP)(Varian Vista Pro manufactured in Australia by Varian)(Table 5.2).

Table 5.2 Chemical properties of Hastings brine

Parameter	Units	Brine
Na	mg L^{-1}	98,000
Mg	mg L^{-1}	1,500
Ca	mg L^{-1}	5,500
Cl	mg L^{-1}	160,000
SO4	mg L^{-1}	1,200
EC	dS m^{-1}	>200
pH		6.9

Some of uncontaminated soil taken from Hastings and Willmar was saturated with Hastings brine and left to equilibrate for 24 hours. The soil was removed from the brine, drained, air-dried, and ground to 2 mm. A sample of uncontaminated soil and a sample of the soil contaminated with brine were sent to Exova in Edmonton, Alberta for chemical analysis (Carter 2007) (Table 5.3).

Table 5.3 Chemical properties of uncontaminated and brine-contaminated soil

Parameter	Units	Hastings - uncontaminated	Willmar - uncontaminated	Hastings - contaminated	Willmar - contaminated
EC	dS m^{-1}	2.88	0.65	195	147
SAR		0.6	0.2	172	142
pH		7.6	7.8	6.7	6.9
Na	mg kg^{-1}	42	4	37,000	21,600
Mg	mg kg^{-1}	151	19.2	1,230	740
Ca	mg kg^{-1}	358	47.7	4,000	2,660
Cl	mg kg^{-1}	8	11	70,800	41,500
SO4	mg kg^{-1}	470	8.3	340	120
NO3	mg kg^{-1}	3.7	<3	10.5	4

The experimental design was a completely randomize design (CRD) with nine treatments and 4 replicates per treatment. The experiment was prepared for the Hastings soil and the Willmar soil (Tables 5.4 & 5.5).

Table 5.4 Treatments and amendment rates for Hastings

	Treatments	Soil (g)	Straw (g)	$Ca(NO_3)_2$ (g)	Gypsum (g)
1	Control	250	-	-	-
2	Straw (field rate)	250	3.1	-	-
3	Gypsum (max. SPIGEC rate)	250	-	-	17.3
4	Calcium Nitrate (max. SPIGEC rate)	250	-	0.5	-
5	Theoretical Gypsum Requirement (TGR)	250	-	-	3.6
6	Theoretical Calcium Nitrate Requirement (TCNR)	250	-	5	-
7	TGR + Straw	250	3.1	-	3.6
8	TCNR + Straw	250	3.1	5	-
9	Calcium Nitrate (high rate)	250	-	24	-

Table 5.5 Treatments and amendment rates for Willmar

	Treatments	Soil (g)	Straw (g)	$Ca(NO_3)_2$ (g)	Gypsum (g)
1	Control	250	-	-	-
2	Straw (field rate)	250	3.1	-	-
3	Gypsum (max. SPIGEC rate)	250	-	-	17.3
4	Calcium Nitrate (max. SPIGEC rate)	250	-	0.5	-
5	Theoretical Gypsum Requirement (TGR)	250	-	-	1.9
6	Theoretical Calcium Nitrate Requirement (TCNR)	250	-	2.5	-
7	TGR + Straw	250	3.1	-	1.9
8	TCNR + Straw	250	3.1	2.5	-
9	Calcium Nitrate (high rate)	250	-	24	-

The following is a description of each of the treatments from Tables 5.4 and 5.5:

1. Control – Brine-contaminated soil with no amendments added.
2. Straw – Brine-contaminated soil with straw added. The amount of straw added was calculated based on a field rated of 1 round bale for 500 m^2 with the average weight of a bale as 400 kg.
3. Gypsum – Brine-contaminated soil with the maximum amount of gypsum added as per Saskatchewan Government guidelines. SPIGEC Guidelines allows for a maximum of 45 t h^{-1} (SPIGEC 1999a).
4. Calcium Nitrate - Brine-contaminated soil with the maximum amount of calcium nitrate added as per Saskatchewan Government guidelines. SPIGEC Guidelines allows for a maximum of 1.135 t h^{-1}.
5. Theoretical Gypsum Requirement (TGR) – The theoretical gypsum requirement is the amount of gypsum needed to supply enough Ca^{2+} to replace all the Na^{+}. This amount of gypsum was added to the brine-contaminated soil. In comparison to the SPIGEC rate, it is 79% less gypsum in the Hastings soil and 89% less gypsum in the Willmar soil.
6. Theoretical Calcium Nitrate Requirement (TCNR) - The theoretical calcium nitrate requirement is the amount of calcium nitrate needed to supply enough Ca^{2+} to replace all the Na^{+}. This amount of calcium nitrate was added to the brine-contaminated soil. In comparison to the SPIGEC rate, it is a 10 fold increase in calcium nitrate in the Hastings soil and a 5 fold increase in calcium nitrate in the Willmar soil.
7. TGR + Straw – Brine contaminated soil with the TGR plus the field rate of straw added.
8. TCNR + Straw – Brine contaminated soil with the TCNR plus field rate of straw added.
9. High Rate Calcium Nitrate – The maximum allowable amount of gypsum (treatment 3) was converted to an equivalent amount of calcium nitrate (supplying the same Ca^{2+}) and this rate of calcium nitrate was added to the brine-contaminated soil.

The rationale for the various amendments was to evaluate their effectiveness in reducing SAR and the risk for soil dispersion during the leaching process to remediate brine contaminated soils. The amendments chosen were those commonly utilized by industry.

The theoretical gypsum requirement (TGR) was calculated using the formula (Karamanos 1996):

$$TGR = \frac{ESP_i - ESP_f}{100} \times CEC \times \rho_b \times D_{soil} \times A$$

where exchangeable sodium percentage $(ESP)_i$ is the initial ESP, ESP_f is the final ESP, CEC is the cation exchange capacity in cmol(+)kg^{-1}, ρ_b is the bulk density in kg m^{-3}, D_{soil} is the depth of soil to be reclaimed in m, and A is the area in m^2. An ESP_f of 15 was used.

The ESP was estimated using the formula (Karamanos 1996):

$$\frac{ESP}{(100 - ESP)} = 0.015(SAR)$$

The SAR was calculated using the formula:

$$SAR = \frac{Na^+}{\sqrt{\frac{1}{2}\left(Ca^{2+} + Mg^{2+}\right)}}$$

where Na^+, Ca^{2+}, and Mg^{2+} are the concentrations (in mmol$_c$ L)

The theoretical calcium nitrate rate (TCNR) was calculated from the TGR assuming equivalent amounts of Ca^{2+} are needed to replace the Na^+. The molecular weight of $Ca(NO_3)_2$ is 236 g/mol compared to 172 g/mol of gypsum.

All treatments were prepared by measuring out 250 g of soil, adding the appropriate amount of amendment(s) (Table 5.4 and 5.5), mixing well, and packing in the core. Gypsum and calcium nitrate were ground and passed through a 0.85 mm sieve and wheat straw was chopped to 2 mm using a Wiley mill.

The soil cores were made from sections of PVC pipe with a 7 cm inside diameter, 15 cm height, and a screen glued on the bottom. Grease was spread around the inside edges of the core to minimize by-pass flow. A core packer, developed by the University of Manitoba Biosystems Engineering Department, was used to pack the core to a bulk density consistent with that observed in the field (Sri Ranjan 1993).

The cores were saturated by placing them in a distilled water bath for 24 hours. The cores were removed, placed in individual leaching stations, and allowed to drain for 24 hours. The leaching station consisted of the core placed in a funnel. The funnel end was placed through a small hole in a wood board with the lower end inserted in the leachate container. Filter paper was put on the soil surface to minimize compaction from the water and to ensure the whole surface of the core would be saturated. Distilled water was gently poured on the soil core using a funnel. When 100 mL of leachate drained from the core, it was collected and the EC and pH were measured. This procedure was repeated four times. During the experiment, the cores were kept in plastic bags to minimize evaporation.

At the conclusion of the experiment, all leachates and soil cores were sent to Maxxam Analytics Inc. The leachates were analyzed for routine water quality parameters (major ions, pH, EC) and the soil was analyzed for salinity (major ions, pH, EC, SAR).

The soil was analyzed using the PROC MIXED procedure in SAS (SAS Institute 2008) with treatment as a fixed effect and rep and rep by treatment as random effects. EC, time, Cl^-, and SO_4^{2-} were $\log_e$-transformed and SAR and Ca^{2+} were square root transformed prior to analysis to meet assumptions of normality (Shapiro Wilk's test). Treatment differences were consider significant if $P < 0.05$ using the Tukey-Kramer method.

Leachate was analyzed using the PROC MIXED procedure in SAS (SAS Institute 2008) with treatment as a fixed effect, rep and rep by treatment as random effects, and volume as a repeated measure. The spatial power [SP(POW)] covariance structure was used in the model for these repeated measure data. Ca^{2+}, $N0_3^-$, Na^+, EC, Cl^-, and time were $\log_e$-transformed and SO_4^{2-} was square root transformed prior to analysis to meet assumptions of normality (Shapiro Wilk's test). Treatment differences were consider significant if P <0.05 using the Tukey-Kramer method.

5.2 Results and Discussion

Analysis of Variance (ANOVA) tables from the soil at the end of the leaching experiment are presented in Tables 5.6 and 5.7. The brine-contaminated soil at Hastings and Willmar was saline-sodic which, by definition, must have an EC >4 dS m^{-1} and a SAR >13. The EC and SAR are discussed in detail in the subsequent sections as changes in these parameters confirmed whether the leaching experiment was successful at remediating the saline-sodic soils. The leaching time is also discussed as it was a predictor of the final SAR. The other parameters analyzed, although not discussed specifically, are shown in Tables 5.6 and 5.7.

Table 5.6 ANOVA Hastings soil

Site	Treatment	EC	SAR	Time	pH	Cl^-	SO_4^{2-}	Na^+	Ca^{2+}
Hastings	1	1.7*bc*	19.4*a*	40.5*a*	8.60*ab*	274*a*	98*de*	375*abc*	20*d*
	2	1.1*d*	12.4*bc*	20.2*b*	8.50*abc*	92*b*	79*e*	268*bc*	25*d*
	3	3.8*a*	3.9*d*	0.51*d*	7.86*e*	26*cd*	2541*a*	378*abc*	572*a*
	4	1.9*b*	20.4*a*	34.9*a*	8.65*a*	263*a*	169*c*	475*a*	29*d*
	5	3.1*a*	5.5*d*	0.89*c*	7.93*e*	23*d*	1770*a*	400*ab*	332*b*
	6	1.3*cd*	16*ab*	40.5*a*	8.62*ab*	109*b*	135*cd*	353*abc*	26*d*
	7	1.6*bc*	9.2*c*	0.72*cd*	8.21*d*	28*cd*	693*b*	303*bc*	60*c*
	8	1.1*d*	12*bc*	18.4*b*	8.30*cd*	46*c*	106*de*	305*bc*	32*cd*
	9	1.1*d*	11.1*c*	0.96*c*	8.42*bc*	42*c*	131*cd*	355*c*	29*d*
		P value							
		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0002	<0.0001

*means with different letters are statistically different (P<0.05 Tukey-Kramer)

Table 5.7 ANOVA Willmar Soil

Site	Treatment	EC	SAR	Time	pH	Cl^-	SO_4^{2-}	Na^+
Willmar	1	2.3*a*	20.8*a*	60.9*a*	8.39*a*	462*a*	94*cd*	475*a*
	2	1.6*b*	15.2*abc*	37.6*b*	8.23*bc*	241*ab*	83*cd*	300*b*
	3	2.9*a*	0.3*f*	0.23*d*	7.93*e*	45*ef*	1949*a*	31.5*e*
	4	1.3*bc*	16.2*ab*	54.1*ab*	8.36*a*	154*bc*	101*c*	275*bc*
	5	1.1*cd*	9.4*cde*	0.56*c*	8.24*bc*	59*def*	322*b*	200*cd*
	6	1*cde*	13.7*cde*	54.4*ab*	8.32*ab*	109*cd*	88*cd*	227.5*bcd*
	7	0.8*de*	7.6*e*	0.44*c*	8.11*d*	51*ef*	257*b*	160*d*
	8	0.8*e*	8.7*de*	36.9*b*	8.15*cd*	30*f*	64*d*	160*d*
	9	1*cde*	8*e*	0.11*e*	8.16*cd*	84*cde*	115*c*	165*d*
		P value						
		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

*means with different letters are statistically different (P<0.05 Tukey-Kramer)

5.2.1 Effect of gypsum on Hastings soil

After four leaching events, the EC was reduced from 195 to <4 dS m^{-1} in all gypsum treatments and in the control (Figure 5.1). However, only the gypsum treatments had a final SAR <13 (Figure 5.2). Treatments 3 and 5 (gypsum – no straw) had a significantly lower SAR than the gypsum treatment with straw (Figure 5.2). There was no difference between the high rate of gypsum (trt 3) and the theoretical gypsum rate (trt 5).

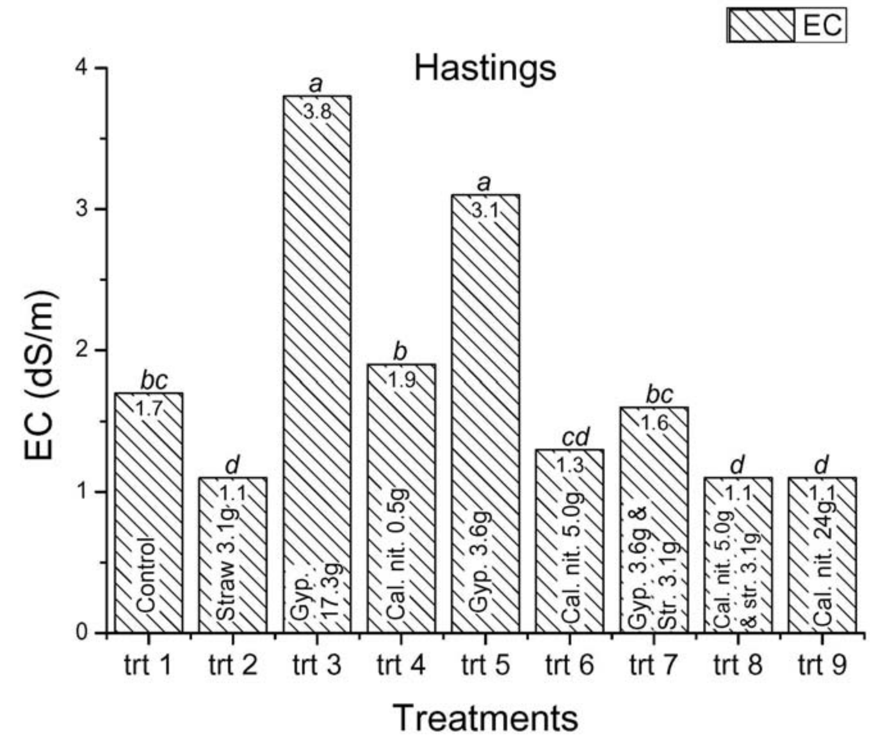


Figure 5.1 Final EC in Hastings soil

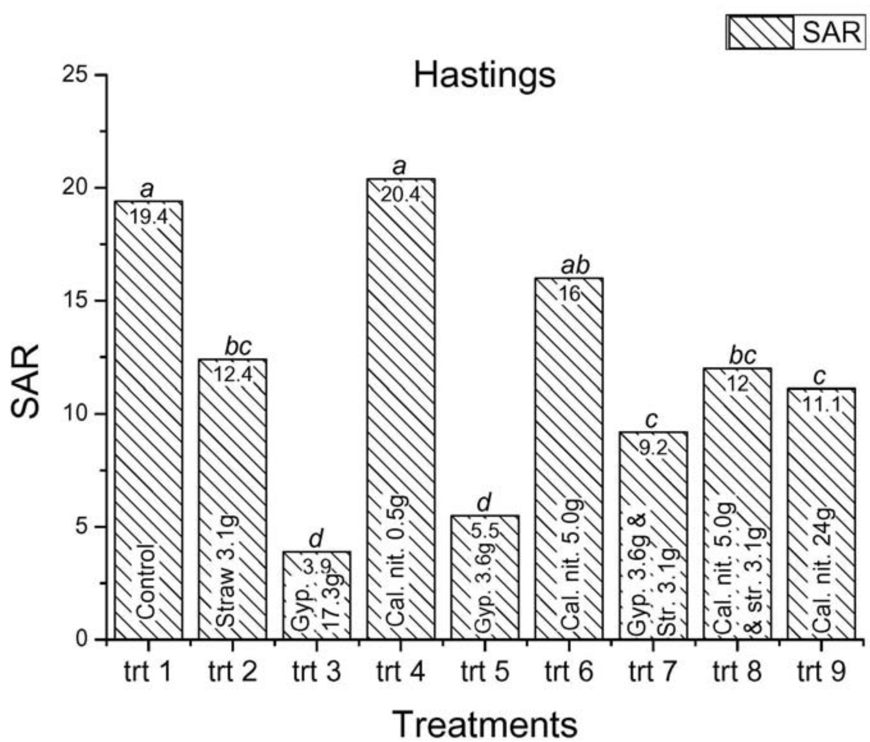


Figure 5.2 Final SAR in Hastings soil

5.2.2 *Effect of calcium nitrate on Hastings soil*

After four leaching events the calcium nitrate treatment was effective at reducing the EC from 195 to <4 dS m^{-1} (Figure 5.1). The highest rate of calcium nitrate (trt 9) and the theoretical calcium nitrate rate with straw (trt 8) were the only treatments which significantly reduced SAR compared to the control (Figure 5.2). A higher concentration of calcium nitrate than the maximum SPIGEC rate (trt 4) was needed to reduce the SAR. The high rate of calcium nitrate (trt 9) was significantly better in reducing the SAR to less than 13.

5.2.3 *Comparison of the effect of gypsum and calcium nitrate on SAR on Hastings soil*

All treatments significantly reduced the SAR from 172 to <21. The maximum SPIGEC rate for gypsum significantly reduced the SAR to <13 while the maximum SPIGEC calcium nitrate rate was not significantly different than control (Figure 5.2). Differences in the effectiveness of treatments 3 and 4 were directly related to the amount of calcium amendment added. The maximum allowable rate of gypsum is 17 times higher than the maximum allowable rate of calcium nitrate. The amount of calcium added in treatment 4 was not enough to reduce the SAR. The calcium nitrate in treatment 4 was not significantly better than the control while gypsum in treatment 3 significantly reduced the SAR to within the SPIGEC criteria for topsoil.

When a higher rate of calcium nitrate (trt 9) was used the SAR result was significantly lower than the SPIGEC rate but not as effective as gypsum (Figure 5.2). Equivalent amounts of Ca^{2+} were added to treatments 3 and 9 but the final SAR's were significantly different. The final SAR of treatment 3 was significantly lower than the final SAR of treatment 9. As well, the amount of Ca^{2+} remaining in the soil in treatment 3 was also significantly higher than treatment 9. Therefore, even though both treatments had the same amount of Ca^{2+} added, most of the Ca^{2+} in the calcium nitrate was leached from the soil. The Ca^{2+} remaining in the soil of treatment 3 was the main reason the SAR of this treatment was lower than treatment 9.

Powdered gypsum and calcium nitrate were mixed into air-dried soil before the soil was packed into soil cores. The soil was hydrated and then the leaching began. The solubility's of calcium nitrate and gypsum are 121 g and 0.24 g, respectively, in 100 mL H2O at 25 ^{o}C (National Gypsum 2009; Hy-Valley Chemical Inc. 2006). The 24 g of calcium nitrate added to treatment 9 would need approximately 20 mL of water to dissolve. It took more than 20 mL to hydrate the air-dried soil core before the leaching began. Therefore all the calcium nitrate was dissolved in the soil prior to the first leaching. To dissolve the 17.3 g of gypsum added to treatment 3, 7,208 mL of water would be needed. The solubility of gypsum (or any salt) is increased when the solution is saline (Oster 1982). Oster (1982) suggested a threefold increase in gypsum solubility. Assuming this increase in solubility, 2,402 mL of water would dissolve the gypsum. There was 400 mL of water leached through the Hastings soil; much less than was needed to dissolve all the gypsum.

If the calcium nitrate in treatment 9 (highest rate) was completely dissolved prior to the start of the leaching, it is probable that all of the Ca^{2+} was removed from the soil during the early leaching events and did not have time to complete the exchange process, thus accounting for the residual high SAR (Figure 5.2). More Ca^{2+} was present in the first two leaching volumes of treatment 9 while more Ca^{2+} was present in the final two volumes of treatment 3 (Table 5.8 and Figure 5.3).

Table 5.8 ANOVA of calcium concentration (mg L-1) in the Hastings leachates

Site	Treatment	1st 100 mL	2nd 100 mL	3rd 100 mL	4th 100 mL
Hastings	1	4,319*c*	4,814*bc*	139*de*	43*b*
	2	4,247*c*	4,726*bc*	333*c*	44*b*
	3	5,794*bc*	3,325*c*	1,423*a*	391*a*
	4	5,513*bc*	4,413*bc*	87*de*	41*b*
	5	5,127*bc*	4,293*c*	162*d*	29*b*
	6	8,796*b*	8,194*ab*	76*e*	38*b*
	7	5,022*bc*	4,186*c*	956*ab*	49*b*
	8	7,502*bc*	9,435*a*	515*bc*	39*b*
	9	32,464*a*	10,050*a*	112*de*	48*b*
		P value			
		<0.0001	<0.0001	<0.0001	<0.0001

*means with different letters are statistically different (P<0.05 Tukey-Kramer)

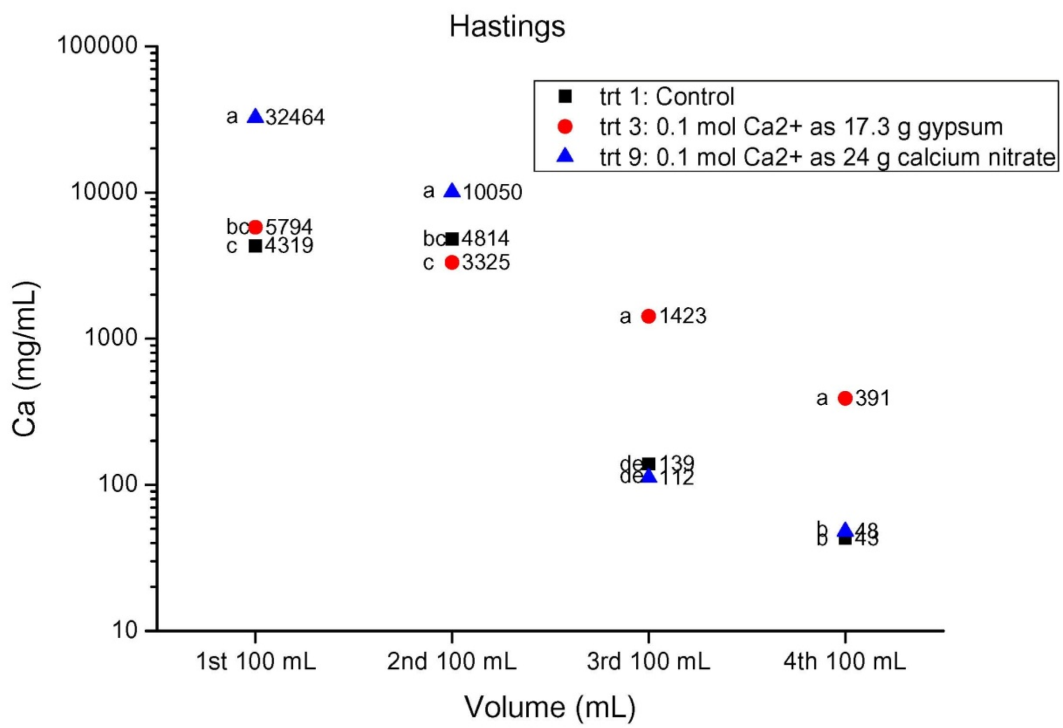


Figure 5.3 Concentration of Ca^{2+} in the leachates after each of the four leaching volumes of 100 mL

In treatment 3, not enough water was added to dissolve all of the gypsum, thus gypsum was present throughout the leaching allowing more time for exchange, resulting in a lower SAR at the end of 4 leaching events (Figure 5.3). It is likely that some of the gypsum still remained in the soil after the leaching process.

5.2.4 Comparison of the effect of gypsum and calcium nitrate on leaching time on Hastings soil

The treatments with the maximum rates of gypsum and calcium nitrate (trts 3 and 9, respectively) had significantly faster leaching times than the control and maximum SPIGEC calcium nitrate rate (trts 1 and 4, respectively) (Figure 5.4). Interestingly, the treatments with the fastest leaching times also had the lowest final SAR. This is an important finding for remediation planning because leaching must be faster than evaporation for net leaching to occur. All gypsum treatments were faster than calcium nitrate with the exception of treatment 9 (Figure 5.4).

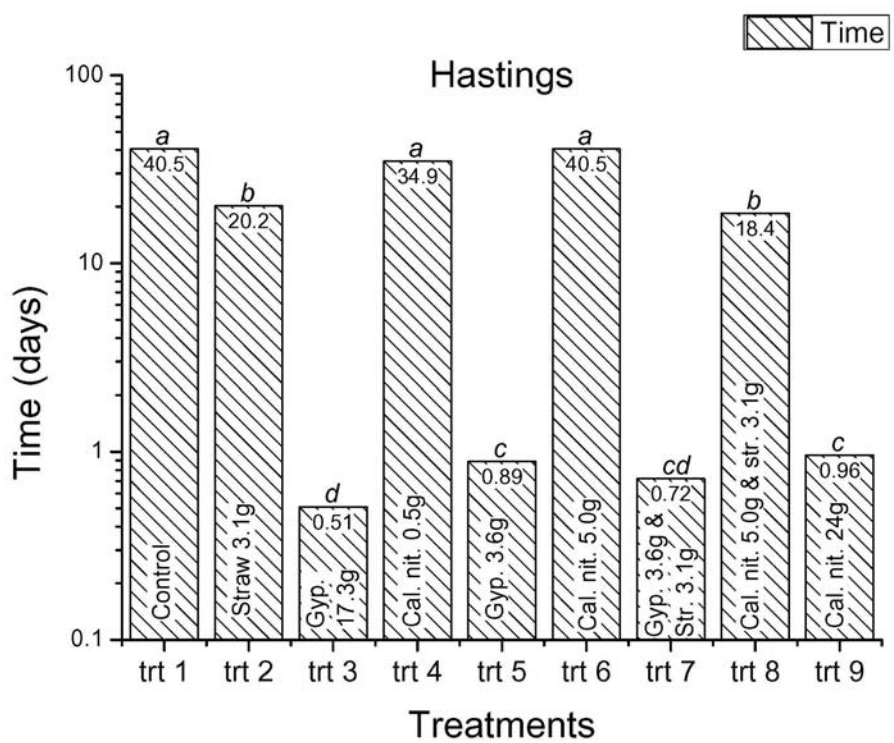


Figure 5.4 Total leaching time in Hastings soil

5.2.5 Effect of straw on Hastings soil

After four leaching events, the treatments with straw showed significantly lower EC and SAR than the control (Figures 5.1 and 5.2). Straw likely increased permeability and facilitated leaching resulting in a lower EC. The lower SAR for the straw treatment could be a result of improved natural cation exchange with the Ca^{2+} already naturally present in the soil (Table 5.3).

Most soils in southeastern Saskatchewan are moderately to highly calcareous (Saskatchewan Soil Survey 1997) and thus have a naturally occurring source of calcium (Table 5.3). Adding straw to a brine-contaminated soil would be more effective than adding no amendments.

5.2.6 Effect of straw combined with gypsum or calcium nitrate on Hastings soil

At the end of four leaching events, the EC was well within remediation guides for all treatments (Figure 5.1). The addition of straw alone (Trt 2) showed significantly lower EC over the control; however the addition of gypsum with straw (Trt 7) showed no improvement over the control, while the addition of calcium nitrate with straw showed no improvement over the straw (Figure 5.1). All the treatments with straw (with and without chemical amendments) significantly decreased SAR compared to the control but there was no significant difference between the treatments (Figure 5.2).

5.2.7 Effect of straw on leaching time on Hastings soil

The addition of straw significantly decreased leaching time compared to not only the control but also the calcium nitrate treatments 4 and 6 (Figure 5.4). Only the gypsum treatments and the high rate of calcium nitrate (trt 9) had significantly faster leaching times compared to straw.

5.2.8 Effect of gypsum on Willmar soil

After four leaching events on the more sandy Willmar soil, all gypsum treatments and the control reduced the EC from 147 to <4 dS m^{-1} (Figure 5.5). Only the treatments with gypsum had a final SAR <13 (Figure 5.6). Treatment 3 with the most gypsum had a significantly lower SAR than the theoretical gypsum treatments (Figure 5.6).

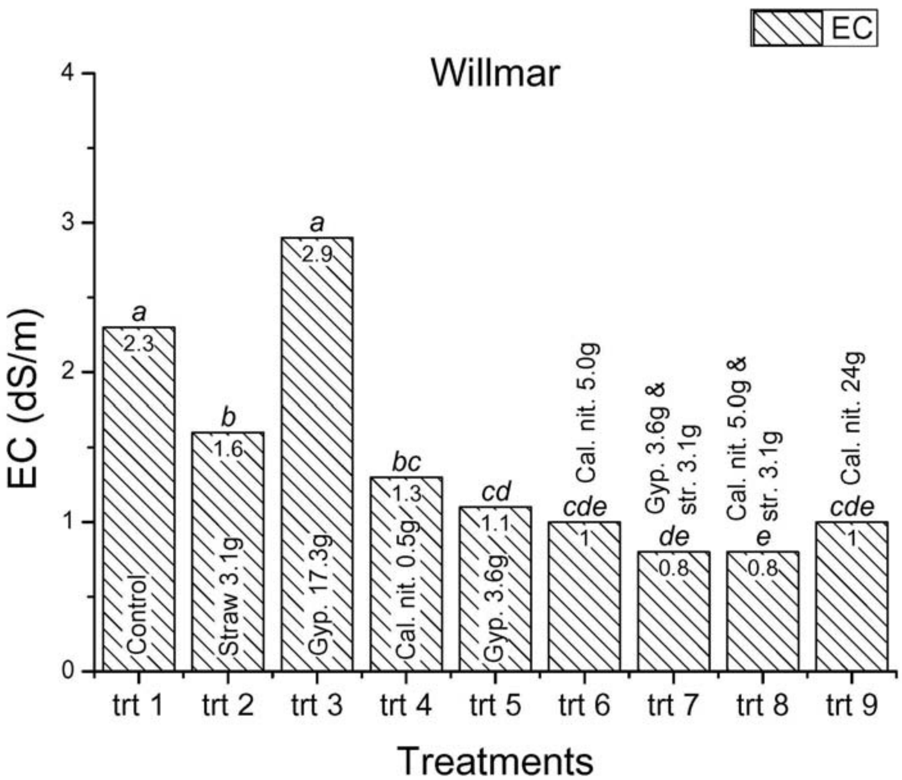


Figure 5.5 Final EC in Willmar soil

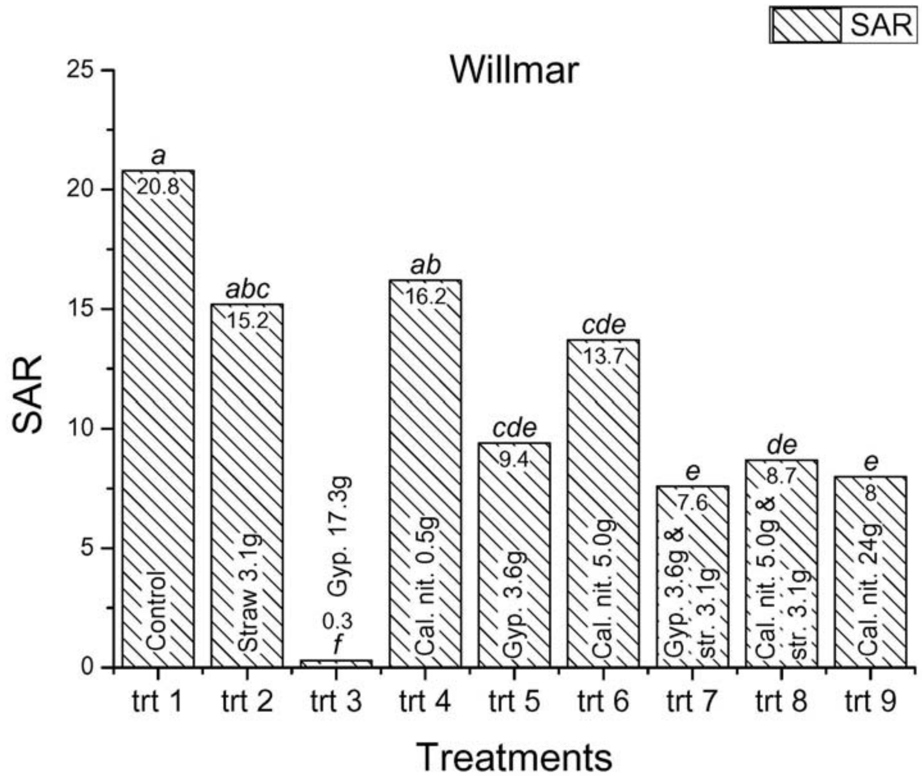


Figure 5.6 Final SAR in Willmar soil

5.2.9 Effect of calcium nitrate on Willmar soil

The leaching process effectively lowered the EC to <4 dS m^{-1} and there was little difference between any of the calcium nitrate treatments (Figure 5.5). Only the highest rate of calcium nitrate (trt 9) and the theoretical calcium nitrate with straw rates significantly reduced SAR <13 (Figure 5.6). The SPIGEC calcium nitrate rate (trt 4) was not sufficient to lower SAR below 13; however, all treatment and control reduced the SAR from 142 to <21.

5.2.10 Comparison of the effect of gypsum and calcium nitrate on SAR on Willmar soil

Differences between the SAR of maximum SPIGEC rate of gypsum and calcium nitrate were similar to the Hastings soil (see 5.2.3 for further explanation). The SPIGEC rate of calcium nitrate did not supply enough Ca^{2+} to reduce the SAR to <13 while the maximum SPIGEC gypsum rate was effective (Figure 5.6). Differences in the effectiveness of treatments 3 and 4 were directly related to the amount of amendment added. The higher rate of calcium nitrate (trt 9) significantly reduced the SAR but was not as effective as gypsum (trt 3) (Figure 5.6). The calcium nitrate was not as effective since Ca^{2+} leached from the soil before exchanging resulting in a higher concentration of Ca^{2+} in the first leaching volumes than the gypsum treatment (Table 5.9 and Figure 5.7).

Table 5.9 ANOVA of calcium concentration ($mg\ L^{-1}$) in the Willmar leachates

Site	Treatment	1st 100 mL	2nd 100 mL	3rd 100 mL	4th 100 mL
Willmar	1		1,284*bc*	59*cd*	35*c*
	2	3,998*d*	2,096*b*	62*cd*	35*c*
	3	5,899*bcd*	762*cd*	495*a*	595*a*
	4	5,849*bcd*	1,234*bc*	54*d*	29*c*
	5	5,821*bcd*	661*d*	135*b*	98*b*
	6	8,567*b*	1,899*b*	55*d*	38*c*
	7	5,597*bcd*	961*cd*	69*cd*	115*b*
	8	7,793*bc*	1,949*b*	57*cd*	34*c*
	9	29,071*a*	5,455*a*	99*bc*	36*c*
		P value			
		<0.0001	<0.0001	<0.0001	<0.0001

*means with different letters are statistically different (P<0.05 Tukey-Kramer)

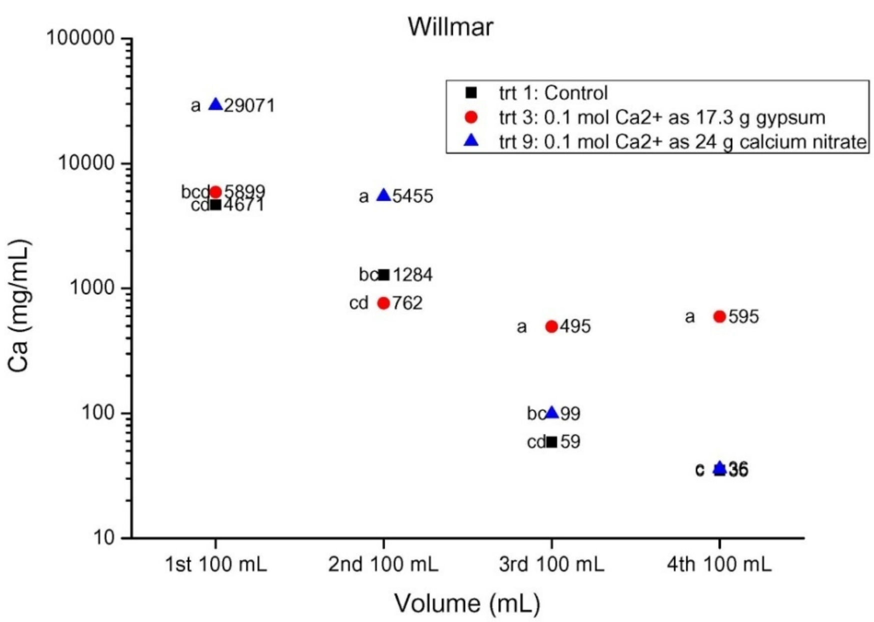


Figure 5.7 Concentration of Ca^{2+} in the leachates after each of the four leaching volumes

5.2.11 Comparison of the effect of gypsum and calcium nitrate on leaching time on Willmar soil

The gypsum treatments and the higher rate of calcium nitrate were significantly faster (Figure 5.8). Like Hastings, leaching times were fastest on the treatments with the lowest final SAR since the Ca^{2+} exchanged Na^{+}, lowered the SAR, and prevented dispersion.

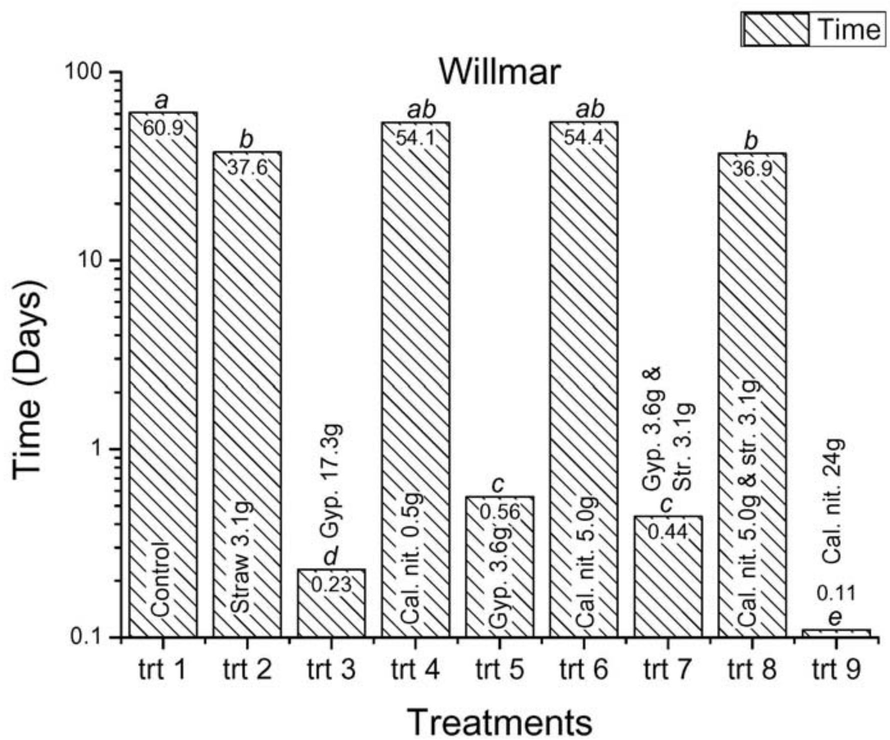


Figure 5.8 Total leaching time in Willmar soil

5.2.12 Effect of straw on Willmar soil

The straw alone treatment (trt 2) resulted in a significantly lower EC (Figure 5.5) but did not significantly decrease the SAR (Figure 5.6). The straw likely increased permeability and facilitated leaching of salts, and thus decreased the EC. Unlike the soil at Hastings where the SAR was significantly reduced, the straw did not have any effect on the SAR. This may be due to less naturally occurring calcium in the soil compared to the Hastings soil (Table 5.3).

5.2.13 Effect of straw combined with gypsum or calcium nitrate on Willmar soil

The straw was effective in significantly lowering EC with and without a chemical amendment (Figure 5.5). The SAR was significantly decreased only when the straw was combined with either gypsum or calcium nitrate (Figure 5.6).

5.2.14 Effect of straw on leaching time on Willmar soil

Like Hastings the addition of straw significantly decreased leaching time compared with the control (Figure 5.8). Unlike Hastings the straw was not significantly different from the calcium nitrate treatments 4, 6 and 8. The gypsum treatments and treatment 9 (high rate of calcium nitrate) were significantly faster.

5.3 Conclusions

Without any amendments, distilled water, reduced the EC from 195 dS m^{-1} at Hastings and 147 dS m^{-1} at Willmar to non-saline levels (<4 dS m^{-1}) in the brine-contaminated soil. SAR was also significantly reduced, from 172 at Hastings and 142 at Willmar, but only treatments with amendments reduced the SAR to <13. Gypsum was the most effective amendment: both the maximum SPIGEC gypsum rate (trt 3) and the theoretical gypsum rate (trt 5) significantly reduced the SAR. The maximum SPIGEC calcium nitrate rate (trt 4) was not effective nor was the theoretical calcium nitrate rate (trt 6). Only the high rate of calcium nitrate (trt 9), which was equivalent to the maximum SPIGEC gypsum rate was effective at reducing the SAR.

The straw treatment (trt 2) significantly lowered the EC and resulted in faster leaching compared to the control. When straw was combined with the theoretical calcium nitrate and gypsum rates (trts 7 and 8, respectively) the SAR was reduced to <13 in the theoretical calcium nitrate compared to theoretical calcium nitrate without straw (trt 6). The straw had no effect on the theoretical gypsum rate because the theoretical gypsum rate without straw (trt 5) was better than straw alone (trt 2).

The hypothesis that calcium nitrate was a better calcium sourced amendment compared to gypsum found to be null in this experiment. Calcium nitrate was less effective than gypsum due to its solubility. All of the calcium nitrate dissolved when the soil cores were hydrated and the Ca^{2+} leached from the core in the first leaching event before exchanging Na^{+}.

In contrast, gypsum dissolved slowly, allowing for Ca^{2+} to exchange with Na^{+} in each leaching event and therefore resulting in a lower final SAR.

6.0 EVALUATION OF FIELD AND LABORATORY RESULTS

Brine from spills and historic oilfield activity has created salt-affected soil in southeastern Saskatchewan. One remediation option was to install a sub-surface tile drainage system to remove the salts from the soil, grow forage on the tiled area, and apply calcium-sourced amendments to the soil surface. Calcium nitrate was the calcium-sourced amendment used and it was applied to the surface to provide Ca^{2+} to exchange with Na^{+} and to mitigate dispersion. Forage was established to promote infiltration and leaching of the salts.

The goal of this thesis was to evaluate the field remediation practices by examining the effect of the tile drainage systems and the effect of common amendments. Two tile drainage systems were examined in a field study and the common amendments (calcium nitrate, gypsum, and straw) were compared in a laboratory leaching experiment.

The two tile drainage systems examined in this study have been effective. Areas that were once bare now support alfalfa or saline-tolerant grasses. The tiled areas were evaluated using climatic, landscape, pedological, EM, soil, and groundwater data. The results determined that the tiles are in an intermediate stage of remediation.

Natural leaching from precipitation had flushed the majority of the salts from the upper rooting zone (0-60 cm); however, not all the salts have flushed down. Some of the lower rooting zone (60-120 cm) is still saline but as the tile system continues to dewater the area these salts will be removed or leached below the rooting zone.

The groundwater under the tile system is saline and since its depth fluctuates within the rooting zone, the risk of re-salinization of the tiled areas is still high if the tile system is not operated.

The effect of common amendments used for the treatment of salt-affected soils was studied and included the amendments calcium nitrate, gypsum and straw. Different amendment rates were chosen based on the Saskatchewan Government guidelines (SPIGEC 1999a) and based on the theoretical amount of amendment needed to remediate the soil. When brine-contaminated soil was mixed with various amendments and distilled water leached through the soil, the EC and SAR were reduced. Even when no amendment was added to the soil, the EC was reduced to non-saline values and the SAR was significantly reduced.

The SPIGEC rate for gypsum was the highest rate of gypsum applied and the SPIGEC rate for calcium nitrate was the lowest rate of calcium nitrate applied. The SPIGEC rate for gypsum was effective while the SPIGEC rate for calcium nitrate was not. The theoretical rate of gypsum and calcium nitrate was lower than the SPIGEC gypsum rate and higher than the SPIGEC calcium nitrate rate. The theoretical gypsum rate was effective both with and without straw. The theoretical calcium nitrate rate was effective only with straw.

Gypsum was the most effective amendment with and without straw. Calcium nitrate was effective only when applied in a high enough concentration and in combination with straw. This concentration was higher than the maximum SPIGEC rate. Straw was found to aid infiltration and was more effective on the calcium nitrate treatments.

7.0 SYNTHESIS

The goal of remediation was to bring the soil to productivity equivalent to background areas in as short a time as possible by removing, containing or treating the contaminants (SPIGEC 1999b). In two key areas, the remediation practices have been very successful: dewatering of the tiles and establishing forage on the tiled area. In the third area, amendments, the remediation practices have room for improvement.

The success of the tile system was due to the removal of the saline soil water through the tile drains. The laboratory leaching experiment showed that even without amendments the majority of salts can be flushed out. The EC was reduced to non-saline values in all treatments including the control.

The tile's success was also due to the forage growth which had helped to increase infiltration and movement of saline soil water to the tile drains. The leaching experiment showed that the straw treatment was better than the control at increasing the infiltration rate. When organic matter such as the roots of plants in the field or the straw incorporated into the soil cores was added to the soil, the permeability was increased and salts were more quickly flushed out.

Based on the laboratory experiment results, the calcium nitrate applied to the surface of the tile system had not been as effective. The calcium nitrate was applied in the field at the maximum SPIGEC rate (SPIGEC 1999a). In the leaching experiment, this rate of calcium nitrate was not more effective than the control at reducing the SAR.

Although the SPIGEC calcium nitrate rate (SPIGEC 1999a) did not significantly reduce the SAR in the soil cores compared to the control, the SAR was significantly lower than the initial SAR values. Therefore even without a calcium sourced amendment, Ca^{2+} naturally present in the soil exchanged with Na^{+} to remediate the soil.

8.0 RECOMMENDATIONS

The remediation practices must continue to dewater the tile systems. This is the first and most important step. The salts must be flushed from the upper rooting zone and the groundwater level must be maintained below the rooting zone for forage to grow.

Second, forage must be established on the area. The forage will increase infiltration and flushing of the salts, trap snow in the winter, and look aesthetically pleasing. Broadcasting of forage seed should occur regularly until the area is fully vegetated.

Third, higher rates of calcium-sourced amendments need to be applied and gypsum should also be used. The SPIGEC rate (1999a) of calcium nitrate was not high enough while the SPIGEC gypsum rate was higher than necessary to remediate the soil. Based on the laboratory leaching experiment, the theoretical rates of calcium nitrate and gypsum worked best.

Gypsum was able to remediate the soil faster than calcium nitrate. Since the current remediation practices do not include gypsum, the most important change to the remediation practices is the recommendation of gypsum.

The tile system should continue to be operated until the salts are flushed from the upper rooting zone and the soil meets SPIFEC criteria (SPIGEC 1999b). At this time, if the groundwater is still saline, measures will be taken to mitigate the groundwater rising into the rooting zone.

8.1 Next step

A field-scale trial of this experiment should be undertaken using the rates and combination of amendments used in the laboratory experiment. The primary goal of the field experiment would be to see if the differences observed in the laboratory between the SPIGEC rates and the theoretical gypsum and calcium nitrate rates are also observed in the field.

There are differences which exist between the soil in the leaching experiment and the soil at the tile sites. These differences would be evaluated in a field study. The conclusions made in the laboratory leaching experiment should be tested in a field trial.

One distinct difference between the field and the laboratory is that the amendment in the leaching experiment was mixed into the whole core whereas in the field the amendment is applied on the surface. Literature on gypsum suggests that gypsum is not very mobile in the soil profile whereas more soluble salts like calcium chloride or calcium nitrate are mobile (Gupta and Singh 1988). Would the higher solubility of calcium nitrate help the Ca^{2+} to infiltrate the soil and possibly exchange more Na^{+}?

Another difference between the laboratory and the field is that the soil in the field may not have as high EC and SAR. Typically a saline-sodic soil would be dispersed (Bresler et al. 1982). The soil in the leaching experiment was not dispersed due to the electrolyte effect (Shainberg et al. 1982). The electrolyte effect only occurs when the EC is high. Once infiltration removes the ions and the EC falls, the soil will disperse if the SAR is still high. In the field, some soil will be dispersed. The effect of calcium nitrate or gypsum applied on the surface of a dispersed soil was not studied.

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10.0 APPENDIX

10.1 Water quality results and pump out volumes from 2003-2011

LSD	SEC	TWP	RNG	MER	Program Description/ Culvert Name	Date Sampled	Yearly Water Volume Disposed (M^3)	Routine/Indicator Parameters EC (µS/cm)	pH	TDS (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Na (mg/L)	DOC (mg/L)
10	10	4	34	1	Pit removed 2003									
					Tile installed 2003									
					Installed by CNRL									
					NORTH	Nov-03		84300	7.43	53200	32200	796	17300	NA
						Jun-04		59100	7.40	47000	26700	940	16000	NA
						Nov-05		26300	7.35	17100	9210	1440	5110	8.0
						May-06		30400	7.54	19000	10500	913	6050	5.8
					Tested for HC - no hydrocarbon s present	Aug-06		41600	7.76	23600	14500	570	6550	4.0
						Nov-06		50000	7.47	36600	21200	1080	11900	4.0
						Jun-07		47300	7.29	30500	17900	542	9940	7.0
						Nov-07		44000	7.72	33800	20700	692	10300	44.0
						May-08								
						Jul-08		46000	7.80	32000	19000	660	10000	101.0
						Oct-08								
						Nov-08	1							
						May-09								
						Jun-09								
						Jul-09								
						Aug-09		51000	7.35	48000	29000	780	16000	
						Sep-09								
						Oct-09	19							
						Jul-10	10				6000			
						Aug-10		42000	7.48	26700	15000	920	8200	
						Sep-10					5600			
						Oct-10								

								Routine/Indicator Parameters						
LSD	SEC	TWP	RNG	MER	Program Description/ Culvert Name	Date Sampled	Yearly Water Volume Disposed (M^3)	EC (µS/cm)	pH	TDS (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Na (mg/L)	DOC (mg/L)
						Aug-11		29000	7.27	18000	10000	830	5400	NA
				1		Oct-11		52000	7.61	33000	19000	910	11000	<10
10	10	4	34	1	**SOUTH**	Nov-03		55800	7.60	26700	15100	815	8800	NA
						Jun-04		34700	7.69	16100	9210	1040	3970	NA
						Nov-05		4520	8.00	2600	1060	247	837	9.0
						May-06		20000	7.78	12200	6590	537	3810	12.9
						Aug-06		34400	7.85	19800	12100	582	5520	5.0
						Nov-06		33700	7.75	24100	13800	1170	7130	3.0
						Jun-07		39500	7.60	25500	15300	643	7400	6.0
						Nov-07		33900	7.61	27200	16000	633	8250	318.0
						May-08								
						Jul-08		43000	7.70	29000	18000	570	8300	424.0
						Oct-08								
						Nov-08	0							
						May-09								
						Jun-09								
						Jul-09								
						Aug-09		34000	7.18	30000	18000	400	8900	
						Sep-09								
						Oct-09								
						Jul-10								
						Aug-10		49000	7.50	32500	19000	580	9600	
						Sep-10								
						Oct-10								
						Aug-11		31000	7.15	19000	12000	610	5400	NA
						Oct-11		9300	7.90	5300	2600	520	1400	<10
10	10	4	34	1	**WEST**	Nov-03	185	95400	7.49	26000	34400	735	16200	NA
						Jun-04	355	13500	7.67	8780	4590	724	2190	NA
						Nov-05	2204	18400	7.71	11600	6400	601	3410	7.0

								Routine/Indicator Parameters						
LSD	SEC	TWP	RNG	MER	Program Description/ Culvert Name	Date Sampled	Yearly Water Volume Disposed (M^3)	EC (µS/cm)	pH	TDS (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Na (mg/L)	DOC (mg/L)
						May-06		57600	7.58	39400	23600	634	12500	3.2
					Tested for HC - no hydrocarbons present	Aug-06		75600	7.58	47300	29200	574	14300	5.0
						Nov-06	221	68800	7.45	53600	32400	607	17000	2.0
						Jun-07		50300	7.51	33200	20100	455	10300	10.0
						Nov-07	130	43600	7.64	35800	22700	481	10300	51.0
						May-08								
						Jul-08		2600	8.20	1300	560	13	360	101.0
						Oct-08								
						Nov-08	0							
						May-09								
						Jun-09								
						Jul-09								
						Aug-09		1800	7.70	1100	520	38	340	
						Sep-09								
						Jul-10								
						Aug-10		19000	7.60	12400	6600	1400	2200	
						Sep-10	166							
						Oct-10								
						Aug-11		28000	6.96	17000	10000	790	4600	NA
						Oct-11	437	16000	7.79	9500	4900	790	2400	31.0
					CUMULATIVE TO DATE:		**3698**							
					Installed by CNRL									
2	2	6	3	2	**CULVERT 1**	Nov-02		18500	8.12	18300	2300	11800	NA	60.7
						Jun-03		94600	7.40	61000	32800	857	23700	NA
						Nov-03		63900	7.89	27800	1530	19500	3080	NA
						Jun-04		25200	7.77	18600	5140	8130	1960	NA
						Oct-05		21900	7.76	16100	6250	3810	NA	28.7

								Routine/Indicator Parameters						
LSD	SEC	TWP	RNG	MER	Program Description/ Culvert Name	Date Sampled	Yearly Water Volume Disposed (M^3)	EC (µS/cm)	pH	TDS (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Na (mg/L)	DOC (mg/L)
						May-06		23300	7.75	14700	8240	306	5100	11.3
						Nov-06		2890	8.01	1780	367	296	501	13.2
						Jun-07		22100	7.79	16600	6830	4040	3300	23.0
						Nov-07		2880	8.29	1870	473	230	579	11.2
						May-09								
						Jul-08		1300	8.00	760	220	93	170	5.2
						Nov-08	342							
						May-09								
						Jun-09								
						Jul-09								
						Aug-09		18000	7.68	14000	7800	350	5100	
						Sep-09								
						Oct-09	400							
						Jul-10								
						Aug-10		22000	7.67	14000	6900	2400	2700	
						Sep-10								
						Oct-10	1644							
						Aug-11		24000	7.07	18000	7500	4100	3200	NA
						Oct-11		25000	7.63	17000	7600	3600	3000	NA
2	2	6	3	2	**CULVERT 2**	Nov-02	1819	23100	7.95	22900	6690	3690	NA	22.5
						Jun-03		89400	7.39	60500	33000	843	23000	NA
						Nov-03	1328	25600	7.74	17400	8160	3780	2560	NA
						Jun-04	1771	35200	7.78	16100	7040	3620	2100	NA
						Oct-05	1007	21500	7.87	15400	5900	3570	NA	24.4
						May-06		20300	7.85	16000	6000	4240	3470	26.3
						Nov-06	967	22400	7.76	18900	8490	3930	3980	22.9
						Jun-07		22300	7.77	16900	7160	4010	3300	26.0
						Nov-07	533	17900	7.78	15400	6980	3560	2550	29.0
						May-08								
						Jul-08		23000	7.60	18000	8000	4100	3300	31.0

								Routine/Indicator Parameters						
LSD	SEC	TWP	RNG	MER	Program Description/ Culvert Name	Date Sampled	Yearly Water Volume Disposed (M^3)	EC (µS/cm)	pH	TDS (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Na (mg/L)	DOC (mg/L)
						Nov-08	0							
						May-09								
						Jun-09								
						Jul-09								
						Aug-09		23000	7.60	16000	6700	4000	2700	
						Sep-09								
						Oct-09								
						Jul-10								
						Aug-10		32000	7.59	21400	11000	3700	3700	
						Sep-10								
						Oct-10								
						Aug-11		5200	7.57	2900	1200	390	710	NA
						Oct-11	823	83000	7.06	55000	33000	1500	16000	NA
2	2	6	3	2	**CULVERT 3**	Nov-02		42100	7.71	41700	16300	341	NA	25.8
						Jun-03		90900	7.37	58000	32100	853	21400	NA
						Nov-03		28300	7.77	16000	9230	442	5240	NA
						Jun-04		24500	7.66	18900	8380	3720	4190	NA
						Oct-05		46900	7.65	31200	17400	445	NA	16.8
						May-06		15900	7.77	11700	4890	3320	1250	21.1
						Nov-06		19500	7.72	18300	8270	4380	1910	30.5
						Jun-07		20800	7.71	18800	4340	8740	2350	62.0
						Nov-07		7190	7.83	6400	1880	2400	590	77.0
						May-08								
						Jul-08		10000	7.50	8200	2500	3100	860	407.0
						Nov-08	0							
						May-09								
						Jun-09								
						Jul-09								
						Aug-09		13000	7.67	9300	3100	2800	1100	
						Sep-09								
						Oct-09								

								Routine/Indicator Parameters						
LSD	SEC	TWP	RNG	MER	Program Description/ Culvert Name	Date Sampled	Yearly Water Volume Disposed (M^3)	EC (µS/cm)	pH	TDS (mg/L)	Cl (mg/L)	SO_4 (mg/L)	Na (mg/L)	DOC (mg/L)
						Jul-10								
						Aug-10		7700	7.57	5410	1400	2000	460	
						Sep-10								
						Oct-10								
						Aug-11		27000	7.01	21000	7300	6400	4300	
						Oct-11		25000	7.58	19000	6400	6500	3500	NA
					CUMULATIVE TO DATE:		**10634**							