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The Impact of Subsurface Physical Characteristics on the Effectiveness of Subsurface Drainage in the Northern Great Plains

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THE IMPACT OF SUBSURFACE PHYSICAL CHARACTERISTICS ON THE EFFECTIVENESS OF SUBSURFACE DRAINAGE IN THE NORTHERN GREAT PLAINS

BY

MEHMET EMIN BUDAK

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THESIS ACCEPTANCE PAGE

Mehmet Emin Budak

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

David E Clay
Advisor Date

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ABBREVIATIONS

ANOVA	Analysis of variance
BMP	Best Management Practices
Bd	Bulk Density
Ca	Calcium
CEC	Cation Exchange Capacity
Cm	Centimeter
$cmol_c$	Centimol charge
dS	DesiSeimen
dw	Bulk Density of Water
EC	Electrical Conductivity
EC_e	Saturated Electrical Conductivity
ESP	Exchangeable Sodium Percentage
FD	Free Drainage
ha	Hectares
hr	Hour
K_{sat}	Saturated Hydraulic Conductivity
L	Loam
LR	Linear Regression
LSD	Least significant difference
m	Meter

M	Molar
Mha	Million Hectares
Mg kg^{-1}	Milligram to Kilograms
ml	Milliliter
mm	Millimeter
Na	Sodium
NGP	Northern Great Plains
NRCS	Natural Resource Conservation Service
P value	Probability of Significance
Pd	Particle Density
PVC	Polyvinyl Chloride
PPM	Parts Per Million
Precip.	Precipitation in mm for growing season
PSI	Pounds per Square Inch
R^2	Coefficient of Determination
S.D.	Standard Deviation
SAR	Sodium Absorption Ratio
SCL	Sandy Clay Loam
SD	South Dakota
USDA	United States Department of Agriculturel

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ABSTRACT

THE IMPACT OF SUBSURFACE PHYSICAL CHARACTERISTICS ON THE EFFECTIVENESS OF SUBSURFACE DRAINAGE IN THE NORTHERN GREAT PLAINS

MEHMET EMIN BUDAK

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World-wide, salinity and sodicity problems are increasing in coastal, irrigated and dryland agricultural systems. Traditional reclamation techniques for saline sodic soils include improving soil drainage by installing subsurface drainage, leaching with high quality water, and applying a source of calcium. However, due to differences in the soil parent material these traditional approach treatments were ineffective in removing sodium and other salts out of the soil profile of South Dakota. Understanding how the surface and subsurface soil characteristics and management interact to affect the sustainability of these systems is the first step in remediation. Each region and soil have a slightly different problems and require site-specific remediation techniques. The objectives of this study were to 1) evaluate the functionality of subsurface drainage to remove the salts out of the soil profile 2) investigate the impact of subsurface physical parameters on the effectiveness of tile drainage. The experimental field was separated into shoulder, back, and toe slope zone that had different soil characteristics. Within each zone, four undisturbed and four disturbed depth soil samples (7.5 cm x 120 cm) were collected in 2018 and 2019. Soil samples (7.5 cm x 7.5 cm) were collected from 0 to 7.5 cm , 50 to 57.5 cm , 82.5 to 90 cm , 92.5 to 100 cm, and 105 to 112.5 cm depths and were analyzed for soil electrical conductivity (EC), pH, Na^+ concentration, soil particle size, available water at field capacity, drainable porosity, soil bulk density, and saturated hydraulic conductivity. From 2018 to 2019, there was a decrease for the EC_e and Na^+ in the surface soil due to the movement of low EC water through the soil. However, this decrease of soil EC_e was associated with an increased in the subsoil dispersion risks. These findings suggest that the increased soil dispersion risks also could reduce the ability of subsurface drainage to remove excess salts. Moreover, other physical properties that are responsible for the effectiveness of tile drainage could be harmed. High bulk densities, low drainable porosities, and low saturated hydraulic conductivities will reduce the effectiveness of subsurface drainage were associated with back and toe slope soils. These results might be attributed to the low saturated hydraulic conductivity rates, low drainable porosity, and high bulk density in the subsurface soil depths. Our findings suggest that subsurface drainage is not recommended to remove the excess sodium and other salts for these soils.

INTRODUCTION

Worldwide, FAO Land Nutrition Management Service in 2008 reported that approximately 400 million hectares (Mha) the world's agricultural land are impacted by saline conditions and over 430 million hectares (Mha) are impacted by sodic soil conditions (Rengasamy, 2006; FAO, 2017; Butcher et al., 2016). Due to differences in the soil parent materials and management practices across the globe each region has unique problems and requires site-specific remediation techniques. Worldwide, the salt affected soils can be characterized into three broad categories; saline (high total salts), sodic (high Na^+), and saline-sodic soils (high total salts and Na^+) (Rhoades and Halverson, 1976; US Salinity Laboratory Staff, 1954). Each group of salt-affected soils has different benchmarks that are based on the electrical conductivity (EC), sodium absorption ratio (SAR) or exchangeable sodium percentage (ESP), and pH (Rhoades, 1982; Szabolcs et al., 1974). Based on the EC_e and SAR, saline soils are classified by an electrical conductivity of saturation extract (EC_e) more than 4 dS m^{-1}, sodium absorption ratio (SAR) less than 13 $mmol_c$ $L^{0.5}$ and pH less than 8.5. Sodic soils are characterized by SAR greater than 13 $mmol_c$ $L^{0.5}$,EC_e less than 4 dS m^{-1}, pH usually between 8.5 and 10, whereas saline-sodic soils have SAR greater than 13 $mmol_c$ $L^{0.5}$, EC_e greater than 4 dS m^{-1}, pH usually higher than 8.5. In the Northern Great Plains, problems occur when the electrical conductivity of saturated extract (dS m^{-1}) is more than 4 dS m^{-1}, and the sodium absorption ratio (SAR) is greater than 5 $mmol_c$ $L^{0.5}$ (Franzen et al., 2019). Moreover, there are different values used to characterize the saline sodic soils in the other areas of the World (Sumner et al., 1998; Rengasamy, 2006).

In the Northern Great Plains (NGP) it has been estimated that saline and sodic conditions affected between 10 to 15 million hectares (Mha) of agricultural land (Seelig, 2000; Millar, 2003; Hopkins et al., 2012; Carlson et al., 2013). The source of Na and other salts in the NGP is marine sediments that underlay a large portion of surface materials. The salinity and sodicity problem are expanding in the NGP as a result of higher spring rainfall and higher water tables increasing capillary movement of salts originally contained within the marine sediments to the soil surface (Schrag, 2011; Melillo et al., 2014; Reistma et al., 2015; Carlson et al., 2016). Traditional approaches to remediating saline sodic soils include: 1) improving soil drainage by installing subsurface (tile) drainage, 2) leaching with water (low electrical conductivity) to remove the excess salts out of the soil profile, 3) applying a source of calcium, such as gypsum and lime. Previous studies by Kharel et al. (2018) and Birru et al. (2019) reported that these traditional remediation methods were ineffective at leaching of soluble salts out of the surface soil in salt affected soils of the Northern Great Plains. Kharel et al. (2018) reported that the applying of the some recommended chemical amendments were ineffective at helping to positively impact saline sodic soils. In a laboratory study, these results were attributed to the soil already containing high amounts of gypsum. Birru et al. (2019) showed that the high soil bulk densities, low drainable porosities, and low saturated hydraulic conductivity rates further restricted traditional remediation techniques.

The main goals of subsurface drainage are to lower the water table, remove the excess soil salts, and enhance the crop yields. A few studies reported that the subsurface drainage considerably affects some of the soil physical properties (Hundal et al., 1976). The subsurface drainage can be an effective tool for lowering the water table, which moves water to the drainage and in turn can increase crop yields. A few studies reported that the installation of subsurface drainage caused the decrease in soil bulk density compared to undrained soils (Baker et al., 2004; Chieng and Hughes-Games, 1995). For example, the bulk density values of surface soil samples in the treatments of undrained and subsurface drainage were 1.55, and 1.48 Mg/m^3, respectively (Hundal et al., 1976).

Much of the previous research has focused on the surface soil characteristics and ignored the subsurface soil characteristics. The subsurface physical characteristics have critical roles that may negatively impact the effectiveness of subsurface drainage system in salt affected soils. The subsoil characteristics of NGP soils have been little studied. Therefore, our objectives were to 1) evaluate the functionally of subsurface (tile) drainage to remove the excess salts out of the subsoil horizons in reclaiming saline sodic soils and 2) investigate the impact of subsurface physical parameters on the effectiveness of subsurface (tile) drainage in salt affected soils of the NGP structured.

MATERIALS AND METHODS

Characteristics of Study Site

The experimental site was located near Stratford / SD at the latitude and longitude coordinates of 45°16′24.55″N and 97°50′13.34″W, respectively (Figure 1), and it was separated into three landscape positions (shoulder slope, back slope, and toe slope). The soil characteristics of samples collected for three model landscape positions are provided in the Table 1. The crop rotation at the site was corn (*Zea mays*) preceded by soybean (*Glycine max*). No-tillage had been practiced in the experimental field for at least ten years. Each site had the dimensions of approximately 12 m by 108 m. In the fall of 2017, subsurface tile drainage was installed at a spacing of 12 m between adjacent drain lines at a depth of 1.05 m in the back and toeslope positions. Soils located in the shoulder area were not drained.

Soils in the shoulder areas were characterized as well-drained soils with low EC and Na^+ values (Soil survey staff, 2018) and the soil-mapping unit was a Great Bend (fine loamy, mixed, super active, Typic Argiustolls; Table 1). The Great Bend series includes the Ap (0-10 cm), Bw (10-18 cm), Bkz1 (18-36 cm), Bkz (36-69 cm), C1 (69-84 cm), and C2 (84-122 cm) soil horizons. In these soils, slopes range from 2 to 6 %. In the Ap horizon, the soil structure was weak fine granular, whereas the Bw horizon was a weak medium subangular blocky (Soil Survey Staff, 2018).

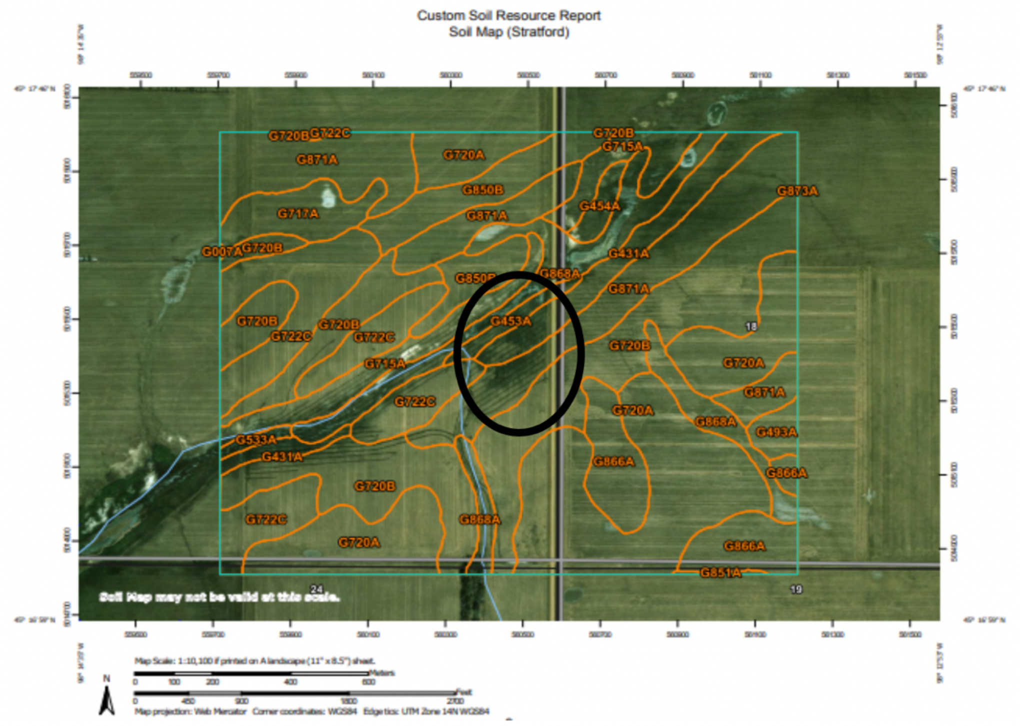


Figure 1. Soil map unit for the experimental field (Web Soil Survey, 2018).

The soils in the back-slope position were moderately drained with moderate EC and Na^+ values and the soil-mapping unit was a Beotia (fine, smectitic, frigid, Pachic Argiudolls; Table 1). The Beotia series contains the Ap (0 - 20 cm), Bw (20 - 33 cm), Bkz1 (33 - 48 cm), Bkz2 (48 - 76 cm), Cz1 (76 - 110 cm), and Cz2 (110 - 132 cm) soil horizons. In these soils, slopes range from 0 to 2 %. In the Ap horizon, the soil structure was a weak fine granular, whereas in the Bkz1 the soil structure was a weak to moderate blocky structure (Soil Survey Staff, 2018). In this mapping unit, the subsurface drainage had been installed in the fall of 2017 at a depth of 1.05 m and spacing between adjacent tile lines was 12 m.

Soils in toe-slope were characterized as poorly drained with high EC and Na^+ values. The soil-mapping unit contained both a Harmony and Aberdeen series (fine silty, smectitic frigid Calcic Natrudolls) (Table 1). The Harmony and Aberdeen series include the Ap (0-13 cm), ABkz (13-28 cm), Bk1 (28-53 cm), Bk2 (53-81 cm), and C (81-122 cm) soil horizons. In this mapping unit, the soil slopes range from 0 to 2 %. In the Ap horizon, the soil structure was a weak medium and fine granular structure, whereas in the ABkz soil horizon, the soil structure was an angular block (Soil Survey Staff, 2018). The growing season (March to August), annual average rainfalls and growing season temperature information for the experimental site in 2017, 2018, and 2019 are provided (Table 2). At the experimental site, 27.4 cm of rainfall was recorded from March through August in 2018. In the following year, 44.7 cm of rainfall was recorded during the growing season (from March to August) (Table 2). This experimental site was characterized as a high-water season during the study in 2019.

Following installation of subsurface (tile) drainage in 2017, the experimental area was seeded with corn (*Zea mays L.*) and soybean (*Glycine max L.*) in 2018 and 2019, respectively in the experimental site.

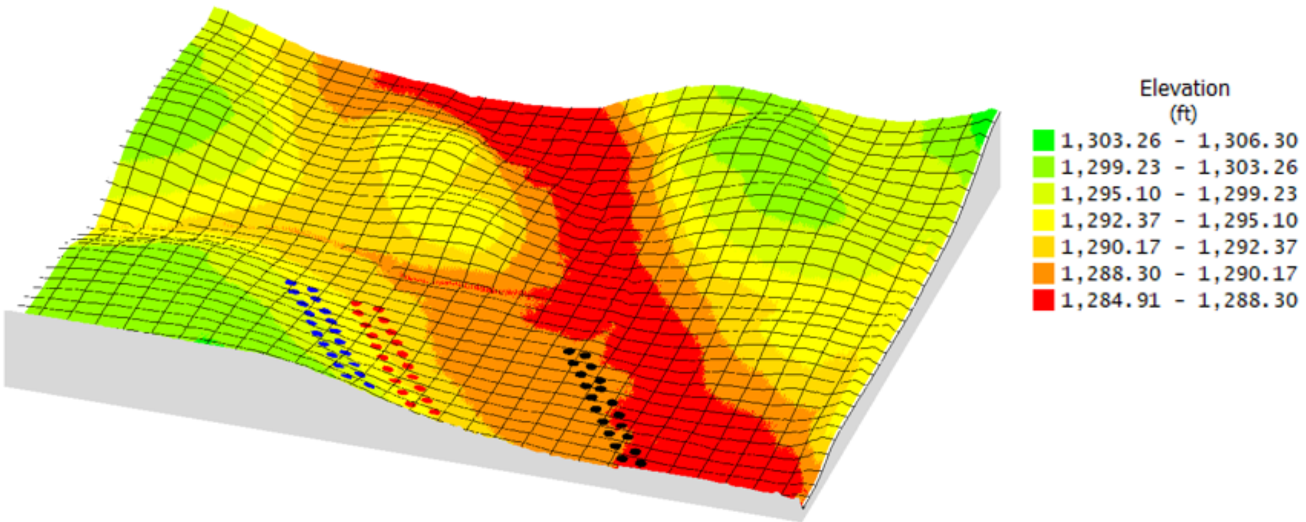


Figure 2. Distribution of surface soil sampling points along the different elevation of the experimental field.

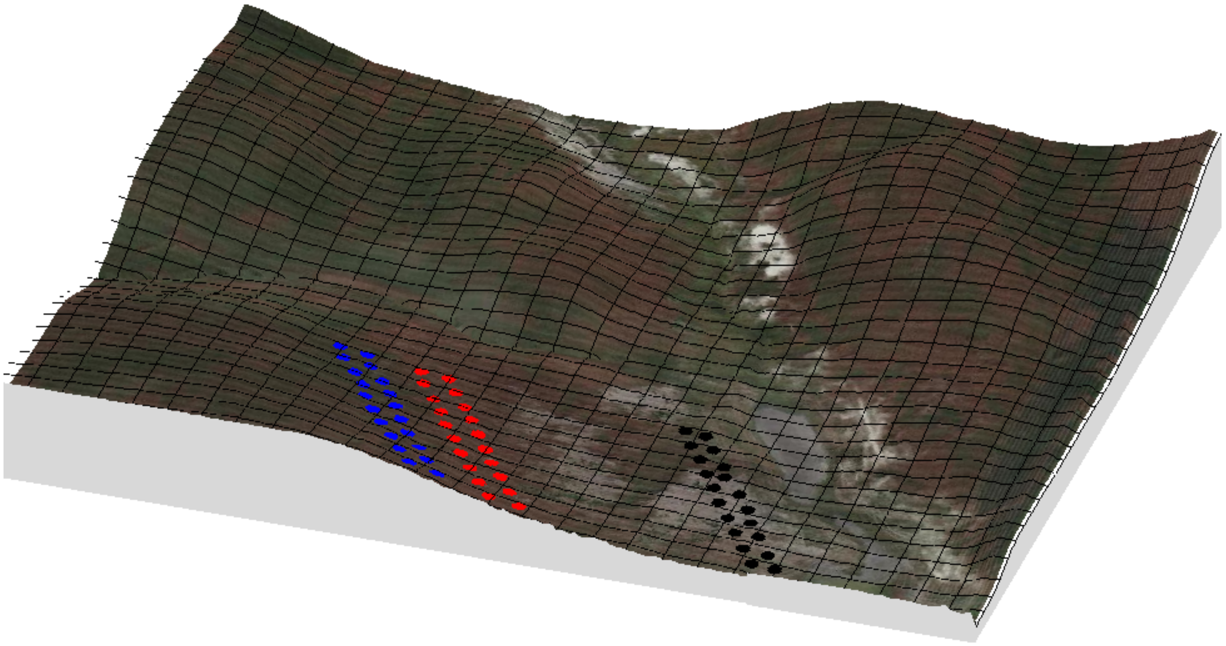


Figure 3. Aerial imagery of the soil salinity field along with sampling points.

Table 1. Slope positions, soil phases, parent materials, and classification of soils located in the experimental field.

Slope Positions	Parent Material	Classification	Drainage
Shoulder	Glaciolacrustrine	Fine loamy, mixed, super active, Typic Argiustolls	Well
Back	Glacialacrustrine	Fine, smectitic, frigid, Pachic Argiudolls	Moderately well drained
Toe	Glaciolacrustrine	Fine silty, smectitic frigid Calcic Natrudolls	Somewhat to poorly drained

Table 2. The average growing season and annual average rainfalls, average growing seasons temperature information for the experimental site in 2017, 2018, and 2019.

Experimental Site	2017	2018	2019
Average growing season rainfall, cm	27.4	27.4	44.7
Average annual rainfall, cm	37	40	65
Average growing season temperature, C^0	13	13	11
Crop	Soybean	Corn	Soybean

Surface and Subsurface Soil Sampling Collection

Surface soil samples from the 0 to 15 and 15 to 30 cm depths were collected from 20 sampling points in the shoulder (undrained), back(drained), and toe (drained) slope areas with a 1.9 cm diameter soil probe in June 2018 and June 2019. These samples were collected approximately 1 and 2 years after the subsurface (tile) drainage had been installed. Soil moisture contents were calculated by subtracting the weight of dry soil from the weight of the wet soil, and then dividing by the weight of the dry soil (air dried) following Cooper (2016).

Four undisturbed and four disturbed depth soil columns (a diameter of 7.5 cm and length of 120 cm) were collected at each landscape position areas using a Giddings truck-mounted hydraulic soil probe in November 2018 and in November 2019. The soils were analyzed for physical and chemical characteristics. Soil for physical characterization were stored for future analysis. All soils were separated into multiple horizons; 0 to 7.5 cm (Surface, S), 50 to 57.5 cm (Above Tile 1, AT1), 82.5 to 90 cm (Above Tile 2, AT2), 92.5 to 100 cm (Above Tile3, AT3), 105 to 112.5 cm (At Tile, AT). These samples were air dried (40^{o} C), ground to pass through a 2 mm sieve, and analyzed for soil pH, EC, Na^{+}, texture, water content capacity at field capacity (0.3 bar), and drainable porosity (soil water content at 0.3 bar subtracted from the water content at saturation capacity) (Richards, 1965). Soil bulk densitiy was determined with 2 replications using the clod method (paraffin-sealed clod) (Ali, 2010) for 5 different depths (0 to 7.5 cm, 50 to 57.5 cm, 82.5 to 90 cm, 92.5 to 100 cm, 105 to 112.5 cm).

Saturated hydraulic conductivity (Ksat) was measured in the laboratory using the undisturbed soil samples with a diameter of 7.5 cm and height of 7.5 cm from the five depths in the shoulder (undrained), back(drained), toe (drained) position areas. Each measurement was conducted on two different cores from the same depth. A wooden bench was used to hold the undisturbed soil columns during the measurements. The columns were prepared by placing a layer of cheesecloth and washed sand (type I water) at the bottom of each soil column (Figure 4). The disturbed columns were placed above the sand and the columns were treated to prevent edge flow. Plasti-Dip spray was used to seal the vertical surfaces of the undisturbed soil columns (P.D.I., Inc., Circle Pines, MN). In order to prevent the water escaping between the surface and subsurface soil core and polyvinyl chloride (PVC) tube column, it was completely filled with molten paraffin wax before the leaching experiments (Weber et al., 1986).

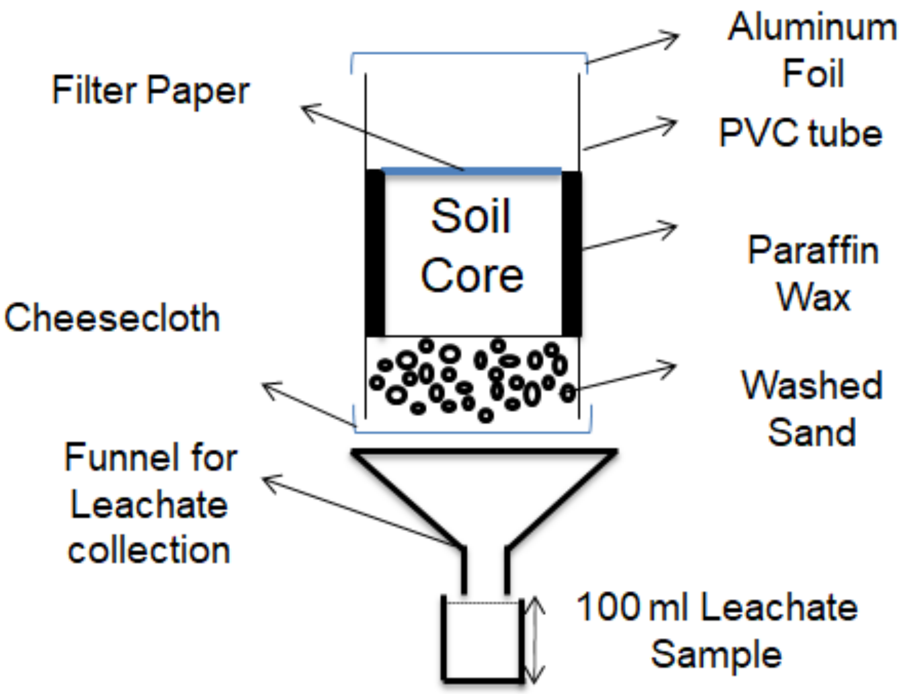


Figure 4. Preparation of undisturbed soil column for the saturated hydraulic conductivity measurements.

To prepare the soil columns for the saturated hydraulic conductivity analysis, each undisturbed soil column was saturated with the high purity deionized nanopore water. Approximately 24 hours later, saturated hydraulic conductivity was measured (Reynolds and Elrick, 1990). In this measurement, the height of the ponded water was 2.3 cm above the top of the soil surface. The nanopure water was added every 5 minutes to replenish the amount that infiltrated into the soil. The saturated hydraulic conductivity measurements were calculated the ratio between the amount of infiltrated water and the time interval for 60 minutes.

During the saturated hydraulic conductivity measurements, an aluminum foil was used about the height of the undisturbed soil core from escape over the paraffin wax. After the type I of water was applied the top was covered to prevent evaporation. The high purity deionized nanopore water was applied to the soil column in the leaching process. During the leaching experiments, leachate water samples were collected from the discharge funnel in amber plastic bottles and stored.

Chemical and Physical Analysis

Surface soil samples from the 0-7.5 cm, 50-57.5 cm, 82.5-90 cm, 92.5-100 cm, 105-112.5 cm in 2018 and 2019 were analyzed for soil $EC_{1:1}$ using the soil to water (1:1) extract method, and Na^+ (Orion Star A215, Thermo Scientific Waltham, MA; accument Excell XL60, Fisher Scientific, Hampton, NH). The $EC_{1:1}$ were converted to EC_e using the equation; $EC_e=1.14+1.91\times EC_{1:1}$ ($r^2=0.82$) (Matthees et al., 2017). In order to prepare Na^+ solution, 20 mL of 1 M ammonium acetate was added 2 g ground soil shaken for 5 minutes and filtered. The Na^+ was removed with 1 M ammonium acetate (1/10 ratio) and analyzed on a Jenway PFP7 flame photometer (Warncke and Brown, 2015). Surface soil samples (0-15 and 15-30 cm) and disturbed soil samples collected from the five depths of 0 - 7.5 cm, 50 - 57.5 cm, 82.5 - 90 cm, 92.5 - 100 cm and 105 - 112.5 cm were analyzed soil particle size using the hydrometer method after the soil organic matter (SOM) was removed using 30% hydrogen peroxide (H_2O_2) (Malo et al., 2014). Soil samples from five different depth increments were analyzed to determine the soil moisture content at field capacity. The field capacity of disturbed soil samples was measured by using a pressure plate apparatus at 0.33 bars or 4.79 psi (Richards, 1965). The differences between soil water content saturation and field capacity is the drainable porosity.

Data and Statistical Analysis

The analysis of variance (ANOVA) Statistical analysis was conducted to determine soil depth and date differences for soil pH, EC_e, soluble Na^+ concentration bulk density, saturated hydraulic conductivity, and drainable porosity values using Analysis of Variance (ANOVA) in the RStudio (V 1.2.1335) for surface and subsurface depth soil samples in 2018 and 2019. After that, LSD test was used to separate differences between the treatments. For the comparison of different soil parameters between 2018 and 2019, student t-test was conducted. In this study, it is implied that the differences are significant at the 5 % level.

RESULTS AND DISCUSSIONS

Change of Soil Salinity Parameters

Surface Soil Samples

Shoulder and back slope surface soils had lower electrical conductivity (EC), pH, and Na^+ than samples collected from toe slope position in 2018 and 2019 (Table 3). In 2018 and 2019, the shoulder and back slope positions samples from the 0 - 15 cm depth had lower EC_e than samples collected from the 15 - 30 cm depth (Table 3). However, in the toe slope position, samples from the 0 -15 cm had higher EC_e than toe slope samples collected from 15 - 30 cm depth in 2018 and 2019. Landscape position differences were attributed to water erosion that moved summit and shoulder soils to the toe slope area and capillary movement of water from the water table to the surface soil. Landscape position differences have been previously reported (Clay et al., 2004).

The shoulder and back slope areas had a loam (L) soil texture in the 0 - 15 cm and 15 - 30 cm depths, whereas the toe slope area in the 0 - 15 cm and 15 - 30 cm depths soils had a sandy clay loam (SCL) soil texture (Table 3). In the shoulder slope area, the EC_e of the 0 - 15 cm depth decreased ($p<0.05$) from 3.64 dS m^{-1} to 1.84 dS m^{-1} from 2018 to 2019

(Table 4). Similar findings were observed in the backslope area where EC_e decreased from 7.16 dS m^{-1} to 4.16 dS m^{-1} from 2018 to 2019, whereas EC_e in the toe slope position decreased from 15.43 dS m^{-1} to 10.82 dS m^{-1} (Table 4). In the shoulder and back slope positions, the EC_e in samples collected from the 15 - 30 cm depth decreased ($p<0.05$) from 4.77 dS m^{-1} to 2.84 dS m^{-1} and from 8.25 dS m^{-1} to 6.25 dS m^{-1} respectively, whereas there was no significant difference soil EC_e values in the toe slope position in the 15 - 30 cm soil depth from 2018 to 2019 (Table 4). In the shoulder, back, and toe slope positions, the decrease in EC_e of the surface soil from 2018 to 2019 was attributed to the transport of cations and anions with percolating water.

The soil Na^+ concentration in the shoulder slope area decreased ($p<0.05$) from 110 mg kg^{-1} to 53 mg kg^{-1} in the 0 - 15 cm depth and decreased ($p<0.05$) from 744 mg kg^{-1} to 228 mg kg^{-1} in the 15 - 30 cm depth from 2018 to 2019 (Table 4). Similar findings were observed in the back slope position where the Na^+ concentrations decreased ($p<0.05$) from 1963 mg kg^{-1} to 1022 mg kg^{-1} in the 0 - 15 cm depth and decreased ($p<0.05$) from 2850 mg kg^{-1} to 2126 mg kg^{-1} in the 15 - 30 cm depth from 2018 to 2019 (Table 4). However, slightly different results were observed in the toe slope position where the Na^+ concentrations in the 0 - 15 cm depth decreased ($p<0.05$) from 8531 mg kg^{-1} to 5395 mg kg^{-1}.However, the Na^+ concentrations were similar in the 15 - 30 cm depth in 2018 and 2019 (Table 4).

In the shoulder slope position, the soil $pH_{1:1}$ value increased ($p<0.05$) from 7.02 to 7.83 in the 0 - 15 cm depth and increased ($p<0.05$) from 7.34 to 8.01 in the 15 - 30 cm depth from 2018 to 2019 (Table 4). In the back slope position, similar results were observed in the 0 to 15 cm soil depth where the $pH_{1:1}$ values increased ($p<0.05$) from 7.03 to 7.65.

In the 15 - 30 cm soil depth, soil $pH_{1:1}$ increased ($p<0.05$) from 7.34 to 7.82 in the 15 - 30 cm depth (Table 4). In the toe slope 0 to 15 cm depth, soil $pH_{1:1}$ increased ($p<0.05$) from 7.80 to 8.09, whereas in the toe slope 15 - 30 cm depth, soil $pH_{1:1}$ increased ($p<0.005$) from 7.86 to 8.25 from 2018 to 2019 (Table 4).In the shoulder, back, and toe slope positions, the soil $pH_{1:1}$ increased ($p<0.05$) in samples collected from the 0 - 15 cm and 15 - 30 cm depths from 2018 to 2019 (Table 4).

In the shoulder and back slope positions the soil moisture contents were lower in the 0 - 15 cm and 15 - 30 cm depths than the toe slope position in 2018 and 2019 (Table 3). However, the soil moisture in the back slope position decreased ($p<0.05$) from 20.69 % to 18.46 % in the 0 - 15 cm depth and decreased ($p<0.05$) from 22.60 % to 19.70 % in the 15 - 30 cm depth from 2018 to 2019 (Table 4). Similar findings were observed from 2018 to 2019 in the toe slope position where the soil moisture decreased ($p<0.05$) from 22.66 % to 20.80 % and decreased ($p<0.05$) from 25.61 % to 22.84 % in samples collected from the 0 - 15 and 15 - 30 cm soil depths, respectively (Table 4). However, there were no differences for the soil moisture contents in the 0 -15 cm and 15 - 30 cm soil depths from 2018 to 2019 in the shoulder slope position (Table 4).

Table 3. Mean values of selected physical and chemical properties of the surface samples from the 0 - 15 cm and 15 - 30 cm depths in the different landscape positions of the experimental field in 2018 and 2019. The 95% CI are provided.

Years	**2018**					**2019**				
Slope	**EC_e dS m^{-1}**	**$pH_{1:1}$**	**Na^+ mg kg^{-1}**	**Soil Moisture %**	**Soil Texture**	**EC_e dS m^{-1}**	**$pH_{1:1}$**	**Na^+ mg kg^{-1}**	**Soil Moisture %**	**Soil Texture**
					0 - 15 cm					
Shoulder	$3.64^{c}\pm0.41$	$7.02^{b}\pm0.14$	$110^{c}\pm17$	20.29^{b}	L	$1.84^{c}\pm0.16$	$7.83^{b}\pm0.18$	$53^{c}\pm13$	20.23^{a}	L
Back	$7.16^{b}\pm0.73$	$7.03^{b}\pm0.13$	$1963^{b}\pm611$	20.69^{b}	L	$4.16^{b}\pm0.39$	$7.65^{c}\pm0.09$	$1022^{b}\pm307$	18.46^{b}	L
Toe	$15.43^{a}\pm1.89$	$7.80^{a}\pm0.08$	$8531^{a}\pm1077$	22.66^{a}	SCL	$10.82^{a}\pm2.27$	$8.09^{a}\pm0.09$	$5395^{a}\pm1565$	20.80^{a}	SCL
P value	< 0.001	< 0.001	< 0.001	< 0.001		< 0.001	< 0.001	< 0.001	< 0.001	
					15 - 30 cm					
Shoulder	$4.77^{c}\pm0.66$	$7.34^{b}\pm0.11$	$744^{c}\pm226$	21.16^{c}	L	$2.84^{c}\pm0.58$	$8.01^{b}\pm0.15$	$228^{c}\pm88$	20.07^{b}	L
Back	$8.25^{b}\pm0.37$	$7.34^{b}\pm0.09$	$2850^{b}\pm405$	22.60^{b}	L	$6.29^{b}\pm0.48$	$7.82^{c}\pm0.06$	$2126^{b}\pm421$	19.70^{b}	L
Toe	$9.98^{a}\pm1.12$	$7.86^{a}\pm0.11$	$5924^{a}\pm621$	25.61^{a}	SCL	$9.91^{a}\pm1.22$	$8.25^{a}\pm0.08$	$5657^{a}\pm1120$	22.84^{a}	SCL
P value	< 0.001	< 0.001	< 0.001	< 0.001		< 0.001	< 0.001	< 0.001	< 0.001	

Table 4. The changes of selected physical and chemical properties in the surface samples from 0 - 15 cm and 15 - 30 cm depths from 2018 to 2019 in the shoulder, back, and toe slope positions of the experimental field. The 95% CI are provided.

	Shoulder slope (0 -15 cm)				**Shoulder slope (15 -30 cm)**			
Years	**EC_e dS m^{-1}**	**$pH_{1:1}$**	**Na^+ mg kg^{-1}**	**Soil Moisture%**	**EC_e dS m^{-1}**	**$pH_{1:1}$**	**Na^+ mg kg^{-1}**	**Soil Moisture%**
2018	3.64 ± 0.41	7.02 ± 0.14	110 ± 17	20.29 ± 0.96	4.77 ± 0.66	7.34 ± 0.11	744 ± 226	21.16 ± 0.99
2019	1.84 ± 0.16	7.83 ± 0.18	53 ± 13	20.23 ± 0.38	2.84 ± 0.58	8.01 ± 0.15	228 ± 88	20.07 ± 0.85
P-value	< 0.001	< 0.001	< 0.001	NS	< 0.001	< 0.001	< 0.001	NS
	Back slope (0 -15 cm)				**Back slope (15 -30 cm)**			
Years	**EC_e dS m^{-1}**	**$pH_{1:1}$**	**Na^+ mg kg^{-1}**	**Soil Moisture%**	**EC_e dS m^{-1}**	**$pH_{1:1}$**	**Na^+ mg kg^{-1}**	**Soil Moisture%**
2018	7.16 ± 0.73	7.03 ± 0.13	1963 ± 611	20.69 ± 1.09	8.25 ± 0.37	7.34 ± 0.09	2850 ± 405	22.60 ± 1.1
2019	4.16 ± 0.39	7.65 ± 0.09	1022 ± 307	18.46 ± 0.65	6.29 ± 0.48	7.82 ± 0.06	2126 ± 421	19.70 ± 0.75
P-value	< 0.001	< 0.001	0.011	0.001	< 0.001	< 0.001	0.02	< 0.001
	Toe Slope (0 - 15 cm)				**Toe slope (15 - 30 cm)**			
Years	**EC_e dS m^{-1}**	**$pH_{1:1}$**	**Na^+ mg kg^{-1}**	**Soil Moisture%**	**EC_e dS m^{-1}**	**$pH_{1:1}$**	**Na^+ mg kg^{-1}**	**Soil Moisture%**
2018	15.43 ± 1.89	7.80 ± 0.08	8531 ± 1077	22.66 ± 0.66	9.98 ± 1.12	7.86 ± 0.11	5924 ± 621	25.61 ± 0.99
2019	10.83 ± 2.27	8.09± 0.09	5395 ± 1565	20.80 ± 0.53	9.91 ± 1.22	8.25 ± 0.08	5657 ± 1120	22.84 ± 0.67
P-value	0.006	< 0.001	0.002	<0.001	NS	< 0.001	NS	< 0.001

Subsurface Soil Samples

Shoulder Slope

In the shoulder slope area, the EC_e and Na^+ values were lower in the 0 - 30 cm than the 50 to 112.5 cm depths in 2018 (Table 3 and 5). In 2019, similar results were observed and the Na^+ and EC_e values were lower in the surface (Table 4) than the subsurface soil depths (Table 5). In the 50 to 112.5 cm depth, the EC_e values decreased ($p<0.05$) from 2018 to 2019. This decrease was attributed to runoff water with low EC values percolating through the soil profile. In all soil depths, ECe values decreased ($p<0.05$) in the shoulder slope from 2018 to 2019. The EC_e values decreased ($p<0.05$) from 7.55 dS m^{-1} to 4.43 dS m^{-1} in samples collected at the above tile 1 (50 - 57.5 cm) and from 7.44 dS m^{-1} to 4.48 dS m^{-1} in samples collected at the above tile 2 (82.5 - 90 cm) from 2018 to 2019 (Table 5). In the above tile 1 (50 - 57.5 cm), there was a decrease in the Na^+ concentration and Na^+ to EC_e ratio. These data suggest that above tile 1 (50 -57.5 cm) the risk of soil dispersion decreased ($p<0.05$) from 2018 to 2019. Similar findings were observed for the above tile 3 (92.5 - 100 cm) depth, the EC_e decreased ($p<0.05$) from 6.90 dS m^{-1} to 4.39 dS m^{-1} from 2018 to 2019 (Table 5). However, the Na^+ concentration did not change in samples collected at the above tile 3, which increased the soil dispersion risk from 2018 to 2019. Similar findings were observed into the 105 - 112.5 cm soil depth, however for this soil depth the soil EC_e decreased ($p<0.05$) and the Na^+ concentration increased ($p<0.05$) (Table 5) which in turn would increase the risk of soil dispersion.

Back Slope

In the back slope, the EC_e and Na^+ were lower in the surface soils (Table 3 and 4) than the subsurface depths in 2018 and 2019 (Table 6). From 2018 to 2019, the soil EC_e decreased ($p<0.05$) from 10.54 dS m^{-1} to 5.90 dS m^{-1} in samples collected at the above tile 1 (50 - 57.5 cm) depth (Table 6). Associate with this decrease was a decrease in the Na^+ concentration and ratio between the Na^+ and EC_e values (Table 6). These data indicate that on the above tile 1, the risk of soil dispersion decreased from 2018 to 2019. However, there were no significant differences for the EC_e in samples collected at the above tile 2, 3 and tile position depths from 2018 to 2019 (Table 6). In sample collected at the above tile 2 (82.5 - 90 cm) and 3 (92.5 - 100 cm) depths, different results were observed from 2018 to 2019. In the above tile 2 (82.5 - 90 cm), even though the EC_e and Na^+ did not change from 2018 to 2019, the ratio between Na^+ to EC_e increased ($p<0.05$) (Table 6). The high ratio between Na^+ and EC_e values suggest that the risk of soil dispersion increased from 2018 to 2019. In the above tile 3 and tile position depths, the soil dispersion risks also increased from 2018 to 2019. The increase ratio between Na^+ and EC_e values for the above tile 2, 3, and tile position depths from 2018 to 2019 could also impact the ability of the subsurface (tile) lines to remove the salts out of the soil.

Toe Slope

In the toe slope area, in 2018, the soil EC_e and Na^+ were lower in the 50 to 112 cm depths (Table 7) than the surface soil samples (Table 3). Similar results were observed in 2019 where the EC_e and Na^+ values were higher in the surface samples (Table 4) than the subsurface soils. In 2018 and 2019, the ratio between Na^+ concentration and EC_e were higher in the subsurface soil samples (Table 7). From 2018 to 2019, the Na^+ and EC_e ratio increased in the surface and subsurface samples collected from above tile lines. These increases indicate that, the soil dispersion risks increased, which would reduce the effectiveness of the subsurface (tile) drainage. There were no significant differences in the toe slope position where the EC_e values did not change in all subsurface sample depths from 2018 to 2019 (Table 7). In addition, the Na^+ value did not change in samples collected above tile 1 (50 - 57.5 cm) from 2018 to 2019. However, the Na^+ concentrations increased ($p<0.05$) in soil collected at the other subsurface depths from 2018 to 2019 (Table 7). The Na^+/EC_e ratio also increased ($p<0.05$) from 517 to 745 in collected samples at the above tile 1 (50 - 57.5 cm) from 2018 to 2019 (Table 7). Similar findings were observed for the ratio between Na^+/EC_e in samples collected at the above tile 2, 3 and tile. Even though the EC_e did not change, the Na^+ and ratio between Na^+ and EC_e increased from 2018 to 2019. The increase ratio between Na^+ to EC_e suggest that the risk of soil dispersion increased at the all above tiles from 2018 to 2019.

Table 5. Changes in the soil salinity parameters for the subsurface sample depths in the shoulder slope position from 2018 to 2019.

Shoulder slope (Above Tile 1) (50-57.5 cm)				**Shoulder slope (Above Tile 2) (82.5-90 cm)**			
Years	**EC$_e$**	**Na$^+$**	**Na$^+$/EC$_e$**	**Years**	**EC$_e$**	**Na$^+$**	**Na$^+$/EC$_e$**
Unit	(dS m^{-1})	(mg kg^{-1})		**Unit**	(dS m^{-1})	(mg kg^{-1})	
2018	7.55	1386	177	**2018**	7.44	1586	213
2019	4.43	151	37	**2019**	4.48	1550	322
p-value	0.002	0.003	0.002	**p-value**	0.002	NS	0.024
Shoulder slope (Above Tile 3) (92.5-100 cm)				**Shoulder slope Tile Position (105-112.5 cm)**			
Years	**EC$_e$**	**Na$^+$**	**Na$^+$/EC$_e$**	**Years**	**EC$_e$**	**Na$^+$**	**Na$^+$/EC$_e$**
Unit	(dS m^{-1})	(mg kg^{-1})		**Unit**	(dS m^{-1})	(mg kg^{-1})	
2018	6.90	2232	324	**2018**	7.33	1602	218
2019	4.39	1875	433	**2019**	5.55	2231	405
p-value	0.002	NS	NS	**p-value**	< 0.001	0.003	0.001

Table 6. Changes in the soil salinity parameters for the subsurface sample depths in the backslope position from 2018 to 2019.

Back slope (Above Tile 1) (50-57.5 cm)				**Back slope (Above Tile 2) (82.5-90 cm)**			
Years	**EC$_e$**	**Na$^+$**	**Na$^+$/EC$_e$**	**Years**	**EC$_e$**	**Na$^+$**	**Na$^+$/EC$_e$**
Unit	(dS m^{-1})	(mg kg^{-1})		**Unit**	(dS m^{-1})	(mg kg^{-1})	
2018	10.54	3576	343	**2018**	9.02	2043	226
2019	5.90	994	168	**2019**	7.57	2826	368
p-value	0.001	< 0.001	< 0.001	**p-value**	NS	NS	< 0.001
Back slope (Above Tile 3) (92.5-100 cm)				**Back slope (Tile Position) (105-112.5 cm)**			
Years	**EC$_e$**	**Na$^+$**	**Na$^+$/EC$_e$**	**Years**	**EC$_e$**	**Na$^+$**	**Na$^+$/EC$_e$**
Unit	(dS m^{-1})	(mg kg^{-1})		**Unit**	(dS m^{-1})	(mg kg^{-1})	
2018	8.39	2599	314	**2018**	6.97	1431	205
2019	7.95	3332	409	**2019**	8.56	3764	434
p-value	NS	NS	NS	**p-value**	NS	0.003	< 0.001

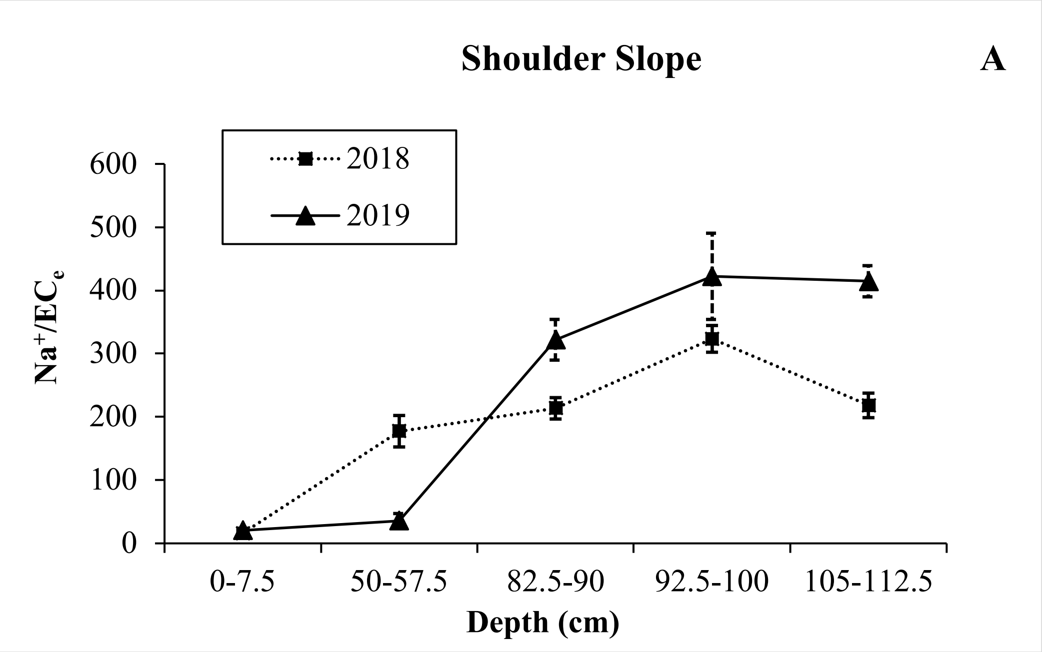
Table 7. Changes in the soil salinity parameters for the subsurface sample depths in the toe slope position from 2018 to 2019.

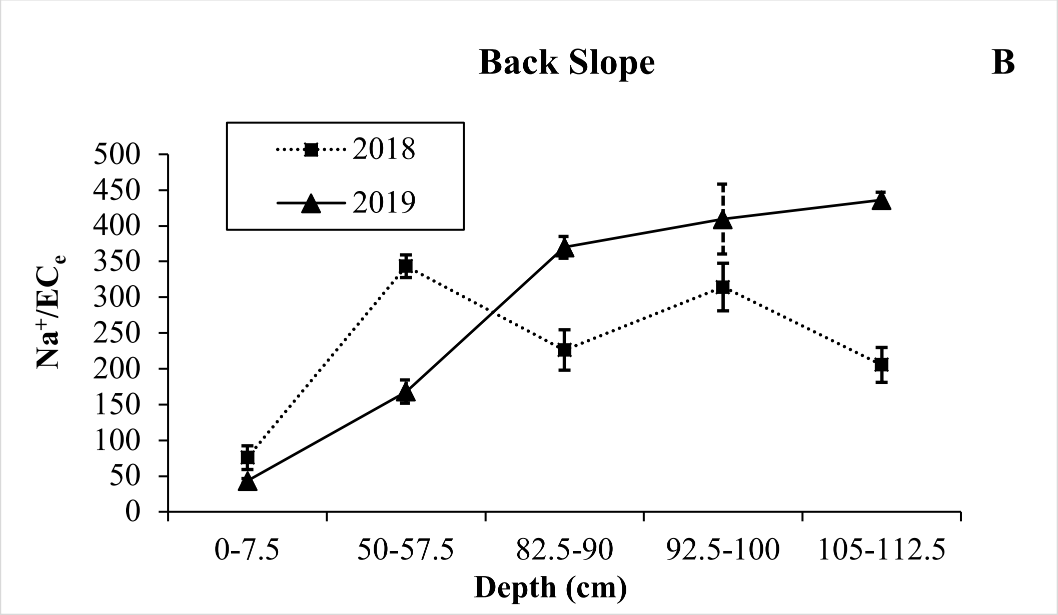
Toe slope (Above Tile 1) (50-57.5 cm)				**Toe slope (Above Tile 2) (82.5-90 cm)**			
Years	**EC_e**	**Na^+**	**Na^+/EC_e**	**Years**	**EC_e**	**Na^+**	**Na^+/EC_e**
Unit	(dS m^{-1})	(mg kg^{-1})		**Unit**	(dS m^{-1})	(mg kg^{-1})	
2018	8.51	4445	517	**2018**	6.68	3418	512
2019	8.00	5953	745	**2019**	7.01	5279	754
p-value	NS	NS	0.002	**p-value**	NS	< 0.001	0.005
Toe slope (Above Tile 3) (92.5-100 cm)				**Toe slope (Tile Position) (105-112.5 cm)**			
Years	**EC_e**	**Na^+**	**Na^+/EC_e**	**Years**	**EC_e**	**Na^+**	**Na^+/EC_e**
Unit	(dS m^{-1})	(mg kg^{-1})		**Unit**	(dS m^{-1})	(mg kg^{-1})	
2018	7.29	3734	510	**2018**	7.32	3859	531
2019	7.20	6426	902	**2019**	6.57	5390	822
p-value	NS	< 0.001	0.002	**p-value**	NS	0.018	0.012

In the backslope position, the Na^+/EC_e ratio values were lower in the 82.5 to 112.5 cm depth in 2018 than the surface and 50 - 57.5 cm depths whereas in 2019, the Na^+/EC_e ratio values were lower in the surface and 50 - 57.5 cm than the 82.5 to 112.5 cm depth (Figure 5). The EC_e values in the subsurface depths were similar in 2018 and 2019. However, in the surface and above tile 1, the sodium concentrations decreased ($p<0.05$) (Table 6). Based on these values it is likely Na^+ moved from the surface to subsoils due to high rainfall amounts, which resulted in high risk for dispersion in samples collected above the tile line. Based on the Na^+ to EC_e ratio, in the surface and above tile 1 depths the soil dispersion decreased whereas the soil dispersion increased above tile 2 (82.5 - 90 cm) and above tile 3 (92.5 - 100 cm) and at the tile (105 - 112.5 cm) from 2018 to 2019 (Figure 5).

Moreover, the subsurface soils had a higher risk of soil dispersion than the compared to the surface soil in the shoulder and back slope areas in 2018 and 2019 (Figure 5).

In the toe slope position, the ratio between soil Na^+ and EC_e were lower in the surface and subsurface soil depths in 2018 than 2019 (Figure 5), and the Na^+ to EC_e ratios increased in many of the subsurface depths from 2018 to 2019 (Figure 5). These findings showed that at this landscape position, Na^+ was highly variable. Based on the Na^+ to EC_e ratio, the risk of soil dispersion increased above tile lines from 2018 to 2019 (Figure 5). In addition, the Na^+ to EC_e ratio at the toe slope position was higher than the shoulder and back slope positions in the surface and all subsurface samples (Figure 5). At the shoulder, back, and toe slope positions, based on the Na^+ to EC_e ratios the soil dispersion can cause in increased erosion and slow water flow movement.





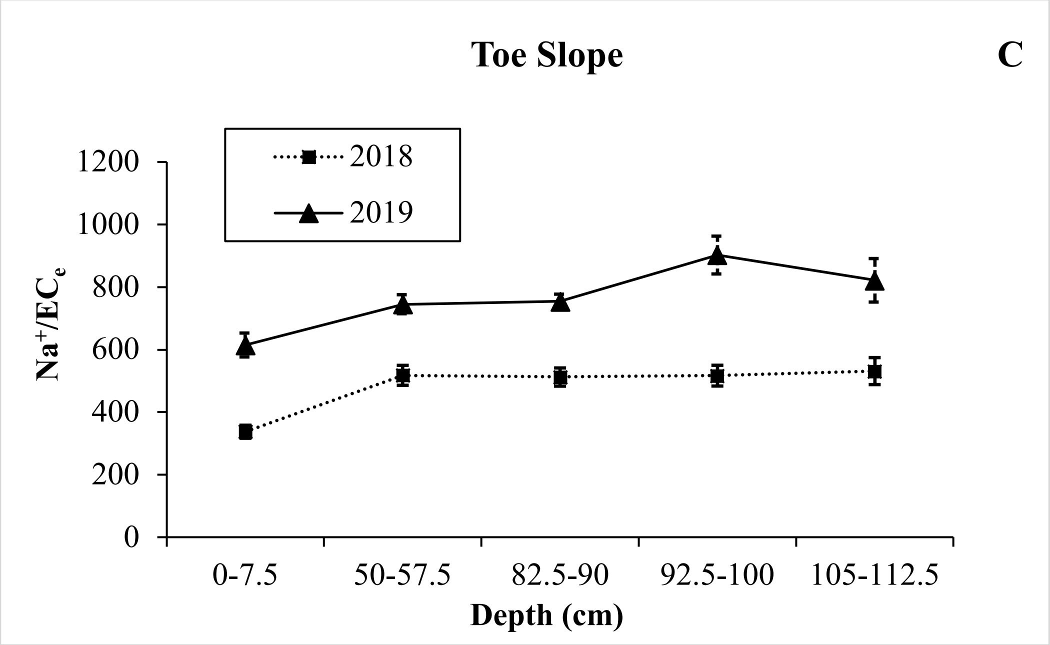


Figure 5. Changing of the Na^+ to EC_e ratio of the surface and subsurface samples in the shoulder (A), back (B), and toe (C) slope position in 2018 and 2019.

Physical Assessment

Saturated hydraulic conductivities were measured in the laboratory conditions using the undisturbed soil cores (7.5 cm and 7.5 cm) from the five different soil depths using the high purity deionized nanopore water. In the shoulder area, the mean saturated hydraulic conductivities were 75, 138, 101, 36, and 52 mm h^{-1} in the 0-7.5 cm, 50-57.5 cm, 82.5-90 cm, 92.5-100 cm, and 105-112.5 cm depths, 9, 85, 28, 33, and 57 mm h^{-1} in the back slope area, respectively (Table 6), whereas, in the toe slope area, the water flow of surface and subsurface soil samples did not have a measurable water movement (Table 8). These findings show that water flow occurred in the shoulder and back slope but not in the toe slope position. The surface soil $Ksat_s$ were lower than the values reported by Birru et al. (2019) (215 ± 89 mm h^{-1}) and higher than (4.6 ± 3.15 mm h^{-1}) Kharel et al. (2018).

In the shoulder area, the bulk densities ranged from 1.8 g cm^{-3} in the surface soil to 1.85 g cm^{-3} in the C2 horizon. The bulk densities were lower in the surface samples than the subsurface soil samples in the shoulder slope position (Table 8). The drainable porosity ranged from 0.13 cm^3 cm^{-3} in the surface soil to 0.07 cm^3 cm^{-3} in the tile position depth. The mean saturated hydraulic conductivity rates were higher in the surface and above tile 1 where compared to the subsurface soil depths (Table 8). These results suggest that the water flow rate was relatively low in the subsurface soil depths. The low water flow rates might be attributed to the high Na^+ concentration (Table 5).

In the backslope area, the bulk densities ranged from 1.83 g cm^{-3} in the surface soil depth to 1.78 g cm^{-3} in the Cz1 soil horizon (Table 8). The drainable porosity ranged from 0.1 cm^3 cm^{-3} in the surface soil to 0.05 cm^3 cm^{-3} in the Cz1 soil horizon. There was a decrease in the saturated hydraulic conductivities from Ap and Bkz soil horizons to the

Cz1 and Cz2 soil horizons. This decrease suggests that the water flow rate was relatively low. From the surface to the subsurface soil horizons, the low water flow rate may be linked to the high Na^+ and the increase ratio between Na^+ and EC_e. Figure 5 showed that the Na^+/EC_e ratio was lower in the surface depth than the subsurface soil depths in the back slope position. In addition, the Na^+ concentration was lower in the surface soil depths than compared to the subsurface soil depths (Table 3 and 6).

In the toe slope area, the bulk densities ranged from 1.86 g cm^{-3} in the surface and in the above tile 1 (50 - 57.5 cm) depths to 1.74 g cm^{-3} in the C soil horizon depth. The drainable porosity values ranged from 0.05 cm^3 cm^{-3} in the surface sample to 0.09 cm^3 cm^{-3} in the subsurface soil depth (Table 8). The mean saturated hydraulic conductivity values in the surface and subsurface soil depths were approximately 0 mm h^{-1}. The water flow rate values were lower for the all soil depths in the toe slope position than the back and shoulder slope positions. The low water flow rates were attributed to the high ratio between the Na^+ to EC_e values (Table 8). Previous studies reported a similar finding and the critical EC_e/SAR_e ratios require to identify the soil dispersion and swelling (Walworth, 2006; He et al., 2013). Kharel et al. (2018) reported that the decrease in the EC_e/SAR_e ratio or increase in the SAR_e/EC_e caused to decrease the water flow rates from the surface to the subsurface soil depths. The ratio between EC_e and SAR_e was required to increase with the decrease of SAR_e to maintain a higher water flow rate.

Moreover, the subsurface horizons have different soil texture in the shoulder, back, and toe slope positions whereas the surface soil samples have loam in the all slope positions (Table 8).

Table 8. Mean values of selected physical parameters at the five different depths from the different soil series located at the experimental field.

Shoulder	**Unit**	**Horizon**				
		Ap	Bkz	C1	C2	C2
Depth	cm	0 – 7.5	50 – 57.5	82.5 - 90	92.5 - 100	105 – 112.5
Soil Texture		Loam	Silt Loam	Silt Loam	Silt Loam	Silt Loam
Bulk Density	g cm^{-3}	1.80	1.81	1.80	1.85	1.83
Drainable Porosity	cm^{3} cm^{-3}	0.13	0.09	0.07	0.06	0.07
Ksat	mm h^{-1}	75.8	138.2	100.5	36	51

Back	**Unit**	**Horizon**				
		Ap	Bkz2	Cz1	Cz1	Cz2
Depth	cm	0 – 7.5	50 – 57.5	82.5 - 90	92.5 - 100	105 – 112.5
Soil Texture		Loam	Clay Loam	Silt Loam	Silt Loam	Sandy Loam
Bulk Density	g cm^{3}	1.83	1.85	1.78	1.79	1.78
Drainable Porosity	cm^{3} cm^{-3}	0.10	0.07	0.01	0.05	0.06
Ksat	mm h^{-1}	8.8	85.3	28.6	33.1	56.9

Toe	**Unit**	**Horizon**				
		Ap	Bk	C	C	C
Depth	cm	0 – 7.5	50 – 57.5	82.5 - 90	92.5 - 100	105 – 112.5
Soil Texture		Loam	Clay Loam	Loam	Sandy Loam	Sandy Loam
Bulk Density	g cm^{-3}	1.86	1.87	1.73	1.74	1.74
Drainable Porosity	cm^{3} cm^{-3}	0.05	0.08	0.01	0.09	0.09
Ksat	mm h^{-1}	0	0	0	0	0

CONCLUSIONS

Worldwide, salinity and sodicity problems are placing soil at the tipping point of sustainability. Each geographical region has a slightly different problem and require unique solutions based on the sites climate and soil characteristics. In the North America northern Great Plains, the rising ground water tables over marine sediments provides the opportunity for sodium and other salts to be transported to the root zone and soil surface through capillary action. Over time, the salt concentrations increase, which in turn results in poor germination and plant growth. Soil columns from shoulder, back slope and foot slope position areas to a depth of over 1 m were collected in 2018 and 2019. Subsurface (tile) drainage was installed in the back and toe slope positions approximately 1 year prior to the study. These columns were separated into different increments and they were analyzed to determine bulk densities, water infiltration, drainable porosities, pH, electrical conductivity (EC), and sodium concentrations.

From 2018 to 2019, the soil EC_e and Na^+ values decreased ($p<0.05$) in the surface soil depth (0 - 30 cm) at the all landscape positions. This decrease in the surface soil was attributed to the movement of low EC water through the soil profile. However, associated with the decrease of soil EC_e was an increased the risk of soil dispersion in the subsoil. However, the decrease soil dispersion risk was attributed to the decrease of Na^+ to EC_e ratio at the above tile 1 depth in the shoulder and back slope positions from 2018 to 2019. These findings suggest that the increase soil dispersion risks could reduce the water flow in the soil profile and also affect the ability of the subsurface drainage to remove the salts out of the soil profile.

In this experiment, the subsurface (tile) drainage recommendation would not be effective of leaching sodium and other salts out of the soil profile. These findings might be attributed to the low saturated hydraulic conductivity rates, low drainable porosity, and high bulk density in the subsurface soil depths. Birru et al., (2019) reported that the use of gypsum in the surface soil samples was not effective to remediate the soil salinity and sodicity. Also, that the leaching process with the chemical amendments were ineffective at promoting Na^+ leaching to leach the salts out of the soil horizons by Kharel et al., (2016).

This experiment showed that the subsurface (tile) drainage also would have limited effectiveness in the back and toe slope soils. Soil physical properties were responsible for the inability of the traditional techniques to remediate these saline-sodic soils in the NGP. Consequently, our findings suggest that subsurface drainage is not recommended for these soils in South Dakota. The lack of effectiveness of subsurface drainage was attributed to low drainable porosity and that the soils were saturated well with gypsum.

This study demonstrates that the installation of subsurface drainage was not effective across the hillslope position for removing the salts in salt affected soils of the NGP structured. Unfortunately, some subsurface soil physical properties and the increase soil dispersion risks were responsible for the inability of the traditional remediation techniques in reclaiming saline sodic soils of South Dakota. Therefore, the management guidelines for saline sodic soils need to consider the subsurface physical parameters before the installing the subsurface drainage and the application of chemical amendments. Therefore, the traditional remediation techniques need to be reviewed again, and maybe new remediation methods might be created to remove the sodium and other salts from the soil profile.

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