

SOILS, HYDROLOGY AND VEGETATION DISTRIBUTION  
ON A SALINE LANDSCAPE AT HAILSTONE  
NATIONAL WILDLIFE REFUGE

by

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of

Master of Science

in

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DEDICATION

I dedicate this thesis to Terri, River and Brooks for their unwavering love and support. Without their patience and understanding, this work would not have been complete. In addition, this thesis is dedicated to the Apsáalooke people that once hunted on the banks of Hailstone Creek.

“The ground on which we stand is sacred ground. It is the blood of our ancestors.”  
-Chief Plenty Coups

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## TABLE OF CONTENTS

1. INTRODUCTION .....	1
Landscape Salinization.....	1
Saline Seep.....	2
Environmental Stress in Plants .....	3
Salinity Stress.....	4
Saturation-Anoxia Stress .....	6
Plants as Indicators of Environmental Condition .....	6
Zonation and Environmental Gradient.....	7
Thesis Purpose and Study Objectives .....	8
2. SALINIZATION OF A NORTHERN ROCKY MOUNTAIN WILDLIFE REFUGE .....	11
Background .....	11
Study Site .....	11
Climate.....	11
Geology.....	13
Soils.....	13
Hydrology .....	14
Saline Seep at Hailstone.....	14
Study Methods.....	16
Vegetation .....	19
Hydrology .....	20
Soils.....	21
Data Compilation and Statistical Analysis .....	23
3. VEGETATION CHARACTERISTICS OF A SALINE LAKESHORE ENVIRONMENT .....	26
Results .....	26
Vegetation Band A.....	26
Vegetation Band B.....	28
Vegetation Band C .....	29
Vegetation Band D.....	30
Plant Diversity .....	31
Wetland Indicator Status by Position.....	33
Common Species within Bands .....	34
<i>Salicornia</i> .....	34
<i>Suaeda calceoliformis</i> .....	36
<i>Distichlis spicata</i> .....	37
<i>Poa pratensis</i> .....	38

## TABLE OF CONTENTS – CONTINUED

Vegetation and Position .....	38
Conclusions .....	38
4. ABIOTIC CONDITIONS OF A SALINE LAKESHORE ENVIRONMENT.....	41
Results .....	42
Landscape Characteristics.....	42
Hydrology .....	42
Position A.....	45
Position B.....	45
Position C.....	45
Position D.....	45
Soils.....	46
Position A.....	46
Position B.....	47
Position C.....	49
Position D.....	49
Position, Saturation, and Salinity.....	50
Nutrients.....	52
Conclusions .....	55
5. DISCUSSION.....	56
Synopsis.....	56
Synthesis .....	57
Biotic Factors .....	60
Applications .....	60
Revegetation Zone 1 .....	65
Revegetation Zone 2 .....	66
Revegetation Zone 3 .....	67
Conclusions .....	71
REFERENCES .....	74
APPENDICES .....	81
APPENDIX A: Vegetation Percent Cover.....	82
APPENDIX B: Tables of Statistical Analysis.....	84

LIST OF TABLES

Table	Page
1. Landscape characteristics.....	19
2. U.S. USFWS Wetland Indicator Categories .....	20
3. Passive hydrologic indicators. ....	21
4. Soil chemistry parameters analyzed.....	22
5. Salt affected soils classification .....	25
6. Vegetation at Hailstone organized by family.....	27
7. Band A vegetation summary.....	28
8. Band B vegetation summary .....	29
9. Band C vegetation summary .....	30
10. Band D vegetation summary.....	31
11. Two diversity indices with richness, by vegetation band position. ....	33
12. Vegetation type and mean percent coverage summary by band.....	34
13. Prioritization of most common species for within-position analysis.....	35
14. Length, height differential from point A to D.....	43
15. Mean sample points distance from water surface .....	43
16. Mean depth to saturation.....	44
17. Soil Summary – Position A.....	47
18. Soil Summary – Position B.....	48
19. Soil Summary – Position C.....	49

## LIST OF TABLES - CONTINUED

Table	Page
20. Soil Summary – Position D.....	50
21. Average depth weighted N, nitrate-N, and ammonium .....	52
22. Average depth weighted total P (Bray-1) and orthophosphate.....	53
23. Average depth weighted potassium and sodium concentrations .....	54
24. Hailstone salinity/saturation conditions by revegetation zone.....	65
25. Hailstone vegetation guide by zone. ....	65

## LIST OF FIGURES

Figure	Page
1. The process of saline seep on a landscape .....	3
2. Environmental conditions examined.....	9
3. Location Map of Hailstone National Wildlife Refuge.....	12
4. 1941 Aerial Photograph of Hailstone Lake .....	15
5. Sample point locations.....	17
6. An example of vegetative banding .....	18
7. Transect 105.....	18
8. Percent bare ground by position .....	32
9. Inverse Simpson's and Shannon Wiener diversity indices. ....	33
10. Percent canopy cover across A-D positions.....	40
11. Position vs. sample point elevation and depth to saturation .....	44
12. Percent OM vs. position by depth.....	47
13. Periodic soil-saturation .....	48
14. Averaged depth-weighted EC.....	51
15. EC depth profile by position.....	51
16. Conceptual model .....	57
17. Scatter plot of depth weighted EC .....	62
18. Mean depth weighted EC for short transects vs. long transects .....	62
19. Revegetation profile for three zones. ....	68

LIST OF FIGURES - CONTINUED

Figure	Page
20. A conceptual map of revegetation zones .....	69
21. Example of vegetated islands and banding .....	71

## GLOSSARY OF TERMS, ABBREVIATIONS AND SYMBOLS

CEC	cation exchange capacity
dS/m	deciSiemens per meter
EC	electrical conductivity
EC <sub>dw</sub>	depth weighted electrical conductivity
halophyte	salt-tolerant vegetation
NRCS	Natural Resources and Conservation Service
NWR	National Wildlife Refuge
OM	organic matter
redox	reduction/oxidization
S	species richness
SAR	sodium adsorption ratio
SAR <sub>dw</sub>	depth weighted sodium adsorption ratio
s.d.	standard deviation of the sample mean
USDA	United States Department of Agriculture
USFWS	US Fish & Wildlife Service
WIS	wetland indicator status
WS	water surface
WSE	water surface elevation

## ABSTRACT

Landscape impacts from saline seep and human induced salinity are increasing across the western United States and are a major concern for global agricultural security (Gleick 1993). At Hailstone National Wildlife Refuge in south central Montana, refuge managers called for dewatering of a saline lake to reduce impacts to wildlife as a result of 80 years of exacerbated salinity. The dewatering has resulted in the rapid exposure of saturated and near-saturated sediments and a potential for wind driven salt mobilization. Prior to dewatering, salt tolerant vegetation was common on the lakeshore and tributaries and colonized in banded patterns. A study was initiated to understand abiotic conditions and species composition in these areas. Transects were established across the vegetated bands and plant species, percent canopy cover, richness, and diversity were sampled. Sample positions were categorized based on most common species. Abiotic conditions analyzed included landscape position, soil salinity and depth to saturation and soil nutrients for each sample point.

*Salicornia rubra* dominated the lowest elevational position on the lakeshore, where prolonged saturation led to anaerobic conditions and the highest sodicity among all positions (electrical conductivity, EC = 34.5 dS/m, SAR= 33.6). Along the elevational gradient above the lake depression, there was gradual reduction of EC and increased depth to saturation. The most common plant species transitioned from *Salicornia rubra* to *Suaeda calceoliformis* and *Distichlis spicata*, and eventually to *Poa pratensis* in the upland position.

Analyses showed that species type and distribution were sensitive to variations in landscape position, soil salinity, and saturation. A combination of these factors demonstrated correlation with plant species occurrence. This study provides evidence that abiotic conditions are an important determinant of vegetation banding across a salinity/saturation/elevation gradient at Hailstone National Wildlife Refuge. The data suggests that further understanding of soil salinity and soil moisture regimes on the exposed lakebed can be used in conjunction with a selection of adapted species to revegetate a saline lakebed.

## INTRODUCTION

### Landscape Salinization

Across the globe, soil salinization has become an important landscape degradation problem. Primary minerals in exposed layers of the earth's crust are the main source of salts and these constituents are mobilized by the process of chemical weathering via hydrolysis, hydration, solution, oxidization, and carbonation (Sandoval and Gould 1978). Naturally occurring salinity on the surface of the landscape prior to modern agricultural practices has been well documented. According to oral history, the Apsáalooke people who migrated throughout the northern and southern plains of North America, "came upon lakes with salt on their banks" (Crow 2012). During their travels across the northern Great Plains in the early 19<sup>th</sup> Century, Lewis and Clark documented many areas where the white crusts of surface salts occurred on the landscape. In these areas, soils contained sufficient salts on the surface to negatively affect the growth of most plants, as William Clark noted in his journals.

"...[T]he granulated salt is found on the surface of a compact and hard earth composed of fine sand with a small proportion of clay producing no vegetable [sic] substance of any kind." (Lewis et al. 2002).

Three factors contribute to depressing plant growth on saline landscapes: 1) salts prevent plant roots from soil water uptake as a result of increased osmotic tension, 2) chemical effects of salts disrupt nutritional and metabolic function in plants, and 3) salts alter soil structure by changing permeability for air and water (Thorne and Peterson

1949). These environmental conditions occur as a result of unique geologic and hydrologic conditions and certain land use practices such as alternate crop fallow can exacerbate salinization of soils and affect water quality.

### Saline Seep

During the early 20<sup>th</sup> century, native grasslands in the Northern Plains were plowed for agricultural production (Holzer et al. 1995). After the 1950's, more efficient farming equipment was used to plow larger areas of native sod while at the same time, widespread initiation of alternative crop-fallow farming systems in the Northern Plains began. The practice of crop-fallow increases soil moisture for subsequent use by crops in the following growing season, and like a plowed field, can increase the rate and amount of water infiltration past the rooting zone. The process of saline seep is initiated when excess moisture leaves the rooting zone and migrates downward. When water encounters soil discontinuity, such as bedrock or clay (aquatard), it moves laterally, solubilizing and mobilizing salts as it travels to a discharge area on the soil surface, creating a seep (Figure 1). As the water evaporates on the ground surface, the salts are left behind. In times of increased rainfall, salinity problems can be more severe due to greater recharge and therefore accumulation of salt-laden water in the recharge zone (Abrol et al. 1988). By 1983 it was estimated that over 800,000 hectares of agricultural production in the United States and Canada had been affected by saline seep (Nelson and Reiten 2009).

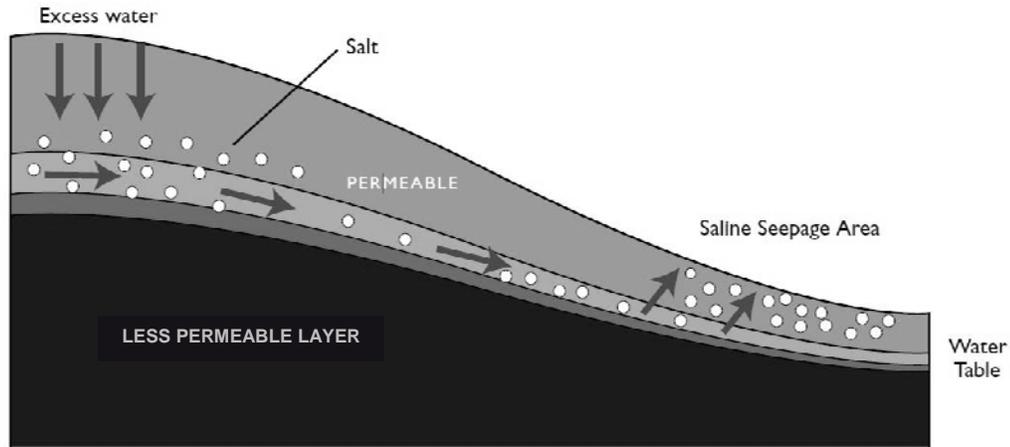


Figure 1. The process of saline seep on a landscape begins with excessive moisture moving past the rooting zone (top left), downward and laterally across a less permeable layer, mobilizing solutes as the water moves down-gradient. If the water interacts with the surface, the solutes are deposited on the soil through evapoconcentration (bottom right) and a seep results. (Figure courtesy of MSU Extension Services, Soil & Water Management Module No. 2. McCauley and Jones 2005.)

Typically, landscapes associated with seep maintain a soil salinity gradient, or a transition from high to low salt concentration in an outward direction, away from the source of water contributing to the seep. Plant species tend to follow these gradients based on their respective toleration to the environmental stress. With advances in seep reclamation over the last two decades, researchers came to the conclusion that salinized soils could be stabilized and their detrimental effects on the landscape could be alleviated by planting *halophytes* (salt tolerant plants) as well as altering hydrologic regimes (Holzer et al. 1995; Sanderson et al. 2008). Understanding the effect of stress on vegetation is crucial in reclamation of saline seep.

### Environmental Stress in Plants

At the plant level, stress can be defined as “any external factor that negatively influences plant growth, productivity, reproductive capacity or survival” (Rhodes and

Nadolska-Orczyk 2001). This includes a wide range of causes, which can be generally separated into two main groups: environmental stress factors (abiotic) and biological stress factors (biotic). At the community level, researchers have posited that environmental stress (both abiotic and biotic) is a primary driver of species composition. Bertness and Callaway (1994) proposed a conceptual model that predicted higher frequency of positive interaction (facilitation) between species at high abiotic stress where tolerant species promote subsequent growth for other species. Concurrently, the frequency of competition is higher at low abiotic stress as a result of the ability of more species to tolerate lower stress levels. Two primary stress factors affecting plant growth at Hailstone are salinity stress and anoxia/saturation stress.

Salinity Stress. Plants vary in their degree of salt tolerance and in the means by which they regulate salt content in their tissues. Most plants are salt sensitive (glycophytes), and these species show little tolerance to elevated root-zone salinity. Excessive salts in the soil (low osmotic potential) limits the uptake of water by plants, and may result in the lowering of tissue turgor, resulting in wilting (Zhu 2001). Many of these naturally occurring saline lands maintain plant communities that have, through evolutionary processes, adapted to these conditions. Halophytes are ecologically, physiologically and biochemically specialized plants, capable of producing green mass and seeds while growing in a saline substrate (Wickens 1989; Shamsutdinov and Shamsutdinov 2009), but most halophytes exhibit decreased growth at extremely high salt concentrations (Nilsen et al. 1996; Glenn et al. 1999; Barrett-Lennard 2002; Tester and Davenport 2003). In addition, salt tolerant plants of arid regions have also become

adapted to harsh xerothermic effects, such as extreme air and soil dryness, as well as high summer and low winter temperatures (Shevyakova et al. 2003).

Halophytes respond to saline environments through tolerance, which is the capability to preserve normal metabolic activity even in the presence of high intracellular salt levels (salt accumulators); and avoidance, where the plants do not allow the penetration of salt ions into their cells (Manousaki and Kalogerakios 2011). Plants utilize avoidance mechanisms in three ways: 1) exclusion through low permeability to salts, 2) excretion of some penetrating ions, and 3) isolation through ion retention (Mozafar and Goodin 1970; Flowers et al. 1977; Ramadan 1998; Glenn et al. 1999). Glycophytes maintain similar function but at lower rates, and are not as effective in reducing salt stress (Nilsen et al. 1996; Nelson et al. 1998).

Plants require macronutrients and micronutrients in various forms for normal functioning and growth as well as to deal with increasing stress. Nutrient levels outside of the optimum level for sufficient plant growth will cause overall health and growth to decline due to either a deficiency or toxicity (Jones and Jacobsen 2005a). Sodium is a functional nutrient for many plants (Subbarao et. al. 2003) but because of its ubiquitous presence in soils, it is rarely considered limiting. Plants utilize three biochemical mechanisms for fixing carbon in tissue growth: C<sub>3</sub>, C<sub>4</sub> and CAM photosynthesis. While C<sub>3</sub> and C<sub>4</sub> plants are named for their carbon molecules present in the first product of carbon fixation, CAM (Crassulacean acid metabolism) is an adaptation for increased efficiency in the use of water and is typically found in plants growing in arid environments (Herrera 2008). In C<sub>4</sub> plants, sodium (Na<sup>+</sup>) is a micronutrient that aids in

metabolism and synthesis of chlorophyll (Kering 2008) and in some species it substitutes for potassium in several roles, such as maintaining turgor pressure and aiding in the opening and closing of stomata (Subbarao et al. 2003). Nevertheless, beyond optimal levels, sodium and salts negatively affect plant growth. In addition to stress induced by salinity, plants also face stress from lack of oxygen in saturated soils.

Saturation-Anoxia Stress. Plant growth is dictated in part by oxygen availability in the soil, as roots require oxygen for cellular respiration, which fuels virtually all metabolic processes in plants. Under aerobic conditions, plants produce up to 19 times more ATP molecules than plants under anaerobic conditions (Barrett-Lennard 2002). Wetland plants have developed physiological adaptations to anoxic conditions to increase oxygen access to the roots. These include 1) aerenchyma: hollow root channels, 2) adventitious roots: that which grows from an unusual location such as the base of a tree to avoid soil saturation/anoxia, and 3) hypertrophy: e.g. enlarged lenticels where cell aggregation creates a channel on the stem surface which allows for gas exchange. Plants species' distribution varies across moisture gradients because of species' varying degrees of tolerance to the effects of saturated soil and because of plants' varying tolerances to lack of moisture.

#### Plants as Indicators of Environmental Condition

The presence of a plant species at an individual location will depend on a variety of edaphic, biotic, and climatic factors as well as the effect of individual factors, such as depth and duration of soil saturation or inundation (Cowardin 1978). In 1988, The U.S.

Fish and Wildlife Service (USFWS) in cooperation with a federal inter-agency review panel developed a national list of plant species that occur in wetlands (Reed 1988; USFWS 1988). This inventory was compiled as a list of over 7,000 plants in 13 separate regions of the United States. A plant's wetland indicator status (WIS) is applied to the species as a whole within each USFWS region where differences exist with ecotypic variation (Tiner 1991). This classification scheme has found widespread use as a general reference tool for grouping plants based on their known tolerance to saturation/anoxia. Utilizing known indices for associating species with tolerance to saturation (or salinity) can form the basis of comparing vegetation characteristics to the formation of zones based on environmental condition.

#### Zonation and Environmental Gradient

Zonation is defined as the formation of distinct features, common physical characteristics or components, (Biology Online 2012) and is a patent growth characteristic of vegetation in many wetlands (Stewart and Kantrud 1971; Snow and Vince 1984; Mitsch and Gosselink 2007). Wetland plant species tend to occupy a characteristic vertical range in relation to a water body, and species assemblages often appear as bands on the landscape. Environmental conditions within each band may represent optimal habitat for resident plant species (Snow and Vince 1984). Sanderson et al. (2008) described how abiotic environmental gradients governed vegetation zonation in an intermountain playa and found through reciprocal transplant experiments that plant species produced maximum biomass in their native zone and plant zonation appeared particularly strong on the most stressful ends of the abiotic gradient. Horsnell et al.

(2009) described the importance of temporal hydroperiod thresholds on the growth of various halophytes, mesophytes, phreatophytes, and xerophytes at a site in Western Australia, and in order to understand sensitivity to waterlogging and salinity, the authors established a ‘coping’ range for plants targeted for conservation.

Waterlogging and salinity at the soil surface are important factors that regulate plant growth and establishment. McFarlane and Williamson (2002) found that waterlogging may be more of an inhibitor to plant growth than salt even at high salt levels. The interaction of salt and water is synergistic for plants; some plants utilize additional water to offset the negative effects of increased salinity via osmoregulation and other adaptive mechanisms (Hasegawa et al. 2000). Studies have also suggested that plants compete more in less stressful conditions and poorer competitors are displaced to more stressful habitats, and that both biotic and abiotic factors play a role in plant species zonation (Bertness and Ellison 1987; Keddy 1989; Rand 2000; Costa et al. 2003).

### Thesis Purpose and Study Objectives

The primary objective of this study was to examine patterns of plant assemblages on a saline lake shoreline and to elucidate the abiotic characteristics occurring in association with them. Although biotic factors (*i.e.* facilitation, competition, etc.) likely played a role in the pattern of vegetation growth at the site, the purpose of this study was to understand the abiotic processes to support future approaches for revegetation of exposed saline soils where little or no vegetation grows.

The study was conducted in the summer of 2010 along the shoreline of Hailstone Lake, the primary landscape feature on a National Wildlife Refuge in south-central Montana. I examined plant species composition, percent ground cover and diversity; landscape position, soil saturation and salinity. Figure 2 depicts the environmental characteristics that were examined and served to guide the approach of the observational study.

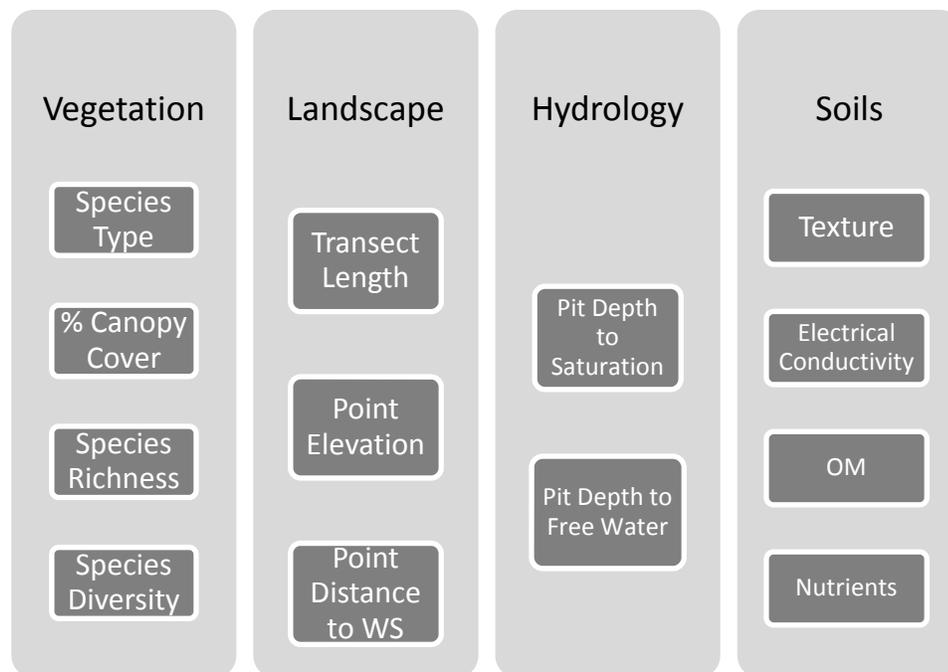


Figure 2. Environmental conditions examined in a study of plant growth characteristics at Hailstone National Wildlife Refuge.

The objectives for the study were as follows:

- 1) Vegetation. Identify vegetation on selected sampling points, measure canopy cover by species, determine species richness and calculate diversity. Classify plants using known indices for anoxia/saturation and saline tolerance.

- 2) Landscape. Measure physical characteristics of transects and sampling points including transect length, point elevation from water surface and point distance from water surface.
- 3) Hydrology. Measure soil depth to saturation and passive indications of hydrologic influence such as drifted organic matter and oxidized root channels.
- 4) Soils. Measure soil chemistry (nutrients, pH, EC), texture-by-feel and visual indications of reduction/oxidation.
- 5) Association. Identify significant associations between abiotic conditions and vegetation characteristics.
- 6) Recommendations. Using collected data and interpretation of associations, provide land managers with recommendations for revegetation.

In the arid Rocky Mountain west, there are increasing pressures on fresh water resources from agriculture, urban development and from potential modification of regional hydrology with changing global climate dynamics. Given these pressures, solutions are needed to address the adverse impacts of salinization and apply knowledge of vegetation response to abiotic factors that affect spatial distributions of vegetation. This thesis will contribute to our understanding of vegetation spatial patterns in inland saline environments.

SALINIZATION OF A NORTHERN ROCKY MOUNTAIN  
WILDLIFE REFUGE

Background

This study was conducted in response to high salinity conditions at Hailstone National Wildlife Refuge in northern Stillwater County (Figure 3), 46° 00' 24" N, 109° 10' 50" W, south-central Montana. Hailstone was characterized as one of the ten most endangered wildlife refuges in the USFWS refuge system (Schlyer 2007) and in 2009, the USFWS identified the primary management challenges as waterfowl and shorebird mortality due to high salt concentrations. Elevated selenium was also a contributing factor to wildlife mortality (although not examined in this study) and these solutes were concentrated in Hailstone reservoir, the primary aquatic feature and waterfowl attractant on the refuge. In addition, blowing salt dust from exposed lakeshore and saline seeps proved to be a nuisance to adjacent landowners and land managers (Nelson and Reiten 2009), and solutions to stabilize exposed soils at the refuge were initiated.

Study Site

Climate

Hailstone and Lake Basin have a semiarid climate with cold winters and hot summers. The local region is at the convergence of the Great Basin and Rocky Mountains, and is climatically influenced by both (Nelson and Reiten 2009). Average precipitation, based on Western Regional Climate Center records, is approximately 33 cm, 43 percent of which falls during April through June (WRCC 2011). Average air

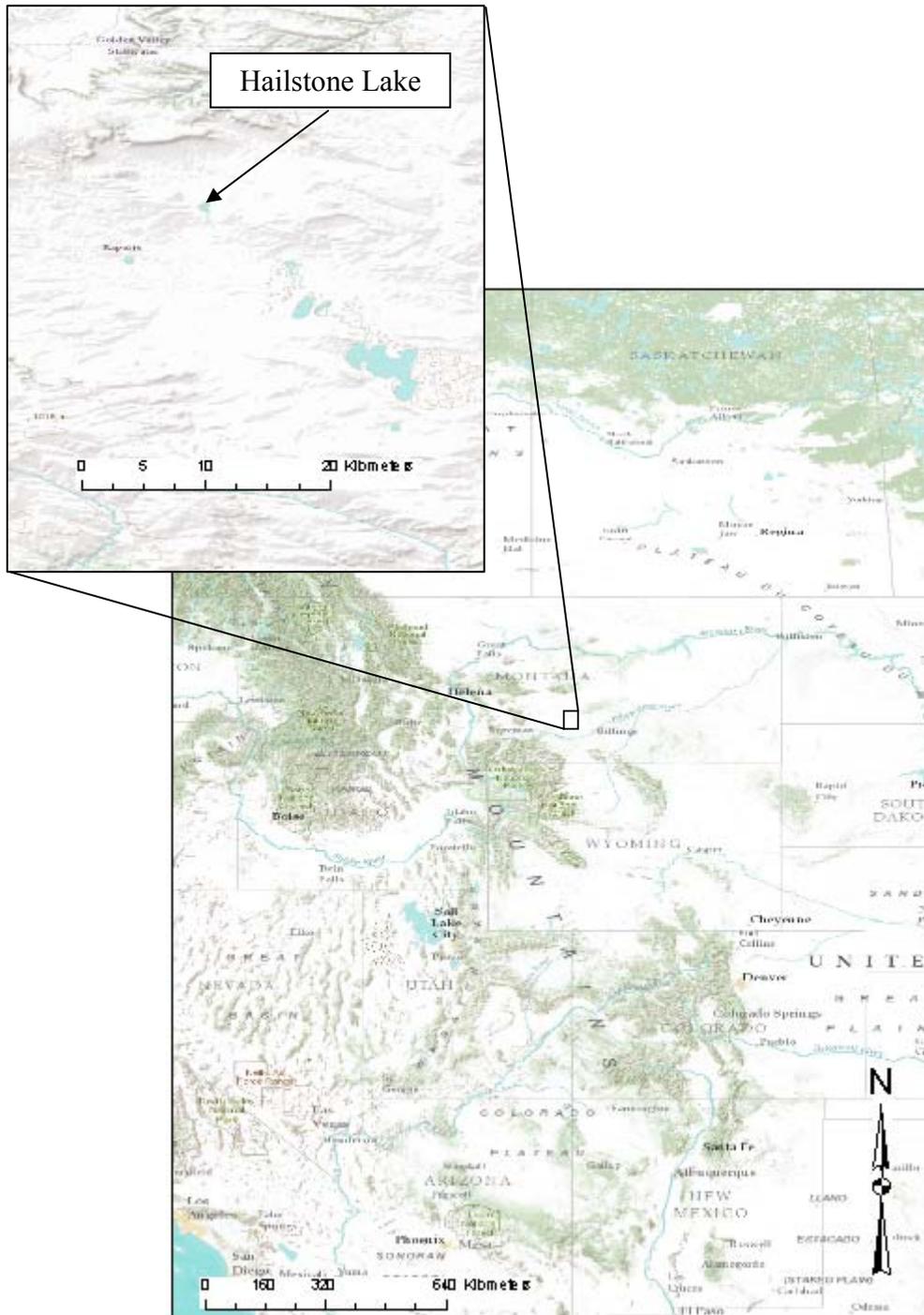


Figure 3. Location Map of Hailstone National Wildlife Refuge, Northern Stillwater County, MT. From USGS-SDSS 2012.

temperature for the region is 9.1 °C with an average maximum of 15.4 °C and a minimum of 2.8 °C. The 30-year average growing degree days for calendar dates March 1<sup>st</sup> through November 26<sup>nd</sup> for the nearby community of Rapelje, MT, is 1,810 (NOAA 2011).

### Geology

Hailstone Basin is located near the crest of the Big Coulee-Hailstone structural dome and is found on the northern fringe of the Lake Basin (Lopez 2000). The northern Hailstone Basin is made of Eagle Sandstone and the southern boundary lies on a fault zone made of steeply dipping rock of the Cretaceous Montana Group. The subsurface of the basin is made up of marine shale, primarily the Niobrara formation and are the source of salts at Hailstone (Nelson and Reiten 2009). This layer acts as a barrier to movement of groundwater (aquatard) and is one cause of exacerbated salinization within the basin. A narrow breach in the fault zone once allowed (albeit infrequently) surface drainage to flow out of Hailstone Basin into the internally drained Lake Basin (Nelson and Reiten 2009).

### Soils

Soils along the lakeshore vary from Lardell clay loam, to Absher clay loam (USDA, NRCS 2012) and though soil survey mapping data are known to omit small-scale soil units (inclusions), they are largely representative of the area.

### Hydrology

The watershed basin is approximately 12,633 hectares in size and prior to refuge establishment, an earthen dam was constructed across Hailstone Creek in 1938 as a Works Progress Administration project (Nelson and Reiten 2009), resulting in the formation of Hailstone Lake. The 1,112-hectare wildlife refuge was created in 1942 as a breeding ground for waterfowl and shorebirds. The lake initially inundated a small oxbow of Hailstone Creek and backwater wetland (Figure 4) approximately 65 hectares in area, but by 1979 expanded to a salty playa of nearly 259 hectares. Hailstone Lake was approximately 226 hectares but rarely did it get high enough to allow water to exit the concrete spillway. Almost all losses were through evaporation, which was the primary cause of elevated salt concentrations in the lake.

Prior to the commencement of dewatering in 2010-11, groundwater flow in the basin moved generally from the edges toward the reservoir and was perched on Niobrara shale (Nelson and Reiten 2009). Recharge potential was greater at the higher permeability margins where loose colluvial sediments from adjacent hill slopes fell, and decreased toward the center of the basin where denser alluvial sediments accumulated. A majority of the earthen embankment and the entire concrete spillway was removed in the summer of 2011, and historic flow regimes were restored to the lower channel.

### Saline Seep at Hailstone

In 1974 the Montana Department of State Lands ranked Stillwater County as having the most saline-affected dryland acres in the state at approximately 9,300 hectares

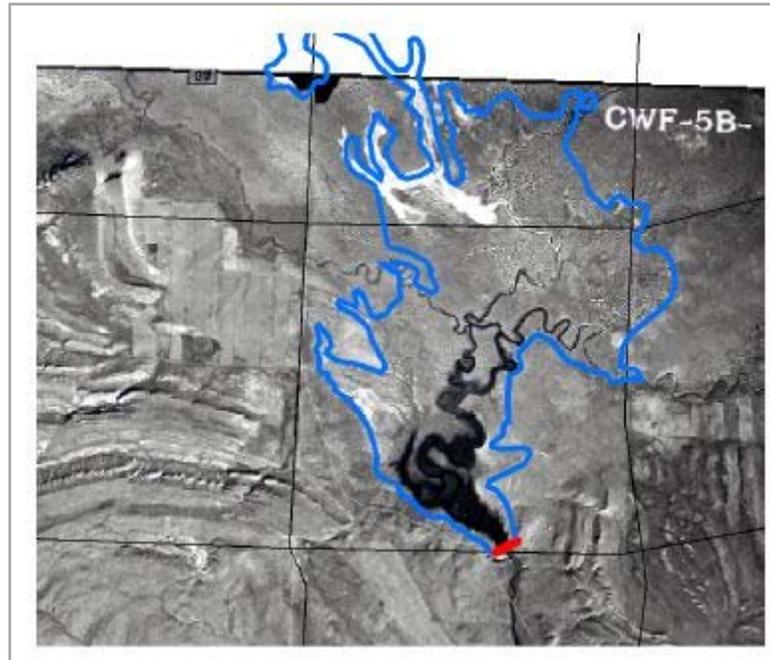


Figure 4. 1941 Aerial Photograph of Hailstone Lake, three years after the earthen dam was constructed on the perennial channel (highlighted in red). Note surface salinity in white at the top of photo. Photo courtesy of Nelson and Reiten 2009.

(Kellogg 1984), and it was estimated in 1980 that saline seeps were increasing at a rate of 10 percent annually (Miller et al. 1980). Inspection of aerial photographs revealed that Hailstone Basin experienced wide development of saline seep since dam construction and crop-fallow farming practices were initiated in the late 1940's. The saline seeps developed in groundwater transitions zones where a slight rise in bedrock forced water toward the land surface (Nelson and Reiten 2009).

Dominant soluble salts found in the soils at Hailstone are sodium, magnesium, calcium chloride, sulfates and bicarbonates. Water moving from the recharge area (as a result of precipitation infiltration) to the discharge area (seep) accumulates approximately 50 mg/L of total dissolved solids (TDS) per foot of movement, depending on rate of

groundwater flow and concentrations of available salts (Nelson and Reiten 2009). A lack of sufficient seasonal flushing resulted in further concentration and accumulation of salts. Miller et al. (1980) calculated that there may be enough sodium in the shallow aquifer to sustain seeps from 25 to 100+ years.

### Study Methods

Vegetation, landscape position, soils and hydrology on the shoreline of Hailstone Lake were the focus of this study. In 2010, ten transects were established along the transition from the shore of the lake and tributaries to adjacent native upland prairie (Figure 5). It was postulated that environmental characteristics would change with the dewatering of the lake, so the study was initiated as a 'point-in-time'.

Transect locations were chosen based on the presence of vegetation bands with visually distinct dominant species. These distinct vegetation assemblages generally paralleled the shoreline and appeared to represent a transition, progressing from wetland to an upland environment (Figure 6). Transects were oriented perpendicularly from the shore (or tributary swale) and across the bands of vegetation. Along each of the 10 transects, 1 sample point was randomly located within each of the 4 vegetation assemblages (n=40). Sample points were labeled A through D; 'A' being closest to the lake (or swale) and 'D' furthest away into the upland position (Figure 7). Landscape characteristics (Table 1) were measured at the 40 sample points.

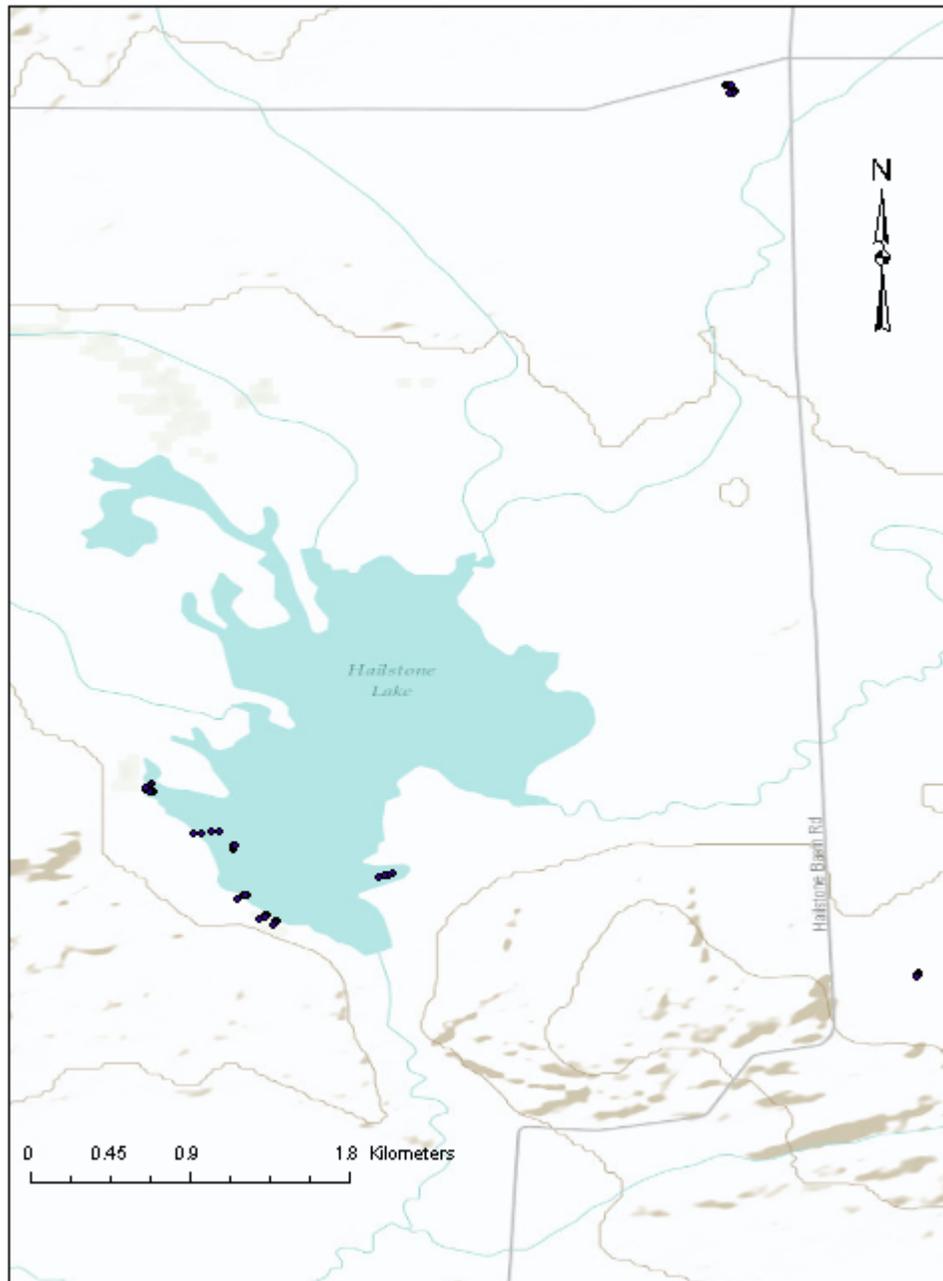


Figure 5. Sample point locations (black circles) at Hailstone National Wildlife Refuge. From USGS-SDSS 2012. Note: Lake level depicted in this map was not reflective of conditions at time of sampling. All transects and sample points were on or outside the margins of the lake.



Figure 6. An example of vegetative banding on the western shore of Hailstone Lake in March 2010.

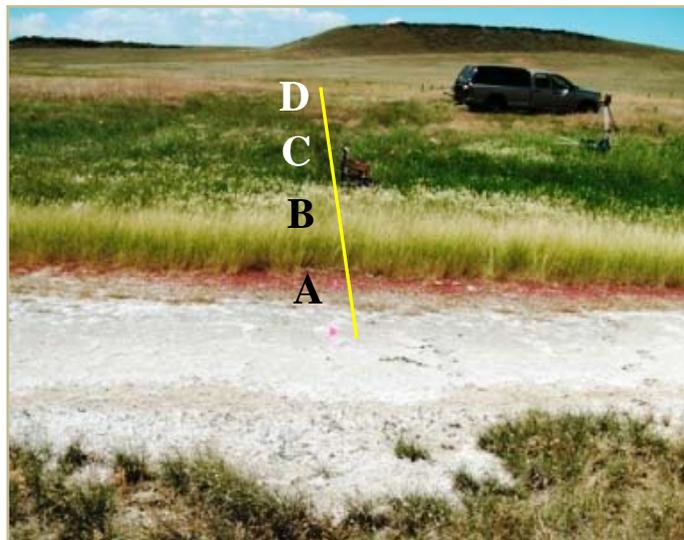


Figure 7. Transect 105 and approximate sample point locations in July 2010 oriented across a dry inflow channel to the northwest of the impoundment. Sample points were codified to reflect their relative position on the landscape; A (channel bottom) through D (upland).

A benchmark was created at each transect origin, representing approximately the closest point of the lake at the time of measurement, or, in the case of tributary transects, the bottom of the channel. (At the time of sampling, July 7 to August 3, 2010, tributaries were not flowing.)

Table 1. Landscape characteristics that were measured for each transect and at sample points.

<b>Physical Parameter</b>	<b>Units</b>
GPS location	lat / long
Elevation from water surface	meters
Point distance from water surface	meters
Transect length from A - D	meters
Transect aspect	northing
General location (lakeshore, tributary)	as applicable

### Vegetation

A 50 cm x 50 cm vegetation sampling frame was randomly placed within each dominant band of vegetation and all plants occurring within the sampling frame were identified to species using Dorn (1984), Flora of North America (1993), and Weeds of the West (Whitson 1991). The Plants Database (USDA, NRCS 2012) was used for final taxonomic nomenclature. Percent foliar cover (percentage of ground covered by aerial portions of the plants) of each species was also estimated and recorded.

Species were categorized using USFWS Wetland Indicator Status (Table 2) for the North Plains Region 4 (Eastern Montana). These indicators reflect the range of estimated probabilities of a species occurring in wetlands versus non-wetlands across the entire known distribution of the species. This classification scheme is not indicative of moisture status throughout the growing season, but rather an indication that sufficient

moisture is available for maintenance of vegetation during the growing season. These classes are intentionally broad and can represent a range of intra- and interspecific moisture tolerances (USFWS 1988). For this study, they were useful in grouping sampling points based on moisture affinity and were not intended to be used as indicators of species abundance.

### Hydrology

Indication(s) of active hydrology (free-water and/or saturation) was examined at each sampling point. In addition to visual observations of conditions on the soil surface, primary observation pits were dug to 60 cm with a shovel and left open for approximately 20 minutes at each sampling point to allow for groundwater seepage (as free-water, where present) to flow into the pits.

Table 2. U.S. USFWS Wetland Indicator Categories used in this observational study. From USFWS Biological Report 88 [26.9] 1988, Revised 1993.

<b>Indicator Code</b>	<b>Wetland Type</b>	<b>Comment</b>
<b>OBL</b>	Obligate Wetland	Occurs almost always (estimated probability 99%) under natural conditions in wetlands.
<b>FACW</b>	Facultative Wetland	Usually occurs in wetlands (estimated probability 67%-99%), but occasionally found in non-wetlands.
<b>FAC</b>	Facultative	Equally likely to occur in wetlands or non-wetlands (estimated probability 34%-66%).
<b>FACU</b>	Facultative Upland	Usually occurs in non-wetlands (estimated probability 67%-99%), but occasionally found on wetlands (estimated probability 1%-33%).
<b>UPL</b>	Obligate Upland	Occurs in wetlands in another region, but occurs almost always (estimated probability 99%) under natural conditions in non-wetlands in the regions specified. If a species does not occur in wetlands in any region, it is not on the National List.
<b>NI</b>	No indicator	Insufficient information was available to determine an indicator status.

In pits having no free-water, saturation depth was measured to the presence glistening soils on the pit walls. This latter condition indicated that water was either actively draining downward or wicking upward at some point between field capacity and saturation. Many factors can affect a soil under this condition but in this study, this assumption was meant to serve as a practical measure of soil water having influence on vegetation at the sample pit. In addition, Table 3 describes passive indications of hydrology, and served to support evidence of hydrologic influence at sample points if seasonal hydrology had ceased or was transitory in nature.

Table 3. Passive hydrologic indicators.

<b>Passive Hydrologic Indicators</b>
High-water Marks
OM Drift Lines
Drainage Patterns
Oxidized Root Channel
Water-stained Leaves

### Soils

At each sampling point, soil samples were taken from a primary pit (approximately 20 cm in diameter) and two smaller pits (for the purpose of composite sampling), all of which were dug approximately within the 0.5 m sample frame location. Soils from all three pits were collected in increments of 0-2 cm (surface), 2-5 cm, 5-10 cm and 10-20 cm, composited in a sealed plastic bag by depth increment, labeled and placed in a cooler. Depth increments were chosen based on the influence that nutrients, salinity and saturation have on plant seed germination (0-2 cm), seedling growth (2-5 cm)

and mature plant establishment (5-20 cm) during various growth stages. Soils were returned to the laboratory, thoroughly mixed, placed in a soil bag, dried at  $43\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$  for no less than one week, shipped to Ag Source Harris (Omaha, NE) and analyzed for soil chemistry. Table 4 lists the parameters and unit value for each parameter.

Table 4. Soil chemistry parameters analyzed.

Soil chemistry parameter	Units
Organic Matter	% of dry soil
N	mg/kg dry soil
P - Bray 1	mg/kg dry soil
K	mg/kg dry soil
pH	- log H <sup>+</sup> in solution
Na	mg/kg dry soil
CEC	meq H <sup>+</sup> /100g
EC	dS/m
Na	meq/l
Ca	meq/l
Mg	meq/l
NH <sub>4</sub>	mg/kg dry soil
NO <sub>3</sub>	mg/kg dry soil
PO <sub>4</sub>	mg/kg dry soil
SAR – Sodium Adsorption Ratio	$[\text{Na}^+] / [(\text{Mg}^{2+} + \text{Ca}^{2+})/2]^{0.5}$ where cation concentrations are in meq/l – Unitless ratio

At each sampling point, the sample core from the primary pit was inspected for the presence or absence of redoximorphic soil characteristics using the USDA Field Indicators of Hydric Soils (USDA, NRCS 2010). This observation was used to compare hydromorphic condition, *i.e.*, physical evidence of inundation and saturation, with plant type and landscape position. In addition, soil texture (Thien 1979) was observed for each soil sample and recorded.

### Data Compilation and Statistical Analysis

Ten transects had 4 sample points for each position A – D, which served as replications. Vegetation, landscape, soils, and hydrologic data was compiled using Microsoft Excel<sup>®</sup>, and basic statistical analysis was done using the IBM<sup>®</sup> SPSS<sup>®</sup> Statistics 19 environment. One-way analysis of variance (ANOVA) was used in comparing means among position for the following soil parameters: percent organic matter (OM), pH, CEC, EC and SAR by position (A, B, C, D). One-way ANOVA was used in comparing pH, CEC, EC and SAR by depth within each position. Data on percent OM by position and SAR by depth (position A) failed Levene's test of equality of error variance so ANOVA was not calculated. Least square difference tests were used for post hoc comparisons of within group means. Statistical significance was determined using p-values at 0.05 or less. Correlations were calculated using Pearson's test. Sigma Plot<sup>®</sup> 10 was also used for graphing box plots, which show mean and first quartile, and the whiskers designate the extreme ends of the variable range (set to extend to 1.5 times the length of the interquartile range). Points located outside the range of the whiskers (dots and stars) were considered to be outliers.

To measure plant diversity, Simpson's (Equation 1) and Shannon-Wiener (Equation 2) indices were calculated for vegetation samples. A vegetation assemblage containing only one species would have a Simpson's value of 1.0; therefore the inverse was used to show greater values representing higher diversity.

Equation 1. Simpson's Diversity Index

$$D = \sum_{i=1}^S \frac{1}{p_i^2}$$

Where:  $n$  = the total proportion (as percent cover or number of individuals) of a particular species

$S$  = species richness

Equation 2. Shannon-Wiener Diversity Index.

$$H' = - \sum_{i=1}^S [p_i \ln(p_i)]$$

Where:  $p_i$  = proportion of organisms (as percent cover) of a particular species relative to the total number of species.

$S$  = species richness

Subscripts are used in reporting and denote soil depth in centimeters or indicate that a depth weighting transformation was performed (*e.g.* EC<sub>dw</sub>) on some soil chemical parameters. Depth weighing is used to simplify sample point values in some analyses and is calculated by multiplying the soil depth increment by the parameter value and dividing the sum of all incremental values by the total sample depth (20 cm).

Equation 3. Depth weighting formula for a 20 cm deep soil sample.

$$dw = \frac{\sum(v[d_i])}{d_t}$$

Where:  $v$  = parameter value

$d_i$  = depth increment (cm)

$d_t$  = depth total (cm)

Sodium adsorption ratio (SAR) measures the relationship between three dominant cations; sodium ( $\text{Na}^+$ ) to magnesium ( $\text{Mg}^{2+}$ ) and calcium ( $\text{Ca}^{2+}$ ) and is useful in determining the proportion of sodium in a soil sample (Equation 4). SAR is calculated as follows and is reported as a unitless measure:

Equation 4. Calculating sodium adsorption ratio (unitless measure) where cation concentrations are in meq/l.

$$\text{SAR} = \frac{[\text{Na}^+]}{\sqrt{([\text{Mg}^{2+}] + [\text{Ca}^{2+}]) \div 2}}$$

Electrical conductivity measures the ability of a saturated soil sample to pass a small electrical charge, and will be higher with increasing abundance of ions such as sodium, magnesium, sulfate and calcium. Elevated EC levels indicate high concentrations of these ions and are characteristic of saline soils. If sodium is elevated in the soils (in proportion to Mg and Ca) it is considered to be sodic. Both saline and sodic conditions can limit a plants' growth potential. Table 5 outlines the chemical conditions which classify soils as saline, sodic or both.

Table 5. Salt affected soils classification (USDA, NRCS 1991).

Soil Classification	EC (dS/m)	SAR	pH
Saline	> 4.0	< 12	< 8.5
Sodic	< 4.0	> 12	> 8.5
Saline-Sodic	> 4.0	> 12	< 8.5

## VEGETATION CHARACTERISTICS OF A SALINE LAKESHORE ENVIRONMENT

Vegetation generally grew in distinct bands that paralleled the shoreline at Hailstone, and I hypothesized that environmental conditions varied among bands. This chapter discusses vegetation characteristics among bands based on the results of the field study. (Chapter 4 addresses the abiotic conditions found at each position.)

### Results

Vegetation bands were referred to as A through D, with A being closest to the lake and generally consisting of wetland vegetation, and D occupying the highest position and generally consisting of upland vegetation. Twenty-one plant species were identified within the 40 sample points, including 9 native and 11 non-native plant species, and 1 unidentified forb. All the species are known to occur in USDA Region 4 (Eastern Montana), which includes Hailstone NWR. (Note: 9 species were not indicated in Stillwater County, MT and gaps are known to occur in NRCS reporting. USDA, NRCS 2012) Species included 3 small shrub species, 11 graminoid species, and 7 forb/herbaceous species (Table 6).

### Vegetation Band A

The range of percent plant cover in the A position for all transects was from 56% to 96%, with a mean cover of 74% (median 76%). This band had the lowest diversity among positions (1.12 and 0.05 for Simpson's and Shannon-Weiner Diversity Indices,

respectively) and a total richness of three species. The A position was dominated by the annual chenopod, *Salicornia rubra* (mean canopy cover of 70%). This obligate wetland species is highly tolerant of salinity and inundation (USDA, NRCS 2012) as are *Puccinellia nuttalliana* (OBL) and *Suaeda calceoliformis* (FACW), which commonly occurred along the shoreline (Table 7). All species in position A had a high tolerance to salinity.

Table 6. Vegetation at Hailstone organized by family. (From USDA PLANTS Database 2012.) Family abbreviations: P=perennial, A/B=annual/biennial, A=annual. Growth habit abbreviations: F/H=forb/herb, S=shrub, G=graminoid. Native status abbreviations: N=native, I=introduced, N/I=native/introduced. Salinity tolerance: H=high, M=medium, L=low

Species	Family	Duration	Growth Habit	Native Status	Saline Toler.
<i>Crepis runcinata</i> Torr. & A. Gray	Asteraceae	P	F/H	N	M
<i>Lactuca serriola</i> L.	Asteraceae	A/B	F/H	I	N/A
<i>Onopordum</i> sp. L.	Asteraceae	B	F/H	I	N/A
Mustard sp.	Brassicaceae	A	F/H	I	N/A
<i>Thlaspi arvense</i> L.	Brassicaceae	Al	F/H	I	M
<i>Bassia prostrata</i> L.	Chenopodiaceae	P	S	I	H
<i>Salicornia rubra</i> A. Nelson	Chenopodiaceae	A	S	N	H
<i>Suaeda calceoliformis</i> Hook. Moq.	Chenopodiaceae	A/P	S	N	H
<i>Medicago sativa</i> L.	Fabaceae	A/P	F/H	I	M
<i>Triglochin maritima</i> L.	Juncaginaceae	P	G	N	H
<i>Alopecurus arundinaceus</i> Poir.	Poaceae	P	G	I	H
<i>Bromus arvensis</i> L.	Poaceae	A	G	I	L
<i>Bromus tectorum</i> L.	Poaceae	A	G	I	L
<i>Distichlis spicata</i> (L.) Greene	Poaceae	P	G	N	H
<i>Hordeum jubatum</i> L.	Poaceae	P	G	N	H
<i>Pascopyrum smithii</i> (Rydb.) Á. Löve	Poaceae	P	G	N	H
<i>Poa pratensis</i> L.	Poaceae	P	G	N/I	L
<i>Poa secunda</i> J. Presl	Poaceae	P	G	N	L
<i>Puccinellia nuttalliana</i> (Schult.) Hitchc.	Poaceae	P	G	N	H
<i>Thinopyrum intermedium</i> (Host) Barkworth & D.R. Dewey	Poaceae	P	G	I	M

Table 7. Band A vegetation summary for 10 sample points including wetland indicator status (WIS), mean, standard deviation (s.d.) of canopy cover and frequency of occurrence calculated by position. Salinity tolerance based on USDA Plants Database.

Position	Species	WIS	mean canopy cover	s.d.	occurrence frequency (n=10)	salinity tolerance
A	<i>Salicornia rubra</i>	OBL	70%	14%	100%	high
	<i>Puccinellia nuttalliana</i>	OBL	3%	9%	20%	high
	<i>Suaeda calceoliformis</i>	FACW	1%	2%	20%	high

### Vegetation Band B

The range of cover in the B position for all sample points was from 4% to 97% with a mean cover of 61% (median 60%). Throughout the study transects, position B had a slightly lower overall plant cover, with an average 39% of bare ground. Vegetation in band B had the second lowest richness (6) and mean diversity of 1.17 and 0.08 for Simpson's and Shannon-Weiner Diversity Indices, respectively.

The vegetation in the B position (Table 8) was a mixture of facultative-wetland (FACW) and obligate (OBL) wetland species, including *Suaeda calceoliformis*, *Distichlis spicata* and *Triglochin maritima*. *Triglochin maritima* (Seaside arrowgrass) was only found in the tributaries and streams upslope of Hailstone Lake. Two species were common in both the A and B bands: *Salicornia rubra* and *Suaeda calceoliformis*. All species in position B are salt tolerant (USDA, NRCS 2012). *Bassia prostrata*, (Kochia), an introduced Eurasian species sometimes used as forage for livestock (USDA, NRCS 2012), consisted as a minor portion of the plant species found at this location. Like position A, all species in position B had a high tolerance to salinity.

Table 8. Band B vegetation summary for 10 sample points including wetland indicator status (WIS), mean, standard deviation (s.d.) of canopy cover and frequency of occurrence calculated by position. Salinity tolerance based on USDA Plants Database.

Position	Species	WIS	mean canopy cover	s.d.	occurrence frequency (n=10)	salinity tolerance
B	<i>Suaeda calceoliformis</i>	FACW	22%	30%	40%	high
	<i>Triglochin maritima</i>	OBL	18%	39%	20%	high
	<i>Distichlis spicata</i>	FACW	11%	29%	30%	high
	<i>Salicornia rubra</i>	OBL	6%	14%	40%	high
	<i>Puccinellia nuttalliana</i>	OBL	3%	8%	20%	high
	<i>Bassia prostrata</i>	NI	1%	2%	10%	high

### Vegetation Band C

Thirteen species were found in the C position (Table 9). There were obligate wetland species in this position but at a lower percent cover (12% OBL), compared to the adjacent B and A positions. There was less bare ground than the neighboring B position and the range of percent canopy cover in the C position for all sample points was 44% to 96% with a mean cover of 74% (median 80%). The C position vegetation was more diverse than A and B positions with values of 1.79 and 0.28 for Simpson's and Shannon-Weiner Diversity Indices, respectively. Of the 13 species identified in the 10 position C sample points, only 2 also occurred in both A and B vegetation bands, *Salicornia rubra* and *Puccinellia nuttalliana*. The rhizomatous species, *Distichlis spicata* also occurred in bands B and D. There was a range from high to low salinity tolerance among species in position C.

Table 9. Band C vegetation summary for 10 sample points including wetland indicator status (WIS), mean, standard deviation (s.d.) of canopy cover and frequency of occurrence calculated by position. Salinity tolerance based on USDA Plants Database.

Position	Species	WIS	mean canopy cover	s.d.	occurrence frequency (n=10)	salinity tolerance
	<i>Distichlis spicata</i>	FACW	16%	26%	30%	high
	<i>Thinopyrum intermedium</i>	UPL	11%	19%	30%	medium
	<i>Poa pratensis</i>	FACU	10%	17%	40%	low
	<i>Crepis runcinata</i>	FAC	8%	17%	20%	medium
	<i>Bassia prostrata</i>	NI	7%	19%	20%	high
	<i>Puccinellia nuttalliana</i>	OBL	6%	19%	20%	high
C	<i>Bromus arvensis</i>	FACU	6%	15%	20%	low
	unk. annual	N/A	6%	19%	10%	n/a
	<i>Salicornia rubra</i>	OBL	1%	4%	20%	high
	Mustard sp.	NA	1%	3%	20%	n/a
	<i>Hordeum jubatum</i>	FACW	1%	3%	10%	high
	<i>Bromus tectorum</i>	UPL	<1%	1%	10%	low
	<i>Thlaspsi arvense</i>	UPL	<1%	1%	10%	medium

### Vegetation Band D

Upland species dominated vegetation band D (Table 10). The range of percent canopy cover for all sample points was from 64% to 100%, with a mean cover of 86% (median 90%). Position D (like C) had a total species richness of 13 and the second highest mean diversity with a value of 1.45 and 0.18 for Simpson's and Shannon-Weiner diversity indices, respectively. *Distichlis spicata*, *Pascopyrum smithii*, *Alopecurus arundinaceous*, *Hordeum jubatum* are species known to have a high tolerance of salinity (USDA, NRCS 2012) and 9 of the 13 species found in the D position are grasses. *Distichlis spicata*, *Thinopyrum intermedium*, *Poa pratensis*, and *Thlaspsi arvense* are also found in the C position. *Bromus tectorum* (cheatgrass) is considered invasive and *Onopordum* (cotton thistle) is listed as non-native. Overall, there is less evenness of

species distribution among the 13 species in position D compared to the 13 species in position C. There are more rare species ( $\leq 1\%$  canopy cover) in position D (7) compared to position C (5). Figure 8 depicts the mean percent bareground for all positions.

Table 10. Band D vegetation summary for 10 sample points including wetland indicator status (WIS), mean, standard deviation (s.d.) of canopy cover and frequency of occurrence calculated by position. Salinity tolerance based on USDA Plants Database.

Position	Species	WIS	mean canopy cover	s.d.	occurrence frequency (n=10)	salinity tolerance
	<i>Poa pratensis</i>	FACU	33%	39%	50%	low
	<i>Distichlis spicata</i>	FACW	12%	21%	30%	high
	<i>Thinopyrum intermedium</i>	UPL	10%	28%	30%	medium
	<i>Poa secunda</i>	FAC	9%	29%	10%	low
	<i>Pascopyrum smithii</i>	FACU	9%	25%	20%	high
	<i>Alopecurus arundinaceus</i>	NI	6%	20%	10%	high
D	<i>Hordeum jubatum</i>	FACW	1%	3%	20%	high
	<i>Lactuca serriola</i>	FACU	1%	2%	20%	low
	<i>Bromus tectorum</i>	UPL	1%	3%	10%	low
	<i>Bromus arvensis</i>	FACU	<1%	1%	10%	low
	<i>Thlaspi arvense</i>	NI	<1%	1%	10%	medium
	<i>Medicago sativa</i>	NI	<1%	1%	10%	medium
	<i>Onopordum</i> sp.	NI	<1%	1%	10%	low

### Plant Diversity

Table 11 shows mean plant diversity using two indices for each position (A-D). The two indices were used to compare the effect of dominant species versus rare species. Simpson's index of diversity considers the number of species (richness), the proportion of the assemblage occupied by each species (as percent cover) and gives more weight to the most dominant species, as a result of squaring the proportion of each species (Simpson 1949).

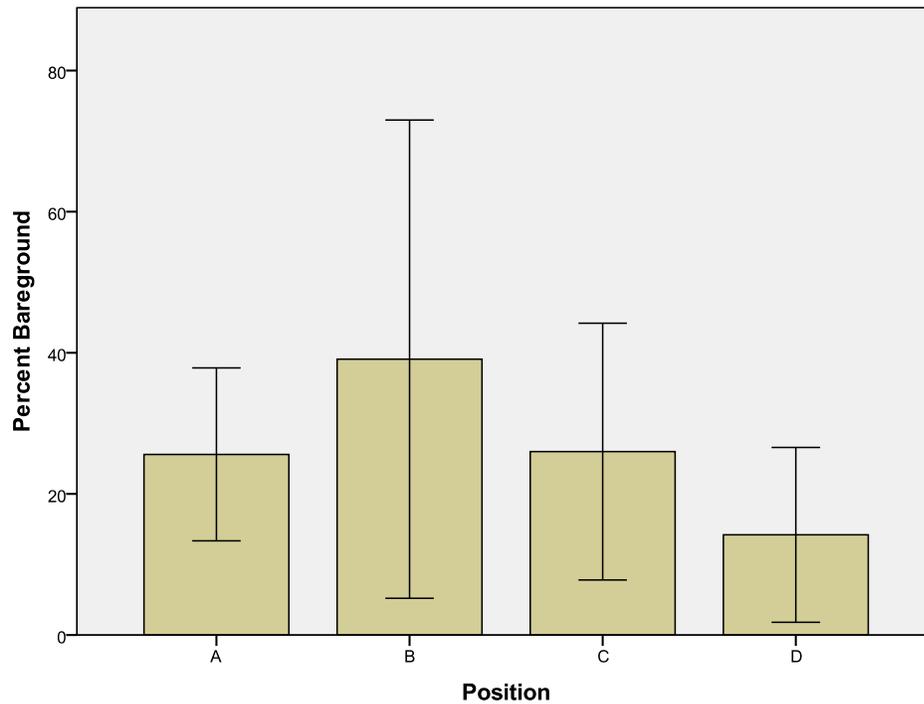


Figure 8. Percent bare ground by position within 10 transects at Hailstone National Wildlife Refuge. Error bars  $\pm 1$  standard deviation.

The Shannon-Weiner index gives more weight to rare species (Shannon 1948), therefore the effective number of species from the Simpson index will always be less than or equal to the effective number of species from the Shannon-Wiener index. The two indices were proportionally equal and generally paralleled each other by position (Figure 9), which indicates that rare species did not affect the diversity in any position. C had the highest mean plant diversity among positions regardless of either weighting scheme followed by position D. Positions A and B have low diversity, lower richness and it can be concluded that more species can tolerate environmental conditions in the higher positions than are adaptable to the lower positions.

Table 11. Two diversity indices with richness (S), by vegetation band position.

Position	Richness (S)	Inverse Simpson's (1/D)	Shannon-Wiener (H')
<b>A</b>	3	1.12	0.05
<b>B</b>	6	1.17	0.08
<b>C</b>	13	1.79	0.28
<b>D</b>	13	1.45	0.18

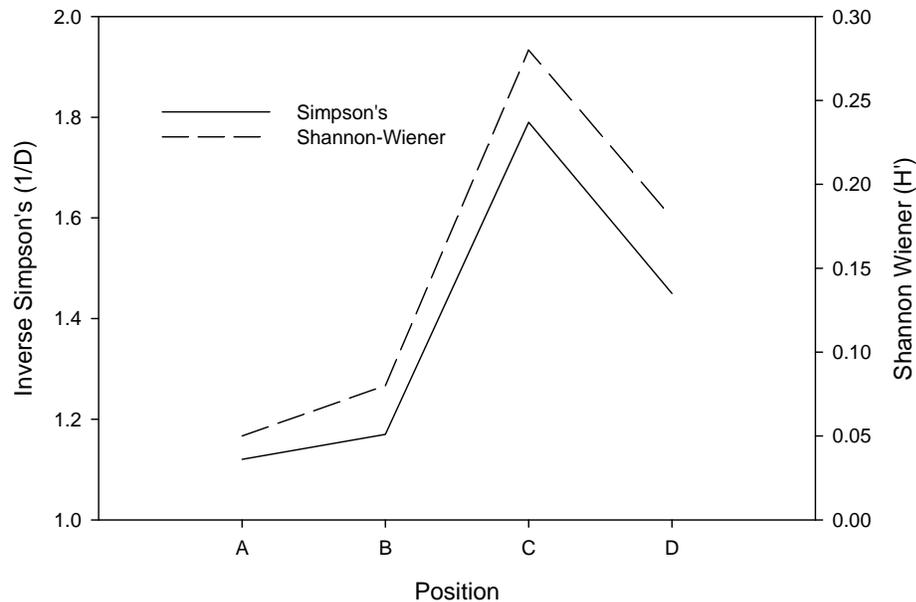


Figure 9. Inverse Simpson's and Shannon Wiener diversity indices plotted by position.

#### Wetland Indicator Status by Position

Table 12 shows the percentage cover and species richness (S) by vegetation type, *i.e.*, WIS, at positions A, B, C, and D. Obligate (OBL) and facultative wetland (FACW) species have greater percentage canopy cover in the lower positions (A and B), and upland plants (UPL) are denser (and more abundant) in drier positions. The distribution and density among positions aligns with wetland plant indicator status assigned to the various species for Region 4 (USDA, NRCS 2012).

Table 12. Vegetation type and mean percent coverage summary by bands A – D. s.d. indicates one standard deviation. (S) = species richness by WIS.

% Cover by Vegetation Type (WIS)															
position	OBL			FACW			FAC			FACU			UPL		
	mean	s.d.	(S)												
A	<b>74</b>	12	(2)	<b>1</b>	2	(1)	<b>0</b>	0	(0)	<b>0</b>	0	(0)	<b>0</b>	0	(0)
B	<b>28</b>	40	(3)	<b>33</b>	31	(2)	<b>0</b>	0	(0)	<b>0</b>	0	(0)	<b>1</b>	2	(1)
C	<b>8</b>	19	(2)	<b>16</b>	25	(2)	<b>8</b>	17	(1)	<b>16</b>	21	(2)	<b>26</b>	27	(6)
D	<b>0</b>	0	(0)	<b>13</b>	22	(2)	<b>11</b>	29	(1)	<b>43</b>	41	(3)	<b>19</b>	31	(7)

### Common Species within Bands

Characterization of plant assemblages using the most common species for description and statistical analysis has been established in other studies (Sanderson et al. 2008). Most common species by position are shown in Table 13. Although present in three positions, *Salicornia rubra* dominated the A position, whereas *Distichlis spicata* was found in relatively even distribution across positions B, C and D. The overlap of some species across vegetation bands may be reflective of species niche, and while certain species dominated the bands, the vegetation in each band was not necessarily a unique community type. The most common species among zones are discussed in detail.

*Salicornia*. *Salicornia* species (common name: glasswort, swamp samphire, pickleweed) is a cosmopolitan genera native to North American, Europe, South Africa and South Asia. They are a pioneer species and are included among a group of halophytes

Table 13. Prioritization of most common species for within-position analysis and these species were selected to represent their respective positions for later analysis. Mean and standard deviation (s.d.) are shown. Salinity tolerance based on USDA Plants Database.

Position	Species	WIS	mean canopy cover	s.d.	occurrence frequency	salinity tolerance
A	<i>Salicornia rubra</i>	<b>OBL</b>	70%	14%	100%	high
B	<i>Suaeda calceoliformis</i>	<b>FACW</b>	22%	30%	40%	high
C	<i>Distichlis spicata</i>	<b>FACW</b>	16%	26%	30%	high
D	<i>Poa pratensis</i>	<b>FACU</b>	33%	39%	50%	low

that benefits from sodium concentrations above a level required as a micronutrient for a majority of plants. Mahall (1976) found increased biomass production of *Salicornia* species with increasingly saline waterlogged soils. Although they can tolerate a wide range of salinities, they exhibit maximum growth at salinity of 10,000 mg/l (approximately 12.5 dS/m) and are outcompeted in soils that lack salt (Zedler 1982; Lewis 1982; Josselyn et al. 1983; Allison 1992). In addition, Noe and Zedler (2001) found that extended spring rainfall may lead to increased germination as a result of salinity dilution during the crucial emergence stage. Ungar et al. (1979) found that competition determines the distributions of many halophytes and species interactions can be especially affected by soil salinity levels. Although *Salicornia* species occur in freshwater sediments (Griffith, unpublished data), it is easily outcompeted by plants better adapted to such conditions (Mahall and Park 1976).

*Salicornia rubra* is a succulent chenopod (C<sub>4</sub> plant), is commonly found in coastal ecosystems as well as inland salty playas and saline seeps, and in USFWS Region 4, *S. rubra* is an obligate wetland plant (OBL). It is an annual plant with a hermaphroditic flower that is wind pollinated and contains a single seed (Flora of North America 1993).

Khan et al. (2001) found that *S. rubra* grew in concentric circles with other salt tolerant species around a saltpan lake near Goshen, UT. This small annual forb was found nearest the saltpan followed by the perennial forb, *Salicornia utahensis*. Pennings and Callaway (1992) concluded that in a southern California salt marsh, competition was the factor limiting establishment of *S. rubra* in the drier and more saline *Arthrocnemum* (Parish's glasswort) zone, but in a central California salt marsh, it was observed competing with non-native upland plants (Wasson and Woolfolk 2011).

*Suaeda calceoliformis*. Like *Salicornia rubra*, *Suaeda calceoliformis* (common name: Pursh seepweed, horned sea-blight), is a succulent halophyte and has been documented to grow in areas of high soil salinity and alkalinity on areas identical to Hailstone; playas, salt flats and other wetlands. It is an annual herb (C<sub>4</sub> plant) and is more common in higher salinity substrates when growing in a prostrate form, where it can retain more water (Youngman and Heckathorn 1997). *Suaeda calceoliformis* is a FACW plant in Region 4 (USDA, NRCS 2012).

Keiffer and Ungar (1997) conducted a germination study of *Suaeda calceoliformis* (among others) by simulating seed exposure to high salinity. Two species had a significant increase in the germination rate when compared to seeds germinated in distilled water. Baseline germination data from seeds placed in 0, 1, 2, and 3% NaCl solutions indicated that *Salicornia europaea* and *Suaeda calceoliformis* were the only species to germinate in the 3% NaCl solution. The author concluded that prolonged exposure to saline solutions can inhibit or stimulate germination in certain species and the

resulting germination and recovery responses are related to the duration and intensity of their exposure to salt in their natural habitats.

*Distichlis spicata*. *Distichlis spicata* (saltgrass) is a halophytic graminoid (C<sub>4</sub> plant) that inhabits upper/high marsh (irregularly flooded) areas, in which the water levels vary between 5 cm above the soil surface and 15 cm below the soil surface. It is also commonly present in the arid west, where it is one of the most drought-tolerant species. Saltgrass is located in both organic alkaline and in saline soils (USDA, NRCS 2012). An important pioneer plant in early stages of succession in saline areas, the sharp-pointed rhizomes of *Distichlis spicata* with its numerous epidermal silica cells, and the aerenchymatous network of the rhizome, leaf sheath, and roots facilitate development of the plant in anoxic conditions; heavy clays, shales, and inundated soils. In salt marshes of southern Utah, *Distichlis spicata* contributes to a hummock-building process (increased OM) that favors localized removal of salts by capillary action and evaporation. The greatest amount of growth of *Distichlis spicata* takes place when temperatures are cool and soil moisture is high during the early spring. During periods of high salt and water stress, morphological and anatomical adaptations of saltgrass are important for survival (Hansen et al. 1976). In a greenhouse investigation, Smart and Barko (1980) grew *Distichlis spicata* from seed on freshwater, brackish and marine sediments. They found that although the availability of nitrogen ultimately determined biomass accrual, sediment salinity negatively affected growth rate.

*Poa pratensis*. Kentucky bluegrass is a cool-season perennial sod-forming grass and is the only C<sub>3</sub> plant of the four most common plants. The roots are shallow, often within the upper 8 cm of the soil surface. Kentucky bluegrass is found most abundantly on sites that are cool and humid. It has become naturalized across North America and often occurs as a dominant species in the herbaceous layer. The active growth stage of *Poa pratensis* begins in late winter/early spring and, by midsummer it is nearly dominant on its sites. Cool temperatures in fall promote growth when other species are dying back. It spreads by rhizomes, produces abundant seed, and can become established on disturbed sites faster than other plant species. It is an aggressive competitor with native species and has a low tolerance to salinity (USDA, NRCS 2012).

#### Vegetation and Position

Figure 10 shows the percent cover for the most common species across the four positions. The composition of plant species occurring in bands may partially reflect differences in the degree of adaptation to saturated conditions at Hailstone. For example *Salicornia rubra* and *Suaeda calceoliformis* predominantly occupy wetter, lower A and B positions, whereas *Poa pratensis* predominantly occupies the higher, drier D position. The FACW species *Distichlis spicata* occurs in mesic and drier upslope positions and seems to tolerate a wide range of growing conditions.

#### Conclusions

Vegetation communities on the shores at Hailstone appear to follow distinct, patterns of colonization that generally follow the topography of the lakeshore. Vegetation

found at near-shoreline positions is predominantly wetland, salt-tolerant and inundation/saturation-tolerant annual halophytes, with a single species dominating the plant community (Figure 10). Moving away from the lake, vegetation occurs in repeated patterns, with differences in amount of canopy cover, species diversity, and wetland indicator status (WIS). The most common plant in the D position, *Poa pratensis* was the only C<sub>3</sub> plant of the four most common species, and the only species to have a low tolerance to salinity. These findings are consistent with previously reported research findings from sites similar to those observed at Hailstone National Wildlife Refuge.

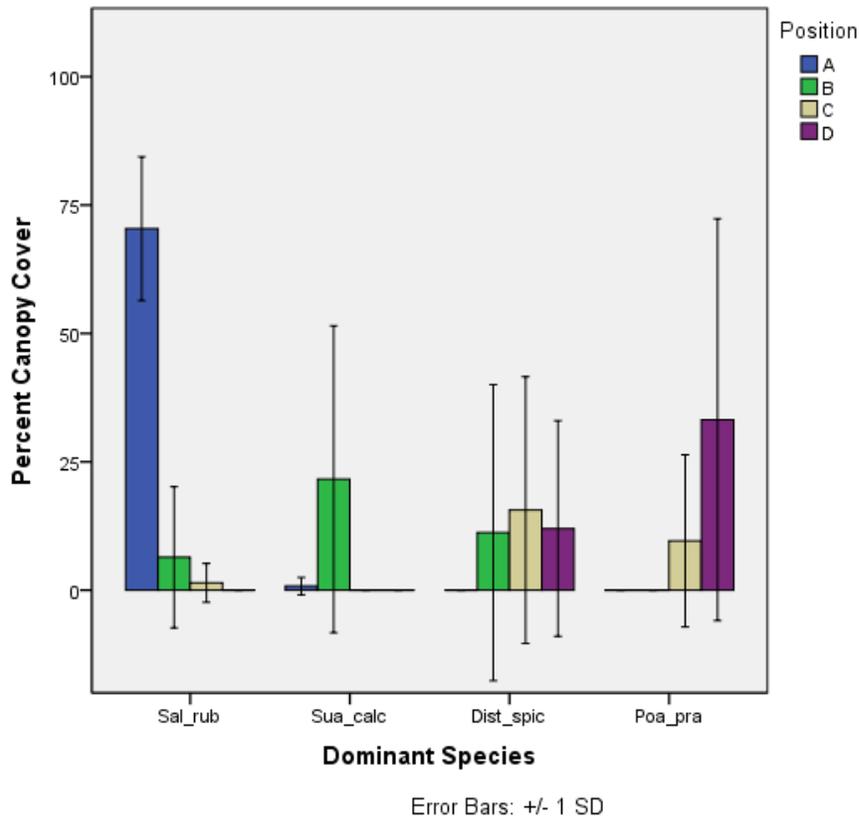


Figure 10. Percent canopy cover across A-D positions for the four dominant species in each sample position at Hailstone National Wildlife Refuge.

Each position had a single predominant species and rare species had little effect on diversity. The pattern of indices among positions, as calculated by two methods, was nearly proportional, and diversity is greatest at position C, followed by position D. Diversity was relatively low and similar for positions A and B. These data support the conclusion that more commonly occurring species are adaptable to positions C and D, farthest from the shoreline (and the abiotic conditions found there) than at positions A and B. Vegetation establishment on positions A and B will likely be limited to only a very few, select species, while on C and D substantially more species are capable of establishing, offering a greater likelihood of success in vegetation establishment at these positions. By comparing vegetation, it became evident that bands likely represented similar abiotic environmental characteristics and further analysis was undertaken to explore similarities or differences in abiotic conditions among vegetated bands.

## ABIOTIC CONDITIONS OF A SALINE LAKESHORE ENVIRONMENT

Abiotic conditions were compared among positions to determine whether salinity and saturation vary significantly among vegetation bands that appear to radiate out from the edges of the lake. This data was analyzed to whether these differences support the occurrence of plants along a saturation/salinity gradient, based on their documented tolerances.

### Results

#### Landscape Characteristics

Sample point elevation above the lake water surface and depth to saturation were examined for the 40 observation points at the Hailstone study site. Transect slope, length, and sample point distance from the lake and/or channel bottom varied widely among transects (Table 14). Vegetated banding occurred along transects of various lengths and slopes and was a repeated visual feature regardless of these conditions.

#### Hydrology

Free-water in the sampling pits was a result of the presence of groundwater at a point above the maximum depth of the pit. However because groundwater levels fluctuate over time, indications of soil saturation were also documented. It should be noted that presence of saturation does not indicate whether the uppermost level of saturation was wicking upward or moving downward with lake dewatering.

Table 14. Length, height differential from point A to D in meters and mean slope for each transect. Slope equals height/length as a percentage. The distribution of the sample population is non-normal, 8 of 10 transect lengths are 25% or less of the maximum value. Mean, minimum, maximum and standard deviations (s.d.) are given to demonstrate the variability among transects.

<b>Transect ID</b>	<b>Length (m)</b>	<b>Height (m)</b>	<b>Slope</b>
101	14.6	1.19	8.1%
102	10.1	0.49	4.9%
103	11.9	0.61	5.1%
104	10.7	0.73	6.8%
105	10.7	0.43	4.0%
106	96.9	1.28	1.3%
107	61.0	0.59	1.0%
108	24.4	1.05	4.3%
109	22.9	0.75	3.3%
110	26.5	0.46	1.7%
<b>mean</b>	<b>29.0</b>	<b>0.8</b>	<b>2.6%</b>
<b>s.d.</b>	<b>28.3</b>	<b>0.3</b>	<b>2.3%</b>
<b>min</b>	<b>10.1</b>	<b>0.4</b>	<b>1.0%</b>
<b>max</b>	<b>96.9</b>	<b>1.3</b>	<b>8.1%</b>

Table 15. Mean sample points distance (m) from water surface for each position; s.d. is one standard deviation. Sample points were not equally spaced across transects and were randomly chosen based on visual homogeneity of plant communities. The flatter transects had longer distances between sample points.

<b>Sample position distance to water surface (m)</b>							
<b>A</b>		<b>B</b>		<b>C</b>		<b>D</b>	
<b>mean</b>	<b>s.d.</b>	<b>mean</b>	<b>s.d.</b>	<b>mean</b>	<b>s.d.</b>	<b>mean</b>	<b>s.d.</b>
1.13	1.84	9.52	8.47	18.90	19.46	30.08	27.65

Table 16 shows mean depth to saturation and standard deviation for all sample points by position. Sample point elevation from the lake water surface is closely tied to saturation depth as seen in Figure 11. As elevation of the sampling point increased (and moved away from the water body), depth to saturation increased; concurrently, saturation

was shallower at the lower positions closer to the lake, as expected. The following subsections outline each position's hydrologic characteristics.

Table 16. Mean depth to saturation and standard deviation by position. s.d. indicates one standard deviation.

Position	Mean depth to saturation	s.d.
A	14.7 cm	24.6 cm
B	22.6 cm	26.5 cm
C	49.7 cm	19.6 cm
D	≥ 60.0 cm	0.0 cm

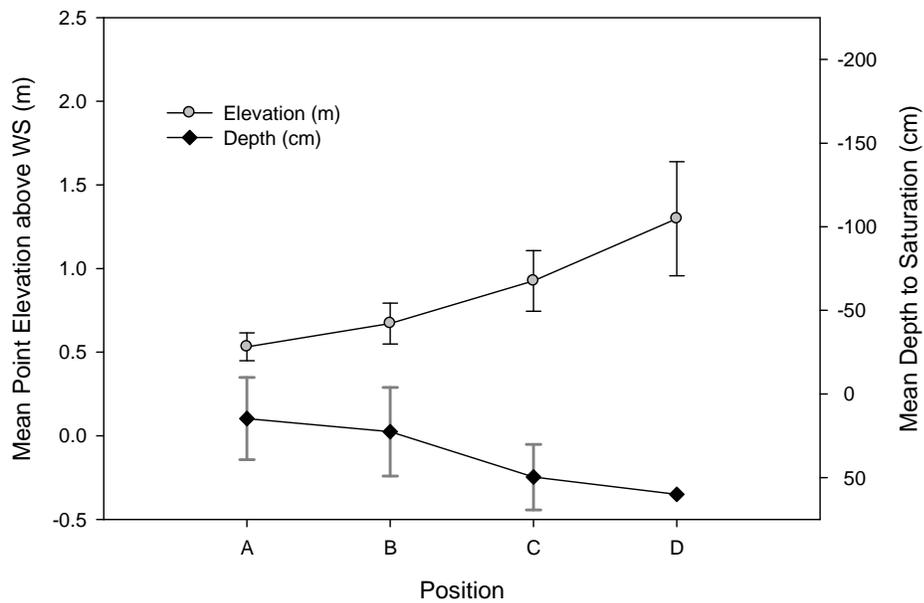


Figure 11. Position vs. mean sample point elevation and mean depth to saturation are shown for all sample values. Error bars represent the 95% confidence level interval.

Position A. In the A position, proximity to the lake influenced pit hydrology (mean depth to saturation 14.7 cm, mean elevation above origin 7 cm). In observation pits that had no free-water during the sampling period, other indications of wetting/drying such as drift lines, oxidized root channels and water stained organic matter were observed. Three pits in the A position had free-water which averaged 24 cm.

Position B. Like Position A, the proximity to the lake influenced hydrology in B (median depth to saturation 10 cm, mean elevation above origin 24 cm) and there were numerous indications of lake influence on the surface such as drift lines and water stained organic matter. During sampling, the mean saturation depth was 22.6 cm and three pits in the B position had free-water at an average depth of 35 cm.

Position C. This position had fewer hydrologic characteristics in common with the two lower, wetter positions. Mean depth to saturation was approximately 50 cm (mean Position C sample point elevation above WS: 45 cm), and there were fewer passive indications of saturation or inundation at this position. In only one position C pit (102 C) was free-water shallower than 60 cm during sampling (57 cm), and can likely be explained by the close horizontal distance of this particular sample point to the lake (10 m). This sampling point was only 15 cm higher than the adjacent B position where depth to saturation was 1 cm.

Position D. Position D is the upland position and all sample pits were dry. The mean elevation of Position D sample points was 87 cm above lake water surface. There was an absence of evidence indicating cyclic wetting-drying and/or aerobic-anaerobic

conditions and there were no passive hydrologic indicators such as drift lines or deposited organic matter from the lake.

### Soils

The soils at the sample sites are mapped primarily as Lardell clay loam (USDA, NRCS 2012b). pH values among sample points and depths ranged from 6.8 to 9.5, and were lowest at the upland positions, typical of semi-arid, calcareous soils of central Montana. Percent OM (Figure 12) did not vary significantly between positions ( $F_{3, 156} = 2.287$ ;  $p = 0.081$ ). Differences in soil chemistry could be seen among positions and data are reported by position.

Position A. Soils in Position A (Table 17) were characterized as saline-sodic (mean  $EC_{0-2}$ : 56 dS/m; average  $SAR_{0-2}$ : 60) and at 20 cm, EC was 30 dS/m. pH and EC differed significantly across the four depths (pH:  $F_{3, 36} = 8.016$ ;  $p < 0.001$ . EC:  $F_{3, 36} = 8.074$ ;  $p < 0.001$ ). Position A had an average pH of 8.9 at the 0-5 cm horizon. Soil texture was primarily sandy silt loam and had a predominance of redoximorphic features providing evidence of seasonal inundation and saturation. Though reduction potential was not quantitatively measured in this study, redox features indicated presence of anoxic condition. Figure 13 shows a typical surface soil at Position A. The white crusts are precipitated salts on the surface and the desiccated plants are *Salicornia rubra* from the previous growing season.

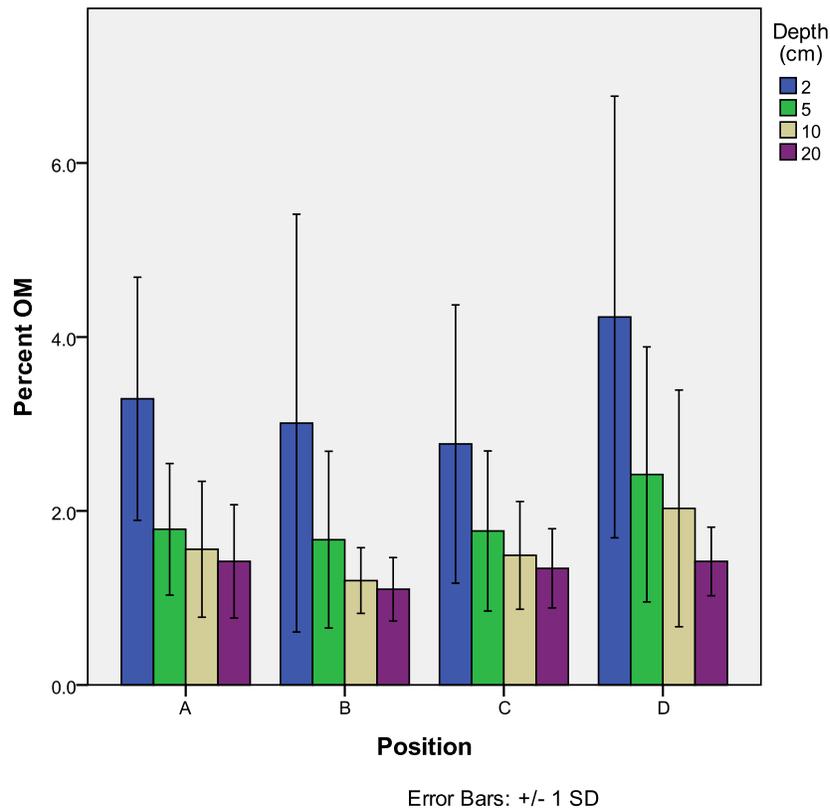


Figure 12. Percent OM vs. position by depth.

Table 17. Soil Summary – Position A by depth mean values and standard deviation (s.d.). Values with different letters indicate significant differences between depths using post hoc analysis and the mean difference is significant at the 0.05 level.

Soil Parameter	A 0-2 cm		A 2-5 cm		A 5-10 cm		A 10-20 cm	
N = 10	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
pH	9.0a	0.2	8.8a	0.3	8.6b	0.2	8.5b	0.2
CEC (cmol+/kg)	76.8	38.5	69.6	34.2	66.8	35.2	59.4	24.6
EC dS/m	59.7a	18.4	35.5b	15.3	30.3b	14.0	31.3b	13.3
SAR (cmol kg <sup>-1</sup> ) <sup>0.5</sup>	64.7	18.2	37.9	11.5	31.0	9.9	27.5	5.1

Position B. The soils here (Table 18), were characterized as saline-sodic (average  $EC_{0-2}$ : 50.4 dS/m; average  $SAR_{0-2}$ : 57). Similar to Position A, this position had significant differences in pH, CEC, EC and SAR values within depth increments (pH:  $F_{3,36} = 3.737$ ;  $p = 0.020$ . CEC:  $F_{3,36} = 6.822$ ;  $p = 0.001$ . EC:  $F_{3,36} = 8.447$ ;  $p < 0.001$ . SAR:  $F_{3,36} =$

16.839;  $p < 0.001$ ). Soils in this position were primarily sandy silt loam and redox features and saturated soil conditions indicated alternating wetting/drying, aerobic/anaerobic, oxic/anoxic conditions. The average pH at the 0-5 cm horizon was 8.9.



Figure 13. Periodic soil-saturation results in the formation of mobile ferrous iron. The migrating groundwater redistributes the iron throughout the soil profile. During drainage, some areas around pores, cracks, and root channels become dry and aerated more quickly than the rest of the soil. Ferric iron precipitates in these places, forming reddish-brown spots. This pattern of spots or blotches of different color or a shade of color interspersed with the dominant color is called soil mottling (from Fletcher and Veneman 2012).

Table 18. Soil Summary – Position B mean values and standard deviation (s.d.). Values with different letters indicate significant differences between depths using post hoc analysis and the mean difference is significant at the 0.05 level.

Soil Parameter	B 0-2 cm		B 2-5 cm		B 5-10 cm		B 10-20 cm	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
<b>N = 10</b>								
<b>pH</b>	9.0a	0.2	8.8ab	0.2	8.6b	0.3	8.7b	0.3
<b>CEC (cmol+/kg)</b>	79.7a	16.0	58.3b	18.5	53.5b	17.6	47.8b	15.3
<b>EC dS/m</b>	50.4a	17.4	28.5b	11.4	26.2b	11.2	24.9b	11.3
<b>SAR (cmol kg<sup>-1</sup>)<sup>0.5</sup></b>	57.4a	18.5	31.2b	10.7	26.2b	9.8	21.9b	7.2

Position C. The Position C soils were characterized as saline-sodic (average  $EC_{0-2}$ : 14 dS/m; average  $SAR_{0-2}$ : 18) but had a much lower level of salinity and sodicity compared to Positions A and B. Unlike the two adjacent, lower positions, there was no significant difference in EC values between depths ( $F_{3,36} = 0.142$ ;  $p = 0.934$ ). Soils in this position were primarily silt loam and had few visual redoximorphic features. Compared to the Positions A and B, these soils were lower in soluble salts and sodium, and had an average pH of approximately 8.4 in the 0-5 cm horizon. Table 19 summarizes mean values for selected soil characteristics for Position C.

Table 19. Soil Summary – Position C mean values and standard deviation (s.d.). Values with different letters indicate significant differences between depths using post hoc analysis and the mean difference is significant at the 0.05 level.

Soil Parameter	C 0-2 cm		C 2-5 cm		C 5-10 cm		C 10-20 cm	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
<b>N = 10</b>								
<b>pH</b>	8.43	.24	8.45	.24	8.45	.28	7.86	.44
<b>CEC (cmol+/kg)</b>	45.10	22.90	35.90	13.01	37.56	11.10	21.32	10.59
<b>EC dS/m</b>	14.02	12.48	12.20	6.82	12.05	5.11	4.19	4.87
<b>SAR (cmol kg<sup>-1</sup>)<sup>0.5</sup></b>	17.7	16.7	16.8	11.6	17.3	9.0	19.6	8.5

Position D. There were significant differences in pH among depths in position D ( $F_{3,35} = 3.95$ ;  $p = 0.016$ ; Table 20). The soils here had an average  $EC_{0-2}$  of 4.2 dS/m and an average  $SAR_{0-2}$  of 5.9, making them saline. There were no significant differences in EC between depths; ( $F_{3,35} = 1.596$ ;  $p = 0.208$ ), and there were no significant differences in SAR levels between depths ( $F_{3,35} = 2.469$ ;  $p = 0.078$ ). Soils in this position were primarily silt loam and had no redoximorphic features. The soils in Position D were comparatively neutral with an average pH of 7.9 at the 0-2 cm horizon. This position had

the highest content of organic matter (mean 4.7 % at 0-2 cm) compared to the averages of the other three positions at the same depth.

Table 20. Soil Summary – Position D mean values and standard deviation (s.d.). Values with different letters indicate significant differences between depths using post hoc analysis and the mean difference is significant at the 0.05 level.

Soil Parameter	D 0-2 cm		D 2-5 cm		D 5-10 cm		D 10-20 cm	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
<b>N = 10</b>								
<b>pH</b>	7.9a	0.4	8.1ab	0.4	8.3bc	0.3	8.4c	0.3
<b>CEC (cmol+/kg)</b>	21.3	10.6	20.4	7.1	26.1	18.90	34.0	18.9
<b>EC dS/m</b>	4.2	4.9	5.0	4.60	6.9	5.2	9.0	5.1
<b>SAR (cmol kg<sup>-1</sup>)<sup>0.5</sup></b>	5.9a	6.6	8.7ab	7.3	12.6ab	9.2	17.1b	12.4

#### Position, Saturation, and Salinity

EC<sub>dw</sub> by position are shown in Figure 14. In the A and B positions, EC is highest on the soil surface compared to other depths. In the C and D positions, EC values are similar throughout the entire soil column (as indicated by their relatively straight salinity curves). Figure 15 shows mean EC depth profiles for all positions. All EC values by position occupy a distinct location, from near shore to far, and from lower EC's at pit bottom to higher EC's on the land surface. There is a bi-directional (vertical and horizontal) salinity concentration gradient at positions A and B.

At Hailstone, soil saturation is a vector for solute transport. Saturated soil solution EC and saturation depth are significantly correlated ( $r = -0.346$ ,  $p < 0.001$ ) across all sample positions. Salinity and saturation follow a gradient from high soil EC and shallow depth to saturation at Position A, to low soil EC and deep depth to saturation at Position D. At the lower, wetter positions closer to the lake, the saturation/salinity profiles suggest that solutes tend to move upward with wicking as driven by evaporation (resulting in

solute concentration at the surface) where at higher positions further from the lake, solutes are moving slightly downward or laterally (see Figure 15).

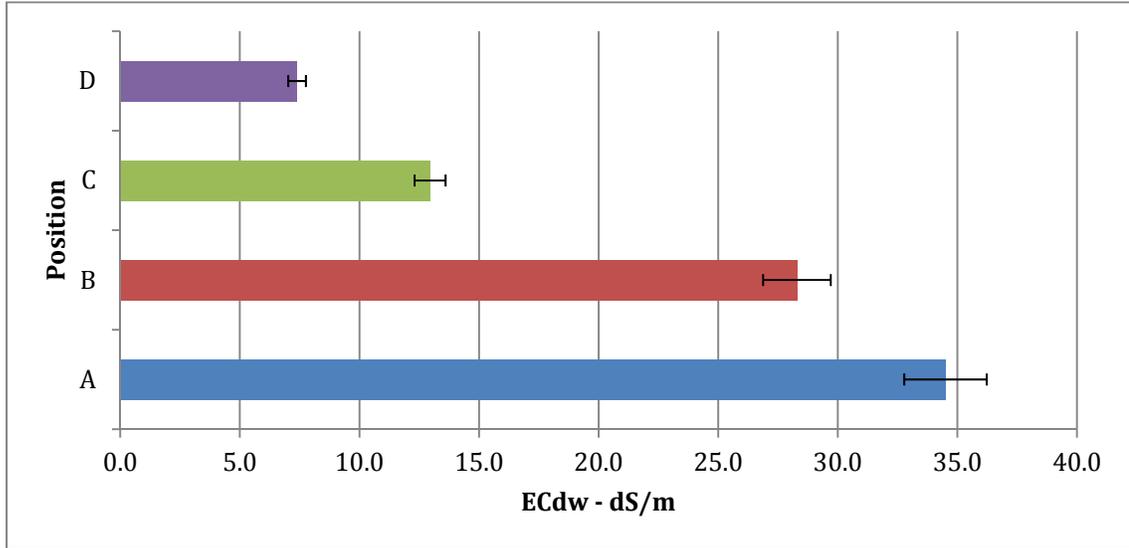


Figure 14. Averaged depth-weighted EC among positions for all sample sites at Hailstone National Wildlife Refuge. Error bars represent 5% of the mean values.

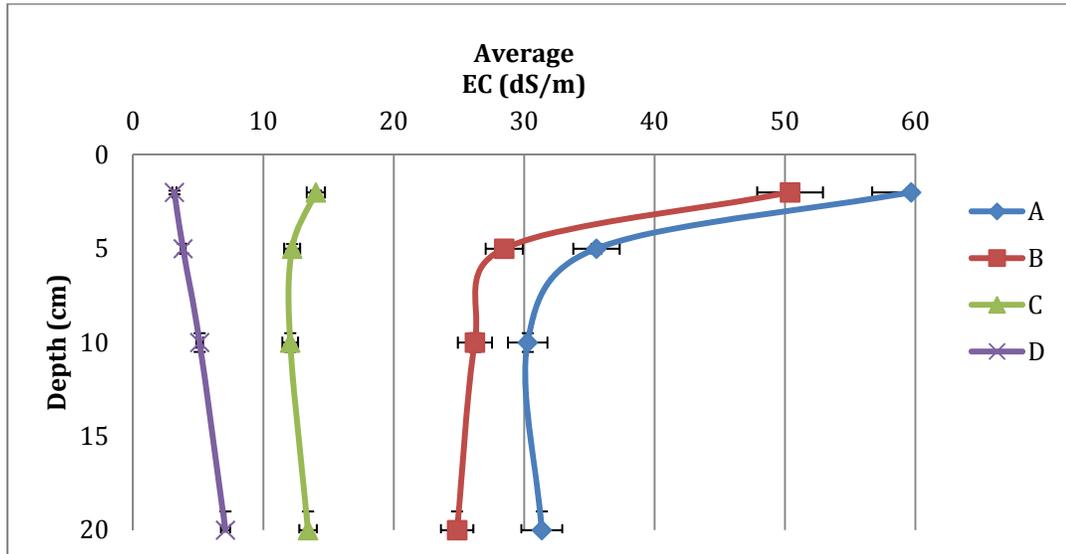


Figure 15. EC depth profile by position. Mean point values and 5% error bars are shown for all sample values. EC values are highest at the surface, closest to the shoreline in positions A and B. At these positions, solutes are carried upward via evapoconcentration, and accumulate on the soil surface.

## Nutrients

Nutrient availability can affect the competitive dynamics between salt tolerant plants and their position across environmental gradients in saturation stress (Emery et al. 2001). Primary macronutrients (N-P-K) concentrations for each position were examined to determine whether nutrient concentrations might limit growth of vegetation at Hailstone.

The levels of depth weighted N ( $F_{3,36} = 1.55$ ;  $p = 0.22$ ),  $\text{NO}_3$  ( $F_{3,36} = 1.44$ ;  $p = 0.25$ ), and  $\text{NH}_4$  ( $F_{3,36} = 0.23$ ;  $p = 0.83$ ) did not differ across positions. Table 21 shows depth-weighted means for all forms of nitrogen. The high cation exchange capacity (CEC) in Hailstone soils may have also tied up plant available  $\text{NH}_4$ , anoxic conditions in lower positions may have increased atmospheric losses via denitrification, and given relative concentrations of all forms, nitrogen may have been moderately limiting to plant growth at the lower positions.

Table 21. Average depth weighted N, nitrate-N, and ammonium mean concentrations across all sampling positions.

Position	Depth weighted mean		
	<sup>1</sup> N mg/kg	<sup>2</sup> NO <sub>3</sub> mg/kg	<sup>2</sup> NH <sub>4</sub> mg/kg
A	2.9	2.7	6.9
B	2.8	2.9	6.1
C	6.3	10.0	6.2
D	3.7	5.4	7.3

<sup>1</sup> was measured as exchangeable. <sup>2</sup> determined by saturated paste extraction (1:1 dilution).

Table 22 shows the means for total  $P_{dw}$  and the highly available plant available orthophosphate ( $PO_4$ ) across all positions. Phosphorus was analyzed using the Bray 1 extraction method and because of higher pH levels, this method likely overestimated plant available P. Total  $P_{dw}$  did not differ among positions (P:  $F_{3,36} = 1.987$ ;  $p = 0.133$ ) and  $PO_4$  levels did not differ among positions ( $F_{3,36} = 1.393$ ;  $p = 0.261$ ). Phosphates adsorb strongly to calcium carbonates ( $CaCO_3$ ), and at pH levels commonly found at Hailstone, calcium carbonates can tie up large amounts of plant available P in the soil (Jones and Jacobsen 2005b). Soil concentrations of  $PO_4$  are considered low for optimal plant growth for all positions at Hailstone.

Table 22. Average depth weighted total P (Bray-1) and orthophosphate concentrations across all sampling positions. Values with different letters indicate significant differences between depths at the position.

Position	Depth weighted mean	
	<sup>1</sup> P mg/kg	<sup>2</sup> PO <sub>4</sub> mg/kg
A	16.5a	0.6
B	11.0a	0.5
C	9.7b	0.4
D	11.4a	0.7

<sup>1</sup> was measured as exchangeable. <sup>2</sup> determined by saturated paste extraction (1:1 dilution).

Potassium (K) concentrations in the soils at Hailstone averaged 236 mg/kg and varied widely (min 115, max 401, s.d. 67 mg/kg). Mean differences did not exist between positions ( $F_{3,36} = 2.508$ ;  $p = 0.074$ ), and K levels may be considered normal for Montana soils. Nevertheless, in soils with high levels of Ca and Mg, competition among exchange sites can limit K uptake. K absorption is most limited by saturated soil conditions (Korb et al. 2002), therefore actual plant available K may be limiting.

Depth-weighted Na levels by position are given in Table 23. Sodium levels were significantly different among positions ( $F_{3,36} = 12.428$ ;  $p < 0.001$ ) and post hoc tests revealed significant differences between the two lowest positions (A and B) and C and D (Table 23). Mean  $SAR_{dw}$  was significantly different along sample positions ( $F_{3,36} = 10.958$ ;  $p < 0.001$ ).

Table 23. Average depth weighted potassium and sodium concentrations across all sampling positions. Values with different letters indicate significant differences between depths at the position.

Position	Depth weighted mean	
	<sup>1</sup> K mg/kg	<sup>2</sup> Na meq/L
A	227.2	4270.6a
B	205.3	3414.7a
C	232.4	2048.3b
D	280.9	1272.3b

<sup>1</sup> was measured as exchangeable. <sup>2</sup> determined by saturated paste extraction (1:1 dilution).

Potassium and sodium are closely tied in their effects on osmoregulation in plant tissues. In order to isolate Na and prevent root uptake in saline environments, plants use K in abundance. In a study by Smart and Barko (1980), analysis of plant tissues and the sediment interstitial water at the end of an investigation revealed selective uptake of potassium and exclusion of sodium. These processes increased the ratio of sodium to potassium in the interstitial waters and also resulted in increased sediment salinities (Smart and Barko 1980).

### Conclusions

The four positions (A-D) studied at Hailstone varied in their abiotic (length, differential elevation and slope), soil chemistry and hydrologic characteristics. pH values were highest at the A position, and the major nutrients did not vary across positions. EC values were greater and depths to saturation were closer to the surface at positions closer to the lake. This data suggests that point proximity to the lake determines soil salinity and depth to saturation among the four positions and saturation and salinity are closely linked at this environment. The connection between landscape position, soil chemistry and hydrologic connectivity at Hailstone may be used to understand the presence of environmental stress gradients and how plants grow near the lake and swales.

## DISCUSSION

Synopsis

Vegetation grew in repeated patterns of plant assemblages, distinct from each other, between the surface water and the upslope areas of Hailstone Lake. These plant assemblages, appearing as banded growth patterns, were monotypic at some positions relative to the lakeshore and consisting of mixed species at other positions relative to the lakeshore. Sample points were chosen randomly within the four vegetated bands closest to the lake, based on visual differences in vegetation type and density. Because of lake basin topography, these sample points were distributed from a low elevation position, to an outward and upward position from the lake depression and were labeled A through D. Species richness was lowest at the A position ( $S=3$ ), and was highest in positions C and D ( $S=13$ ). Species diversity was highest in the C position.

Depth to saturation was shallowest near the lakeshore and increased to  $\geq 60$  cm in the upland D positions. Salinity (EC) was highest closest to the lake and incrementally lower with adjacent positions away from the lakeshore. In positions A and B, salinity was highest at the surface and decreased with depth (20 cm) and salinity (EC) and saturation (depth) were correlated ( $r = -0.346$ ,  $P < 0.001$ ). The following conceptual model (Figure 16) represents the relationships between dominant vegetation and the abiotic environmental characteristics that will be used as the basis for discussion.

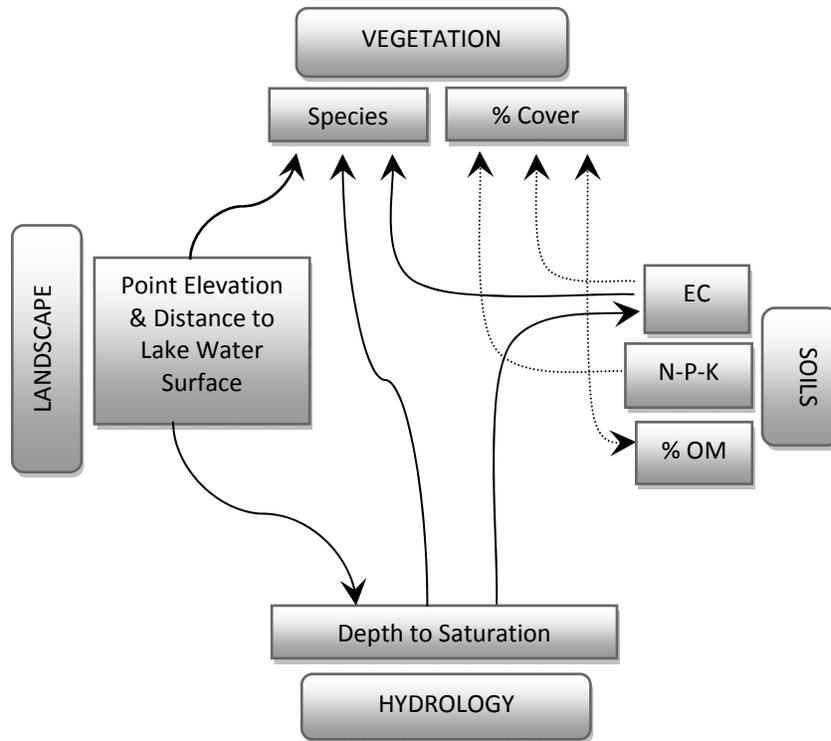


Figure 16. Conceptual model used for synthesizing the various parameters examined in this study. Arrowheads indicate direction of influence and dashed lines are for visual differentiation.

### Synthesis

The percent cover of the most common species for each of the four positions was compared to two abiotic conditions, depth to saturation and salinity (EC). Depth to saturation was the least beneath the plant communities closest to the lakeshore and greatest beneath the plant communities farthest from the lakeshore. This relationship held true for circumstances where the communities extended either over short or long distances from the shoreline, leading to the conclusion that it was not physical proximity to the shoreline, but abiotic condition that was suitable for a limited number of species in

some instances, *i.e.*, positions A and B. These conditions likely represented the two most stressful abiotic factors potentially affecting plant growth at Hailstone.

The A position was dominated by *Salicornia rubra* (OBL) but no other positions had a single dominant species. *S. rubra* only occurred twice in position C and once in position D. *Salicornia rubra* can be considered a pioneer species on the salty lakeshore. As a short statured annual, it may have difficulty competing with perennial obligate halophytes that also tolerate saturation and high salinity under circumstances which favor alternate species to grow. In a personal observation, *Puccinellia nuttalliana* (Nuttall's alkaligrass) was found in higher abundance in the A positions (after field sampling) in later months of 2010 and in 2011. Other factors (not explored in this study) may have contributed to this condition including facilitation by *Salicornia rubra*, lower lake and soil salinities during germination (as a result of above average precipitation in 2010 and 2011), and cooler springtime temperatures, which led to optimal establishment conditions.

*Suaeda calceoliformis* (Pursh seepweed), the most abundant species in position B, occurred in the wetter, more saline A position only twice (both points 4%) and did not occur in the drier, higher C and D positions. The most abundant species in position C, *Distichlis spicata* (inland saltgrass) can survive in areas of both fresh and salt waters (lacunae tissue allows for gas exchange and survival in inundated conditions) and is also one of the most drought-tolerant species in the dry, western interior of the United States (Kitzes and Connor 2003). Its wide tolerance to wetness, drought, and salinity aligns with its presence at Hailstone in a mesic position (C). *Poa pratensis* (Kentucky bluegrass)

does not tolerate extended anoxia and soil salinity (USDA, NRCS 2012) which makes it a very good candidate for establishment and growth at the higher (elevational) position along the saturation/salinity gradient within position D.

In the two years the study was conducted, the lower observation points (A and B) were completely inundated in the spring. Moving away from the lake, saturation/salinity stress was incrementally lower in positions C and D. These positions were occupied by thirteen species apiece and had higher diversity. Based on these observations, the three most prevalent species in positions A, B and D may be used to distinguish stress gradients at Hailstone. Position C's most abundant species, *Distichlis spicata*, grows well along much of the saturation/salinity gradient, and, as a result, it is a difficult species for which to characterize preferential soil chemistry and saturation tolerance alone on the landscape. This species likely finds a niche within the mesic position as a result of adaptation to salinity and saturation where other species cannot. Furthermore, even though this species is extremely well adapted to a wide range of conditions, it most often occurs in distinct bands across the study plots at Hailstone.

Lower positions may experience a different type of abiotic (physical) stress: wave action and ice scour/deposition, which could inhibit seedling establishment, survival, and/or growth, resulting in lower density and species richness. In the A position *Salicornia rubra* may be less affected by harsh winter conditions as an annual plant, and in the C position the highly rhizomatous saltgrass may be able to tolerate physical scouring. Steeper slopes may be more affected by wave action whereas longer, flatter transects tend to attenuate and dissipate wave energy across a longer distance.

Given the open and flat landscape of Hailstone, there are likely only small differences in solar insolation (albeit without field measurement) that would affect plant growth. This circumstance likely normalizes the differences in evapotranspiration, solar gain, heat units, etc., at the landscape scale. However, based on anecdotal observations of the effects shading/surface roughness has on the growth of plants, these factors may play a critical role in lowering sun and wind driven evaporation, reducing soil temperature, and generally conserving moisture at the plant scale.

Biotic Factors. The effects of competition and facilitation should not go unmentioned in the process of vegetation zonation. Hacker and Gaines (1997) described an increase in species diversity at the harsh end of the environmental stress gradient because of facilitation; species colonize areas where they would not normally be able to tolerate as a result of benefit derived from the presence of other species. This was not observed at the A position at Hailstone and the lack of observed facilitation there may be a result of the extreme salinities found in the lake and along the lakeshore. Facilitation may be more of a factor in determining species diversity in the B and C positions where salinities are reduced. Nevertheless, organic matter inputs from the accumulation of biomass may alleviate the negative effects of salinity as well as change the hydrologic response of precipitation inundation via preferential flow along rooting channels.

### Applications

Figure 17 shows a scatter plot of  $EC_{dw}$  with distance to the origin (lake). Although this data represents a bimodal data distribution (*i.e.*, 36 of the values cluster

between 0 and 30 m from the water and 4 values, 3 of which are  $< 10$ , fall more than 40 m out from the water), it represents a salinity gradient that took many years to develop. The final location of the restored Hailstone Creek will ultimately drive the formation of a new salinity/saturation gradient that will likely look much different from that of the existing shoreline, based on years of submersion by highly saline waters. Salinity profiles may not vary much along similar transect lengths, and it may take many human generations for stable profiles to develop as fresh rainwater pushes surface salts downward in the highest positions, or as wicking drives salinity upward in the lowest areas. Hailstone Creek salinity will also affect soil salinities in the areas adjacent to the stream.

Figure 18 shows the mean  $EC_{dw}$  values of the two shortest, steepest transects and two longest, flattest transects. These data suggest that there is no difference in depth weighted  $EC_{dw}$  between short-steep and long-flat slope at positions C or D. There are larger differences in  $EC_{dw}$  between the two transects types at the A and B positions. This may be indicative of longer seasonal inundation (and solute residence time) at the lower positions in the long-flatter transects.

In the absence of detailed depth to saturation and salinity data across much of the exposed lakebed, lakebed elevation from the water (Hailstone Creek) may be a useful metric to predict potential plant responses to altered hydrology. Combined with the data from this study and a small number of field measurements, a conceptual design for revegetation planning could be generated.

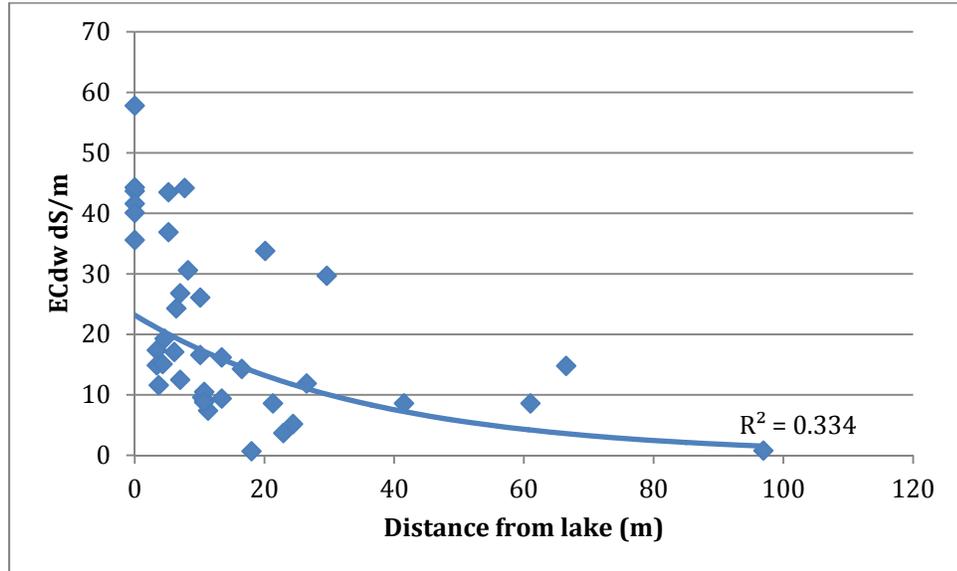


Figure 17. Scatter plot of depth weighted EC and distance from the origin (lake). The trend line (exponential) shows that  $EC_{dw}$  values decrease with increasing distance from lake.

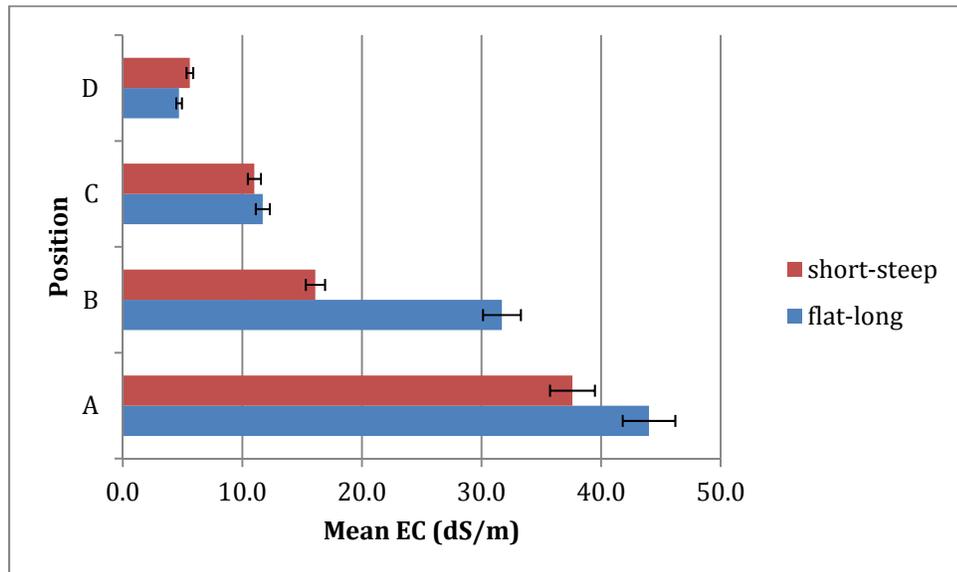


Figure 18. Mean depth weighted EC for short transects vs. long transects by position. Error bars represent 5 % value.

Based on salinity/saturation and vegetation by position, the advancement of conceptual revegetation zones is put forth here. Zonation determination in this conceptual model was based on several assumptions:

- 1) As shown in the data, saturation is closely tied to salinity and will be an important factor in determining species germination, establishment and long term survival. It is uncertain at what location lakebed saturation will equilibrate with stream water and groundwater (as tied to the influence of the surrounding geohydrology) until the effects of dewatering are fully realized.
- 2) Following the evacuation of a majority of lake water in 2011, a single soil sample was taken from the exposed lakebed between the A position and the new water surface on the western shoreline. Soil  $EC_{dw}$ , was approximately 32 dS/m, a value that fell between the A and B positions from the 2010 study. It is important to emphasize that actual soil salinities may vary across the lakebed and can only be confirmed by multiple samples. It is assumed in this model that the newly exposed lakebed will likely have soil salinities close to the single 2011 sample point which is similar to the salinities found at the 2010 A and B study positions.
- 3) It is unlikely that salinity conditions found at the study position D will be found at any location on the exposed lakebed. Only through slow movement of salts downward with precipitation will the exposed landscape return to an upland environment comparable to the D position, therefore, conceptual revegetation zones contain species only found in positions A through C. Some species observed in this study are considered invasive or have deleterious effects to livestock. The use of these species or additional

species not found on the site, but having potential reclamation application, should be reviewed by USFWS botanists prior to initiation of revegetation activities.

4) At the time of this writing, conditions at Hailstone were not conducive to vehicle traffic on the lakebed. It is unknown to what extent conditions will improve based on soil drainage patterns and groundwater influences on soil stability. These conditions will affect the type of revegetation techniques that can be deployed on site. In addition, certain constituents in the soil and water are toxic to humans (selenium) and a thorough analysis of their mobilization, transport and fate should be understood prior to exposing personnel to disturbed soils.

The primary criteria used for establishment of zones were projections and assumptions of developing salinity and saturation conditions. Table 24 outlines the depth to saturated soil and  $EC_{dw}$  values for each proposed zone. The justification for each zone was based broadly on the primary abiotic conditions observed during the 2010 field study between positions A, B and C. The threshold values for depth to saturation and  $EC_{dw}$  between zones are very broad and meant to be a general guideline. In some instances, these model parameters should be adjusted for actual field conditions. For instance, if there are areas of surface saturation within Zone 3, OBL plants not listed for that zone should be used within the saturated area.

Table 25 outlines the 9 species recommended for planting in 3 zones. These species are a mix of the most salt tolerant native plants found on the A, B and C positions during the study and was the first criterion used for selection. The next criterion used was adaptation to anoxia/saturation and the selected species were positioned within their

respective zones in terms of their relative tolerance of this condition. Figure 19 shows a lakebed profile with revegetation zones in order to illustrate their position and relative elevation on the lakebed surface.

Table 24. Hailstone salinity/saturation conditions by revegetation zone.

Revegetation Zone	Depth to Saturation (cm)	EC <sub>dw</sub> (dS/m)
1	≤ 15	> 30
2	15 – 30	25 ± 5
3	30 - 60	< 20

Table 25. Hailstone vegetation guide by zone. Species shown are only those found in the species pool in this study and some species are recommended in more than one zone. The use of introduced and invasive species may or may not be practicable, only as allowed by USFWS management. N= native, I= introduced, H= high salt tolerance, M= medium salt tolerance.

Revegetation Zone	Species	WIS	Native Status	Saline Toler.
1	<i>Salicornia rubra</i>	OBL	N	H
	<i>Puccinellia nuttalliana</i>	OBL	N	H
	<i>Triglochin maritima</i>	OBL	N	H
2	<i>Suaeda calceoliformis</i>	FACW	N	H
	<i>Triglochin maritima</i>	OBL	N	H
	<i>Distichlis spicata</i>	FACW	N	H
	<i>Hordeum jubatum</i>	FACW	N	H
3	<i>Distichlis spicata</i>	FACW	N	H
	<i>Pascopyrum smithii</i>	UPL	N	H
	<i>Alopecurus arundinaceus</i>	NI	I	H
	<i>Thinopyrum intermedium</i>	UPL	I	M

Revegetation Zone 1. This zone is closest to the restored Hailstone Creek and will be most similar in hydrology to Position A. There will likely be a wetted perimeter extending along the margins of the creek and backwater channels. Depths to saturation in

this zone must support obligate wetland species of plants and therefore should be within 15 cm of the soil surface as was found in Position A in the 2010 study. The width of the wetted perimeter that will support obligate wetland species will likely vary depending on streambank slope, and although the stream is now slow moving, solute residence time may be shorter in this zone than that found in position A, depending on seasonal precipitation patterns and flushing. In contrast to the increasing and constant salinization within the lake, seasonal flushing may lower salinities (compared to existing conditions) along the wetted perimeter of the creek. Ultimately, source water salinities will drive accumulation or flushing of salts from the streambank soils. If salinities are lower during crucial germination periods (seasonal high-water), conditions may favor species such as *Puccinellia nuttalliana*. This obligate wetland species is well adapted to all soil types, has high tolerance to anoxia, does not require a cold stratification and grows in a wide range of soil pH (USDA, NRCS 2012). *Triglochin maritima* has also been selected for use in Zone 1 as a result of its observed rooting potential in the swale sample transects. This species may be a good candidate for streambank slope stabilization but, this species is also known for producing cyanogenic compounds (prussic acid) in the mesophyll cells (leaf tissues) and may be harmful to livestock (NDSU 2012).

Revegetation Zone 2. As discussed, soil salinities may be relatively homogenous across the new lakebed and expected EC levels throughout Zone 2 will be similar to Zone 1. Unlike the lower zone, saturation will likely be deeper here (15-30 cm) and plants must be more adapted to these hydrologic conditions, yet still have high tolerance to salinity. Species selected for this zone will overlap with Zones 1 and 3 and depending on actual

topography (and relative depth to groundwater) this zone may vary widely in species composition. The first three species have been discussed previously in detail and their ecologic characteristics are well suited for this position. The last species, *Hordeum jubatum* is a facultative wetland plant that has a high tolerance to salinity, a wide range of moisture regimes and pH levels. *Hordeum jubatum* is a pioneer species and rapidly invades areas exposed by a receding water table (USDA, NRCS 2012). This is a native species and has been found useful in reclamation of saline lands, but is considered a weedy species and has been identified to be harmful to wildlife and livestock as a result of its upward-pointing barb-like awns becoming easily embedded into an animal's tissue, causing irritation. These less desirable traits should be carefully weighed against potential reclamation benefits prior to widespread use, but it is likely that this plant will colonize naturally at Hailstone.

Revegetation Zone 3. This zone will be limited to plants that can tolerate both arid and saline conditions. As discussed previously, obligate and facultative wetland, salt tolerant plants are able to utilize the available water in order to osmoregulate tissue turgor and function optimally, but at Zone 3, water will not likely be available at depths shallower than 60 cm (post-dewatering). The most stressful end of the environmental gradient may eventually be found here. Species chosen for this zone have characteristics of salinity tolerance as well as some adaptation to drier conditions. *Distichlis spicata* has been discussed in detail and this species will likely be a primary candidate across the entire site for revegetation. *Alopecurus arundinaceus* is an introduced cultivar that has a high rate of spread and can be invasive. It may be a useful species because of its highly

rhizomatous roots and high tolerance to salinity. Western wheatgrass (*Pascopyrum smithii*) has been shown to tolerate high salinities and a wide range of soil pH, and is moderately tolerant of anoxic conditions (USDA NRCS 2012). It is a rhizomatous plant and has a rapid rate of growth. In conjunction with intermediate wheatgrass (*Thinopyrum intermedium*), these species can provide decent forage for wildlife and livestock. *Thinopyrum intermedium* may be most suited for the highest positions on the lakebed as it has the lowest tolerance to salinity of all chosen species (medium).

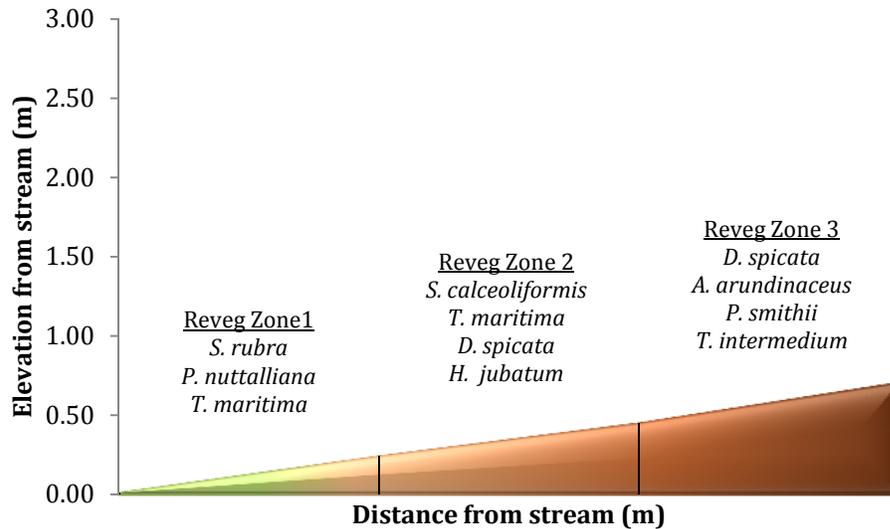


Figure 19. Revegetation profile for three zones. Distance from stream varies by location.

Figure 20 depicts a preliminary revegetation model for three planting zones based on a land and lake bathymetry survey (Ducks Unlimited 2009). Revegetation zones were generally based on the predicted lakebed elevations from Hailstone Creek as related to depth to groundwater. It cannot be overemphasized that confirmation of depth to saturation should be made prior to initiating any revegetation planting.

### Hailstone NWR - Conceptual Revegetation Zones

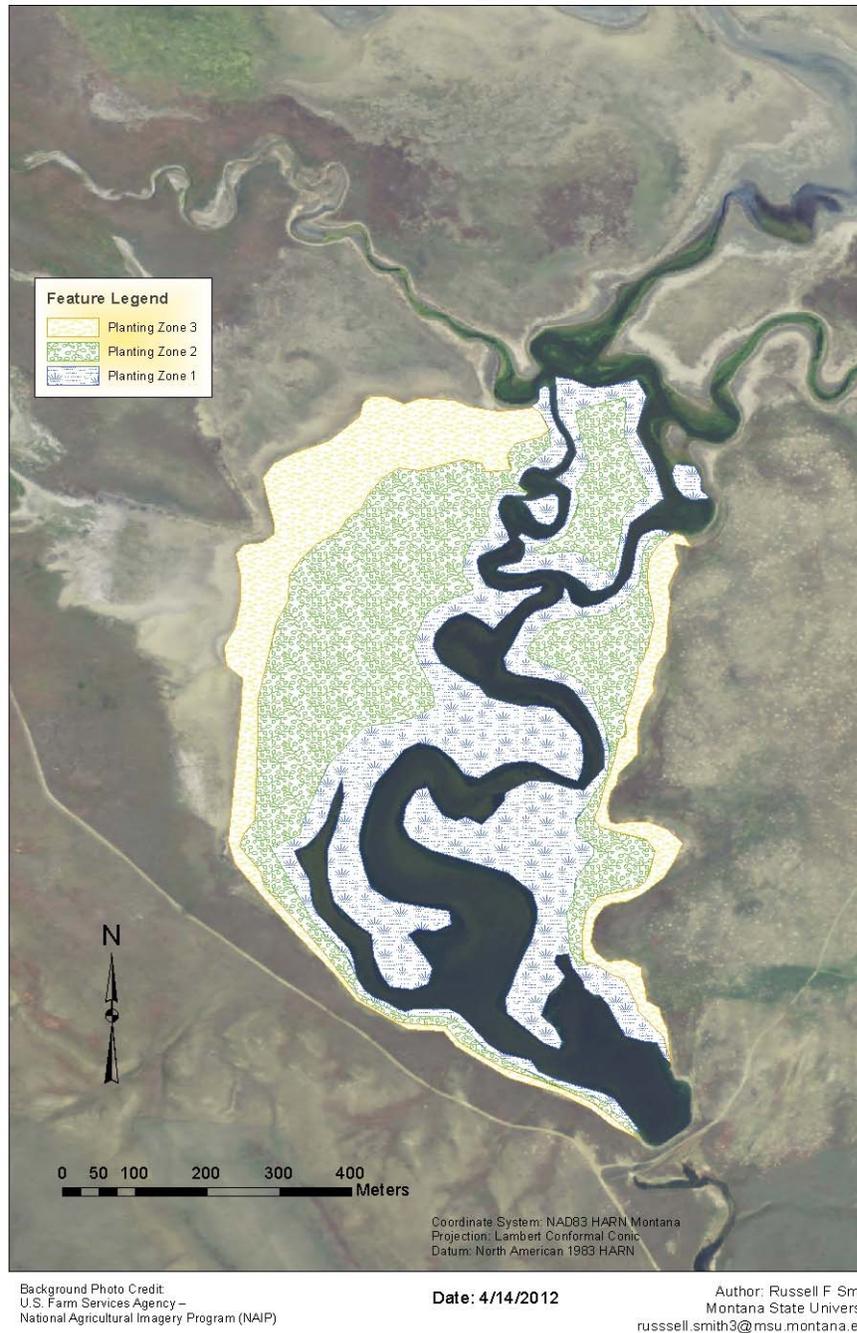


Figure 20. A conceptual map of revegetation zones based on digital elevation modeling using lake bathymetry and land survey points to predict hydrologic response to dewatering and partial dam removal.

The newly exposed lakebed will be difficult to access by machinery and people while sediments drain and dry. Places close to the creek and tributaries may be indefinitely unrealistic to access as a result of persistent saturation. A large-scale revegetation effort may also be unrealistic in terms of available financial resources. Therefore, phased treatments should be considered. As opposed to a large scale seeding, smaller 'islands' or banded patterns of vegetation should be considered (Figure 21). Once established, these areas may encourage OM accumulation and natural spreading of vegetation. Utilization of limited fresh-water precipitation and organic matter accumulation (leaf litter) by islands or bands will facilitate further plant growth by enhancing root macropore development and infiltration (salt flushing). Increasing surface roughness also assists in aeolian deposition of OM and seed. Vegetated bands could be positioned at inflow seeps, perpendicular to the slope to intercept incoming water. Surface runoff intercepted by these bands will become run-on and infiltrate water on the up-slope side. The band may move gradually upslope as OM accumulates. Bare areas between bands or islands will be smoother and form soil crusts and these inter-canopy areas will allow rainfall to flow downslope into other bands and infiltrate beneath the larger plants. The larger plants will harvest rainfall from the ground immediately up-slope (Tongway and Ludwig 2001).

As allowable, larger plant sizes (pre-grown containerized nursery stock) should be used as a method of increasing plant establishment. Deeper roots in a containerized plant may have access to soil depths where salinities are lower and supporting soil water is present. Supplemental OM along with soil manipulation (roughening) and creation of

shade-inducing structures should also be considered to enhance growth performance in focused revegetation areas. These treatments may be most important and relevant in Revegetation Zone 3 where soil moisture is lowest and salinities are high.



Figure 21. Example of vegetated islands and banding within Revegetation Zones 2 and 3.

### Conclusions

At Hailstone Lake, up-gradient saline seeps, eighty years of impounded lake water and the lack of precipitation have resulted in exacerbated soil and water salinization. In this study, I learned that the four positions varied in their physical, soil chemistry and hydrologic characteristics. The connection between landscape position,

soil chemistry and hydrology were used to understand the presence of plant distributions. Vegetation responds to soil salinity and saturation levels, and it is likely that the banded growth patterns are indicative of a combination of the stress tolerance of the individual species and their ability to colonize, occupy, or compete for suitable sites (*e.g.* higher diversity of species found in C and D positions).

Environmental stress gradients in plant community ecology have been studied in detail and abiotic environmental stress (*e.g.* prolonged saturation/anoxia and high salinity, drought, extreme cold) is a primary cause of lower species richness (Keddy 1989; Engels 2010). Where species' distributions overlap, biotic factors such as interspecies competition may be important in determining the observed banding patterns. Although not a focus of this study, biotic effects of competition and facilitation almost certainly play a role in vegetation assemblage formation at Hailstone, particularly at positions C and D. Ultimately, understanding salinity and saturation conditions will likely determine what suite of plants will be most appropriate to focus on future revegetation efforts.

The information elucidated in this study can be used to stabilize and revegetate landscapes impacted by saline seep, abandoned saline-sodic lakebeds and other denuded lands. Halophytes, selected for a high degree of salinity tolerance, could be grown specifically for the planting on the exposed lakebed, and when guided by predicted saturation/salinity conditions as modeled from existing data sources, could provide for long term establishment of vegetation. The challenge in performing these activities under a yet unknown hydrologic regime must not go unmentioned. Nevertheless, understanding

the nature of fluctuating hydrology, plant ecophysiology and saline soil chemistry, coupled with the use of selected plant materials on the newly exposed lakebed, could increase the potential for revegetation success over time.

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APPENDICES

APPENDIX A

VEGETATION PERCENT COVER

Vegetation Percent Cover

	S rub	P nut	T mar	D spi	H jub	L lat	S calc	P pra	B jap	C run	L ser	K pro	T int	B tec	P smi	A lyr	T arv	M sat	Ono	A aru	must	Ann	A cri	S het
101A	0.56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102A	0.48	0.28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
103A	0.56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
104A	0.72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
105C	0.92	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
106A	0.76	0	0	0	0	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
107A	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
108A	0.84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
109A	0.76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110A	0.64	0	0	0	0	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
101B	0	0	0	0.92	0	0	0	0	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0	0
102B	0	0	0	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
103B	0.44	0.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
104B	0	0	0.88	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
105B	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
106B	0.04	0	0	0	0	0	0.36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
107B	0.12	0.04	0	0	0	0	0.68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
108B	0	0	0.96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
109B	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110B	0	0	0	0	0	0	0.72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
101C	0	0	0	0	0	0	0	0.24	0.2	j	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102C	0	0.6	0	0	0	0	0	0	0	0	0	0	0.32	0	0	0	0	0	0	0	0	0	0	0
103C	0.02	0	0	0.44	0	0	0	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0
104C	0	0	0	0	0	0	0	0.04	0	0.28	0	0	0.28	0	0	0	0	0	0	0	0	0	0	0
105E	0	0	0	0	0.08	0	0	0.24	0	0	0	0	0.52	0.04	0	0	0	0	0	0	0	0	0	0
106C	0	0	0	0.68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0
107C	0.12	0	0	0	0	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0	0	0.08	0	0	0
108C	0	0	0	0	0	0	0	0.48	0	0.48	0	0	0	0	0	0	0	0	0	0	0	0	0	0

109C	0	0	0	0.44	0	0	0	0	0.44	0	0	0	0	0	0	0	0.04	0	0	0	0	0	0	0	
110C	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0	0
101D	0	0	0	0	0	0	0	0.92	0	0	0	0	0	0	0	0	0	0	0.02	0	0	0	0	0	0
102D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0
103D	0	0	0	0	0	0	0	0	0	0.16	0	0	0	0	0	0	0	0	0	0.64	0	0	0	0	0
104D	0	0	0	0	0.08	0	0	0.8	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0	0
105A	0	0	0	0.32	0	0	0	0.24	0	0	0	0	0	0.08	0	0	0	0	0	0	0	0	0	0	0
106D	0	0	0	0	0	0	0	0.92	0	0	0	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0
107D	0	0	0	0.6	0	0	0	0	0.04	0	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0
108D	0	0	0	0.28	0.04	0	0	0.6	0	0	0.04	0	0	0	0	0	0	0.04	0	0	0	0	0	0	0
109D	0	0	0	0	0	0	0	0.76	0	0	0	0	0	0	0.12	0	0.04	0	0	0	0	0	0	0	0
110D	0	0	0	0	0	0	0	0	0	0	0	0	0.88	0	0	0	0	0	0	0	0	0	0	0	0
count if	16	6	2	9	3	0	6	10	3	3	2	3	6	2	2	0	2	1	1	1	2	1	0	0	0
freq	0.35	0.13	0.04	0.20	0.07	0.00	0.13	0.22	0.07	0.07	0.04	0.07	0.13	0.04	0.04	0.00	0.04	0.02	0.02	0.02	0.04	0.02	0.00	0.00	0.00

APPENDIX B

TABLES OF STATISTICAL ANALYSIS

Tables of Statistical Analysis**ANOVA**

Dependent Variable: OM pct

Source	df	F	Sig.
Corrected Model	3	2.287	.081
Intercept	1	313.308	.000
Position	3	2.287	.081
Error	156		
Total	160		
Corrected Total	159		

a. R Squared = .042 (Adjusted R Squared = .024)

**Levene's Test of Equality of Error Variances<sup>a</sup>**

Dependent Variable:OM\_pct

F	df1	df2	Sig.
13.475	3	156	.000

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Depth\_cm

Position A - pH x depth

**ANOVA**

Dependent Variable:pH

Source	df	F	Sig.
Depth_cm	3	8.016	.000
Error	36		
Total	40		
Corrected Total	39		

**ANOVA**

Dependent Variable:pH

Source	df	F	Sig.
Depth_cm	3	8.016	.000
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .400 (Adjusted R Squared = .351)

**Multiple Comparisons**

pH

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	.150	.138
	5	.350*	.001
	10	.440*	.000
3	2	-.150	.138
	5	.200	.051
	10	.290*	.006
5	2	-.350*	.001
	3	-.200	.051
	10	.090	.369
10	2	-.440*	.000
	3	-.290*	.006
	5	-.090	.369

Based on observed means.

The error term is Mean Square(Error) = .049.

\*. The mean difference is significant at the 0.05 level.

A – EC x Depth

**Tests of Between-Subjects Effects**

Dependent Variable: EC

Source	df	F	Sig.
Depth_cm	3	8.074	.000
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .402 (Adjusted R Squared = .352)

**Multiple Comparisons**

EC

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	24.130 <sup>*</sup>	.001
	5	29.402 <sup>*</sup>	.000
	10	28.323 <sup>*</sup>	.000
3	2	-24.130 <sup>*</sup>	.001
	5	5.272	.449
	10	4.193	.546
5	2	-29.402 <sup>*</sup>	.000
	3	-5.272	.449
	10	-1.079	.876
10	2	-28.323 <sup>*</sup>	.000
	3	-4.193	.546
	5	1.079	.876

Based on observed means.

The error term is Mean Square(Error) = 236.922.

**Multiple Comparisons**

EC

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	24.130 <sup>*</sup>	.001
	5	29.402 <sup>*</sup>	.000
	10	28.323 <sup>*</sup>	.000
3	2	-24.130 <sup>*</sup>	.001
	5	5.272	.449
	10	4.193	.546
5	2	-29.402 <sup>*</sup>	.000
	3	-5.272	.449
	10	-1.079	.876
10	2	-28.323 <sup>*</sup>	.000
	3	-4.193	.546
	5	1.079	.876

Based on observed means.

The error term is Mean Square(Error) = 236.922.

\*. The mean difference is significant at the 0.05 level.

A – CEC x Depth

**ANOVA**

Dependent Variable: CEC

Source	df	F	Sig.
Depth_cm	3	.458	.713
Error	36		
Total	40		
Corrected Total	39		

**ANOVA**

Dependent Variable: CEC

Source	df	F	Sig.
Depth_cm	3	.458	.713
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .037 (Adjusted R Squared = -.044)

SAR<sub>dw</sub> by Position**ANOVA**

Dependent Variable: SAR\_DW

Source	df	F	Sig.
Position	3	10.958	.000
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .477 (Adjusted R Squared = .434)

**Multiple Comparisons**

SAR\_DW

LSD

(I) Position	(J) Position	Mean Difference (I-J)	Sig.
A	B	5.730	.148
	C	15.220*	.000
	D	20.070*	.000

B	A	-5.730	.148
	C	9.490*	.019
	D	14.340*	.001
C	A	-15.220*	.000
	B	-9.490*	.019
	D	4.850	.219
D	A	-20.070*	.000
	B	-14.340*	.001
	C	-4.850	.219

Based on observed means.

The error term is Mean Square(Error) = 75.020.

\*. The mean difference is significant at the .05 level.

A – SAR x depth

#### Levene's Test of Equality of Error Variances<sup>a</sup>

Dependent Variable: SAR

F	df1	df2	Sig.
6.753	3	36	.001

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Depth\_cm

Position B- pH x depth

### ANOVA

Dependent Variable:pH

Source	df	F	Sig.
Depth_cm	3	3.737	.020
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .237 (Adjusted R Squared = .174)

### Multiple Comparisons

pH

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	.230	.059
	5	.360*	.004
	10	.320*	.010
3	2	-.230	.059
	5	.130	.277
	10	.090	.450
5	2	-.360*	.004
	3	-.130	.277
	10	-.040	.736
10	2	-.320*	.010
	3	-.090	.450
	5	.040	.736

Based on observed means.

The error term is Mean Square(Error) = .069.

**Multiple Comparisons**

pH

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	.230	.059
	5	.360*	.004
	10	.320*	.010
3	2	-.230	.059
	5	.130	.277
	10	.090	.450
5	2	-.360*	.004
	3	-.130	.277
	10	-.040	.736
10	2	-.320*	.010
	3	-.090	.450
	5	.040	.736

Based on observed means.

The error term is Mean Square(Error) = .069.

\*. The mean difference is significant at the 0.05 level.

B – CEC x depth

**ANOVA**

Dependent Variable: CEC

Source	df	F	Sig.
Depth_cm	3	6.822	.001
Error	36		
Total	40		
Corrected Total	39		

**ANOVA**

Dependent Variable: CEC

Source	df	F	Sig.
Depth_cm	3	6.822	.001
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .362 (Adjusted R Squared = .309)

**Multiple Comparisons**

CEC

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	21.430*	.007
	5	26.260*	.001
	10	32.000*	.000
3	2	-21.430*	.007
	5	4.830	.527
	10	10.570	.171
5	2	-26.260*	.001
	3	-4.830	.527
	10	5.740	.453
10	2	-32.000*	.000
	3	-10.570	.171
	5	-5.740	.453

Based on observed means.

The error term is Mean Square(Error) = 285.927.

\*. The mean difference is significant at the 0.05 level.

B – EC x depth

**ANOVA**

Dependent Variable: EC

Source	df	F	Sig.
Depth_cm	3	8.447	.000
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .413 (Adjusted R Squared = .364)

**Multiple Comparisons**

EC

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	21.923 <sup>*</sup>	.001
	5	24.168 <sup>*</sup>	.000
	10	25.532 <sup>*</sup>	.000
3	2	-21.923 <sup>*</sup>	.001
	5	2.245	.704
	10	3.609	.541
5	2	-24.168 <sup>*</sup>	.000
	3	-2.245	.704
	10	1.364	.817
10	2	-25.532 <sup>*</sup>	.000
	3	-3.609	.541
	5	-1.364	.817

Based on observed means.

The error term is Mean Square(Error) = 171.316.

\*. The mean difference is significant at the 0.05 level.

B- SAR x depth

**ANOVA**

Dependent Variable: SAR

Source	df	F	Sig.
Depth_cm	3	16.839	.000
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .584 (Adjusted R Squared = .549)

**Multiple Comparisons**

SAR

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	26.194*	.000
	5	31.148*	.000
	10	35.465*	.000
3	2	-26.194*	.000
	5	4.954	.373
	10	9.271	.100
5	2	-31.148*	.000
	3	-4.954	.373
	10	4.317	.437
10	2	-35.465*	.000
	3	-9.271	.100
	5	-4.317	.437

Based on observed means.

The error term is Mean Square(Error) = 150.603.

**Multiple Comparisons**

SAR

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	26.194*	.000
	5	31.148*	.000
	10	35.465*	.000
3	2	-26.194*	.000
	5	4.954	.373
	10	9.271	.100
5	2	-31.148*	.000
	3	-4.954	.373
	10	4.317	.437
10	2	-35.465*	.000
	3	-9.271	.100
	5	-4.317	.437

Based on observed means.

The error term is Mean Square(Error) = 150.603.

\*. The mean difference is significant at the 0.05 level.

Position C- pH x depth

**ANOVA**

Dependent Variable:pH

Source	df	F	Sig.
Depth_cm	3	.140	.935
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .012 (Adjusted R Squared = -.071)

C - CEC x depth

**ANOVA**

Dependent Variable: CEC

Source	df	F	Sig.
Depth_cm	3	1.162	.338
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .088 (Adjusted R Squared = .012)

C- EC x depth

**Tests of Between-Subjects Effects**

Dependent Variable: EC

Source	df	F	Sig.
Depth_cm	3	.142	.934
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .012 (Adjusted R Squared = -.071)

## C - SAR x Depth

**ANOVA**

Dependent Variable: SAR

Source	df	F	Sig.
Depth_cm	3	.104	.957
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .009 (Adjusted R Squared = -.074)

## Position D – pH by depth

**ANOVA**

Dependent Variable :pH

Source	df	F	Sig.
Depth_cm	3	3.945	.016
Error	35		
Total	39		
Corrected Total	38		

a. R Squared = .253 (Adjusted R Squared = .189)

**Multiple Comparisons**

pH

LSD

(I) Depth_cm	(J) Depth_cm	Mean Difference (I-J)	Sig.
2	3	-.102	.484
	5	-.322*	.032
	10	-.442*	.004
3	2	.102	.484
	5	-.220	.127
	10	-.340*	.021
5	2	.322*	.032
	3	.220	.127
	10	-.120	.400
10	2	.442*	.004
	3	.340*	.021
	5	.120	.400

Based on observed means.

The error term is Mean Square(Error) = .099.

\*. The mean difference is significant at the 0.05 level.

D - CEC x depth

**ANOVA**

Dependent Variable:CEC

Source	df	F	Sig.
Depth_cm	3	2.353	.089
Error	35		
Total	39		
Corrected Total	38		

a. R Squared = .168 (Adjusted R Squared = .097)

D – EC x depth

**ANOVA**

Dependent Variable: EC

Source	df	F	Sig.
Depth_cm	3	1.596	.208
Error	35		
Total	39		
Corrected Total	38		

a. R Squared = .120 (Adjusted R Squared = .045)

D – SAR x depth

**ANOVA**

Dependent Variable: SAR

Source	df	F	Sig.
Depth_cm	3	2.469	.078
Error	35		
Total	39		
Corrected Total	38		

a. R Squared = .175 (Adjusted R Squared = .104)

N<sub>dw</sub> x position**ANOVA**

Dependent Variable: N\_DW

Source	df	F	Sig.
Position	3	1.552	.218
Error	36		
Total	40		
Corrected Total	39		

**ANOVA**

Dependent Variable: N\_DW

Source	df	F	Sig.
Position	3	1.552	.218
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .114 (Adjusted R Squared = .041)

NO<sub>3</sub><sub>dw</sub> x position**Tests of Between-Subjects Effects**

Dependent Variable:NO3\_DW

Source	df	F	Sig.
Position	3	1.439	.248
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .107 (Adjusted R Squared = .033)

NH<sub>4</sub><sub>dw</sub> x Position**ANOVA**

Dependent Variable: NH4\_DW

Source	df	F	Sig.
Position	3	.292	.831
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .024 (Adjusted R Squared = -.058)

Position		N mg/kg	NO3 mg/kg	Position	NH4 mg/kg		
<b>A<sub>a</sub></b>	<b>0-2 cm A</b>	<b>mean</b>	<b>4.3</b>	<b>A</b>	<b>10.9</b>		
		s.d.	6.1		6.4		
	<b>2-5 cm A</b>	<b>mean</b>	<b>2.8</b>		<b>6.6</b>		
		s.d.	1.2		2.8		
	<b>5-10 cm A</b>	<b>mean</b>	<b>2.5</b>		<b>2.1</b>	<b>6.3</b>	
		s.d.	0.7		1.0		
	<b>10-20 cm A</b>	<b>mean</b>	<b>2.8</b>		<b>1.7</b>	<b>6.4</b>	
		s.d.	1.0		0.8	3.5	
	<b>B<sub>a</sub></b>	<b>0-2 cm B</b>	<b>mean</b>		<b>4.2</b>	<b>B</b>	<b>9.2</b>
			s.d.		4.0		6.5

	<b>2-5 cm B</b>	<b>mean</b>	<b>3.1</b>	<b>3.1</b>		<b>5.7</b>
		s.d.	2.2	3.0		2.4
	<b>5-10 cm B</b>	<b>mean</b>	<b>2.6</b>	<b>2.5</b>		<b>5.0</b>
		s.d.	1.1	2.3		1.6
	<b>10-20 cm B</b>	<b>mean</b>	<b>2.6</b>	<b>2.5</b>		<b>6.2</b>
		s.d.	1.1	2.2		2.4
	<b>0-2 cm C</b>	<b>mean</b>	<b>12.6</b>	<b>20.2</b>		<b>9.9</b>
		s.d.	14.6	25.7		5.3
<b>C<sub>b</sub></b>	<b>2-5 cm C</b>	<b>mean</b>	<b>7.5</b>	<b>13.0</b>	<b>C</b>	<b>6.6</b>
		s.d.	7.8	18.3		3.4
	<b>5-10 cm C</b>	<b>mean</b>	<b>6.3</b>	<b>9.5</b>		<b>5.9</b>
		s.d.	8.3	15.5		2.5
	<b>10-20 cm C</b>	<b>mean</b>	<b>4.6</b>	<b>7.3</b>		<b>5.5</b>
		s.d.	5.4	13.8		2.1
	<b>0-2 cm D</b>	<b>mean</b>	<b>6.2</b>	<b>11.2</b>		<b>14.0</b>
		s.d.	4.8	10.7		18.0
<b>D<sub>ab</sub></b>	<b>2-5 cm D</b>	<b>mean</b>	<b>4.1</b>	<b>6.9</b>	<b>D</b>	<b>7.8</b>
		s.d.	3.4	7.2		7.0
	<b>5-10 cm D</b>	<b>mean</b>	<b>3.6</b>	<b>4.9</b>		<b>7.0</b>
		s.d.	2.7	6.1		5.0
	<b>10-20 cm D</b>	<b>mean</b>	<b>3.2</b>	<b>4.0</b>		<b>5.9</b>
		s.d.	3.2	6.7		2.3

## Phosphorus

			<b>P mg/kg</b>	<b>PO<sub>4</sub> mg/kg</b>	
<b>A<sub>a</sub></b>	<b>0-2 cm A</b>	<b>mean</b>	<b>29.3</b>	<b>2.3</b>	
		s.d.	14.0	1.0	
	<b>2-5 cm A</b>	<b>mean</b>	<b>17.1</b>	<b>0.6</b>	
		s.d.	5.3	0.5	
	<b>5-10 cm A</b>	<b>mean</b>	<b>14.1</b>	<b>0.5</b>	
		s.d.	5.2	0.4	
	<b>10-20 cm A</b>	<b>mean</b>	<b>15.0</b>	<b>0.4</b>	
		s.d.	7.1	0.3	
	<b>B<sub>a</sub></b>	<b>0-2 cm B</b>	<b>mean</b>	<b>22.9</b>	<b>1.7</b>
			s.d.	17.3	1.5
		<b>2-5 cm B</b>	<b>mean</b>	<b>14.0</b>	<b>0.5</b>
			s.d.	9.4	0.3
<b>5-10 cm B</b>		<b>mean</b>	<b>9.4</b>	<b>0.4</b>	
		s.d.	6.1	0.2	
<b>10-20 cm B</b>	<b>mean</b>	<b>8.5</b>	<b>0.3</b>		
	s.d.	5.0	0.2		
<b>C</b>	<b>0-2 cm C</b>	<b>mean</b>	<b>22.4</b>	<b>1.2</b>	
		s.d.	15.3	1.2	
	<b>2-5 cm C</b>	<b>mean</b>	<b>12.2</b>	<b>0.4</b>	
		s.d.	8.4	0.3	
	<b>5-10 cm C</b>	<b>mean</b>	<b>8.6</b>	<b>0.4</b>	
		s.d.	6.5	0.2	
<b>10-20 cm C</b>	<b>mean</b>	<b>7.0</b>	<b>0.3</b>		
	s.d.				

	s.d.	4.7	0.2
<b>0-2 cm D</b>	<b>mean</b>	<b>26.0</b>	<b>1.5</b>
	s.d.	18.6	1.1
<b>2-5 cm D</b>	<b>mean</b>	<b>15.5</b>	<b>0.9</b>
<b>Da</b>	s.d.	10.6	0.7
<b>5-10 cm D</b>	<b>mean</b>	<b>10.4</b>	<b>0.7</b>
	s.d.	7.5	0.6
<b>10-20 cm D</b>	<b>mean</b>	<b>7.8</b>	<b>0.5</b>
	s.d.	7.8	0.3

P<sub>dw</sub> by position

#### ANOVA

Dependent Variable: P\_DW

Source	df	F	Sig.
Position	3	1.987	.133
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .142 (Adjusted R Squared = .071)

PO<sub>4 dw</sub> x position

**ANOVA**

Dependent Variable: PO4\_DW

Source	df	F	Sig.
Position	3	1.393	.261
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .104 (Adjusted R Squared = .029)

K<sub>dw</sub> by position

**ANOVA**

Dependent Variable: K\_DW

Source	df	F	Sig.
Position	3	2.508	.074
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .173 (Adjusted R Squared = .104)

			<b>K mg/kg</b>	<b>Na mg/kg</b>
<b>A<sub>a</sub></b>	<b>0-2 cm A</b>	<b>mean</b>	<b>254.0</b>	<b>5630.6</b>
		s.d.	71.5	3167.9
	<b>2-5 cm A</b>	<b>mean</b>	<b>226.1</b>	<b>4381.9</b>
		s.d.	62.4	1903.2
	<b>5-10 cm A</b>	<b>mean</b>	<b>232.1</b>	<b>4251.2</b>
		s.d.	68.8	2065.1
	<b>10-20 cm A</b>	<b>mean</b>	<b>219.8</b>	<b>3975.0</b>
		s.d.	62.7	1781.1
<b>B<sub>a</sub></b>	<b>0-2 cm B</b>	<b>mean</b>	<b>274.4</b>	<b>4634.8</b>
		s.d.	92.8	1049.1
	<b>2-5 cm B</b>	<b>mean</b>	<b>229.0</b>	<b>3617.5</b>
		s.d.	92.6	934.9
	<b>5-10 cm B</b>	<b>mean</b>	<b>204.0</b>	<b>3307.1</b>
		s.d.	80.9	1116.7
	<b>10-20 cm B</b>	<b>mean</b>	<b>185.0</b>	<b>3163.6</b>
		s.d.	66.1	1201.0
<b>C<sub>a</sub></b>	<b>0-2 cm C</b>	<b>mean</b>	<b>288.8</b>	<b>1797.1</b>
		s.d.	63.3	1355.4
	<b>2-5 cm C</b>	<b>mean</b>	<b>253.7</b>	<b>1830.5</b>
		s.d.	50.8	1186.0
	<b>5-10 cm C</b>	<b>mean</b>	<b>237.8</b>	<b>1972.5</b>
		s.d.	58.8	1018.9
	<b>10-20 cm C</b>	<b>mean</b>	<b>212.1</b>	<b>2201.7</b>
		s.d.	52.2	1027.1
<b>D</b>	<b>0-2 cm D</b>	<b>mean</b>	<b>333.2</b>	<b>513.4</b>

	s.d.	118.2	685.9
<b>2-5 cm D</b>	<b>mean</b>	<b>321.7</b>	<b>716.3</b>
	s.d.	117.7	632.2
<b>5-10 cm D</b>	<b>mean</b>	<b>298.0</b>	<b>1187.7</b>
	s.d.	60.8	963.4
<b>10-20 cm D</b>	<b>mean</b>	<b>249.7</b>	<b>1633.1</b>
	s.d.	64.4	1093.3

Na<sub>dw</sub> by position

#### ANOVA

Dependent Variable: Na\_DW

Source	df	F	Sig.
Position	3	12.428	.000
Error	36		
Total	40		
Corrected Total	39		

a. R Squared = .509 (Adjusted R Squared = .468)

#### Multiple Comparisons

Na\_DW

LSD

(I) Position	(J) Position	Mean Difference (I-J)	Sig.
A	B	855.960	.121
	C	2222.390 <sup>*</sup>	.000
	D	2998.370 <sup>*</sup>	.000
B	A	-855.960	.121
	C	1366.430 <sup>*</sup>	.016

	D	2142.410*	.000
C	A	-2222.390*	.000
	B	-1366.430*	.016
	D	775.980	.159
D	A	-2998.370*	.000
	B	-2142.410*	.000
	C	-775.980	.159

Based on observed means.

The error term is Mean Square(Error) = 1456460.703.

\*. The mean difference is significant at the 0.05 level.

**Levene's Test of Equality of Error Variances<sup>a</sup>**

Dependent Variable: EC\_DW

F	df1	df2	Sig.
5.036	3	36	.005

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Position

**Correlations**

		Saturation_Depth	EC
Saturation_Depth	Pearson Correlation	1	-.346**
	Sig. (2-tailed)		.000
	N	160	160
EC	Pearson Correlation	-.346**	1
	Sig. (2-tailed)	.000	
	N	160	160

\*\* . Correlation is significant at the 0.01 level (2-tailed).

## Correlations

		depth_saturation
Sal_rub	Pearson Correlation	-.497**
	Sig. (2-tailed)	.001
	N	40
Sua_calc	Pearson Correlation	.173
	Sig. (2-tailed)	.285
	N	40
Dist_spic	Pearson Correlation	.056
	Sig. (2-tailed)	.733
	N	40
Poa_pra	Pearson Correlation	.291
	Sig. (2-tailed)	.068
	N	40

\*\* . Correlation is significant at the 0.01 level (2-tailed).

## Correlations

		EC_0-2 cm
Sal_rub	Pearson Correlation	.665**
	Sig. (2-tailed)	.000
	N	40
Sua_calc	Pearson Correlation	.315*
	Sig. (2-tailed)	.048
	N	40
Dist_spic	Pearson Correlation	-.229
	Sig. (2-tailed)	.154
	N	40
Poa_pra	Pearson Correlation	-.429**
	Sig. (2-tailed)	.006
	N	40

**Correlations**

		EC_0-2 cm
Sal_rub	Pearson Correlation	.665**
	Sig. (2-tailed)	.000
	N	40
Sua_calc	Pearson Correlation	.315*
	Sig. (2-tailed)	.048
	N	40
Dist_spic	Pearson Correlation	-.229
	Sig. (2-tailed)	.154
	N	40
Poa_pra	Pearson Correlation	-.429**
	Sig. (2-tailed)	.006
	N	40

\*\* . Correlation is significant at the 0.01 level (2-tailed).

\* . Correlation is significant at the 0.05 level (2-tailed).