EFFECTS OF SALINE-SODIC WATER ON EC, SAR, AND WATER RETENTION

by

Kimberly Marie Robinson

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APPROVAL

Of a thesis submitted by

Kimberly Marie Robinson

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Dr. James W. Bauder ______________________________ ____________
Chairperson, Graduate Committee Date

Approved for the Department of Land Resources and Environmental Sciences

Dr. Jeffrey S. Jacobsen ______________________________ ____________
Head, Major Department Date

Approved for the College of Graduate Studies

Dr. Bruce R. McLeod ______________________________ ____________
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ABSTRACT

There is significant concern regarding the potential impact of discharges of saline-sodic water from coal bed methane development sites within the Powder River Basin onto irrigated acreages of the area.

The specific objective of this study was to assess soil chemical and physical responses upon wetting with saline-sodic water. This was accomplished by exposing soil material collected from sites within the Powder River Basin to various combinations of two water qualities and three wetting/irrigation regimes. Water quality treatments consisted of either synthesized Powder River water or synthesized CBM product water. Wetting and irrigation regimes consisted of: 1) a single wetting event, 2) a five-time wet/dry cycle and 3) a five-time wet/dry cycle followed by a single flood (flushing) event with distilled water.

Repeated irrigation with saline-sodic water or water with a chemical signature comparable to the CBM product water used in this study will result in a general increase in the soil salinity and sodicity. It is likely that elevated soil salinity levels will be substantially higher than published thresholds for some irrigated crops. The impact of rainfall on reducing EC and SAR is more predominant when salt concentrations are high, and in coarser-textured soils. Distilled water applications simulating rainfall resulted in a much greater lowering of EC than for SAR.

To assess the effects of saline-sodic water on the physical properties of the soil, water content was measured after the soils were exposed to the various water qualities and treatment scenarios at five different pressure potentials. It was found that water content associated with matric potential differed significantly due to predominant soil textures. Although statistically significant differences were detected among water quality treatments, differences were not considered large enough to have a significant ecological impact. It was determined that CBM product water applied at these levels did not have a consistent significant impact on soil physical properties.

CHAPTER 1

Introduction

The growing need for new sources of energy has spurred development of the coal bed methane (CBM) industry in the western United States. CBM has a wide variety of energy-related uses and is generally considered a cleaner form of energy than traditional coal and oil. Conservative estimates suggest that there are approximately 141 trillion cubic feet (TCF) of economically recoverable CBM within the continental United States (Nelson, 1999). CBM is an attractive energy source, as exploration costs are low and wells used to extract CBM are cost effective to drill.

Environmental concerns have arisen with the increased emphasis on the extraction of the CBM resource. The extraction of CBM involves pumping large volumes of water from the saturated, coal-bearing aquifers in order to release water pressure that is trapping the gas in the coal. The quality of this pumped water coproduced with methane is a source of concern. This coproduced water (called CBM product water in this paper) has a modestly high salinity hazard and often a very high sodium hazard based on standards used for irrigation suitability. CBM product water also contains a significant bicarbonate (HCO_3) component, which enhances the precipitation of relatively insoluble carbonate minerals (Rice, 2000).

Much of the current CBM development is occurring in the Powder River Basin of Montana and Wyoming (Figure 1). The Powder River Basin encompasses both the

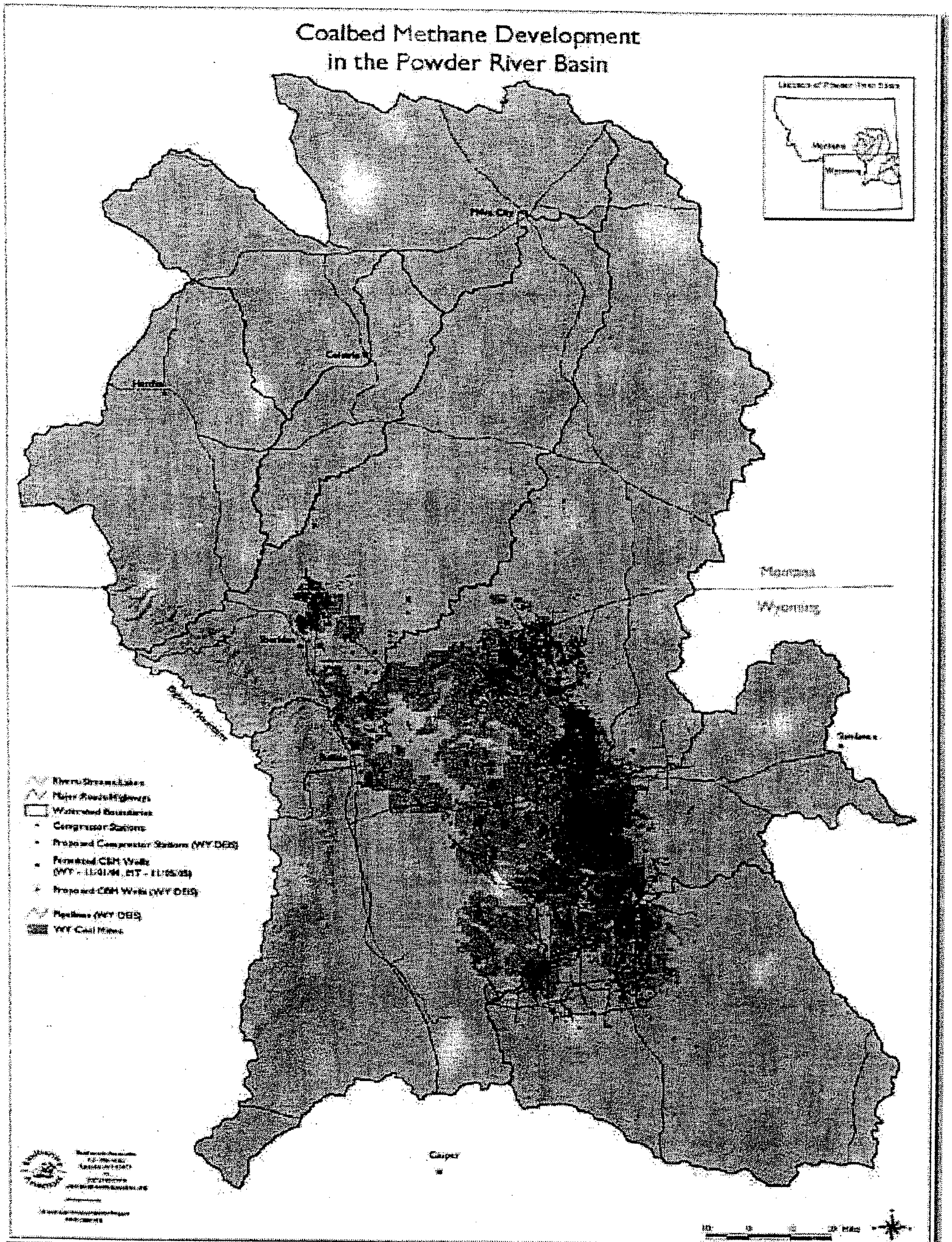

Figure 1. The Powder River Basin. Black dots represent permitted CBM wells. (Source: www.biodiversityassociates.org)

Powder River and the Tongue River watersheds. The Powder River originates in north-central Wyoming, flowing northward, where it joins the Yellowstone River near Terry, Montana. The soil survey for Powder River County, Montana (USDA, 1971) indicates that soils along the river within the basin consist primarily of silt loams, silty clay loams, and silty clays. These soils have historically been irrigated with Powder River water, roughly 4500 hectares in Montana (Brock, 1991). The Powder River Basin receives minimal precipitation, less than 35 cm annually. The basin's structural geology consists mostly of tertiary sandstones and shales (Thompson, 1991). The combination of these factors creates a flow within the Powder River that has an inherently high salt content, especially during periods of low flows. Suitability of Powder River water for irrigation varies seasonably. Figures 2-5 represent thirty years of water quality data collected by the United States Geological Society (USGS) on the Powder River at Moorhead, Montana. These figures show that water within the river is of marginal quality with respect to salinity and sodicity standards generally considered acceptable for irrigation.

Objectives

The present study assessed the effects of waters having a range of EC x SAR on chemical and physical properties of selected soil materials. A laboratory experiment was conducted that subjected soils of varying clay content to diverse wetting/drying regimes using two water qualities. It was hypothesized that saline-sodic water at the treatment levels used would have deleterious effects on chemical and physical

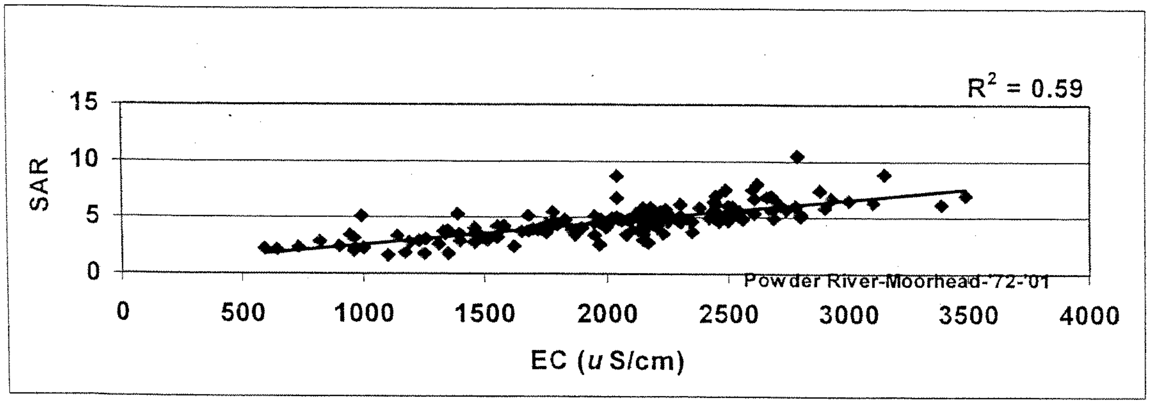

Figure 2. EC (electrical conductivity, uS/cm) vs. SAR (sodium adsorption ratio) for the Powder River. (Source: USGS-Station #06324500)

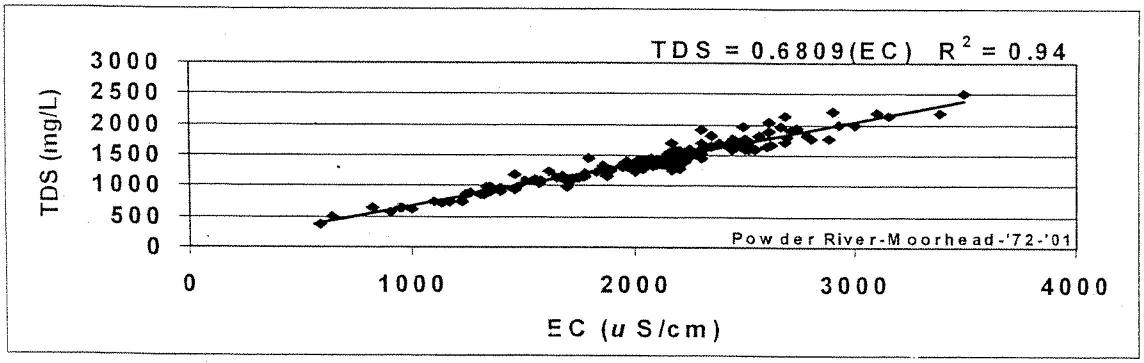

Figure 3. EC (uS/cm) vs. TDS (total dissolved solids, mg/L) for the Powder River. (Source: USGS-Station #06324500)

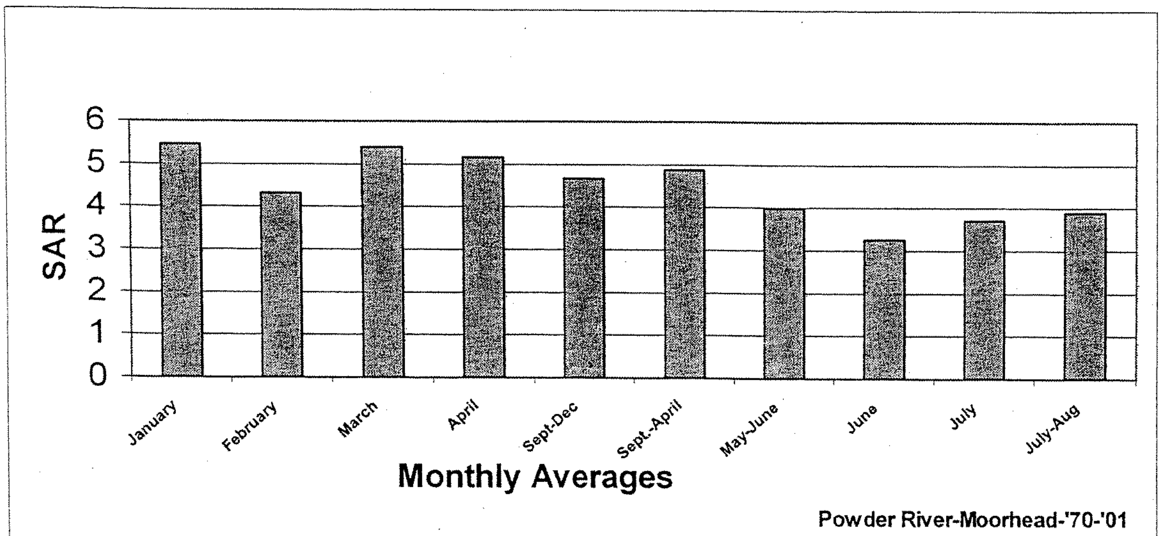

Figure 4. Monthly and seasonal numeric average SAR for the Powder River, non-flow weighted. (Source: USGS-Station #06324500)

properties of the soil. The overall goal was to determine the suitability of irrigating with marginally saline-sodic waters, while still maintaining the sustainability of the soil.

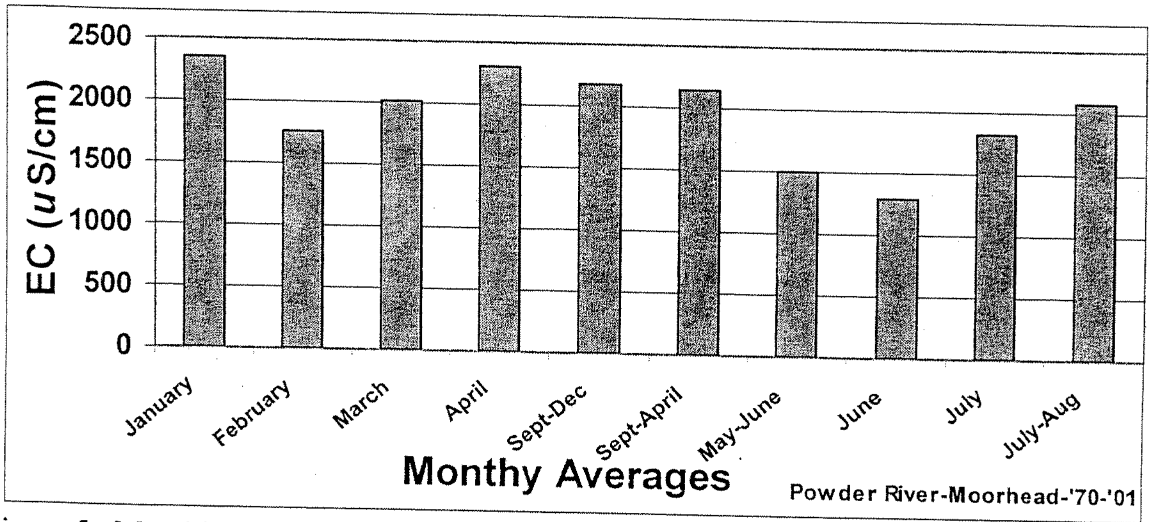

Figure 5. Monthly and seasonal numeric average EC (*u*S/cm) for the Powder River, non-flow weighted. (Source: USGS-Station #0634500)

Literature Review

Irrigation Water Quality

Land managers across the globe are increasingly being forced to use water of poor quality for irrigation. Two of the most critical criteria for accessing irrigation water quality are salinity and sodicity (Rhoades, 1972). Irrigation water containing excessive salts can have deleterious effects on soil physical and chemical properties.

Salinity Impacts

Ghassemi et al. (1995) argues that salinity is the most important criterion for evaluating irrigation water quality because it represents a total concentration of ions, which most crops respond to rather than individual concentrations of specific salts. Electrical conductivity (EC) is used to estimate water and soil solution salinity. The EC of the soil saturation extract is approximately equal to 1.5 to 3 times the salt concentration of the irrigation water with a 15% leaching factor (Western Fertilizer Handbook, 1995). The amount of extra water added to leach the soil is referred to as the leaching requirement or leaching fraction. Saline soil water reduces crop growth if the average root zone salinity exceeds the threshold level of the crop. The suitability of water for irrigation, in terms of salinity thresholds, depends primarily on the kind and amounts of salts present, the soil type in question, specific plant species and growth stage, and the leaching fraction (Ayers and Westcot, 1976; Hanson et al., 1999; Rhoades, 1977; USDA, Natural Resources Conservation Service, 2002; Western Fertilizer Handbook, 1995).

Salinity becomes a problem when an excess amount of soluble salts restrict the ability of a plant to withdraw water effectively from the surrounding soil (Bauder and Brock, 2001; Hanson et al., 1999; USDA, Natural Resources Conservation Service, 2002; Western Fertilizer Handbook, 1995). Osmotic forces, resulting from the salt concentration, will hold water tighter, and make it less available for plant uptake. Elevated salinity levels also decrease evapotranspiration (Chhabra, 1996).

Salinity largely influences soil physical properties by its ability to keep a soil flocculated. High salinity promotes a structurally stable soil (Buckland et al., 2002). Elevated electrolyte concentrations cause fine particles to aggregate, resulting in a pore size distribution that contains larger void spaces than a non-flocculated soil. A well-flocculated soil will exhibit good permeability and enhance the hydraulic conductivity (HC) of a soil. Soils with good aggregation will also shrink less than structureless soils, and will be less susceptible to cracks under field conditions (Mitchell and van Genuchten, 1992).

Sodicity Impacts

Sodicity is another important issue when assessing irrigation water suitability. It is not uncharacteristic of soils in arid and semi-arid regions to contain high amounts of exchangeable sodium (Quirk and Schofield, 1955). Exchangeable sodium, if found in amounts excessive to calcium and magnesium, can have deleterious effects on the soil. High amounts of exchangeable sodium can also lead to aggregate slaking and crust formation.

The sodium adsorption ratio (SAR) is used as an assessment of the sodicity hazard of the soil solution or applied water, while the exchangeable sodium percentage (ESP) reflects the degree to which the soil exchange complex is saturated with sodium. The ESP of the soil can be related to the SAR of the applied solution or soil solution, varying according to the soil/solution ratio of soil extracts examined (Halliwell et al., 2001). Therefore, the SAR of the irrigation water may be used as an index of the sodicity hazard of the water, providing it is relatable to the resultant SAR of the equilibrated soil water (Rhoades, 1972). Soil dispersion is the primary physical process associated with elevated sodium (Na) concentrations (Ayers and Westcot, 1976; Bauder and Brock, 2001; Buckman and Brady, 1967; Chen and Banin, 1975; Frenkel et al, 1978; Hanson et al., 1999; Miller and Gardiner, 2001).

Soil Swelling/Dispersion. The primary processes responsible for the physical disintegration of soil structure and reductions in infiltration or hydraulic conductivity (HC) of soils affected by exchangeable sodium are swelling and dispersion (Halliwell et al., 2001; Levy et al., 1999; Miller and Gardiner, 2001; So and Aylmore, 1993). Characteristics of the sodium ion (large size, single charge, and hydrated radius) tend to cause physical separation of soil particles. Quirk states, "The swelling of clay domains and their consequent destruction, resulting from the interaction of diffuse double layers in micropores, is quite clearly the primary cause of decreased permeability" (2001). Soil swelling and/or dispersion change the geometry of soil pores (Bresler et al., 1982), reducing pore size, causing bond weakening and particle separation (Curtin et al., 1994). This in turn reduces soil permeability (Mace and Amrhein, 2001). McNeal et al. (1968) quantified the relationship between soil swelling factors and hydraulic conductivity with the following function:

$$1 - y = cx^n / (1 + cx^n) \qquad \text{[Equation 1]}$$

where y = relative soil HC; x = swelling factor (the calculated interlayer swelling of soil montmorillonite); and c and n = constants for a given soil within a range of ESP values ($n = 1$ for $ESP < 25$, 2 for $25 < ESP < 50$, and 3 for $50 < ESP$). McNeal provides the following nomogram that predicts interlayer swelling on the basis of ESP and soil solution salt concentration combinations.

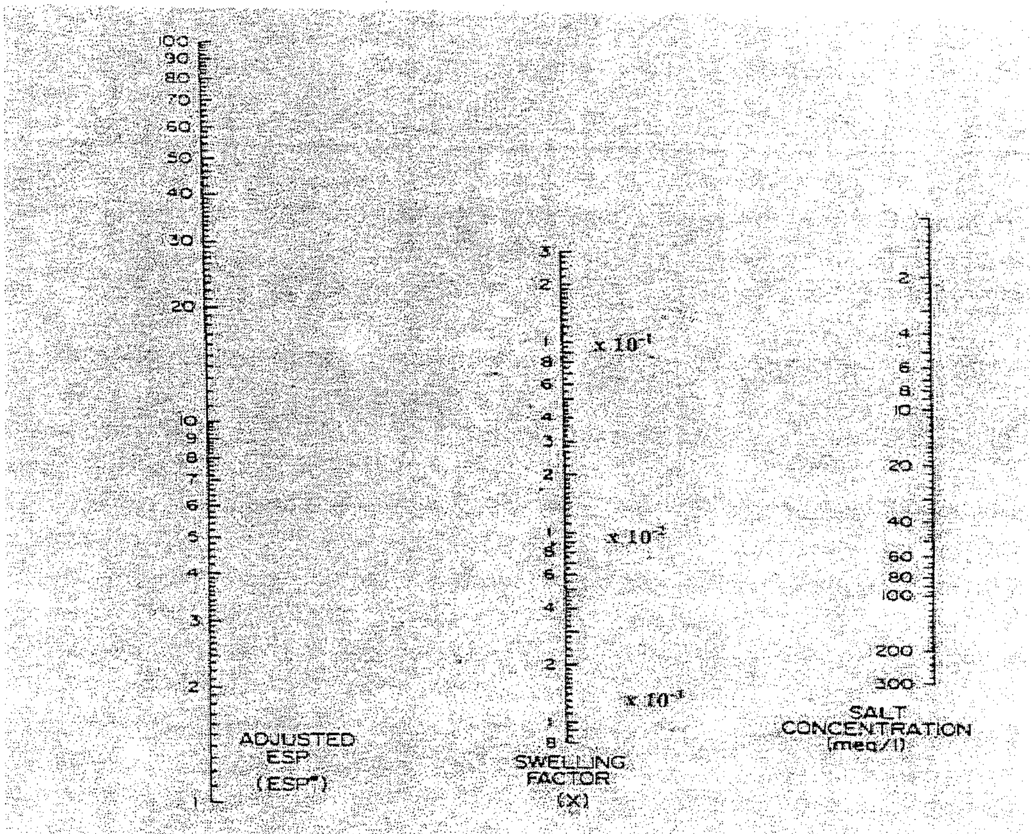

Figure 6. Swelling factor as a function of adjusted ESP and salt concentrations of the soil solution. (Source: McNeal, 1968).

This predictive relationship defines the relative degree to which the hydraulic conductivity (HC) will vary with the salt concentration of the solution and the soil ESP. Increasing the adjusted ESP or decreasing the salt concentration caused an increase in the swelling factor.

Mace and Amrhein (2001) leached synthetic drainage waters of varying SAR and EC concentrations through machine-packed soil columns to evaluate the effects of clay dispersion and swelling on HC. They reported that internal soil swelling decreases the number of macropores in a soil, thereby increasing the water holding capacity at low tension. Shainberg et al. (2001) conducted a similar study. Soils with varying levels of initial ESP were leached with saline water. When the salt concentration of the leaching water was 3 meq/l, reductions in HC and clay dispersion decreased only when ESP values were greater than 12, whereas when distilled water was used to leach the soil, reductions in HC and dispersion where observed at ESPs of 1 and 2. Accordingly, Curtin et al. (1994) reported extensive swelling of soil clays when the ESP exceeded 10. Results from the study suggest that initial decreases in HC are attributable to swelling occurring at high salt concentrations, while dispersion becomes more important as electrolyte concentration decreases. In another study, researchers investigated whether the addition of sodium to water in an early irrigation would decrease infiltration during subsequent irrigation. Results showed that the infiltration rate decreased, with the reduction attributed to chemically induced dispersion of the soil (Hopmans et al., 1990).

Aggregate Slaking. Aggregate slaking is also another physical process associated with sodicity (Coughlan et al., 1991). The slaking of macroaggregates into microaggregates reduces the number of macropores, which in turn limits soil permeability (Oster and Shainberg, 2001). When a soil is structurally stable, the volume of transmitting pores, macropores, is high and the HC is high (Shainberg et al., 2001). Increasing sodium either in the soil solution or on soil exchange complex causes soil aggregates to disperse or slake into domains, which are reduced in size to the extent that they are transported with the water, thereby blocking the larger pores, and reducing the hydraulic conductivity (So and Aylmore, 1993). Crescimanno et al. (1995) saw this trend in their research, as they found reductions of 25% in HC when aggregate stability decreased, thereby increasing the susceptibility of the soil to cracks.

Bauder and Brock (1992) reported that irrigation with relatively high Na concentration water reduced surface soil macroporosity more than irrigation with relatively low Na concentration water. As clay swells into water conducting pores, and clay deposits within the pores, permeability decreases (Oster and Shainberg, 2001). Accordingly, Buckland et al. (2002) found that irrigation waters characterized by increased salinity/sodicity generally decreased aggregate stability.

Crust Formation. Crust formation is yet another characteristic of sodium-affected soils that may detrimentally affect the hydraulic properties of soils. The primary causes of surface crusting are physical dispersion due to impact of irrigation water/rainfall and chemical dispersion dependent on soil ESP and irrigation water EC (Agassi et al., 1981). Crust structure consists of two parts: 1) an upper skin seal caused by raindrop impact; and 2) a washed in zone formed by the accumulation of dispersed particles (McIntyre, 1958). Agassi et al. (1981) found that crust formation due to rainfall is greatly enhanced by clay dispersion and movement in the soil. Accordingly, Gal et al. (1984) studied the effect of soil sodicity and electrolyte concentration on the formation of structural crusts. Their study consisted of exposing sandy loam soil with an ESP of 1.0 or 11.6 to distilled water. At an ESP of 1.0, only a thin layer of compacted aggregates sealing the soil surface was observed. Yet, at an ESP of 11.6, the clay dispersed, and downward movement of the clay particles caused accumulation in the washed-in layer, causing crust formation and decreasing infiltration rates.

Another type of crust affected by salt concentration is depositional crusts, which refer to crusts formed by the movement of fine particles and their deposition a particular distance from their original location (Chen et al, 1980; Shainberg and Singer, 1985). Agassi et al. (1985) suggest that the high susceptibility of depositional crusts to salt concentrations of the irrigation water is similar to that of a structural crust. Shainberg and Singer (1985) studied the effects of salt concentration on the HC of depositional crusts. They measured the hydraulic conductivity of two soils as a function of the volume of suspension infiltrated and salt concentration of the applied water, in a range # .005M. When the EC of the applied water was below 0.3 dS/m, the HC of the depositional crust was 2 to 3 orders of magnitude lower than that of bulk soils. When the EC exceeded 0.3 dS/m, the permeability increased markedly. Shainberg and Singer (1985) also reported that saturated HC of depositional crusts made of flocculated particles was much higher than saturated HC of crusts made of dispersed clay and silt particles.

<u>Texture implications.</u> A soil's texture will govern how it responds; texture largely reflects the clay content of a soil. Clay has a large specific surface area, which makes it more active in physiochemical processes than sand or silt (Keren and Shainberg, 1981). In semi-arid and arid regions, especially where marine deposition has been a predominant source of parent material, montmorillonite clay is often the dominant clay type. Because of its high specific surface area (~800 m^2g^{-1}), it is the most active clay in clay-solution interactions (Keren and Shainberg, 1981). Therefore, the physical and chemical effects of saline-sodic percolating waters on soil properties may be exacerbated when the clay mineralogy of an area is predominantly montmorillonite.

Understanding the colloidal properties of clays is essential to understanding the effect of exchangeable Na and electrolyte concentration on the physical properties of soils. The diffuse double layer formed at clay surfaces by adsorbed sodium ions creates high swelling pressures, and forms single clay platelets which tend to persist in dilute solutions (Keren and Shainberg, 1981). The repulsion forces between clay particles increases with increasing sodicity or decreasing salinity (Oster and Shainberg, 2001). In the Curtin et al. (1994) study, each soil type studied exhibited the same general response to different SAR and EC concentrations, i.e., soils that were predominantly clay textured were very sensitive to the composition of the applied solution. Data collected from this study suggest that fine textured soils would not be suitable for irrigation with sodic water because of poor sodium stability.

EC/SAR Relationship

The interactive relationship between the salt concentration of the irrigation water, SAR of the irrigation water, and physical properties of the soil is well defined in the literature. The permeability of a soil to water depends both on the ESP of the soil and on the salt concentration of the percolating solution (EC or salinity), tending to decrease with increasing ESP and decreasing salt concentration (McNeal et al., 1968; Quirk and Schofield, 1955). The greater the SAR, the greater the potential reduction of HC, yet the effects of a high SAR are greatly decreased as the total salt concentration increases (Curtin et al., 1994; McNeal, 1968; Shainberg et al., 1981; Mace and Amrhein, 2001). Many factors influence the permeability of a soil in accordance to the EC by SAR interaction. These factors include organic matter, inorganic agents stabilizing soil aggregates and mechanical disturbance (Quirk and Schofield, 1955).

Quirk and Shofield (1955) were the first to qualify this relationship with respect to permeability. Hanson et al. (1999) also quantified this interactive effect of EC and SAR based on data initially reported by Ayers and Westcot (1976). Ayers and Westcot (1976) initially reported that even at a very high solution SAR, reductions to infiltration/permeability will be less severe if the EC of the irrigation water is maintained sufficiently high enough, irrespective of the constituency of the salinity component.

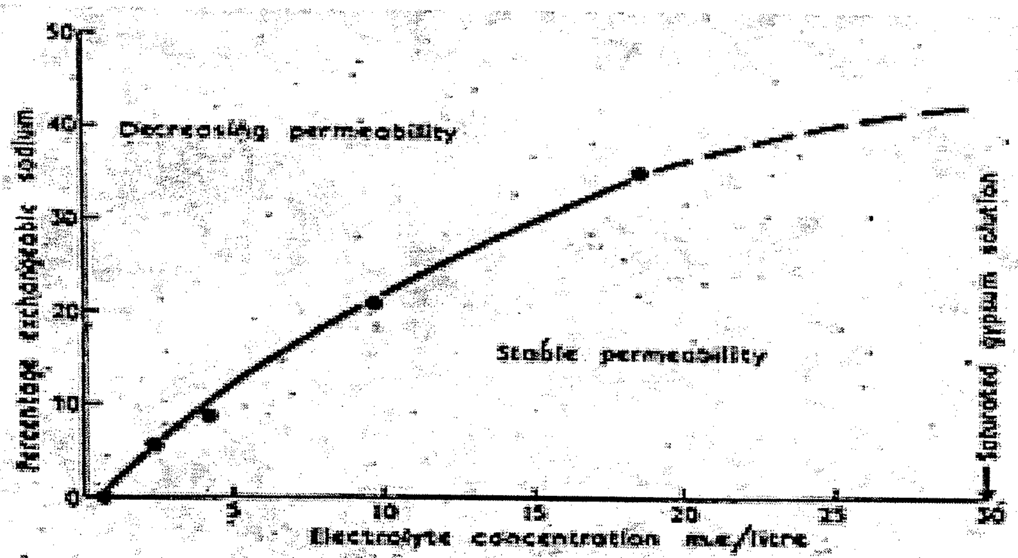

Figure 7. Permeability of soils as defined by the interaction between electrolyte concentration and the exchangeable sodium percentage. (Source: Quirk and Schofield, 1955)

Curtin et al. (1994) assessed the effects of SAR on a wide variety of soils. They reported that disproportionately high salt concentrations were needed to ensure satisfactory soil structure at high SAR values. VanOlphen (1977) reported that the soil water salinity necessary to maintain flocculation of a Na-montmorillonite soil is 12 to 16 meq/l (276-368 mg/l). Oster et al. (1980) reports flocculation values for Ca and Na saturated montmorillonite with ESPs of 10 and 20 are 3 and 6 meq/l, respectively. These flocculation values correspond to salinities of approximately 300 and 600 uS/cm.

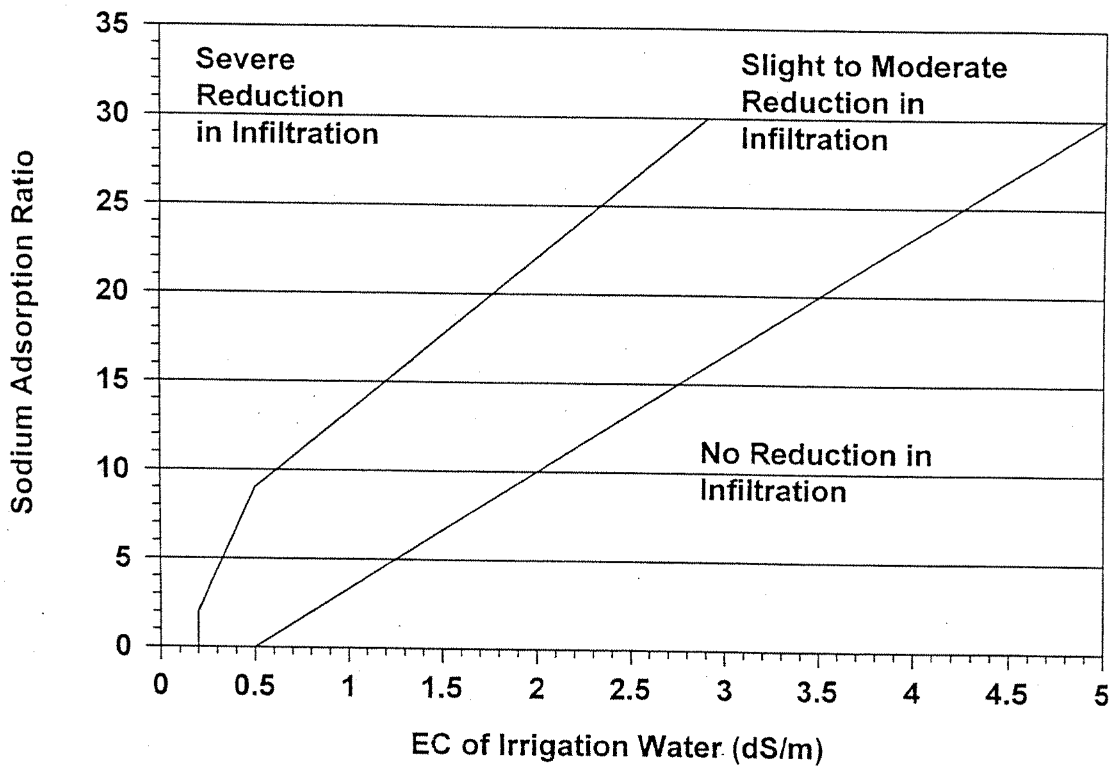

Figure 8. Reductions in infiltration as defined by the interaction between the EC and the SAR of the irrigation water. (Source: Hanson et al., 1999)

Rainfall Effects

The effects of rainfall on soil dispersion have significant implications in saline/sodic conditions. Leaching and rainfall affect soil solution chemistry and consequently relate to soil physical properties (Oster, 1994). In many cases, rainfall may cause more alteration both chemically and physically to a soil than irrigation waters. Rainfall essentially has an electrical conductivity of zero, which does not promote or enhance the flocculation of soil with high amounts of exchangeable sodium. Irrigation with a non–saline water or rainfall will reduce the EC of the soil water near the surface of a soil, but will not reduce the ESP the same magnitude as the EC reduction (Oster, 1994). The ESP will be reduced to a much lesser extent. This disproportionate reduction in EC relative to the reduction in SAR relates to the number of exchangeable ions on the exchange sites of the soil, which is as much as 500 times greater than the number of ions in soil water. This means that the number of calcium and magnesium ions in the soil solution originating from precipitation or non-saline water is insufficient to replace the amount of exchangeable sodium within the soil.

Most irrigation water has a salt concentration much greater than that of rainwater. During the irrigation season, salt concentrations within the soil solution and in the irrigation water are usually elevated to an extent, thus reducing the potential for physical degradation due to dispersion. Yet, when the water source changes to rainwater, soil water within the upper soil layer is displaced by rain water, causing dilution, and increasing the possibility of degradation to the physical properties of the soil (Shainberg et al., 1981). Disproportionate lowering of the EC to the SAR or ESP will likely upset the balance between flocculation promoted by the electrolyte concentration and dispersion promoted by sodicity. The Shainberg et al. (1981) study demonstrates this effect. While the impacts of sodicity on surface soils are almost immediate with rainfall, subsurface soils will eventually be impacted if sufficient amounts of rainfall infiltrate

(Oster and Shainberg, 2001). Thus, the effects of exchangeable sodium are much more evident during the rainy season than during irrigation periods (Levy et al., 1994).

Shainberg et al. (1981) report that some soils are more susceptible to clay dispersion than others when leached with distilled water or rainfall. Rainfall produced structural deterioration in Na-soils, and thus rainfall effects need to be accounted for when evaluating the sodicity hazard of irrigation water. Buckland et al. (2002) likewise found that infiltration properties were significantly greater with irrigation water than with distilled water.

Raindrop Impact. The impact action of raindrops can also alter the physical properties of soil. Agassi et al. (1985) studied the effects of raindrop impact and applied water salinity on infiltration of sodic soils. They reported that soils experiencing high-energy rain were more sensitive to lower levels of ESP, compared to soils receiving low-energy rain. This could be explained by the beating action of the rain, which broke down aggregates at the soil surface. Accordingly, Shainberg et al. (2001) reported that aggregates are more stable and much less susceptible to the impacts of sodicity when exposed to wetting rates less than 10 mm/h. Agassi et al. (1985) suggests that during rainstorms, reductions in the infiltration rate result from crust formation.

Salinity/Sodicity Thresholds

Historically, the critical values used to define sodic conditions were an SAR of 12 and an ESP of 15 (U.S. Salinity Laboratory, 1954). This threshold was based on the assumption that deterioration of the soil would occur when the ESP exceeds the value of

15, which corresponds to the SAR of 12. Accepted ESP thresholds vary around the world, in large part due to the different mineralogy of soils (Halliwell et al., 2001). In Australia, sodic soils are defined as soils with ESP values greater than 5, according to McIntyre (1979) or soils exhibiting an ESP greater than 6, according to Northcote and Skene (1972).

More recent literature suggests that these numbers need to be redefined. Researchers have found that soil degradation often takes place at ESP/SAR values much lower than historically accepted thresholds. Cresimanno et al. (1995) suggests that an effective hazard of soil degradation can be shown in soils with ESP values of 2 to 5. Accordingly, Shainberg et al. (1981) suggest even an ESP of 5 can be detrimental to soil properties when high-quality water displaces the soil solution. Curtin et al. (1994) proposed that the acceptable SAR increases as the clay content of a soil decreases.

It is also substantiated in the literature that SAR/ESP thresholds depend on the corresponding salt concentration. Quirk and Schofield (1955) introduced the idea of a threshold electrolyte concentration (TEC), which is defined as a critical value that the electrolyte concentration of the soil solution must exceed to ensure that soil permeability can be maintained. Rhoades (1972) noted that one of the major difficulties in establishing permissible limits with which to evaluate the sodicity hazard of irrigation water is a lack of quantitative information on the interplay of exchangeable sodium, electrolyte concentration, and soil properties on soil permeability. He also notes that it is presently impractical and non-justifiable to set precise standards of wide applicability for irrigation water quality.

Crescimanno et al. (1995) investigated the effects of SAR on the physical properties of soils (aggregate stability, rate of selling-shrinkage, and saturated and unsaturated hydraulic conductivity) irrigated with water having a range of solution salt concentrations. The objective of their study was to gain a better understanding of the relationship between these soil properties and ESP, and to verify if a critical ESP threshold existed. They reported that structural stability of the soil decreased, the water content corresponding to specific matric suctions decreased, and aggregate slaking occurred across a continuum of ESP values, indicating that a critical ESP threshold was not representative of soil structural response to ESP.

Quirk and Schofield (1955) indicate that since the permeability of a soil is related to both the exchangeable sodium percentage and the electrolyte concentration, there is no basis for dividing soils into sodic or non-sodic categories at an ESP of 15. Sumner (1993) reports that sodicity effects may be observed at any ESP. So and Aylmore (1993) state that in pure clay water systems a critical ESP threshold can be shown, but in real soils too many factors influence the relationship between ESP and other soil physical parameters, making it difficult to establish the critical ESP value.

Salinity thresholds, unlike sodicity thresholds, are questioned to a lesser extent. The scientific literature reports no instances where salinity alone is related to soil properties; thresholds for salinity are generally set in the context of crop performance. Frenkel (1984) suggests that salinity classifications are rigid and don't take into account other factors that are necessary in determining the potential use of a water. Ghassemi et al. (1995) suggest that an assessment must be made in relation to crop tolerance to salinity, leaching fraction, and equilibrated soil water salinity after irrigation water is applied.

Soil-Water Retention

One way to examine the effects of saline-sodic water on the physical properties of a soil is by assessing the effect of salinity and sodicity on the soil-water retention curve. Soil-water retention curves, also known as the soil water characteristic (SWC) or water release characteristic curves, define the relationship between soil water content and matric potential under equilibrium conditions (Bresler et al., 1982). The SWC is an important property in understanding the hydraulic characteristics of a soil, from the distribution of pore space, both size and interconnectedness, to many other characteristics (Or et al., 2002). The SWC is a highly nonlinear relationship influenced by texture and structure of the nonporous medium.

Texture i.e., the particle size distribution, largely shapes a soil water retention curve. Finer-textured soils have a higher water holding capacity than coarser textured soils. Accordingly, Rawls et al. (1982), using multiple linear regression analysis of soil water content at 12 soil water potentials, documented that clay content is the most important texture factor affecting SWC. Clay percentage within a soil will determine the amount of small micropores in a soil. As a soil begins to dry out, water will drain first from the larger pores. Smaller pores, like the micropores in the clay, will hold water longer and tighter. This explains why at the wet end of a water retention curve, the relationship is primarily influenced by structure and pore size distribution, as opposed the dryer end, which is influenced more by specific surface area and texture of the particular soil.

In addition to texture, soil structural properties are influential on SWC relationships. A soil that is well aggregated will have more total pore space, a proportionally greater percentage of large pores, and greater overall water-holding capacity than a poorly aggregated soil. Likewise, a compacted soil will hold less total water, but will have a greater proportion of small and medium sized pores, which hold water tighter than do larger pores (Brady and Weil, 1999).

There are several ways to measure the required parameters for a SWC curve. One method often used within the laboratory is a pressure plate apparatus. Lima et al. (1990) estimated hydraulic conductivity using pressure chambers. Samples were treated with solutions of various SAR, and then water retention was measured during the drainage process over varying capillary pressure heads (matric potentials). Salinity effects on soil-water retention curves were then measured. Results indicated that increasing the amount of sodium or decreasing the electrolyte solution increased the water holding capacity of a soil for a specific pressure. Figure 9 shows the effects of concentration and composition of the soil solution on the water content of soils containing smectite clays. Soil water content increases as the salt concentration of the soil solution decreases or as the sodium concentration relative to calcium ratio (R) of the soil solution increases. This figure also illustrates that at a given water content, the amount of energy required to remove water increases as R increases. This energy requirement can be related to pore radius size.

Figure 9 shows that the pore size required to hold a particular amount of water decreases as R increases.

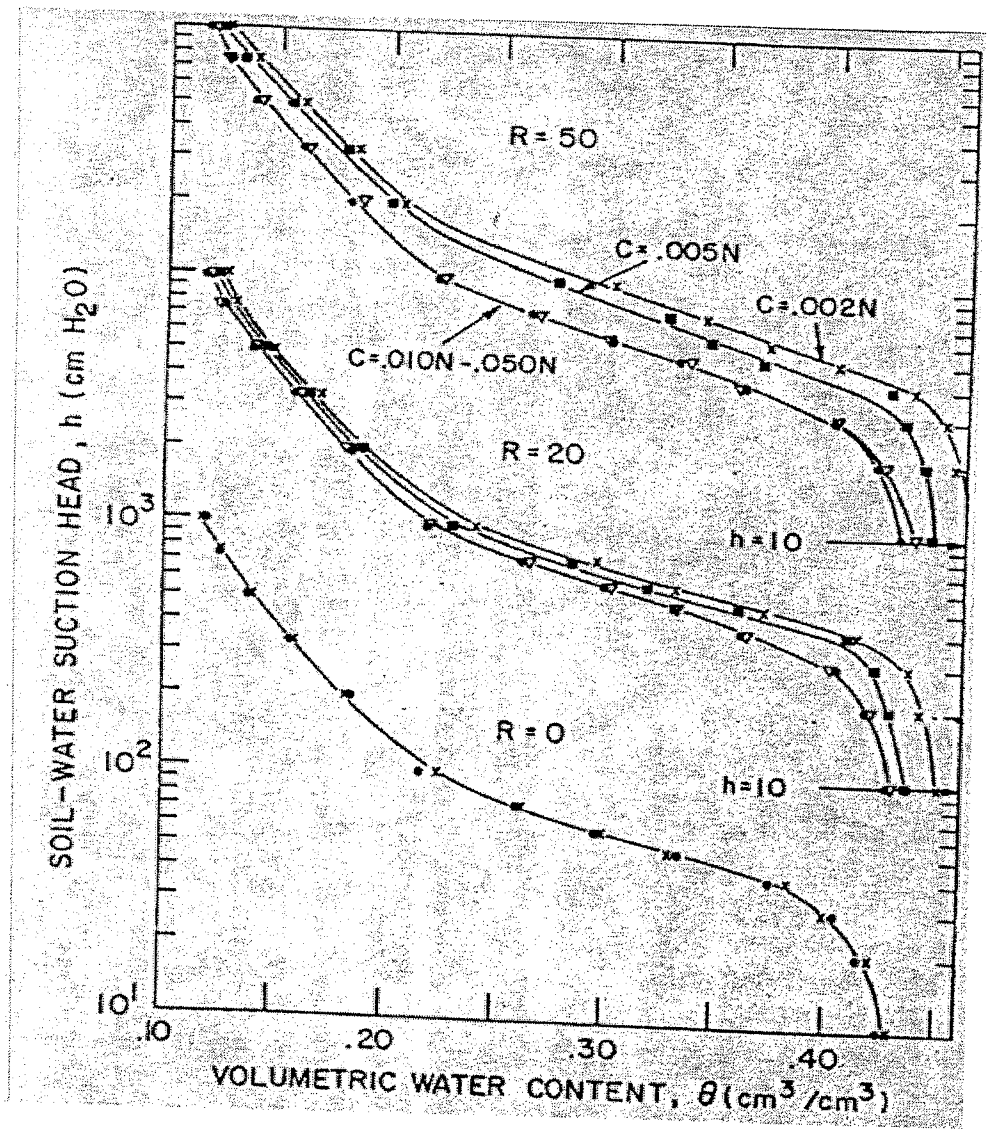

Figure 9. Soil-water suction head (h) as a function of the volumetric water content (theta) and equilibrium-solution concentration for three cationic (sodium to calcium) ratios (R). (Source: Bresler et al., 1982)

CHAPTER 2

STUDY OF SOIL CHEMICAL RESPONSES

Materials and Methods

Soil Sampling

A detailed assessment of soil series being irrigated with, or with the potential for irrigation along the Powder River and within the boundaries of the Buffalo Rapids Irrigation District (Prairie, Custer, Dawson, and Powder River counties) was completed (Table 1). Soil series data and irrigable acreages were obtained from the Buffalo Rapids Irrigation District in collaboration with Natural Resource Conservation Service (NRCS) soil scientists (VanFossen, personal communication[1]).

Table 1. Soil series with largest amounts of irrigable acres within the Buffalo Rapids Irrigation District.

Soil Series	*Taxonomy*	*Texture*	*Acres*
Cherry	Fine-silty, mixed, frigid Typic Ustochrepts	sicl	6052.4
Marias	Fine, smectitic, frigid Chromic Haphsturts	sic	3527.1
Spinekop	Fine-loamy, mixed, superactive, frigid Aridic Haplustepts	sicl	3045.3
Trembles	Coarse-loamy, mixed, calcareous, frigid Typic Ustifluvents	fsl/l	2640.8
Havre	Fine-loamy, mixed (calcareous) frigid Ustic Torifluvents	sil/sicl	2157.8
Busby	Coarse-loamy, mixed Borollic Camborthids	fsl	2002.1

[1] Steve VanFossen, Resource Soil Scientist, Lower Yellowstone Natural Resource Area, 3120 Valley Drive East, Miles City, MT, 59301-5500, (406)232-7905.

Resulting from the assessment, four predominant soil textures were identified for sampling and inclusion within the study (fine sandy loam - fsl, silt loam – sil, silty clay loam - sicl, and silty clay – sic). Using published and unpublished soil survey data and assistance from NRCS soil specialists, sixteen representative sites were selected for sampling, representing four of each dominant textural category (Figure 10). A sampling site representing each dominant soil textural category was located in each of the four previously identified counties. A soil pit was excavated at each site to a depth of 30 inches (75 cm) (Figure 11). Approximately 60 pounds (25 kg) of bulk soil material was collected from each of the top four soil horizons of each sampling site.

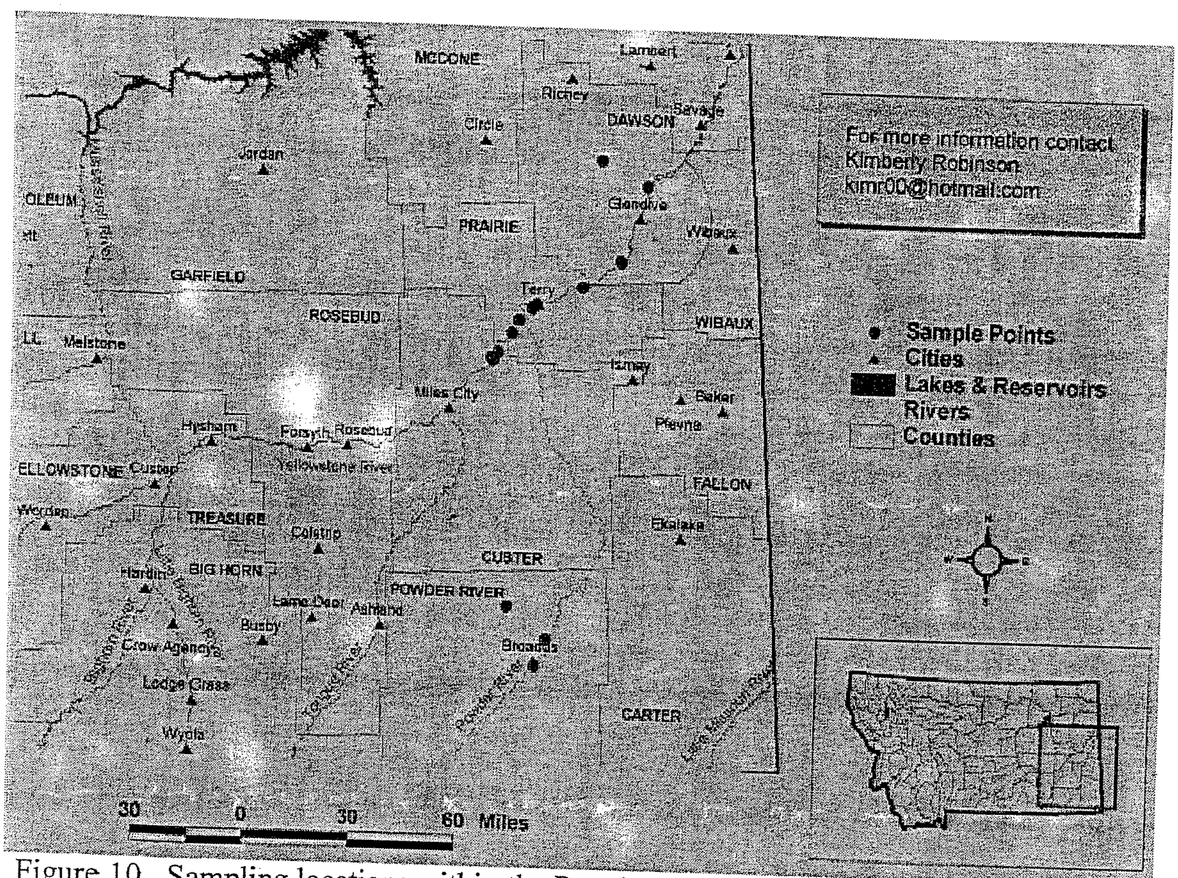

Figure 10. Sampling locations within the Powder River watershed, Prairie County Conservation District, and Buffalo Rapids Irrigation District.

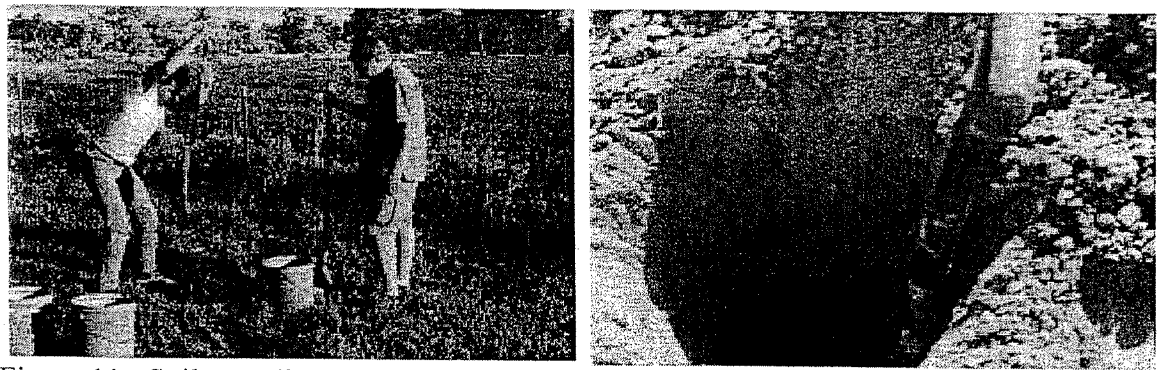

Figure 11. Soil sampling along the Powder River Basin, MT. July, 2001

A total of 54 horizons were sampled. These bulk samples, identified as baseline, were appropriately identified, labeled, and returned to the lab where they were air-dried and subsequently stored.

Laboratory Analysis

All chemical analyses of samples reported herein were completed on a contract basis by MDS Farmer Services (Harris Laboratories), Lincoln, NE. In an effort to achieve consistency in test procedures, this same laboratory completed all subsequent chemical analyses. Sub-samples of all baseline samples were oven dried (105 °C) and sieved (2 mm). Approximately 50 grams of each sub-sample were sent to Harris Laboratories for analyses of soluble saturated paste extracts and exchangeable base cations. The laboratory reported results as mg/L, meq/100g, and % CEC.

Quality Assurance/Quality Control-Soils

Quality control measures consisted of sending two check samples of a known soil each time batch soils were sent to the lab (Appendix A). Harris Laboratories also had their own quality control program. It consisted of daily check samples, daily duplicate samples, weekly rerun trays, and blind check samples. The lab also works with the North American Proficiency Testing (NAPT) program. The daily check samples are run approximately every 30-40 samples. All laboratory QA/QC parameters were within control limits and there were no associated limits (data flags) to the use of the resulting data.

Baseline Characterizations

Baseline (pre-existing) chemical characterization for all soil materials is illustrated in Figure 12. Baseline conditions were assessed to provide a foundation to determine changes that occurred in soil chemistry when soil materials were exposed to treatment combinations.

Particle size analyses were also completed on each sample using the hydrometer method as described by Gee and Bauder (1986). Results were summarized as sand, silt, and clay fractions in g/100g of soil. Samples were then defined on the textural triangle (Figure 13). From this analysis soil samples were separated into four classes or categories. They were identified as: Textural Class 1- clay content-0-11%, loamy sand, sandy loam, loam; Textural Class 2- clay content-12-22%, sandy loam, loam, silt loam; Textural Class 3- clay content-23-33%-loam, silty clay loam; Textural Class 4- clay content-greater than 33%-silty clay loam, silty clay, clay.

The primary clay mineral present in a soil governs the response of a soil both chemically and physically. It was therefore important to determine the predominate clay mineralogy of soil samples. Six sub-samples, ranging in clay content from 34% to 67%, were sent to the North Dakota State University Minerals Characterization Laboratory for

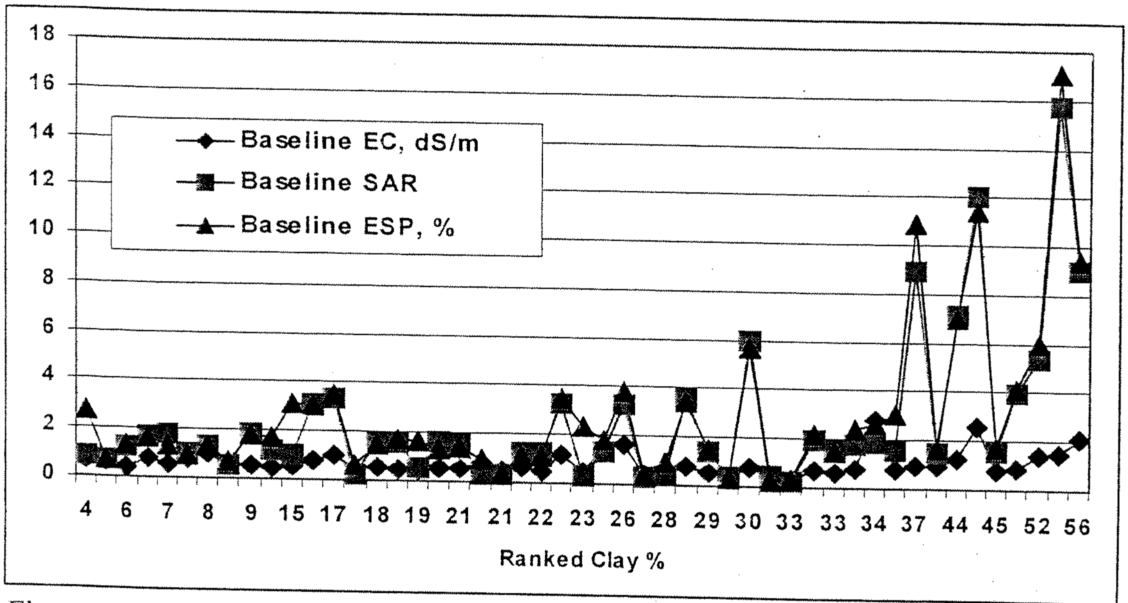

Figure 12. Pre-existing salinity (EC_{sat}) and sodicity (SAR) of soil solution saturated paste extract and exchangeable sodium percentage (ESP) of soil solid phase exchange complex versus clay (g clay/100g bulk soil) of individual soil materials.

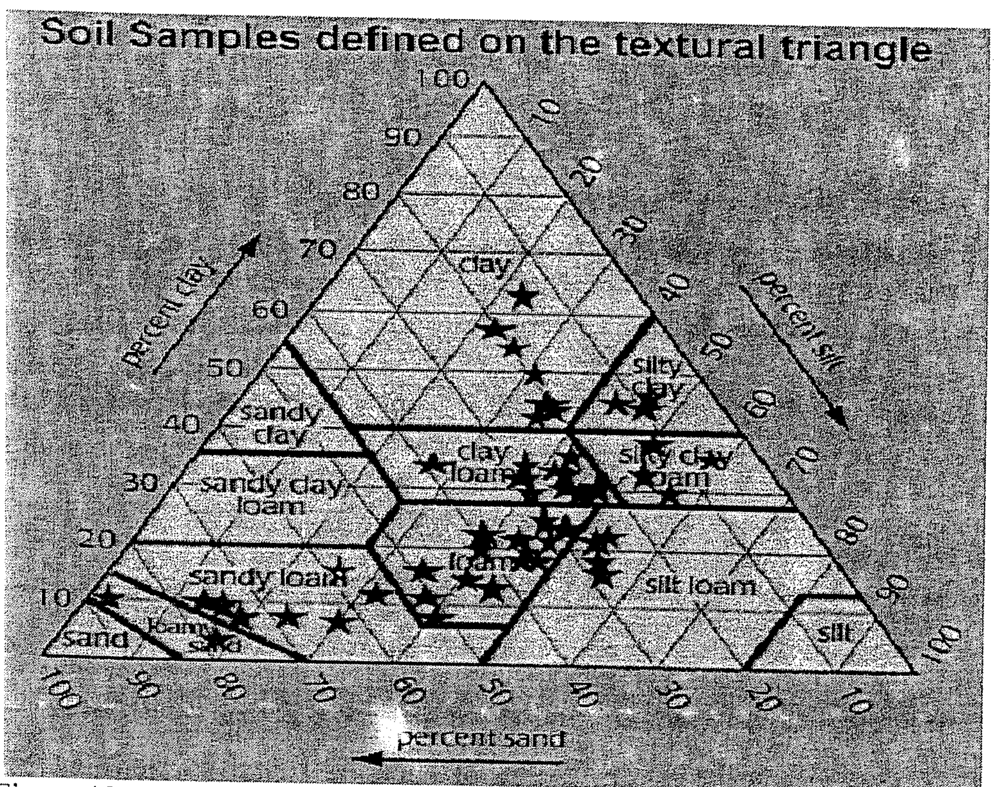

Figure 13. Soil textural triangle, illustrating representation of individual soil materials of study. Percent values reported were determined on a dry mass basis, (g/100g) x 100.

X-ray diffractometry (XRD) analysis. These samples were representative of the clay mineral fraction of soils within the ephemeral and perennial stream channels and adjacent up gradient terraces and benches where irrigation is currently practiced. XRD can determine the abundance of the differing clay mineral phases. Results showed that smectite was the dominant clay mineral in all samples (Appendix B).

Treatments

Treatments consisted of six different water quality x wetting regime combinations (Table 2). Soils from each horizon were treated with each of these combinations. Water quality treatments consisted of either synthesized Powder River water or synthesized CBM product water.

Table 2. Water quality x wetting regime treatment combinations.

Synthesized Water Quality	**Wetting Regime**
PR (Powder River) EC = 1.56 dS/m SAR = 4.54 pH = 8.03	1 X wet/dry with P.R. 1 X wet/dry with CBM 5 X wet/dry with P.R. 5 X wet/dry with CBM
CBM (Product Water) EC = 3.12 dS/m SAR = 13.09 pH = 8.22	5 X wet/dry with P.R. followed by leaching with 1 pore volume distilled water 5X wet/dry with CBM followed by leaching with 1 pore volume distilled water

Selection of target signatures for Powder River and CBM water was based on an extensive analysis of the chemistry of Powder River surface water and permitted CBM

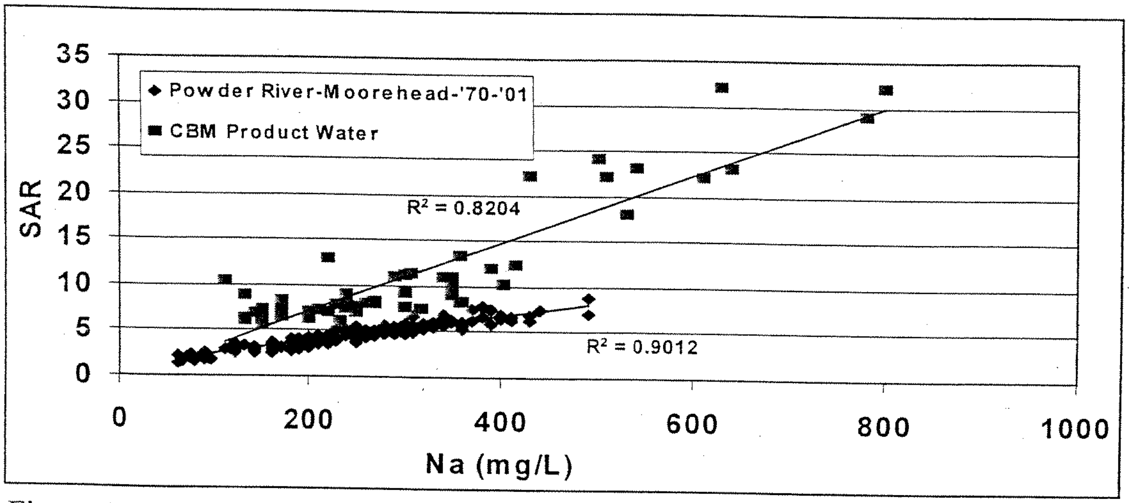

Figure 14. Na (sodium, mg/L) versus SAR of Powder River discharges of record in Montana and of permitted CBM discharges of record within the Powder River Basin, as of October, 2001. (Source: USGS-Station #06324500, USGS-Central Region Energy Resource Team, 2001).

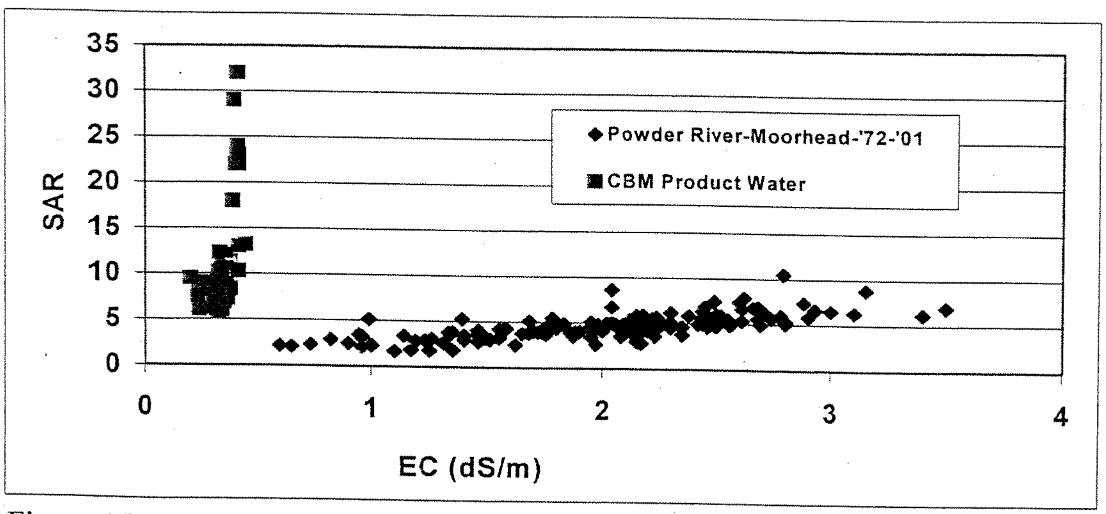

Figure 15. EC (dS/m) versus SAR of Powder River discharges of record in Montana and of permitted CBM discharges of record within the Powder River Basin, as of October, 2001. (Source: USGS-Station #06324500, USGS-Central Energy Team, 2001).

outfalls (discharges) within the Powder River watershed, as of October 2001 (Figures 14 - 15). Target water qualities were selected based on 10-90 percentile values or ranges, i.e., the thresholds were derived by deleting the values falling in the < 10 percentile groups and the values falling in the > 90 percentile group. Using the chemistry synthesis model MINTEQ2 (USEPA, 1991), a recipe was determined to create synthetic CBM product water and Powder River water. Chemical reagent combinations were combined with 60 liters of distilled water in approximately 200 liter barrels to create this water (Figure 16). A small submersible pump (1 gpm) was placed within each barrel to facilitate continuous mixing of the water. A new supply of water was synthesized weekly.

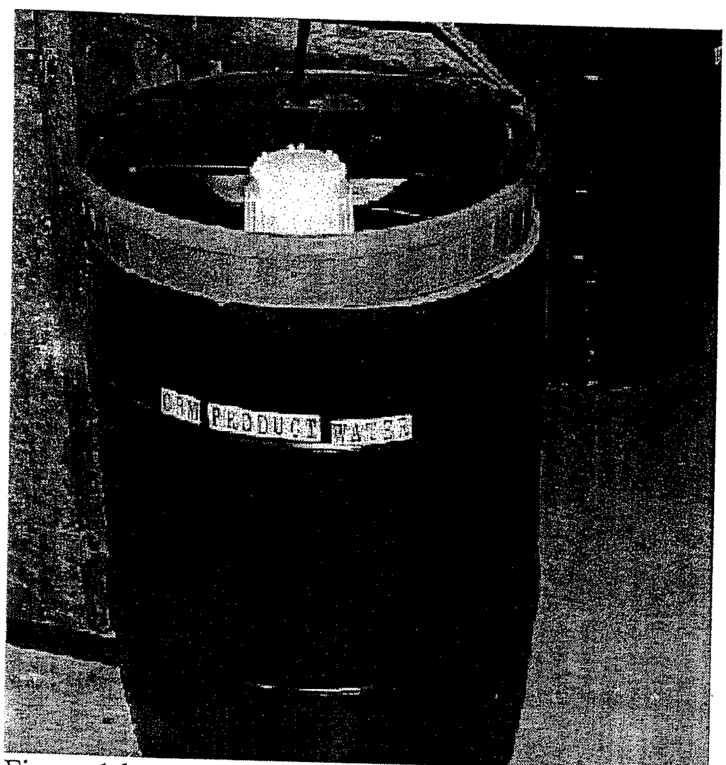

Figure 16. Barrel holding synthesized CBM water.

Water quality analyses were completed by Agvise Laboratories, Northwood, ND. Two 100 mL samples from the bulk supply (i.e., one of synthesized Powder River water and one of CBM product water) were submitted weekly to ensure that the bulk supply of water was within the water quality parameters set forth in the treatment standards (Appendix A). Water samples were analyzed for Mg, Ca, Na, EC, and pH.

Quality Assurance/Quality Control-Water

Agvise Laboratories quality controls consist of the following measures. 1) The ICP that tested the cations rechecks the standards after every forty samples tested in order to check the calibration of the instrument. The standards must be +/- 10%, or the run data are discarded and the batch samples are retested. 2) A laboratory check program totals the sum of the cations and compares it with the EC readings of each batch. All data is put into an Excel spreadsheet, and then the check program is overlaid to the data spreadsheet to ensure the cation data matches the EC readings. If any data points do not match, then they are retested. All QA/QC parameters were within control limits and there were no associated limits (data flags) to the use of the resulting data.

Experiment Construction

Drain holes were drilled in the bottom of plastic drinking cups (266 mL). Cheesecloth was cut and placed in the bottom of each cup. Each cup was then filled to the top with one of the 54 soil materials. Cups with the sample soil were then placed in large plastic containers, so that the appropriate treatment water could be poured into the container. This allowed for the soil to soak the treatment water from the bottom up, and also provided for wetting nearly to saturation. Soils were allowed to imbibe water for a 24-hour period.

Soil samples receiving the 1X treatment (both P.R. and CBM), were then transferred to aluminum plates and were oven dried (105E C). These samples were ground, sieved (2 mm), and sent to Harris Laboratories for the same chemical analyses as baseline samples.

Samples receiving one of the 5X treatments were placed in the oven and dried at 35E C for 24 hours following the first wetting (Figure 17). This wetting/drying cycle was then repeated until completion of the fifth wetting event. Final drying for the 5X treatments (P.R. and CBM) was completed the same as the 1X treatments (oven dried at 105E C). These samples were likewise ground, sieved, and sent to Harris Laboratories.

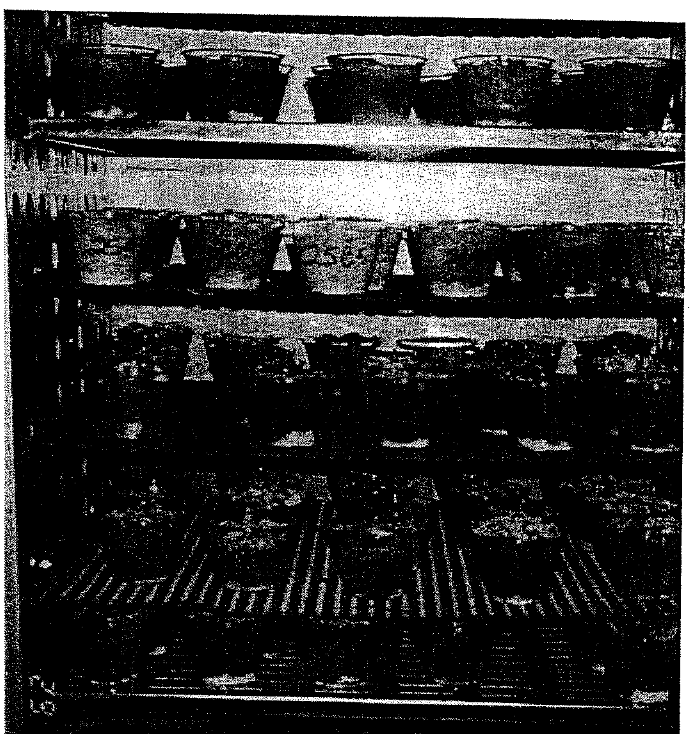

Figure 17. Soil samples were dried to 35°C between wetting regimes.

The final treatment cycle consisted of a 5X treatment (as described previously), followed by a distilled water leaching application. For this treatment, racks were constructed to allow water to drain from the bottom of the soil filled cups. Following the fifth wet/dry cycle, empty cups were placed underneath each sample cup (Figure 18). Approximately one pore volume of distilled water was then poured on the surface of each sample. Leachate water was allowed to drain for 24 hours. After this 24-hour period, soil samples were oven dried in the same way as was done in the final drying period for the other treatments and likewise sent to Harris Laboratories for analyses.

Statistical Analyses

Analysis of variance (ANOVA) and mean separation tests were used to ascertain whether significant differences were present at the 95% level of confidence ($P = 0.05$). Data that exhibited non-normal characteristics were either log or square root transformed. Statistical analyses were first made by running a two-factor ANOVA with no interactions. Factors were textural category and water quality treatment x wetting regime with unequal replications. Data were then partitioned by textual category and one-way ANOVAs were run on each texture with the factor being water quality x wetting regime treatment. Significant differences at $P \leq 0.05$ were separated using the Student-Newman-Keuls method of pairwise multiple comparison for equal size data sets. Least-squares regression was used to evaluate associations between independent and dependent variables. These analyses were conducted using SigmaStat version 2.0 software (Jandel, 1995).

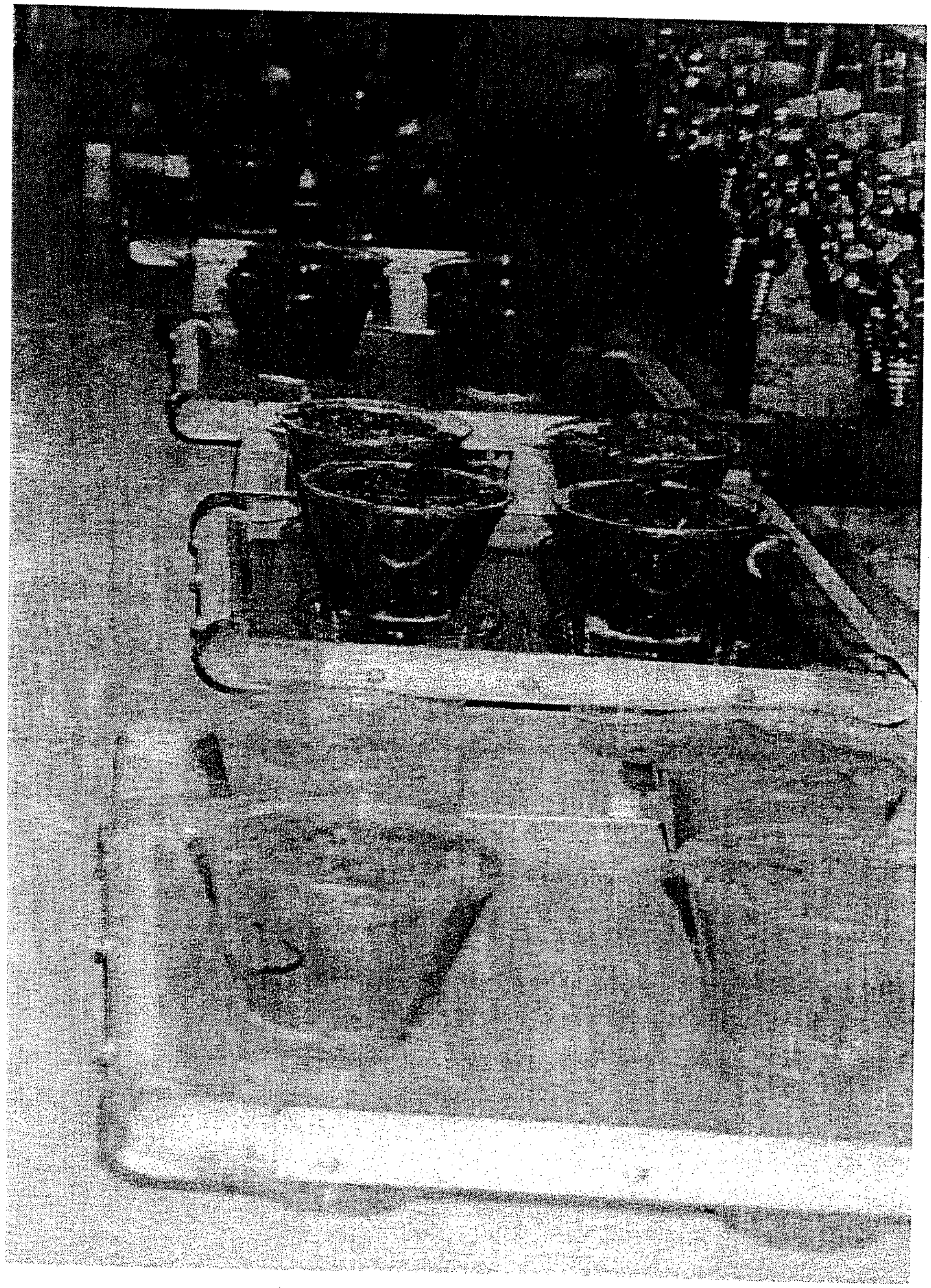

Figure 18. Samples were placed on mesh racks, so that distilled water would leach through the soil. This was the 5X + d treatment.

Results and Discussion

Soil Chemistry

Treatment effect on soil solution chemistry was evaluated by monitoring the resultant saturated paste extract EC and SAR and comparing the results with baseline conditions. Initial inspection indicated that the complete data set exhibited a bimodal distribution. This bimodal distribution was determined to be a consequence of diversity in response to treatment due to textural class differences and non-uniform treatment spacing. Subsequent comparisons were made by analyzing data based on textural class grouping.

Salinity

In almost all cases, the lowest baseline salinity (EC) values were measured in the coarser-textured soils (Figure 19, solid diamond symbols). Results indicate that differences in EC among textural classes 1, 2, and 3 following treatment were not significantly different (Table 3). Only textural class 4 had a significantly higher mean EC over all water quality treatments of 3.78 dS/m. This trend was expected as well-drained, coarser-textured soils naturally have greater leaching fractions and inherently lower salinity levels than fine-textured soils.

Salinity levels were significantly different between the water quality treatments and the baseline. Highest mean EC among all water quality treatments was 6.93 dS/m and was exhibited after soils received the 5X CBM treatment (Table 3).

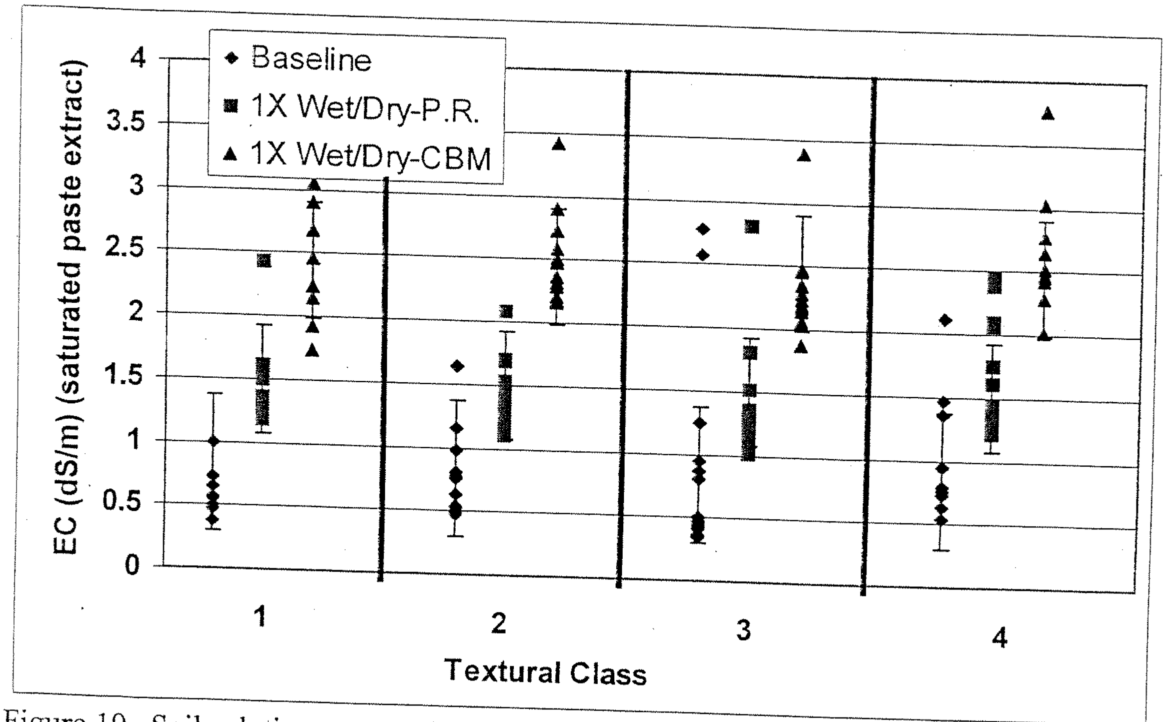

Figure 19. Soil solution saturated paste extract (EC_{sat}) versus textural class prior to treatment (baseline) and following a one-time wet/dry cycle with synthesized P.R. and CBM water qualities. Error bars represent +/- one standard deviation from the mean of each water quality treatment across all textural categories. The standard deviation within each textural class and water quality treatment is tabulated in Appendix C. Graphed data show the increase in EC from baseline levels (diamonds) after treatments (squares, 1X Wet/Dry-P.R.; triangles, 1X Wet/Dry-CBM) were imposed.

Water Quality Effects on EC. After a one-time wet/dry regime with synthesized CBM product water (EC = 3.12), the salinity of the solution extract of soils with the least baseline EC increased approximately 1.5 dS/m, to a value slightly greater than 2 dS/m (Figure 19, Table 4). The resultant increase in EC upon wetting with both Powder River and CBM product water was least for soils with the greatest initial EC. In general, EC of the saturated paste extract increased approximately 2 dS/m when the soil initially had an EC < 1.0 dS/m and was wet only once with CBM product water. The increase in EC was only approximately 1 dS/m when the baseline EC was > 1.0 dS/m.

Table 3. Mean EC and SAR by texture and mean EC and SAR by water quality treatment.

		n	Mean EC (dS/m)[+]	Mean SAR[+]
Textural Class				
	1	9	3.08 a	6.06 a
	2	13	3.39 a	6.04 a
	3	16	3.28 a	5.34 a
	4	11	3.78 b	7.91 b
Water Quality Treatment				
	Base	49	0.82 a	2.56 a
	1X P.R.	49	1.51 b	5.94 b
	1X CBM	49	2.46 c	3.92 b
	5X P.R.	49	3.21 d	4.94 b
	5X P+d	49	3.02 e	4.86 b
	5X CBM	49	6.93 f	11.31 c
	5X C+d	49	5.73 g	10.85 c

[+] Within treatment means followed by the same letter in the same column are not significantly different at $P \leq 0.05$.

As would be expected, a wetting-drying regime of 5 treatment cycles resulted in a significant increase in EC of the saturated paste extract (Figure 20). Results indicate that EC increased in all textural categories when irrigated with a 5X treatment. EC increased 4-6 dS/m above the baseline when repeatedly wetted with CBM product water. This represents more than a two-fold increase over the EC of the synthesized CBM product water. After the 5X CBM and 5X C+d treatments, mean saturated paste extract EC greatly exceeded the acceptable EC threshold (3 dS/m), thereby classifying these soils as saline. After the 5X P.R. and 5X P+d treatments, mean EC was significantly higher than baseline (3.21, 3.02 dS/m, respectively), and equilibrated just above this salinity threshold (Table 3, Figure 20).

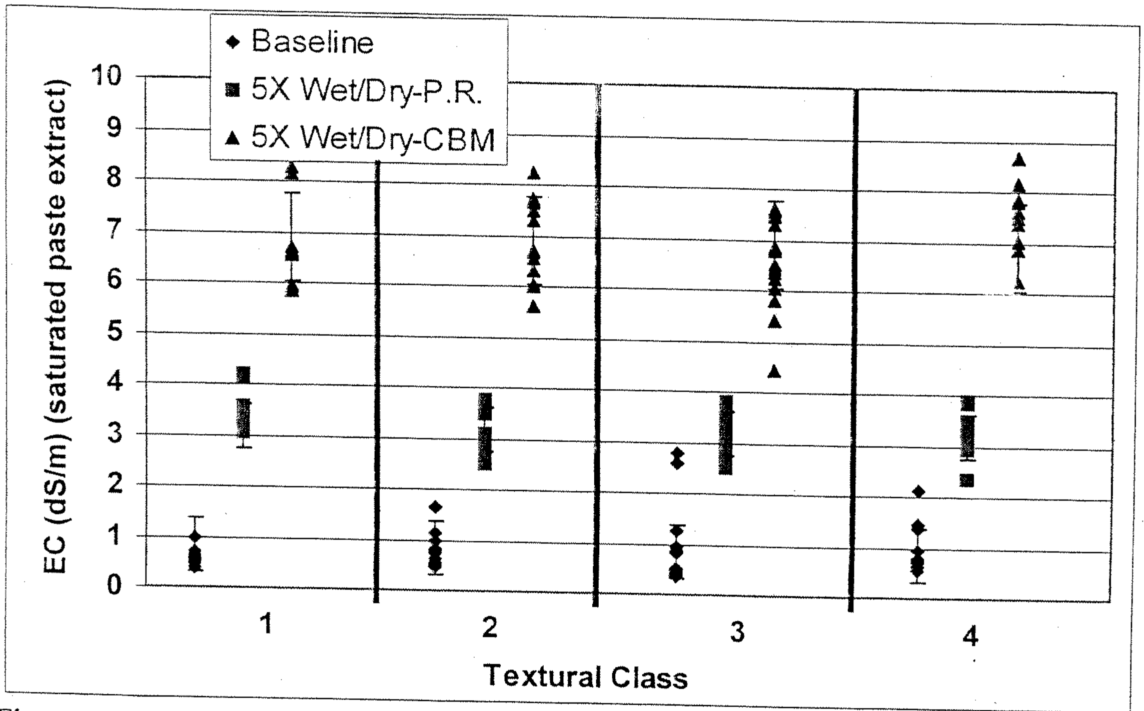

Figure 20. Soil solution saturated paste extract (EC_{sat}) versus textural class prior to treatment (baseline) and following a five-time wet/dry cycle with synthesized P.R. and CBM water qualities. Error bars represent +/- one standard deviation from the mean of each water quality treatment across all textural categories. The standard deviation within each textural class and water quality treatment is tabulated in Appendix C. Graphed data show the increase in EC from baseline levels (diamonds) after treatments (squares, 5X Wet/Dry-P.R.; triangles, 5X Wet/Dry-CBM) were imposed. Note: Scale change from Figure 19.

Subsequent wetting (following the 5X treatment) with a single time distilled water application resulted in a decrease in the EC of 41 of 49 samples (Figure 21). This decrease, averaging approximately 2 dS/m, represents a significant change when considering the flocculating effect of salinity in countering sodium-induced dispersion. Figure 21 shows that after a distilled water application to soils previously treated with CBM product water, the EC was still greater than acceptable standards. This would suggest that sporadic rainfall alone cannot reduce soil salinity to acceptable levels, yet is important when addressing EC x SAR interactions in soils.

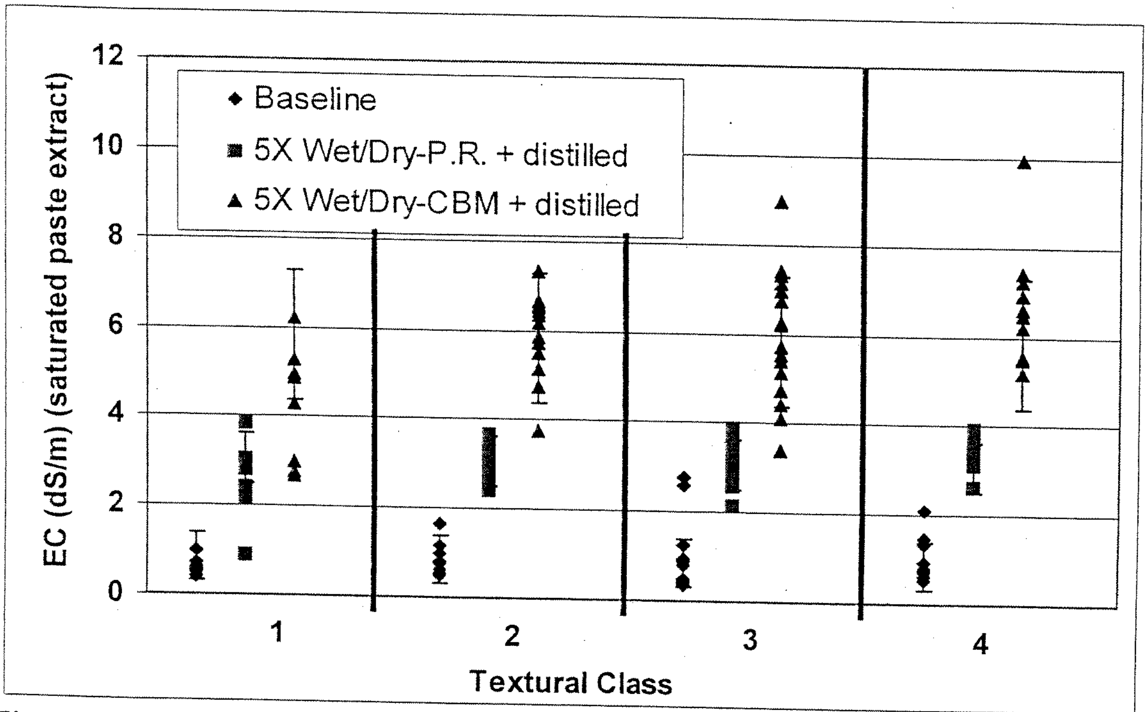

Figure 21. Soil solution saturated paste extract (EC_{sat}) versus textual class prior to treatment (baseline) and following a five-time wet/dry cycle with synthesized P.R. and CBM water qualities followed by distilled water. Error bars represent +/- one standard deviation from the mean of each water quality treatment across all textural categories. The standard deviation within each textural class and water quality treatment is tabulated in Appendix C. Graphed data show the increase in EC from baseline levels (diamonds) after treatments (squares, 5X Wet/Dry-P.R. + distilled; triangles, 5X Wet/Dry-CBM + distilled) were imposed. Note: Scale change from Figure 20.

Textural Effects on EC. Significant differences in EC were detected between all treatments within textural class 1, except in the 1X CBM treatment and the 5X P+d treatment (Table 4). This suggests that on coarse-textured soils, a one time wetting with CBM will result in an average EC that is not significantly different from wetting the soil five times with Powder River water and then leaching with distilled water. Greatest mean EC (6.74 dS/m) within the textural class 1 was detected in the 5X CBM treatment. Distilled water applications to this textural group resulted in significant reductions in EC regardless of previous water qualities.

In textural class 2, mean EC was significantly different among all treatments except the 5X P.R. and the 5X P+d. Results indicate a distilled water application on this soil textural group did reduce EC levels in soils treated with the 5X CBM treatment but not when these soils received the same treatment with PR water. This indicates that distilled water, i.e. rainfall, has a greater ability to reduce EC when salt concentrations are higher, as found in soils treated with CBM product water. Highest mean EC (6.92 dS/m) occurred after soils underwent the 5X CBM treatment cycle (Table 4). This represents a 6-fold increase from baseline, which also occurred in textural class 1.

Significant differences of EC within the textural class 3 mimicked results found within textural class 2. EC associated with all treatments was significantly different except the 5X P.R. and the 5X P+d, which were the same. As in textural class 2, this would suggest that distilled water decreases EC most when salt concentrations are high. Mean EC was highest in the 5X wet/dry cycles and was nearly equal to mean EC values in textural groups 1 and 2 receiving this same treatment.

Within the textural class 4, the EC did not differ significantly between the 1X CBM, 5X P.R. and 5X P+d treatments. This suggests that irrigation once with CBM product water will result in salinity values similar to soils that received 5X P.R. and 5X P+d treatments. EC of treatments of 5X CBM and 5X C+d were significantly greater than all other treatment mean ECs but did not differ significantly from each other. This effect was only observed with textural class 4. This suggests that the greater clay content within the textural class 4, as compared with the other textural classes, reduces the effectiveness of distilled water applications at lowering EC. Higher exchange capacities

Table 4. Treatment mean saturated paste extract EC and SAR for textural classes by water quality treatment.

SOIL TEXTURE	n	Water Quality Treatment	Mean EC (dS/m)[+]	Mean SAR[+]
Textural Class #1	9	Base	0.60 a	1.16 a*
		1X P.R.	1.45 b	3.08 b
Mean EC = 3.08a		1X CBM	2.38 c	5.90c
Mean SAR = 6.06a		5X P.R.	3.53 d	4.50 d
		5X P+d	2.57 c	3.90 e
		5X CBM	6.74 e	12.44 f
		5X C+d	4.32 f	11.36 g
Textural Class #2	13	Base	0.77 a	2.15 a
		1X P.R.	1.43 b	3.40 b
Mean EC = 3.39a		1X CBM	2.48 c	5.63 c
Mean SAR = 6.04a		5X P.R.	3.16 d	4.47 d
		5X P+d	3.08 d	4.50 d
		5X CBM	6.92 e	11.53 e
		5X C+d	5.90 f	10.65 f
Textural Class #3	16	Base	0.87 a*	1.97 a
		1X P.R.	1.36 b	3.10 b
Mean EC = 3.28a		1X CBM	2.23 c	5.02 c
Mean SAR = 5.34a		5X P.R.	2.93 d	4.10 d
		5X P+d	3.05 d	4.07 d
		5X CBM	6.57 e	9.57 e
		5X C+d	5.96 f	9.51 e
Textural Class #4	11	Base	1.05 a**	4.96 a**
		1X P.R.	1.82 b	6.11 b
Mean EC = 3.78b		1X CBM	2.74 c	7.20 b
Mean SAR = 7.91b		5X P.R.	3.23 c	6.68 b
		5X P+d	3.39 c	6.88 b
		5X CBM	7.49 d	11.69 c
		5X C+d	6.72 d	11.87 c

[+] Within treatment means followed by the same letter in the same column are not significantly different.

* Data analyzed using square root transformed data. Means reported in this table are actual means, derived from saturated paste extracts.

**Data analyzed using log transformed data. Means reported in this table are actual means, derived from saturated paste extracts.

of finer textured soils and greater percentages of non-readily draining interstitial spaces result in the ability of the soil to absorb and retain higher concentrations of salts.

Sodicity

Baseline sodicity (SAR) values were lowest in the coarser textured soils, consistent with EC measurements (Figure 22). Results indicate that differences in SAR associated with texture were only significantly greater in textural group 4(Table 3). Lowest mean SAR across all textural classes was 5.34, while the highest mean SAR was 7.91 in textural class 4. The baseline data clearly suggest that only three of the sampled soils were at the risk of substantial dispersion (SAR = 12) at the time of initial sampling (Figure 12).

Soil SAR responded differently to water quality treatment than did EC (Table 3). All water quality treatments resulted in significantly higher SAR levels than the baseline. However, mean SAR values for 1X P.R., 1X CBM, 5X P.R., and 5X P+d treatments were not significantly different from each other. This response was important with respect to the behavior of EC as opposed to the resultant SAR as a consequence of distilled water applications. Significant reduction in mean EC occurred after distilled water applications while there were no significant decreases in SAR when distilled water was applied. This is important when addressing the interaction between EC and SAR.

The 5X CBM and the 5X C+d treatments also were not significantly different from each other. As was the case in EC, the greatest mean SAR across all soil textural categories (11.31) was found in the 5X CBM water quality treatment (Table 3). Within of finer textured soils and greater percentages of non-readily draining interstitial spaces result in the ability of the soil to absorb and retain higher concentrations of salts.

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The 5X CBM and the 5X C+d treatments also were not significantly different from each other. As was the case in EC, the greatest mean SAR across all soil textural categories (11.31) was found in the 5X CBM water quality treatment (Table 3). Within soil textural categories, the greatest mean SAR (11.87) occurred within textural class 4 after soils were treated with 5X C+d (Table 4).

Water Quality Effects on SAR. Similar to EC, SAR values increased in association with the SAR of the treatment water (Table 4). Soils with the lowest baseline SAR showed the greatest increase in SAR upon wetting with CBM water. A single wetting with Powder River water increased SAR approximately two units in soils with lowest initial solution SAR (Figure 22). For soils with baseline SAR values greater than about 3, a single wetting with either Powder River water or CBM water had little effect on solution SAR. In general, resultant SAR after a single wet/dry cycle of P.R. and CBM water qualities did not exceed 8, and therefore soils such as these studied here do not appear to be at risk of dispersion when exposed to single applications of CBM product water such as that used in this study.

Treatment involving a regime of five wetting-drying cycles with either Powder River water or CBM product water resulted in solution SAR values nearly equal to the SAR of the treatment water, i.e., SAR approaching values of 4-5 and 10-12 , respectively (Figure 23). Hence, it is reasonable to conclude that if the soil solution equilibrates with the applied water EC, soil solution SAR will equilibrate at a value equal to or greater than the SAR of the applied water over time. Upon repeated addition of CBM water approximately only 15% of SAR values exceed 12. These data indicate that on average, a five-time application of either Powder River or CBM product water under the conditions of forced leaching used in this study does not elevate the soil SAR to a greater than acceptable standard (SAR of 12), regardless of soil textural class (Table 4). Most of the samples with elevated SARs were in the coarser textural categories, i.e. soils less inclined to disperse.

Treatment involving a five-time wet/dry cycle plus the application of distilled water exhibited the same trends in SAR as the 5X treatment across all soil textures and water quality treatments (Figure 24). Mean values show that the SAR of the soil solution changed little when the 5X cycle was followed by distilled water (Table 3). Only in the case of textural class 1 and 2 did the addition of distilled water cause a significant difference in SAR (Table 4). This was different from the significant reductions in EC

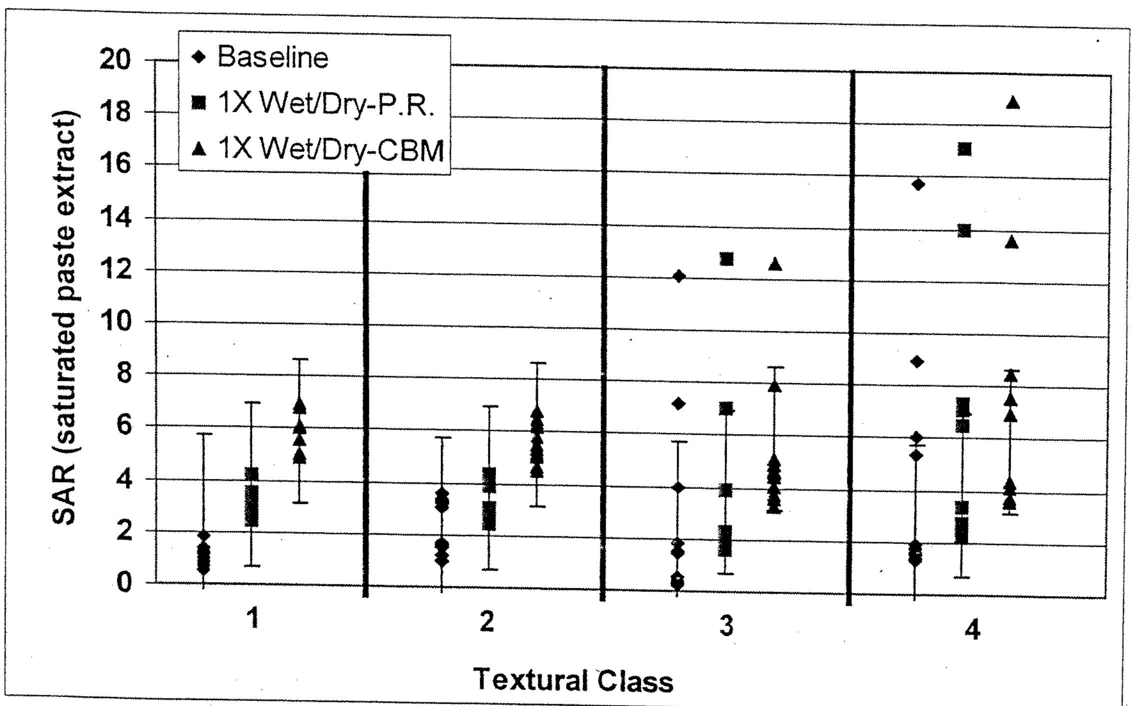


Figure 22. Soil solution saturated paste extract SAR versus textural class prior to treatment (baseline) and following a one-time wet/dry cycle with synthesized P.R. and CBM water qualities. Error bars represent +/- one standard deviation from the mean of each water quality treatment across all textural categories. The standard deviation within each textural class and water quality treatment is tabulated in Appendix C. Graphed data show the increase in SAR from baseline levels (diagonals) after treatments (squares, 1X Wet/Dry-P.R.; triangles, 1X Wet/Dry-CBM) were imposed.

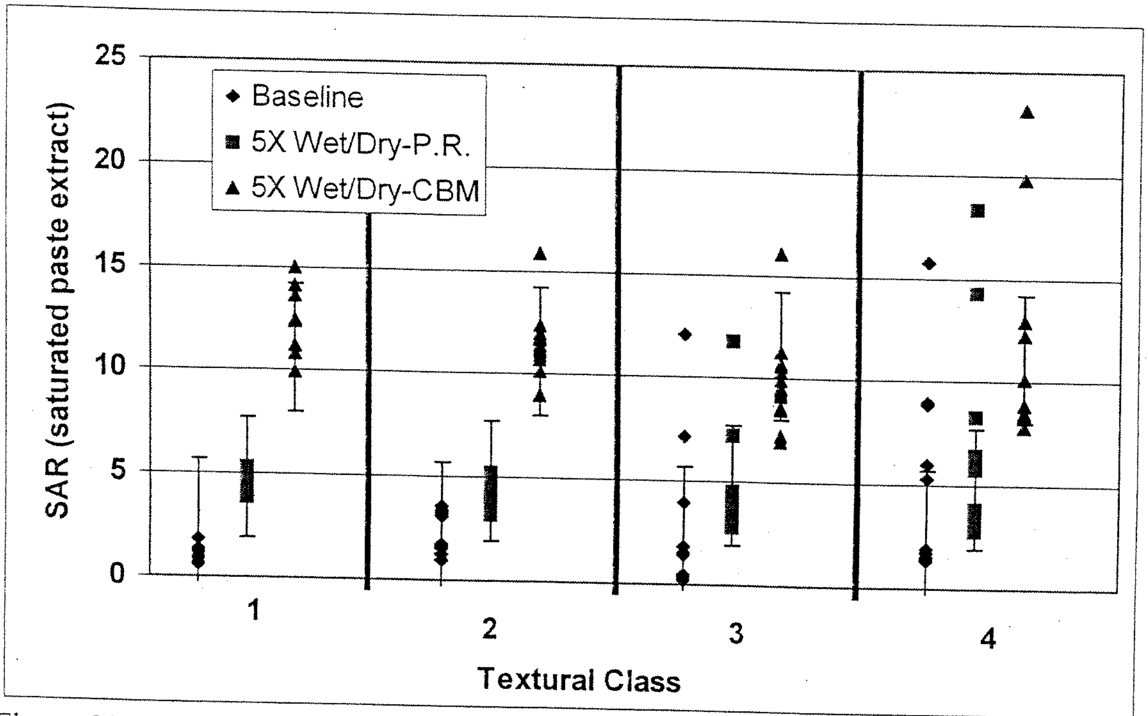


Figure 23. Soil solution saturated paste extract SAR versus textural class prior to treatment (baseline) and following a five-time wet/dry cycle with synthesized P.R. water and CBM water qualities. Error bars represent +/- one standard deviation from the mean of each water quality treatment across all textural categories. The standard deviation within each textural class and water quality treatment is tabulated in Appendix C. Graphed data show the increase in SAR from baseline levels (diamonds) after treatments (squares, 5X Wet/Dry-P.R.; triangles, 5X Wet/Dry-CBM) were imposed. Note: Scale change from Figure 22.

that occurred as a result of a distilled water application meant to simulate a rainfall event. This disproportionate lowering of EC in relation to the SAR is important when assessing the impact of irrigation waters on soil solution chemical properties. The implication of this is that the flocculating effect of salinity or EC may be reduced during rainfall events, thereby exacerbating the dispersive effects of sodium.

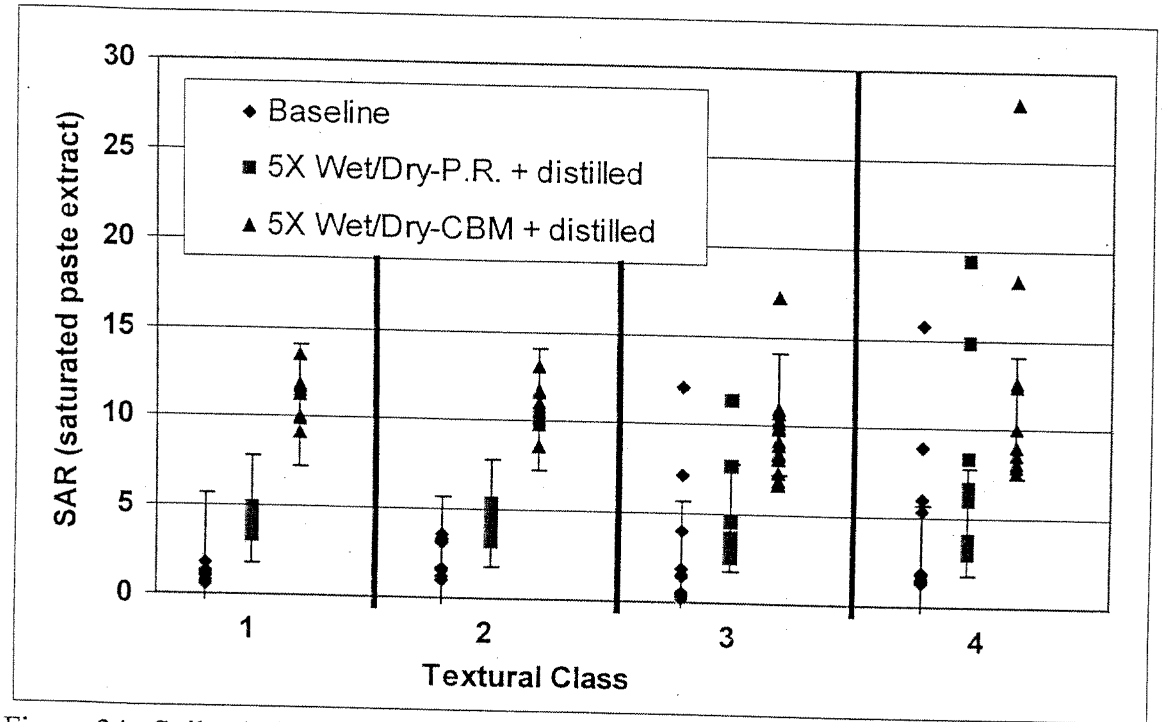


Figure 24. Soil solution saturated paste extract SAR versus textural class prior to treatment (baseline) and following a five-time wet/dry cycle with synthesized P.R. and CBM water qualities plus distilled water application. Error bars represent +/- one standard deviation from the mean of each water quality treatment across all textural categories. The standard deviation within each textural class and water quality treatment is tabulated in Appendix C. Graphed data show the increase in SAR from baseline levels (diamonds) after treatments (squares, 5X Wet/Dry-P.R. + distilled; triangles, 5X Wet/Dry-CBM + distilled) were imposed. Note: Scale change from figure 23.

Textural Effects on Sodicity. In textural class 1, significant differences in SAR were detected between all treatments (Table 4). Within this class, distilled water applications resulted in significant reductions of SAR. Greatest mean SAR (12.44) resulted from the 5X CBM treatment, a more than ten-fold increase from the baseline SAR of 1.16. This was the largest increase in all textures from mean baseline values. Within the textural class 1, the 5X CBM treatment elevated the SAR to an unacceptable level.

Within textural class 2, all treatments caused significant differences in SAR except the 5X P.R. and the 5X P+d (Table 4). In this textural class, results show that rainfall following irrigation with CBM water lowered SAR but did not when irrigating with Powder River water. This was the same trend that occurred in the EC data. This likewise would suggest that distilled water has a greater flushing effect when salt concentrations are higher.

Significant differences in SAR within textural class 3 were similar to the differences in textural group 2 (Table 4). The exception was that SAR values resulting from the 5X CBM and 5X C+d treatments were not significantly different from each other. This was different from the EC measurements, in that a significant reduction was determined with these two treatments. Within this textural class there is a disproportioniate lowering of EC relative to SAR.

In textural group 4, the SAR did not differ significantly between the 1X P.R., 1X CBM, 5X P.R. and 5X P+d treatments. These results indicate on soil textures included within this class, effects on SAR are likely to be the same whether irrigated one time with Powder River water, once with CBM water, 5 times with Powder River water or 5 times with Powder River and then followed by rainfall. Essentially, water quality treatments have less of an impact on increasing or lowering SAR levels in textual class 4.

Implications using previously published data

Data collected in this experiment have meaningful implications relative to previously published soil salinity x sodicity relationships (Figures 25-26). Based on these diagrams predictions can be made in respect to accepted irrigation water quality standards and dispersion risk thresholds.

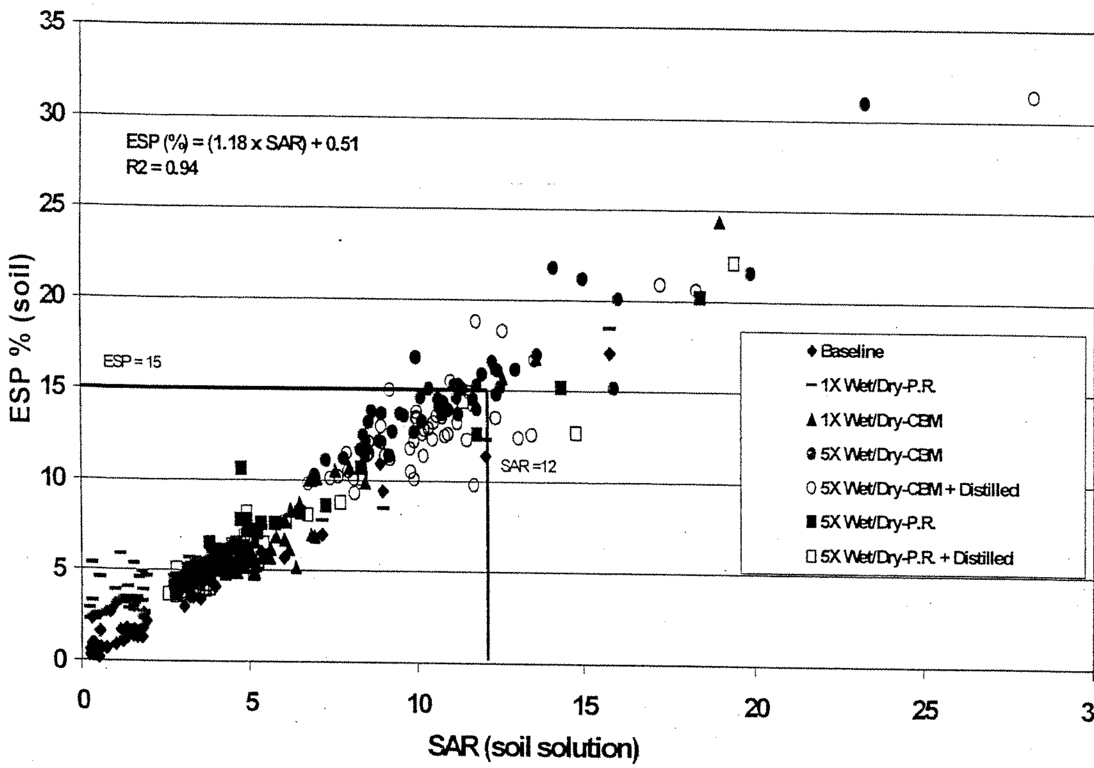


Figure 25. Soil solution SAR versus exchangeable sodium percentage (ESP) of soil solid phase exchange complex prior to treatment (baseline) and following treatment with various water quality x wetting regimes. Solid lines represent previously reported dispersion risk thresholds for ESP (15%) and SAR (12).

Previously published research reports a relationship between SAR of applied water and ESP of the soil as ESP of 15% = SAR of 12, i.e., SAR = 0.8 x ESP with respect to assumed risk of dispersion of fine material (U.S. Salinity Laboratory, 1954).

Data presented in Figure 25, derived from these studies, follow this same relationship, suggesting that the soil solution SAR is generally representative of the applied water SAR and the SAR can be used to approximate or estimate the resultant ESP. Using such criteria when referring to Figure 25, it becomes apparent that either repeated wetting/drying or wetting/drying followed by a single application of distilled water (simulating rainfall) elevates the ESP and SAR closer to previously published thresholds of SAR = 12, ESP = 15 (U.S. Salinity Laboratory, 1954).

Figure 26 illustrates the soil saturated paste extract EC and SAR following each of the treatment combinations. Imposed on this figure are two different sets of previously published threshold values. The two diagonal lines correspond to the thresholds reported by Hansen et al. (1999) with respect to EC x SAR combinations distinguishing no risk, moderate risk and severe risk of dispersion. These values were derived from earlier studies reported by Ayers and Westcot (1976). The 90-degree vertical x horizontal lines represent the EC threshold for salinity (i.e., EC = 3.0 dS/m) and the SAR value normally considered the diagnostic for sodic soils (i.e., SAR > 12), respectively. Similarly, these values were reported by Hanson et al. (1999) and were initially reported by Richards (1954). As can be seen, the data points cluster, relative to the EC x SAR combination of the respective treatment, with one exception. A single wetting with distilled water following a regime of five wet-dry cycles with CBM product water results in a shift of most data points left, closer to the threshold criteria (solid circles shift to open circles).

On initial inspection of Figure 26, a logical conclusion is that all data points falling to the right of the right-most diagonal line represent EC x SAR combinations that pose little or no risk with respect to dispersion. This would suggest that dispersion is generally not at a high risk under conditions of the study reported herein. However, with respect to salinity, data presented in this figure depict a higher risk situation. Relying solely on the published plant tolerances to salinity (threshold of EC = 3 dS/m), three

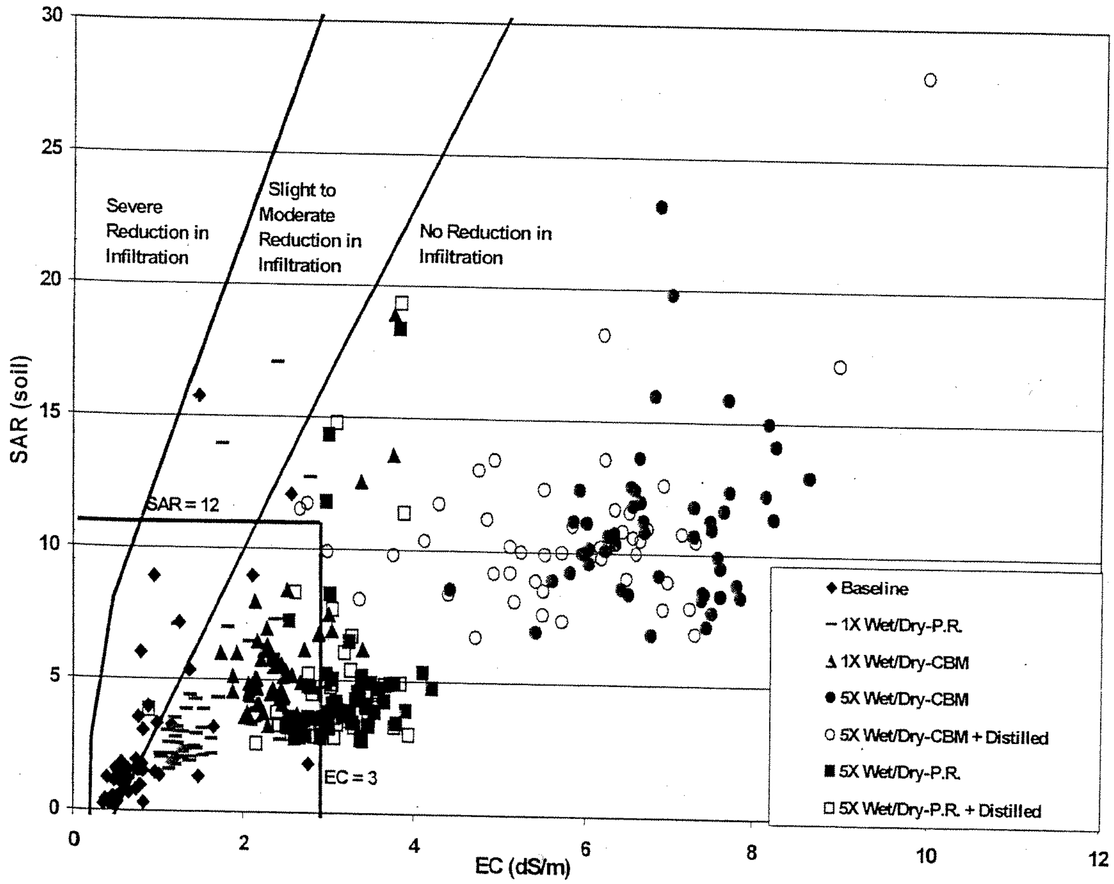


Figure 26. Soil solution saturated paste extract (EC_{sat}) versus soil solution SAR of soil material prior to treatment (baseline) and following treatment with various water quality x wetting regimes. Solid lines represent salinity and dispersion risk thresholds previously reported by Ayers and Westcot (1976), Hanson et al. (1999), Miller and Donahue (1995) and others. These lines are modified from published data lines resulting from personal communication with Blaine Hanson (2002).

significant points become evident from this figure: 1) essentially all of the EC data points associated with repeated wetting and drying with simulated CBM product water exceed the 3 dS/m threshold; 2) subsequent wetting with simulated rainfall does not result in sufficient reduction in salinity to lower than 3 dS/m following repeated wetting with CBM product water; and 3) with repeated wetting and drying with simulated Powder River water, many soils demonstrate EC values greater than the 3 dS/m threshold. These latter soils are thus approaching the categorization of saline.

Resultant soil solution chemical data as depicted in Figures 25-26 would suggest that in many cases repeated irrigation with water of EC x SAR combinations used here to simulate CBM product water or in-stream mixed water may not pose an immediate risk of dispersion on most of the irrigable soils used in this study. Yet, the resultant salinity levels are likely to have significant adverse effect on plant production when salt intolerant plants are grown. Furthermore, in the event of significant rainfall during the irrigation season, availability of water of lower EC for irrigation, or repeated rainfall events during the non-irrigation season, it is likely that soil salinity values will be sufficiently lowered. Yet, this lower EC will reduce the offsetting effect of electrolyte-induced flocculation to the point where dispersion becomes more probable.

Summary and Conclusions

The following observations were made during this study:

1. Repeated irrigation with saline-sodic water or water with a chemical signature comparable to the CBM product water used in this study will result in a general increase in the soil salinity and sodicity.

2. Repeated irrigation or dispersal of CBM product water to irrigable land is likely to result in elevated soil salinity levels substantially higher than published thresholds for some irrigated crops.
3. It appears that soil solution salinity will equilibrate at an EC value approximately 2-3 times the EC of the applied water; in contrast, soil solution SAR appears to equilibrate at a level comparable to the SAR of the applied water as long as leaching occurs. These results are consistent with previously reported findings.
4. Application of salt-free water following elevation of soil solution salinity and SAR through repeated wetting effectively reduced soil solution salinity while having little or no effect on sodicity. The implication of this is that the flocculating effect of salinity may be reduced, thereby exacerbating the dispersive effects of sodium, as a consequence of uncontrollable rainfall or dispersals of relatively salt-free spring runoff to soils previously irrigation with saline-sodic water.
5. The lowering impact of rainfall on EC and SAR is more predominant when salt concentrations are high, and in coarser textured soils.
6. The greatest increases in EC and SAR upon wetting with either CBM or P.R. water were in coarser-textured soils.
7. Based on previously published EC x SAR combination thresholds for protection against particle dispersion, in few instances of this study were soil solution salinity x sodicity combinations measured which exceed these thresholds following single wetting events. In essentially all instances where saline-sodic water was repeatably

applied, the resulting soil solution salinity and sodicity were significantly elevated to levels in close proximity to the previously published EC x SAR standards.

8. Results of this study appear to be consistent with previously published reports of the relationship between exchangeable sodium percentage (ESP) and solution SAR, i.e., SAR = 0.8 x ESP (approximately). Utilizing an ESP threshold of 15, the majority of treated soil samples exceeding this value resulted from alternate wetting regimes with CBM product water followed by simulated rainfall.

CHAPTER 3

STUDY OF SOIL PHYSICAL RESPONSES

Materials and Methods

Experiment Construction

A system of four pressure plate apparati to measure soil water retention was assembled in the laboratory at Montana State University. Pressure was supplied to the pressure plate apparati via PVC tubing connected to an air compressor (Figure 27). A pressure regulator and gage was installed at the inflow line at each apparatus to regulate and monitor the applied pressure. Each apparatus was equipped with outflow ports to drain water off the plates.

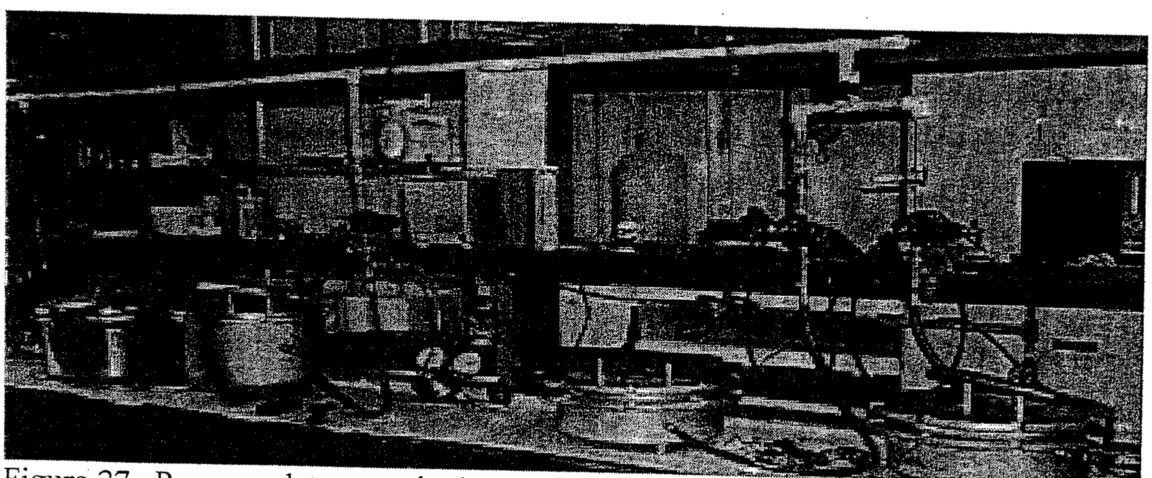


Figure 27. Pressure plate setup in the laboratory to measure water retention.

Treatments

Treatments consisted of six different water qualities x wetting regime combinations (Table 2), following the same treatment combination scenario described in Chapter 2. As described in the previous chapter, water qualities consisted of either synthesized Powder River water or synthesized CBM product water. After treatment combinations were imposed on sample soils using procedures described for the chemistry portion of this study, water retention of these soils was then measured at -1/10, -1/3, -1, -5, -15 bars of applied pressure. Equilibrium pressure was equated with matric potential, but with a sign change. Each treatment combination was replicated three times at each matric potential. The 1X P.R. treatment was categorized as the "control" treatment in all subsequent statistical analyses.

Soils

Soil used in this phase of the investigation was from the same collection of soil materials used in the study of soil chemical responses (Chapter 2). Soil used in this experiment was air dried, ground, and passed through a 4 mm sieve before exposure to the respective water quality x wetting regimes.

Experimental Design and Treatments

Ceramic pressure plate dimensions allowed for 14 rings (14 samples) to be placed on each plate. One sample of check soil was placed on each plate. One bar ceramic plates were used to measure water retention at -1/10 bar and -1/3 bar pressures; 5 bar ceramic plates were used to measure retention at -1 and -5 bars; and 15 bar ceramic plates were used to measure retention at -15 bars of pressure. Plates were left in the pressure apparati under applied pressure for varying time according to the pressure prescribed for the particular treatment: -1/10 bar-2 days; -1/3 bar-3 days; -1, -5, -15 bars-5 days. This was done to allow soils to reach equilibrium with the applied pressures. Time constraints and a pre-study assessment justified that 15 bar plates should be left on for five days. Numerous references recommend up to 2 weeks equilibration time for -15 bar moisture content determinations. To justify the shortened time period used here, a mini-experiment was conducted prior to the study where -15 bars of pressure was applied to a subset of "control" samples for 3 days, 5 days, 7 days, 10 days, and 14 days. All data were compared to 14-day data. The best linear correlation was found with samples left on for 5 days (Appendix A). Based on the correlation and linear regression of known 5-day and 15-day equilibration water contents, the following adjustments were made to subsequent data: $Pw < 0.13$ – no change, $Pw > 0.13$ # 0.18 subtract 0.03, $Pw > .18$ subtract 0.05, where Pw was the gravimetric water content determined following a 5-day equilibration period at -15 bars applied pressure.

Another modification of the procedure which was instituted to minimize non-treatment induced variability was as follows: metal weights were placed on top of samples that received -1, -5, or -15 bars of pressure to ensure that samples were kept in contact with plates at all times.

For the 1X treatment, retaining rings were placed directly on the ceramic plates and soil was placed within the ring. Treatment water was administered by continual application of the designated synthetic water quality around the rings on the plate until the soils were completely saturated. Samples were allowed to sit overnight so that complete saturation was assured. The following day synthesized treatment water was again applied to the plates. Saturated soil samples were then placed inside the pressure chamber (Figure 28). Pressure was increased to the designated level and moisture was forced from the soil sample. Excess water in each soil sample moved through the porous membrane and was deposited outside the chamber. At the end of the run, the soil samples were removed from the chamber and transferred to aluminum weighing tins. Samples were then weighed, dried (105EC), and re-weighed (Figure 29). Thus, for known pressure (equilibrated with matric potential), the moisture content of the soil on a gravimetric basis was accurately determined.

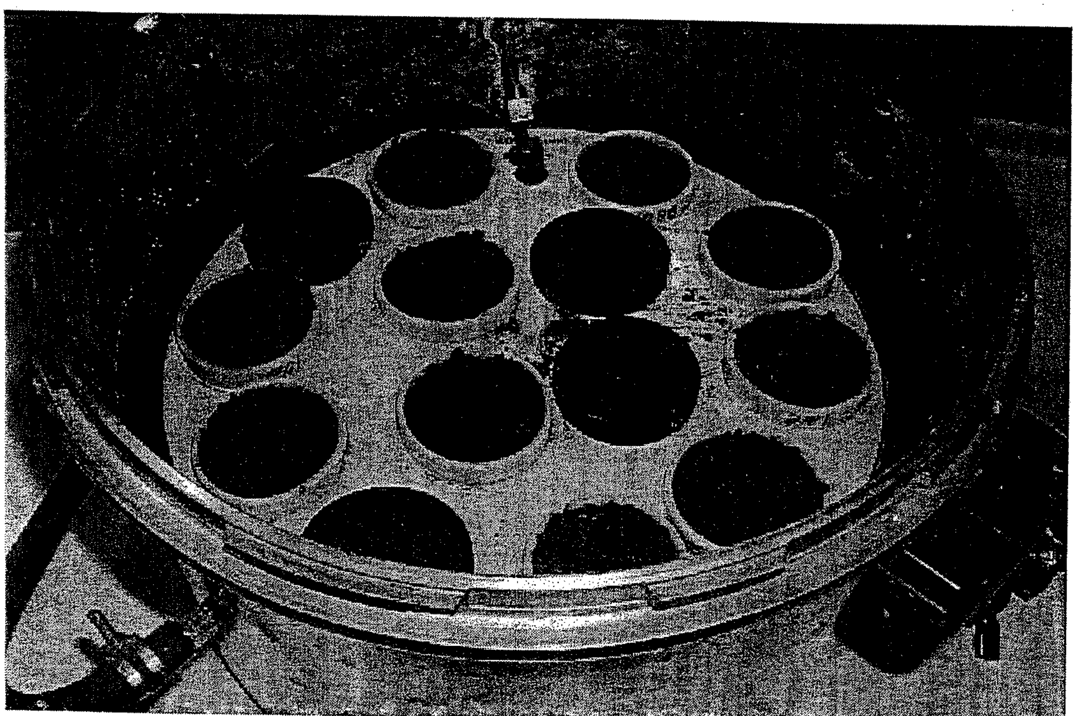


Figure 28. Ceramic plates with rubber rings containing soil were placed within the pressure chamber. This particular pressure plate holds four plates (52 samples, 4 checks).

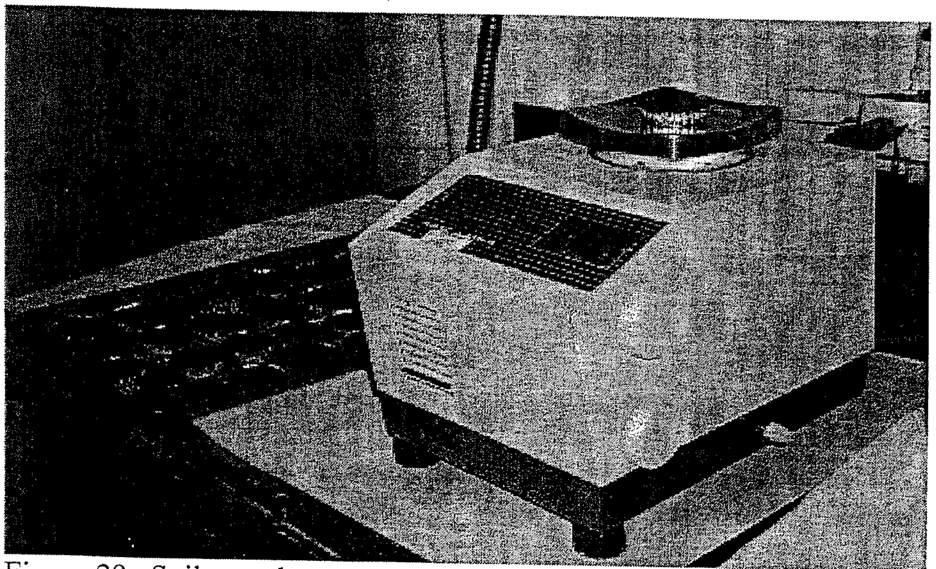


Figure 29. Soil samples were transferred to aluminum tins where they could be weighed.

The procedure of the 5X treatments was somewhat different from the 1X treatments. Rings of sample soil were placed on wire mesh racks (the same as described in the soil chemistry phase of this project). These racks were then placed in plastic containers. The synthetic water quality was poured around the racks up to the point where soils soaked up the water, allowing for complete saturation (Figure 30 - 31).

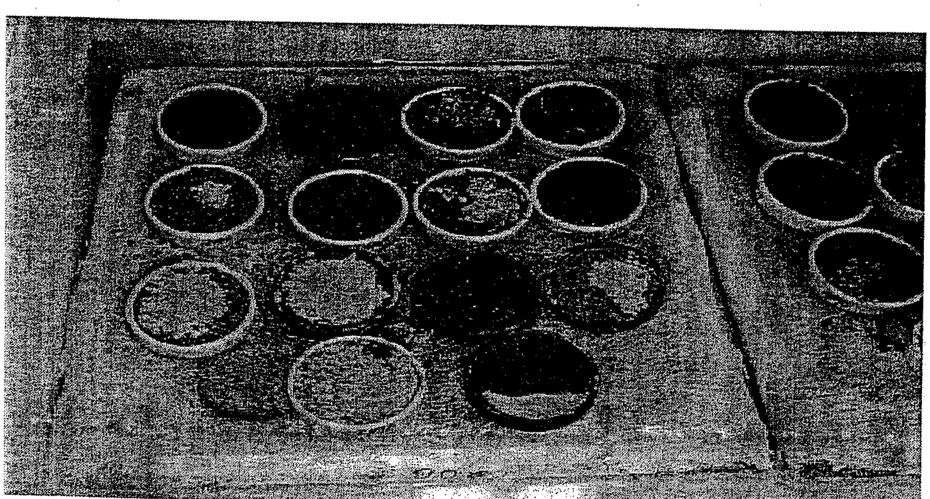
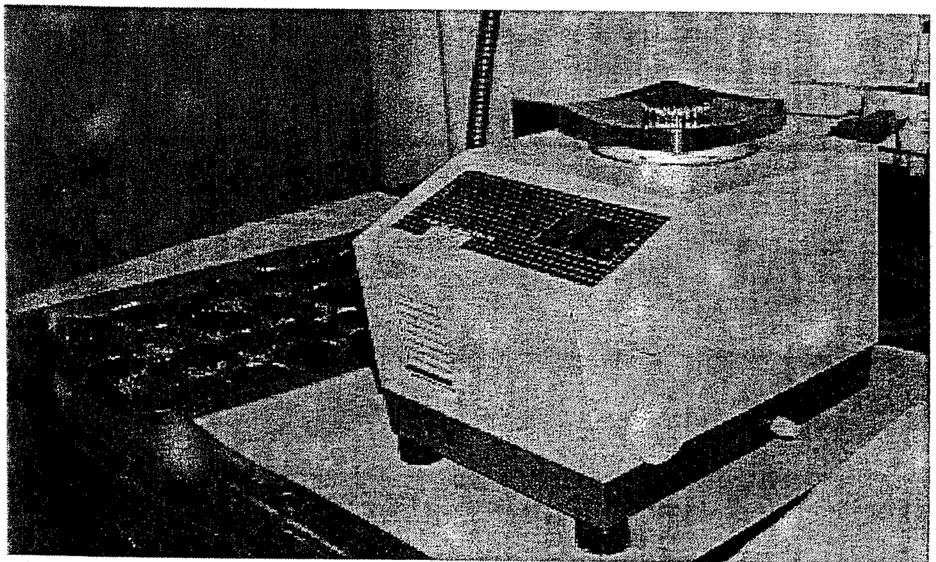


Figure 30. Sample soils on racks are soaking up synthetic water poured around the racks.



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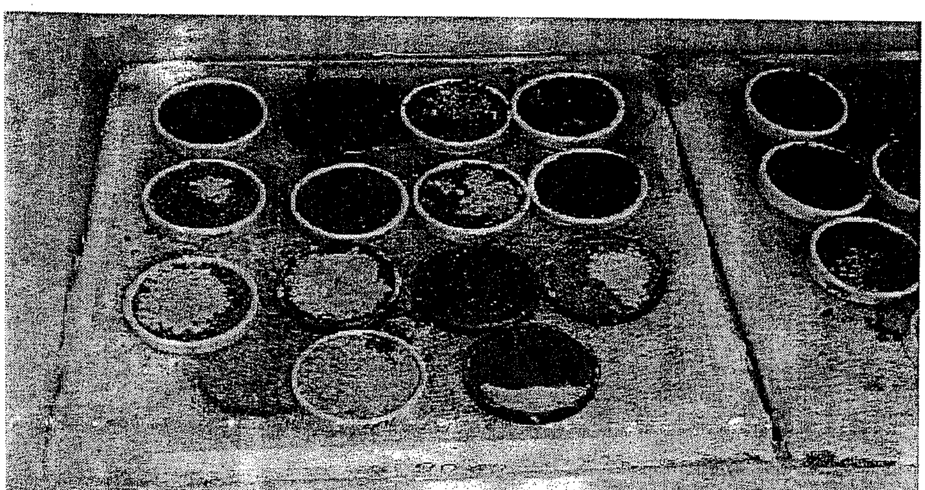

Figure 30. Sample soils on racks are soaking up synthetic water poured around the racks.

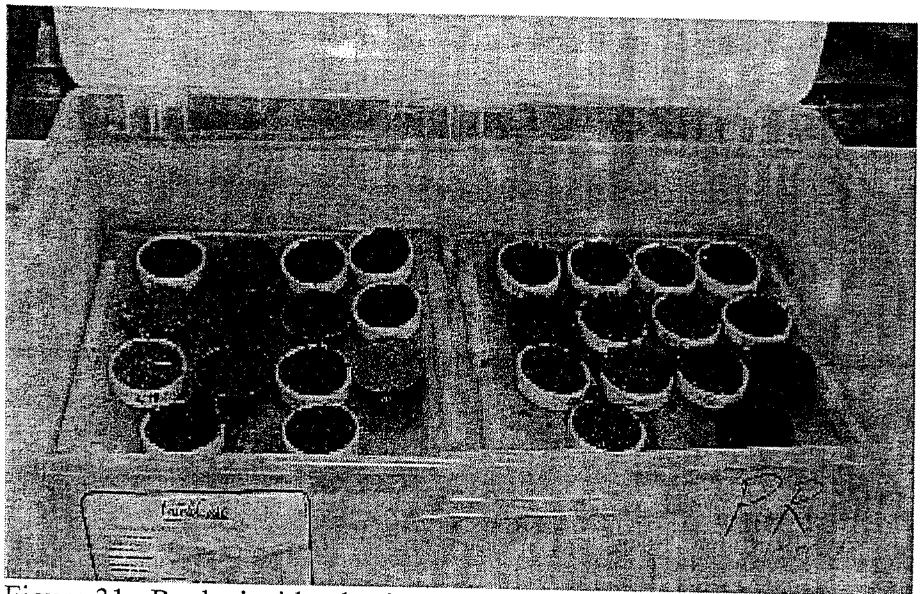

Figure 31. Racks inside plastic containers that hold soils saturated with synthetic waters.

After saturation, racks holding these soils were transported to the dryer, and were dried to 35EC for 24 hours (Figure 32). At the end of this period, racks were transported back to the plastic containers and the process was repeated. For the final wetting, samples were transported from the racks to the ceramic plates. As with the 1X treatment, samples were allowed to saturate overnight, rewet the following morning, and were then placed in the pressure chamber.

The same procedure was followed for the 5X + d treatments. Final wetting on the plates consisted of a distilled water application. After samples were saturated with distilled water, the plates were placed in the pressure chambers. The chamber was then closed and an hour was allowed to pass before the pressure was applied.

Figure 32. Racks holding soil samples were dried to 35°C between wetting regimes.

Quality Assurance/Quality Control

Two 100 mL water samples from the bulk supply (i.e., one of synthesized Powder River water and one of CBM product water) were submitted weekly to Agvise Laboratory, Northwood, N.D to ensure that the bulk supply of water was within the water quality parameters set forth in the treatment standards. Quality control procedures of this laboratory are identified in Chapter 2.

To ascertain accuracy within pressure plates a ring of check soil was placed on each ceramic plate within pressure apparati for each run. The check soil was subjected to the same treatment as the other soils on the plate. Thus, this check detected differences between plates within the particular chamber. Check samples indicated that there were no associated limits (data flags) to the use of the resulting data (Appendix B).

Statistical Analysis

Analysis of variance techniques and mean separation tests were used to ascertain whether significant differences due to textural category of water quality x wetting regime were present at the 95% level of confidence ($P = 0.05$). Statistical analysis was first completed by running a two-factor ANOVA with no interactions. Factors were texture and water quality treatment with unequal replications. One-way ANOVAs were then run on each texture with the factor being water quality treatment. Because of the non-equality of spacing of the matric potential steps and the prior assumptions that: 1) there would be significant differences due to matric potential treatment, and 2) comparisons among matric potentials was not an interest of this study, matric potential was not analyzed as a source of variation in outcomes.

In some instances the resultant data sets failed normality tests. Where possible, the data were log transformed to overcome this inadequacy. Some data were not transformable. The lack of positive tests of normality does not necessarily always subject the data to question or negate the use of traditional ANOVA in data analysis. Data sets can fail the normality test for several reasons. In numerous instances, Monte Carlo simulation has been used to document the lack of validity of the assumptions associated with tests of normality. Normality means that data are normally distributed and therefore are dependent on a treatment method that is consistently and repeatedly applied or treated with the same conditions. Normality is also an assumption of equally or uniformly spaced treatment. It is also dependent of a large sampling population and variation among replications. The necessary minimum sample size to show significance increases as the magnitude of the effect to be demonstrated decreases. Typical minimum data sets for normality include n values in excess of 50 and often approaching n = 100. Under these conditions many data sets do not pass normality tests, as was the case in the data that will be presented. There are several reasons that would explain the non-normal behavior of this data. For one, the data set size was small (only 3 replications per treatment). There were not enough observations to develop a curve that would depict normality. Limitations of data set size were necessitated by time constraints, lab equipment, expense, and labor. Secondly, the variance among reps was minimal (Table 4). Differences between reps were sufficiently small that there was no significant test of variation or distribution. Therefore, a normally distributed population was not expected.

Non-normal data that was unable to be transformed into a normal distribution was analyzed using Kruskal-Wallis one-way analysis of variance on ranks. This is a nonparametric test that does not have a normal distribution and equal variance assumptions. All pairwise multiple comparisons of non-normal data were made using the Tukey test. Pairwise comparisons on normally distributed data were made using the Student-Neuman-Keuls test. These analyses were made using Sigma Stat version 2.0 software (Jandel, 1995).

Table 5. Examples of variation between replications of four different soil materials.

Texture				- 1/10 bar	-1/3 bar	-1 bar	-5 bar	-15 bar
	Sample	Treatment	Rep					
FSL	1	1X PR	1	0.30	0.14	0.10	0.08	0.05
	1	1X PR	2	0.32	0.18	0.09	0.07	0.06
	1	1X PR	3	0.34	0.16	0.09	0.06	0.05
	Variance			0.0004	0.0004	2E-05	0	2E-06
SiL	20	5X PR	1	0.36	0.23	0.14	0.10	0.09
	20	5X PR	2	0.34	0.24	0.13	0.10	0.09
	20	5X PR	3	0.34	0.24	0.14	0.11	0.10
	Variance			0.0001	3E-05	2E-05	0	5E-05
SiCL	42	5X CBM	1	0.40	0.30	0.15	0.11	0.09
	42	5X CBM	2	0.41	0.27	0.17	0.11	0.08
	42	5X CBM	3	0.42	0.28	0.17	0.10	0.08
	Variance			1E-04	0.0002	2E-04	0	1E-05
SiC	50	5X CBM + distilled	1	0.38	0.27	0.21	0.17	0.11
	50	5X CBM + distilled	2	0.39	0.27	0.20	0.16	0.13
	50	5X CBM + distilled	3	0.39	0.29	0.20	0.16	0.13
	Variance			3E-05	0.0001	3E-05	0	2E-04

Results and Discussion

Soil Physical Properties

Treatment effects on soil physical properties were evaluated by monitoring resultant water content of soils after coming into equilibrium with various pressure potentials.

Texture implications. Equilibrium water retention (on mass basis) was significantly different among all textural categories at each equilibrium matric potential (Table 6). Greatest mean water content across all water quality x wetting regimes and among all matric potentials occurred textural group 4. This was expected inasmuch as finer-textured soils typically have more total pore space and lesser bulk densities than coarser-textured soils. While there were significant differences in water retention within all matric potentials as a function of texture, the largest ranges in water retention between textural classes were found at -1/10 and -1/3 bar potentials (Table 6). The response seen at this potential is directly associated with the texture of those soils.

The effects of water quality treatment on mean water content were substantially less apparent than textural effects on water content (Table 6). Although there were reportable significant differences due to water quality, water content was generally similar among all matric potentials and water quality treatments within a given matric potential treatment (Table 6).

Table 6. Mean gravimetric water content at -1/10, -1/3, -1, -5 and -15 bars as a function of textural category and water quality treatment.

		Matric Potential				
		-1/10 bar	-1/3 bar	-1 bar	-5 bar	-15 bar
Texture		Mean gravimetric water content (g H_2O/ g dry soil)[+]				
	1	0.25 a	0.11 a	0.06 a	0.05 a	0.04 a
	2	0.33 b	0.21 b	0.13 b	0.10 b	0.08 b
	3	0.39 c	0.28 c	0.20 c	0.15 c	0.11 c
	4	0.45 d	0.32 d	0.23 d	0.18 d	0.14 d
Water Quality Treatment						
	1X P.R.	0.37 a	0.23 a	0.16 a	0.12 a	0.09 a
	1X CBM	0.37 a	0.22 a	0.16 a	0.12 a	0.09 a
	5X P.R.	0.35 b	0.23 a	0.14 b	0.12 a	0.09 a
	5X P+d	0.35 b	0.23 a	0.16 a	0.12 a	0.09 a
	5X CBM	0.35 b	0.23 a	0.15 c	0.12 a	0.09 a
	5X C+d	0.35 b	0.23 a	0.16 a	0.12 a	0.09 a

[+] Within treatment means followed by the same letter in the same column are not significantly different.

At -1/10 bar, the gravimetric water contents associated with the 1X treatments with P.R. water and CBM product water were not significantly different from each other. Yet, these treatments resulted in significantly greater water contents than the 5X treatments with P.R. and CBM water and the subsequent distilled water treatments. Ghezzehei and Or (2000) reported that successive wetting and drying cycles can cause aggregate coalescence and the reduction of interaggregate porosity. Coalescence would happen more effectively at the 5X treatment than at the 1X treatment, because at the 5X treatment level there would be a greater opportunity for particle migration. This explains the reduction in water retention observed after the 5X treatment. This process is also more evident in coarser-textured soils that exhibit a larger range in particle size as opposed to the finer textured soils. There were no significant differences in gravimetric water content at -1/3 bar as a consequence of water quality treatment. Water content at -1/3 bar matric potential ranged from 0.22 - 0.23 g H_20/g dry soil.

At -1 bar, significant differences in water content occurred between the 5X P.R. and the 1X P.R. or 1X CBM treatments (Table 6). Water contents of the 5X P.R. and 5X CBM treatments at -1 bar matric potential were significantly different from each other and from resultant water contents of the distilled water application treatments, which were not significantly different from each other.

There were no significant differences in water content among water quality treatments at -5 and -15 bars. Water content at -5 bars of pressure was 0.12 g H_20/g dry soil across all water quality treatments. Water content at -15 bars of pressure was 0.09 g H_20/g dry soil across all water quality treatments. This suggests in the drier range of moisture release curves water quality treatments have less of an effect on the physical properties of a soil.

Water Quality Treatment Effects. Within textural class 1, significant differences among water quality treatments were only found to occur at -1/10 bar of pressure (Table 7). This was expected as differences in coarser-textured soils are more likely to occur at higher matric potentials because of the dominance of large pore spaces. The water contents associated with 1X P.R. and 1X CBM treatments were not significantly different from each other, but were significantly greater than the water content resulting from 5X treatments with either P.R. water and CBM product water and the subsequent

Table 7. Mean water content at -1/10, -1/3, -1, -5 and -15 bars for each textural class by water quality treatment.

Texture			-1/10 bar	-1/3 bar	-1 bar	-5 bar	-15 bar
Textural Class #1	WQ Trt	N	Median	Mean	Mean	Median	Median
	1X P.R.	27	0.29 a	0.11 a	0.06 a	0.04 a	0.04 a
	1X CBM	27	0.28 a	0.10 a	0.06 a	0.05 a	0.04 a
	5X P.R.	27	0.24 b	0.11 a	0.06 a	0.05 a	0.04 a
	5X P+d	27	0.25 b	0.11 a	0.06 a	0.04 a	0.04 a
	5X CBM	27	0.24 b	0.12 a	0.06 a	0.05 a	0.04 a
	5X C+d	27	0.25 b	0.12 a	0.06 a	0.05 a	0.04 a
Textural Class #2	WQ Trt	N	Median	Median	Median	Median	Median
	1X P.R.	39	0.36 a	0.22 a	0.15 a	0.10 a	0.08 a
	1X CBM	39	0.35 a	0.22 a	0.14 a	0.11 a	0.08 a
	5X P.R.	39	0.31 b	0.21 a	0.13 a	0.10 a	0.08 a
	5X P+d	39	0.32 b	0.20 a	0.13 a	0.10 a	0.08 a
	5X CBM	39	0.32 b	0.21 a	0.13 a	0.10 a	0.08 a
	5X C+d	39	0.32 b	0.22 a	0.14 a	0.10 a	0.08 a
Textural Class #3	WQ Trt	N	Median	Median	Median	Median	Median
	1X P.R.	51	0.39 a	0.26 a	0.19 a	0.14 a	0.11 a
	1X CBM	51	0.39 a	0.26 a	0.19 a	0.14 a	0.11 a
	5X P.R.	51	0.41 a	0.27 b	0.17 a	0.14 a	0.11 a
	5X P+d	51	0.38 a	0.26 b	0.19 a	0.14 a	0.11 a
	5X CBM	51	0.41 a	0.28 b	0.18 a	0.14 a	0.11 a
	5X C+d	51	0.38 a	0.27 b	0.20 a	0.15 a	0.11 a
Textural Class #4	WQ Trt	N	Median	Median	Median	Median	Median
	1X P.R.	39	0.43 a	0.30 a	0.22 a	0.17 a	0.13 a
	1X CBM	39	0.42 a	0.29 a	0.22 a	0.17 a	0.13 a
	5X P.R.	39	0.41 a	0.31 a	0.20 b	0.16 a	0.13 a
	5X P+d	39	0.40 a	0.29 a	0.21 a	0.16 a	0.13 a
	5X CBM	39	0.42 a	0.29 a	0.20 b	0.16 a	0.13 a
	5X C+d	39	0.41 a	0.29 a	0.21 a	0.16 a	0.13 a

+ Within treatment means, i.e., textural category or matric potential, followed by the same letter in the same column are not significantly different.

treatments with distilled water. Addition of saline sodic water, whose effects are best demonstrated at the 5X and 5X + d treatment levels, resulted in reductions to water retention when the soil was near saturation. These significant reductions detected at -1/10 bar matric potential are a consequence of a loss of porosity.

As was the case in textural class 1, significant differences within textural class 2 due to water quality treatment were only found to occur at -1/10 bar of pressure (Table 7). Again the water contents at -1/10 bar resulting from the 1X cycles with P.R. and CBM were not significantly different from each other, but were significantly greater than the -1/10 bar water contents resulting from all other water quality treatments. As was the case in textural group 1, the significant reductions that occurred within this textural class are attributed to the loss of large pores and the loss of the interstitial spaces between these pores. As previously reported (Bresler et al., 1982; Curtin et al., 1994; So and Aylmore, 1993), possible mechanisms include: 1) pore loss through swelling, 2) pore loss through structural collapse, and 3) pore loss through plugging subsequent to slaking.

A different trend appeared in textural class 3. Within this texture, significant differences due to water quality treatment were only found at -1/3 bar. As was the case in the previous two textural groups, the water contents resultant from the 1X treatments with P.R. or CBM water were not significantly different from each other, but were significantly greater than the water contents associated with all subsequent water quality treatments.

In finer-textured soils, differences in water retention are more likely to occur at lower potentials (greater applied pressure). Within textural class 4, significant differences among water quality treatments occurred at -1 bar of pressure. The water content associated with the 5X treatments with either P.R. or CBM water were not significantly different from each other, but were significantly lower than the rest of the water contents resulting from the other water quality treatments. Typically, soils within this textual group will have few large pore spaces that can be lost due to saline-sodic water when the soil is saturated. Therefore, in this textural category there is a loss of finer spaces, which likely would only have significance at greater applied pressure, i.e., lesser matric potential and when the soil is drier.

Results indicate that saline-sodic water of the qualities applied at these levels did not have a preponderance of significant impacts on soil physical structure, i.e., water retention. While statistically significant differences were detected among water quality treatments, the differences do not appear to be large enough to have a significant impact on the long-term soil physical properties of the soils studied.

Changes from Baseline. For purposes of comparison the baseline condition was the 1X P.R. treatment. This treatment represented an irrigation scenario that would likely occur under present management conditions. Differences in water content from the baseline due to water quality treatment within a single textural category are illustrated in Figures 33-37. Treatments applied to the textural groups 1 and 2 at -1/10 bar behaved similarly with respect to the differences observed in water retention from baseline (Figure 33). For the most part, treatments within these textural groups resulted in very small reductions in retained water. At -1/10 bar (Figure 23) the reductions observed were likely due to the loss of large pore spaces and the lack of formation of small pore spaces resulting from repeated wetting and drying cycles. Results within textural class 3 show an entirely different trend (Figure 33). While there were reductions in water retention from baseline to the same extent as found in the previous textural classes, a large portion of the treated soils were found to have greater water contents than the baseline (up to 0.15g H_20/g dry soil). The largest increase from baseline across all textural categories and all matric potentials was measured at -1/10 bar matric potential. The increases are likely due to texture and matric potential, as the greater clay content would provide more small pores to hold water when large pores are lost and a soil close to saturation would not yet exhibit any of the effects related to elevated sodium levels. Within the textural group 4, there was some increase in water retention from the baseline although the majority of soils exhibited small reductions.

Differences in water retention from the baseline at -1/3 bar were similar across all textures (Figure 34). The large majority of data show that water content ranged from 0.05g H_20/g dry soil greater than the baseline to 0.05g H_20/g dry soil less than the baseline.

At -1 bar, there were minimal changes in water retention from the baseline (Figure 35). The largest differences were found in the finer-textured soils; the observed reductions were minimal (-0.05 g). Differences at -5 and -15 bars of applied pressure from the baseline were minimal as well (Figures 36-37). With the exception of a couple of outliers, water retention remained between 0.05g H_20/g dry soil and -0.05g H_20/g dry soil greater and smaller than baseline levels. These data reiterate some of the observations made previously. That is, the largest differences and variability in the water retention of the soils studied are found at matric potentials closer to saturation. This occurs because at the wet end of the spectrum, a majority of retained water is held in the

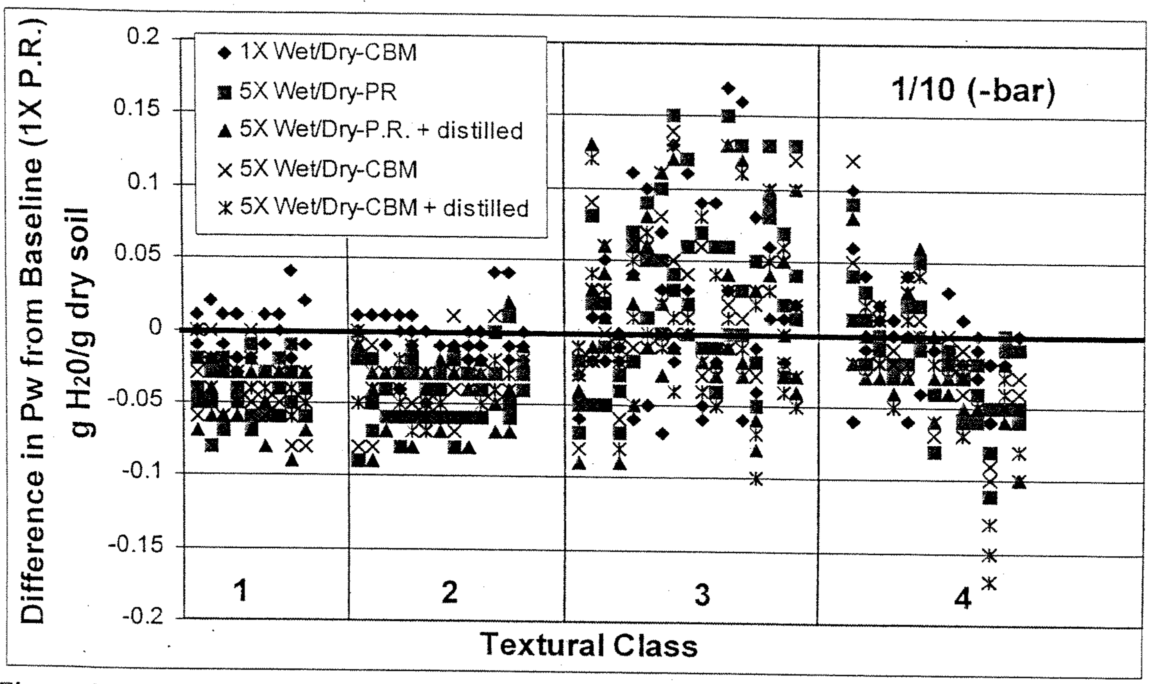

Figure 33. Differences in water retention from the baseline (Pw) at -1/10 bar applied pressure after undergoing water quality treatments for each textural class.

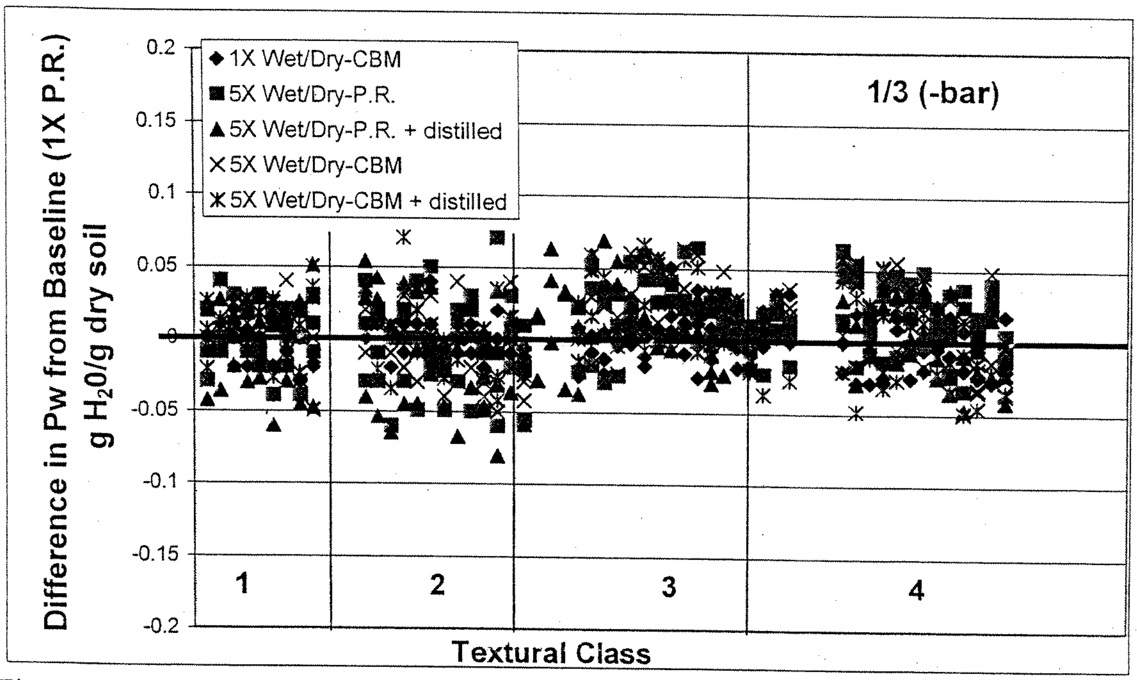

Figure 34. Differences in water retention from the baseline (Pw) at -1/3 bar applied pressure after undergoing water quality treatments for each textural class.

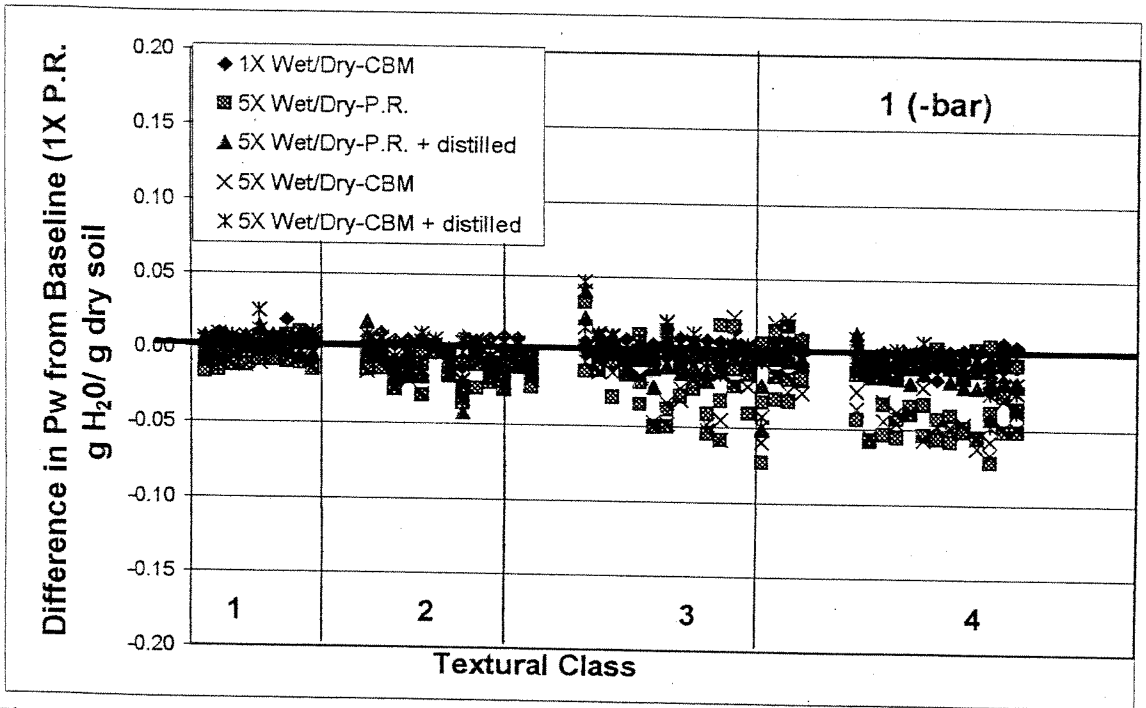

Figure 35. Differences in water retention from the baseline (Pw) at -1 bar applied pressure after undergoing water quality treatments for each textural class.

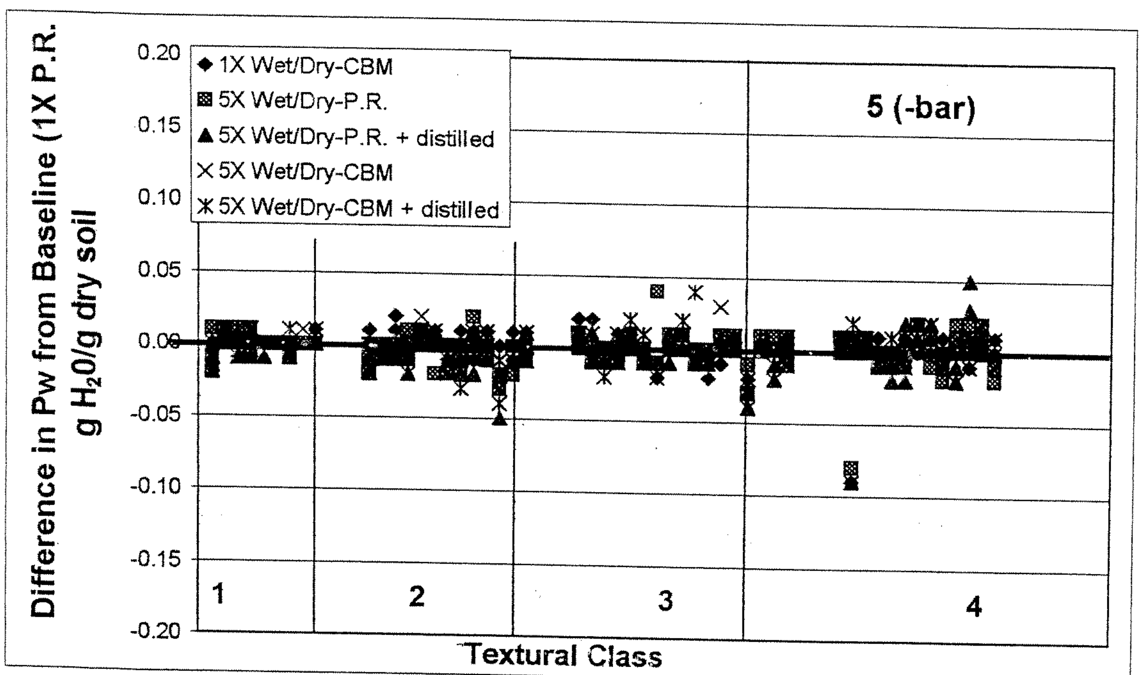

Figure 36. Differences in water retention from the baseline (Pw) at -5 bar applied pressure after undergoing water quality treatments for each textural class.

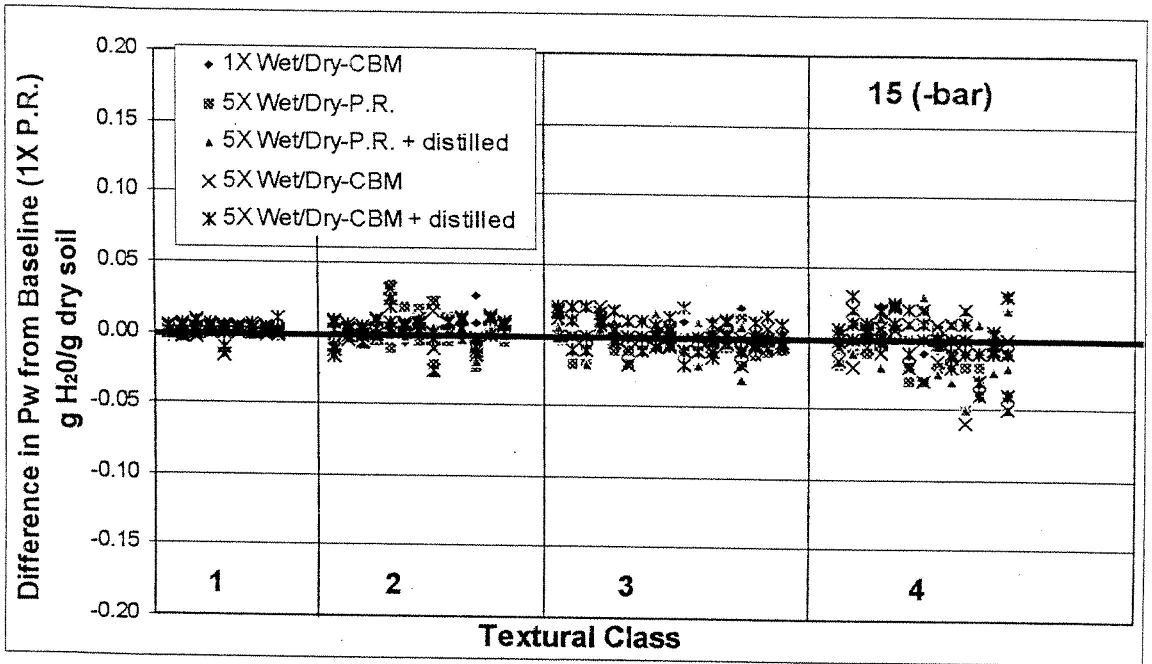

Figure 37. Differences in water retention from the baseline (Pw) at -15 bar applied pressure after undergoing water quality treatments for each textural class.

large diameter pores. The loss of these large diameter pores would likely result in a loss of total pore space at the wet end, but not at the drier end.

Water Characteristic Determinations. The analysis of variance provides a means for identifying the sources of variation in the water content measurements that can be attributed to water quality x wetting regime (Table 7). However, it does not provide a means for comparing the complete moisture release curves for each textural class by wetting regime combination (Figures 38-41). For purposes of comparison, moisture release curves were derived using linear regression of transformed data. A log-log transformation was applied to the data. All transformations were made on absolute data values. The slope of the linear regression of log transformed matric potential versus log transformed water content (Table 8) is the rate at which log water content decreases as log matric potential decreases. This rate represents the change in water retention as the soil goes to a lesser potential. For all water quality treatments, as the clay content increased the slope decreased, indicating that clayey soils retain more water at lesser potentials. The regression slope coefficients (Table 8) and the moisture release curves indicate that the changes in water content at the matric potentials studied were the same regardless of water quality treatment applied.

Table 8. Regression of matric potential on water content by treatment for each textural class.

W.Q. Treatment	Textural Class	Equation	r^2	Regression Slope
1X P.R.	Fine Sandy Loam	log10(Water Content) = -1.090 - (0.373 * log10(Matric Potential)	0.782	0.373
1X P.R.	Silt Loam	log10(Water Content) = -0.814 - (0.302 * log10(Matric Potential)	0.765	0.302
1X P.R.	Silty Clay Loam	log10(Water Content) = -0.684 - (0.234 * log10(Matric Potential)	0.817	0.234
1X P.R.	Silty Clay	log10(Water Content) = -0.601 - (0.227 * log10(Matric Potential)	0.794	0.227
1X CBM	Fine Sandy Loam	log10(Water Content) = -1.099 - (0.356 * log10(Matric Potential)	0.750	0.356
1X CBM	Silt Loam	log10(Water Content) = -0.812 - (0.291 * log10(Matric Potential)	0.741	0.291
1X CBM	Silty Clay Loam	log10(Water Content) = -0.675 - (0.244 * log10(Matric Potential)	0.855	0.244
1X CBM	Silty Clay	log10(Water Content) = -0.607 - (0.227 * log10(Matric Potential)	0.812	0.227
5X P.R.	Fine Sandy Loam	log10(Water Content) = -1.108 - (0.346 * log10(Matric Potential)	0.788	0.346
5X P.R.	Silt Loam	log10(Water Content) = -0.844 - (0.284 * log10(Matric Potential)	0.740	0.284
5X P.R.	Silty Clay Loam	log10(Water Content) = -0.682 - (0.256 * log10(Matric Potential)	0.793	0.256
5X P.R.	Silty Clay	log10(Water Content) = -0.615 - (0.232 * log10(Matric Potential)	0.809	0.232

Table 8. continued.

W.Q. Treatment	Textural Class	Equation	r^2	Regression Slope
5X CBM	Fine Sandy Loam	log10(Water Content) = -1.097 - (0.347 * log10(Matric Potential)	0.791	0.347
5X CBM	Silt Loam	log10(Water Content) = -0.832 - (0.280 * log10(Matric Potential)	0.751	0.280
5X CBM	Silty Clay Loam	log10(Water Content) = -0.673 - (0.250 * log10(Matric Potential)	0.872	0.250
5X CBM	Silty Clay	log10(Water Content) = -0.615 - (0.228 * log10(Matric Potential)	0.803	0.228
5P + d	Fine Sandy Loam	log10(Water Content) = -1.166 - (0.263 * log10(Matric Potential)	0.660	0.263
5P + d	Silt Loam	log10(Water Content) = -0.865 - (0.251 * log10(Matric Potential)	0.622	0.251
5P + d	Silty Clay Loam	log10(Water Content) = -0.686 - (0.224 * log10(Matric Potential)	0.770	0.224
5P + d	Silty Clay	log10(Water Content) = -0.623 - (0.201 * log10(Matric Potential)	0.696	0.201
5C + d	Fine Sandy Loam	log10(Water Content) = -1.080 - (0.344 * log10(Matric Potential)	0.797	0.344
5C + d	Silt Loam	log10(Water Content) = -0.828 - (0.285 * log10(Matric Potential)	0.761	0.285
5C+d	Silty Clay Loam	log10(Water Content) = -0.671 - (0.242 * log10(Matric Potential)	0.859	0.242
5C+d	Silty Clay	log10(Water Content) = -0.608 - (0.215 * log10(Matric Potential)	0.822	0.215

[+] Median values followed by the same letter in the same column are not significantly different. Ln (x) = -log of matric potential; y = predicted gravimetric water content g H_20/g dry soil.

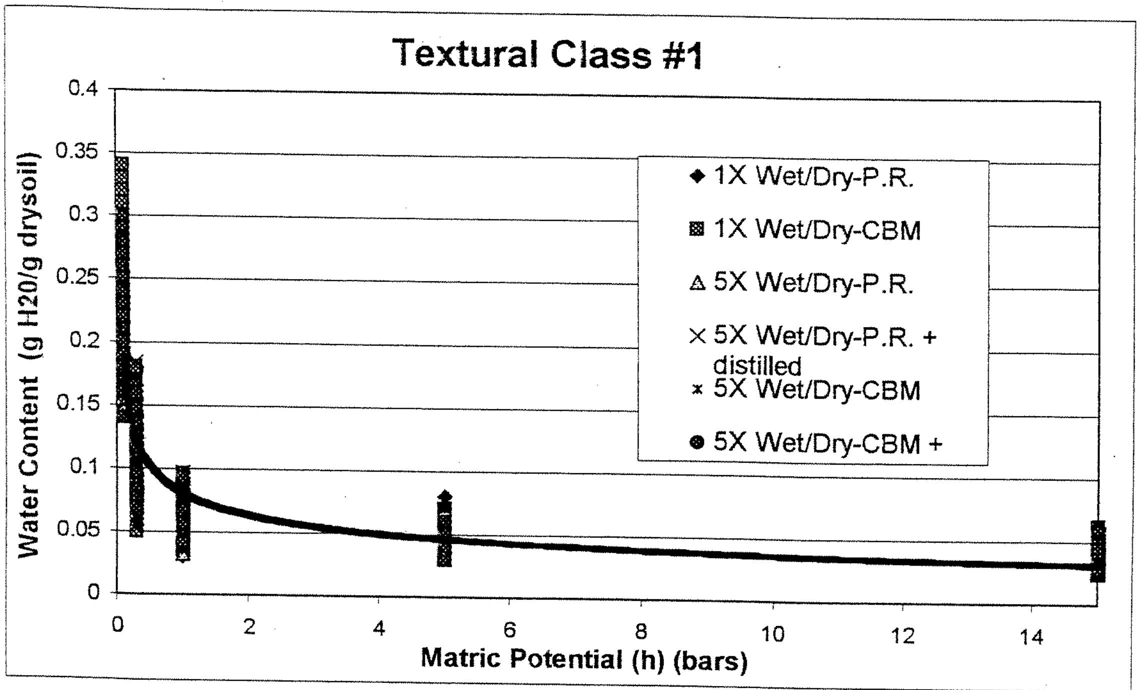

Figure 38. Water content as a function of matric potential within textural class 1. Fitted lines between data points represent logarithmic trend lines.

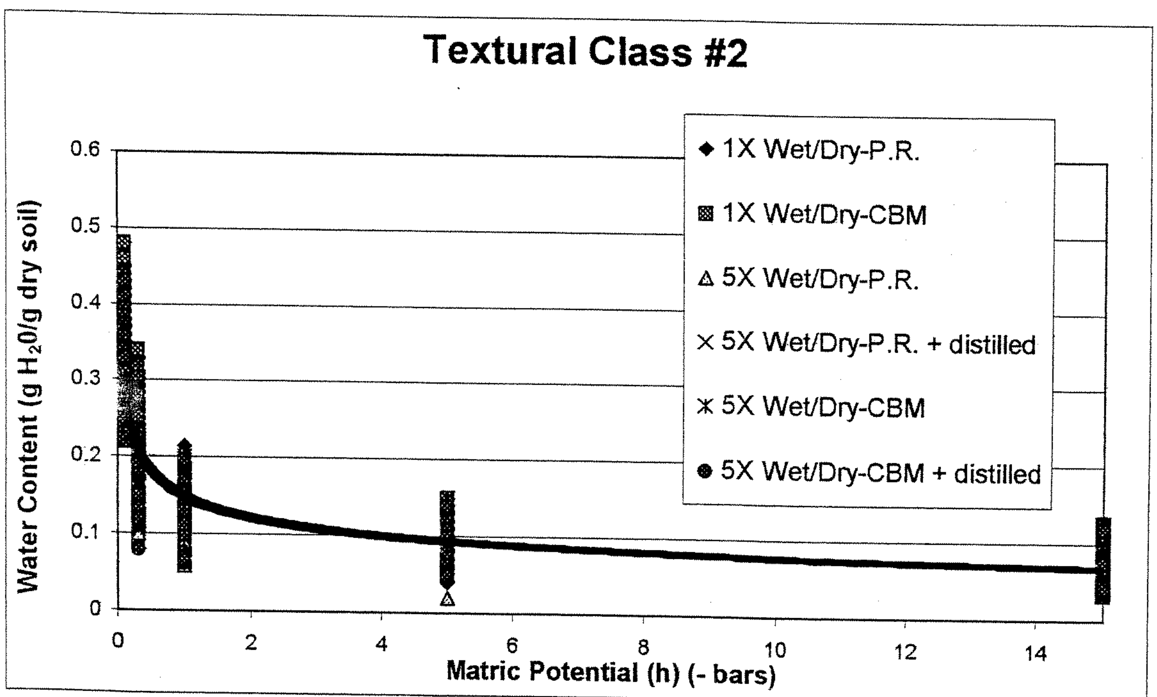

Figure 39. Water content as a function of matric potential within textural class 2. Fitted lines between data points represent logarithmic trend lines.

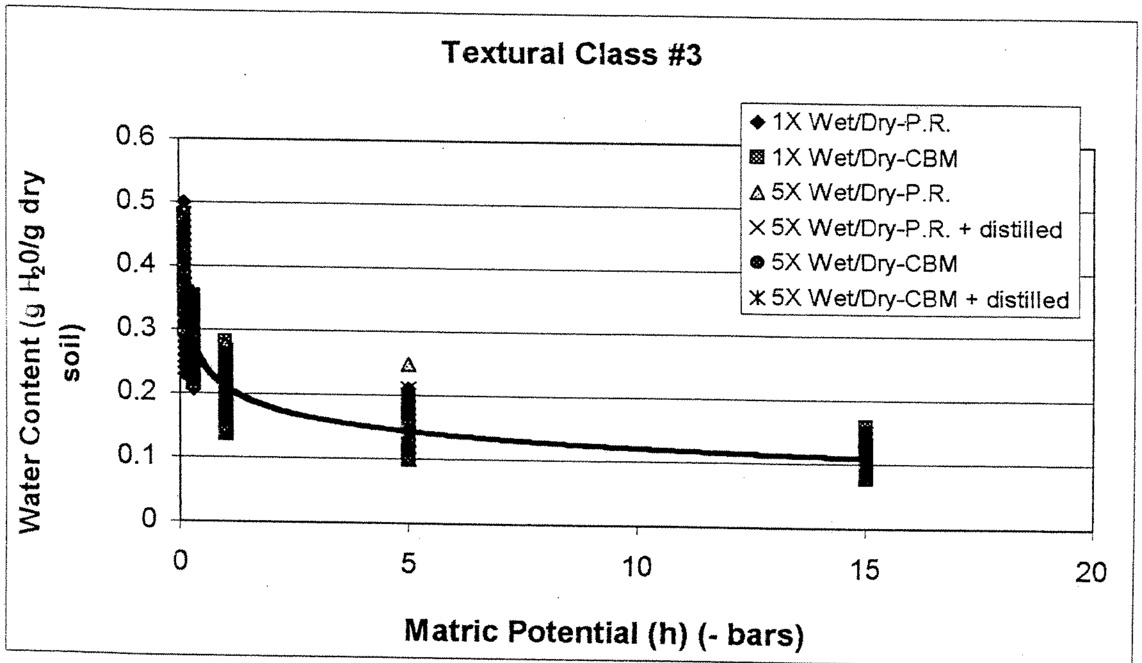

Figure 40. Water content as a function of matric potential within textural class 3. Fitted lines between data points represent logarithmic trend lines.

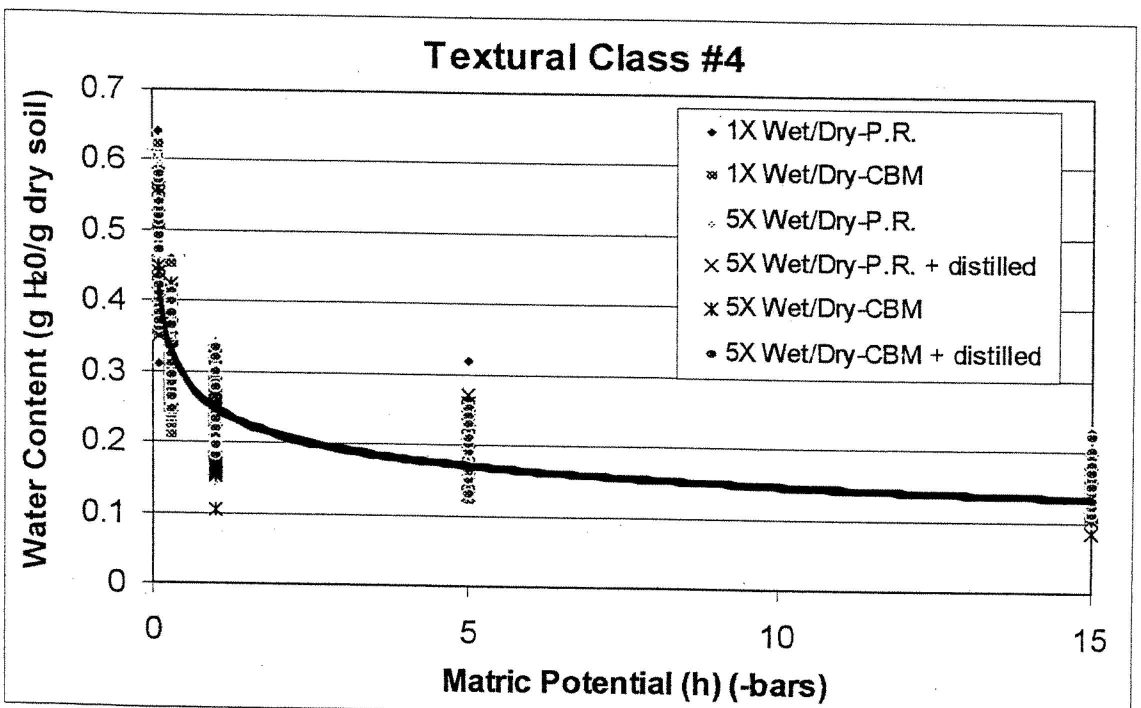

Figure 41. Water content as a function of matric potential within the textural class 4. Fitted lines between data points represent logarithmic trend lines.

Summary and Conclusions

The following observations were made during this study:

1. Water content associated with matric potential differed significantly due to predominant soil texture at all matric potentials investigated in this study.
2. Significant differences in water holding capacity of coarser-textured soils occur due to water quality treatment more often at greater matric potentials (wetter conditions). In finer-textured soils, differences in water holding capacity due to water quality treatment are more likely to occur at lower potentials (drier conditions).
3. Significant changes in water holding capacity due to water quality treatment are only on the order of 0.02-0.04 g H_20/g dry soil. The change reflected a decrease in water holding capacity of textural classes 1 and 2 and an increase in water holding capacity of textural class 3.
4. Reductions in water retention in coarser-textured soils are attributable to the loss of large pore spaces.
5. The addition of saline-sodic water had the greatest effect on soil physical properties when the soil is near saturation. Changes in water holding capacity are likely to have non-discernible impact on irrigation suitability.
6. Successive wetting/drying cycles can cause aggregate coalescence and the loss of interaggregate porosity; this appeared to occur more often in the coarser-textured soils.

7. CBM product water applied at these levels did not have a consistent significant impact on soil physical properties, i.e., water-holding capacity.

CHAPTER 4

SUMMARY AND CONCLUSIONS

The specific objective of this study was to understand what possible effects modestly saline and sodic water, intended to simulate CBM product water, might have on irrigable acreages within the Powder River Basin of Montana and Wyoming. The study consisted of a two-part laboratory project. The first part assessed soil chemical responses to wetting with saline-sodic water, and the second assessed soil physical responses to wetting with saline-sodic water.

Repeated irrigation with modestly saline-sodic water or water with a chemical signature comparable to the CBM product water used in this study resulted in a general increase in the soil salinity and sodicity. Single wetting events with either Powder River water or CBM signature product water resulted in the elevation of both ESP and SAR. However, the resultant levels do not appear to pose a risk of dispersion or salt stress to commonly grown crops for the most part. Repeated wetting and drying with CBM signature water, such in the case of sprinkler irrigation or routine flooding, resulted in significant elevation of EC, SAR, and ESP with resultant values closer to, or in some cases greater than, previously published thresholds of SAR = 12, ESP = 15%. These results validate that the previously reported ESP-SAR relationship holds, even in the event of native soils and/or those soil materials irrigated with CBM signature water. Consistent with previously findings, soil solution salinity will equilibrate at an EC value approximately 2-3 times that of the applied water. In contrast, soil solution SAR will equilibrate at a level comparable to the SAR of the applied water as long as leaching occurs. Repeated irrigation with CBM product water resulted in elevated soil salinity levels substantially higher than published thresholds for some irrigated crops. Subsequent leaching with simulated rainfall significantly reduced soil solution salinity, but had little or no effect on sodicity. This implies that the flocculating effect of salinity may be reduced, thereby exacerbating the dispersive effects of sodium, as a consequence of uncontrollable rainfall or dispersals of relatively salt-free spring runoff to soils previously irrigated with saline-sodic water. Yet, with the water quality values used in this study (Table 2), in few instances were resultant soil solution salinity x sodicity combinations found to be exceeding the threshold categories where reductions in infiltration occur according to thresholds published by Ayers and Westcot (1976), Hanson et al. (1999), and Miller and Donahue (1995).

The greatest increases in soil solution EC and SAR after treatment with either CBM or P.R. waters were found in the coarser-textured soils. Rainfall, i.e. single distilled water application, was found to have a greater impact on reducing EC and SAR when salt concentrations were high, and in coarser-textured soils. Across all water quality application treatments, textural group 4 had a significantly greater mean EC and SAR of 3.78 dS/m and 7.91, respectively. Higher exchange capacities of finer textured soils and greater percentages of non-readily draining interstitial spaces result in the ability of finer soils to absorb and retain higher concentrations of salts upon leaching. Across all textural classes, greatest mean EC and SAR (6.93 dS/m and 11.31, respectively) occurred after soils received the 5X CBM water quality treatment.

Soil water retention was used as an indicator to determine the impacts of CBM signature water on the physical properties of a soil. As expected, the water content differed significantly among the textures of the soils investigated at all matric potentials. Differences in water retention due to water quality treatment of coarser-textured soils occurred more often at greater matric potentials, while significant difference in water retention in finer-textured soils were more likely to occur at lower potentials. Significant changes in water retention due to water quality treatment were only on the order of 0.02-0.04g H_20/g dry soil. The change reflected a decrease in water retention of textural classes 1 and 2 and an increase in water holding capacity of the textural class 3. These changes, although statistically significant, were not considered large enough to have a significant ecological impact. This was apparent in the moisture release curves that were constructed for each texture. The curves indicated that changes in water retention at the matric potentials studied were the same regardless of water quality treatment applied. It was concluded that modestly saline-sodic water applied at these levels did not have a consistently significant impact on soil water retention. Thus, the standards used in this project defining CBM product water (EC = 3.12; SAR = 13.09) can be considered to be protective of soil physical properties.

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APPENDICES

APPENDIX A

QUALITY CHECKS

Table 9. Sub-samples of bulk water supply to monitor water chemistries.

ID	Mg (ppm)	Ca (ppm)	Na (ppm)	EC (mmhos/cm)	pH	Calculated SAR	Date
CBM	28	59	459	3.01	8.44	12.15	3/20/02
P.R.	24	66	173	1.47	8.40	4.57	
CBM	29	31	471	3.07	8.30	14.39	3/28/02
P.R.	27	41	177	1.46	8.28	5.19	
CBM	29	53	469	2.84	8.16	4.75	4/03/02
P.R.	23	53	469	2.84	8.16	12.68	
CBM	29	27	463	3.07	8.46	14.53	4/10/02
P.R.	22	32	171	1.35	8.35	5.61	
CBM	28	60	452	3.12	8.2	11.91	4/18/02
P.R.	23	64	172	1.54	8.12	4.63	
CBM	29	32	475	2.97	8.44	14.43	4/24/02
P.R.	23	33	179	1.39	8.26	5.77	
CBM	28	48	461	2.98	8.23	12.89	5/01/02
P.R.	21	55	162	1.36	8.21	4.64	
CBM	27	80	455	2.88	7.87	11.05	5/23/02
P.R.	23	103	182	1.67	7.76	4.16	
CBM	28	89	452	3.37	8.11	10.56	6/05/02
P.R.	23	101	170	1.80	7.94	3.92	
CBM	29	50	472	3.16	8.10	12.96	6/12/02
P.R.	24	58	180	1.61	8.57	4.95	
CBM	31	100	484	3.36	7.95	10.69	6/19/02
P.R.	25	87	175	1.66	8.06	4.20	
CBM	30	42	482	3.52	8.50	13.68	6/27/02
P.R.	25	54	183	1.74	8.09	5.09	
CBM	30	62	488	3.35	8.16	12.55	7/03/02
P.R.	23	51	171	1.48	8.14	4.92	
CBM	30	48	502	3.28	8.21	13.08	7/10/02
P.R.	22	32	170	1.41	7.98	5.58	
CBM	28	62	449	3.37	8.10	11.72	7/31/02
P.R.	23	70	175	1.72	7.99	4.57	
CBM	29	73	452	3.44	8.45	11.16	8/08/02
P.R.	23	60	170	1.54	7.99	4.66	
CBM	30	52	481	3.12	8.60	12.96	8/14/02
P.R.	25	56	176	1.34	8.36	4.85	
CBM	29	62	454	3.08	8.06	11.76	8/28/02
P.R.	24	60	180	1,63	8.12	4.89	
CBM	30	25	490	3.05	8.44	15.41	9/04/02
P.R.	24	40	187	1.42	8.31	5.69	
CBM	29	31	486	3.03	8.29	14.86	9/11/02
P.R.	24	58	177	1.49	8.06	4.86	

Table 9 cont.

ID	Mg (ppm)	Ca (ppm)	Na (ppm)	EC (mmhos/cm)	pH	Calculated SAR	Date
CBM	28	38	471	2.97	8.12	13.94	9/19/02
P.R.	24	24	185	1.39	8.16	6.29	
CBM	22	72	454	2.83	7.77	11.8	10/04/02
P.R.	24	96	177	1.43	7.85	4.13	
CBM	29	61	470	3.04	7.92	12.23	10/11/02
P.R.	23	99	172	1.48	7.95	3.99	
CBM	29	58	466	2.78	8.09	12.30	10/16/02
P.R.	24	63	185	1.36	8.24	4.96	
CBM	28	53	454	2.91	7.85	12.37	10/23/02
P.R.	24	63	181	1.50	7.87	4.85	
CBM	29	45	488	3.01	8.05	13.75	11/07/02
P.R.	25	50	187	1.44	7.98	5.31	
CBM	28	49	466	2.83	8.15	12.96	11/14/02
P.R.	23	44	176	1.30	8.17	5.27	
CBM	27	33	446	2.94	8.44	13.74	11/22/02
P.R.	23	39	169	1.41	8.10	5.23	
CBM	27	23	460	2.81	8.11	15.19	12/09/02
P.R.	23	37	181	1.33	8.12	5.68	

Table 10. Check sample chemistry analysis. Two reps of check soil were sent to Harris Laboratories with each batch of soil. Four batches of samples were analyzed.

Sample	pH	EC	Na	Ca	Mg	K	HCO3	Date
		mmhos/cm	Meq/L	Meq/L	Meq/L	Meq/L	Meq/L	
BATCH 1-1	7.7	0.44	0.8	2.5	1.0	0.1	2.1	11/8/01
BATCH 1-2	7.7	0.37	0.6	2.2	0.9	0.1	3	11/8/01
BATCH 2-1	7.9	0.4	0.7	2.5	1	0.2	2.8	3/19/02
BATCH 2-2	7.9	0.38	0.8	2.7	1	0.2	2.8	3/19/02
BATCH 3.1	7.7	0.36	0.6	2.6	1	0.2	3.5	5/20/02
BATCH 3-2	7.7	0.36	0.6	2.6	1	0.1	3.5	5/20/02
BATCH 4-1	7.8	0.47	1.1	3.1	1.1	0.1	2.5	6/21/02
BATCH 4-2	7.7	0.43	0.8	3	1	0.1	3.1	6/21/02

Table 11. Water content of check soil for P.R. and CBM water qualities for each pressure plate run.

POWDER RIVER					
MATRIC POTENTIAL	TREATMENT	SAMPLE ID	REP 1	REP 2	REP 3
-1/10 BAR	1X	56	0.46	0.47	0.47
		57	0.47	0.46	0.48
		58	0.45	0.46	0.44
		59	0.44	0.43	0.44
	5X	56	0.41	0.41	0.41
		57	0.41	0.42	0.41
		58	0.42	0.43	0.41
		59	0.41	0.43	0.41
	5X+d	56	0.40	0.42	0.40
		57	0.40	0.41	0.38
		58	0.41	0.40	0.40
		59	0.39	0.40	0.39
-1/3 BAR	1X	56	0.25	0.33	0.28
		57	0.29	0.34	0.29
		58	0.31	0.28	0.30
		59	0.33	0.29	0.30
	5X	56	0.28	0.24	0.26
		57	0.29	0.26	0.29
		58	0.31	0.28	0.28
		59	0.32	0.30	0.28
	5X + d	56	0.27	0.24	0.31
		57	0.27	0.26	0.30
		58	0.28	0.28	0.28
		59	0.29	0.29	0.29
-1 BAR	1X	56	0.18	0.18	0.18
		57	0.19	0.18	0.17
		58	0.20	0.18	0.18
		59	0.19	0.18	0.17
	5X	56	0.18	0.17	0.15
		57	0.18	0.18	0.17
		58	0.15	0.15	0.17
		59	0.15	0.16	0.17
	5X + d	56	0.17	0.18	0.19
		57	0.17	0.18	0.16
		58	0.17	0.17	0.16
		59	0.18	0.18	0.16
-5 BAR	1X	56	0.14	0.16	0.13
		57	0.12	0.13	0.13
		58	0.13	0.13	0.13
		59	0.12	0.13	0.12
	5X	56	0.12	0.13	0.13
		57	0.12	0.13	0.13
		58	0.14	0.12	0.13
		59	0.13	0.12	0.12
	5X + d	56	0.13	0.12	0.13
		57	0.13	0.13	0.13
		58	0.13	0.13	0.13
		59	0.13	0.13	0.12

Table 11 cont.

MATRIC POTENTIAL	TREATMENT	SAMPLE ID	REP 1	REP 2	REP 3
-15 BAR	1X	56	0.11	0.12	0.11
		57	0.11	0.12	0.09
		58	0.12	0.13	0.11
		59	0.12	0.12	0.12
	5X	56	0.10	0.11	0.11
		57	0.10	0.10	0.12
		58	0.10	0.11	0.12
		59	0.11	0.11	0.12
	5X + d	56	0.11	0.10	0.10
		57	0.11	0.10	0.11
		58	0.11	0.12	0.11
		59	0.11	0.11	0.12
CBM					
-1/10 BAR	1X	56	0.44	0.46	0.44
		57	0.45	0.47	0.46
		58	0.45	0.46	0.44
		59	0.44	0.44	0.44
	5X	56	0.40	0.42	0.40
		57	0.40	0.43	0.41
		58	0.41	0.42	0.43
		59	0.42	0.43	0.42
	5X + d	56	0.40	0.41	0.42
		57	0.41	0.40	0.42
		58	0.40	0.39	0.39
		59	0.37	0.40	0.40
-1/3 BAR	1X	56	0.26	0.30	0.27
		57	0.27	0.33	0.28
		58	0.32	0.27	0.30
		59	0.32	0.29	0.33
	5X	56	0.27	0.25	0.28
		57	0.28	0.30	0.28
		58	0.31	0.29	0.31
		59	0.31	0.27	0.34
	5X + d	56	0.27	0.30	0.30
		57	0.26	0.32	0.30
		58	0.29	0.29	0.27
		59	0.30	0.27	0.30

Table 11 cont.

MATRIC POTENTIAL	TREATMENT	SAMPLE ID	REP 1	REP 2	REP 3
-1 BAR	1X	56	0.18	0.18	0.19
		57	0.18	0.19	0.17
		58	0.20	0.18	0.18
		59	0.19	0.18	0.17
	5X	56	0.18	0.18	0.15
		57	0.18	0.17	0.16
		58	0.15	0.16	0.17
		59	0.16	0.16	0.17
	5X + d	56	0.17	0.18	0.16
		57	0.17	0.18	0.16
		58	0.18	0.18	0.17
		59	0.18	0.17	0.16
-5 BAR	1X	56	0.13	0.14	0.13
		57	0.13	0.14	0.13
		58	0.13	0.13	0.13
		59	0.13	0.14	0.13
	5X	56	0.13	0.13	0.14
		57	0.13	0.13	0.14
		58	0.13	0.13	0.13
		59	0.14	0.13	0.13
	5X + d	56	0.13	0.12	0.13
		57	0.13	0.12	0.13
		58	0.14	0.13	0.13
		59	0.15	0.13	0.14
-15 BAR	1X	56	0.11	0.12	0.11
		57	0.12	0.12	0.12
		58	0.14	0.12	0.14
		59	0.13	0.12	0.13
	5X	56	0.10	0.11	0.12
		57	0.11	0.12	0.12
		58	0.12	0.11	0.11
		59	0.11	0.11	0.12
	5X + d	56	0.11	0.11	0.12
		57	0.12	0.10	0.11
		58	0.08	0.11	0.12
		59	0.12	0.11	0.11

Table 12. Moisture retention at -15 bars for sample soils for periods of 3 and 14 days.

ID #	Days	Wet Weight	Dry Weight	Moisture Content	Days	Wet Weight	Dry Weight	Moisture Content
1	3	25.10	23.88	0.05	14	32.44	30.76	0.05
15	3	26.98	25.08	0.08	14	29.17	26.71	0.09
27	3	26.02	22.58	0.15	14	31.24	26.54	0.18
28	3	24.18	20.60	0.17	14	27.13	23.40	0.16
39	3	26.10	22.40	0.17	14	28.57	25.05	0.14
49	3	25.83	22.19	0.16	14	25.56	22.04	0.16
1	3	27.97	26.39	0.06	14	26.15	24.91	0.05
15	3	29.56	27.22	0.09	14	29.30	27.00	0.09
27	3	27.61	23.51	0.17	14	27.32	23.53	0.16
28	3	26.47	22.25	0.19	14	26.38	23.12	0.14
39	3	29.86	24.83	0.20	14	27.97	24.77	0.13
49	3	31.75	26.90	0.18	14	21.88	19.24	0.14

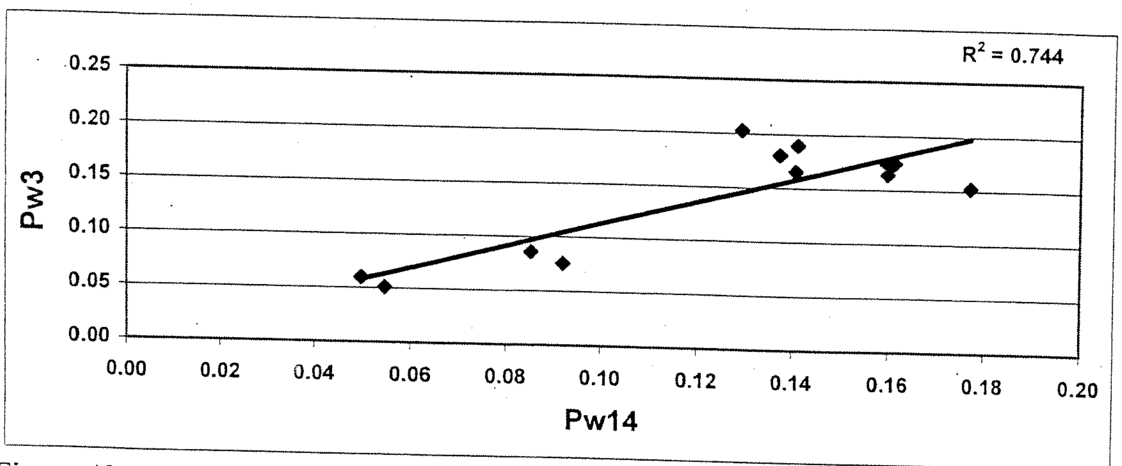

Figure 42. Moisture retention of sample soils at -15 bars left on the pressure plate for 3 days vs. samples left on for 14 days.

Table 13. Moisture retention at -15 bars for sample soils for periods of 5 and 14 days.

ID #	Days	Wet Weight	Dry Weight	Moisture Content	Days	Wet Weight	Dry Weight	Moisture Content
3	5	25.59	24.52	0.04	14	25.25	24.28	0.04
9	5	28.37	27.64	0.03	14	30.59	29.65	0.03
19	5	30.41	28.12	0.08	14	27.07	24.88	0.09
31	5	25.10	21.67	0.16	14	27.79	23.81	0.17
46	5	27.50	24.38	0.13	14	27.59	24.52	0.13
53	5	33.05	26.04	0.27	14	30.45	25.28	0.20
3	5	26.10	24.92	0.05	14	25.79	24.91	0.04
9	5	30.80	29.63	0.04	14	34.83	33.90	0.03
19	5	28.09	25.80	0.09	14	29.31	27.05	0.08
31	5	26.73	22.75	0.17	14	30.80	26.92	0.14
46	5	32.10	28.26	0.14	14	29.33	26.45	0.11
53	5	33.30	27.43	0.21	14	28.51	24.34	0.17

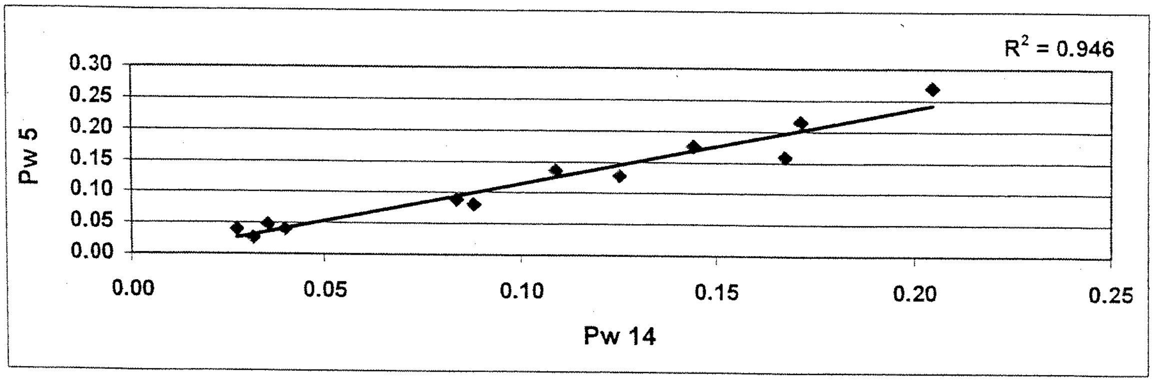

Figure 43. Moisture retention of sample soils at -15 bars left on the pressure plate for 5 days vs. samples left on for 14 days.

Table 14. Moisture retention at -15 bars for sample soils for periods of 7 and 14 days.

ID #	Days	Wet Weight	Dry Weight	Moisture Content	Days	Wet Weight	Dry Weight	Moisture Content
6	7	28.50	27.29	0.04	14	29.87	28.49	0.05
20	7	23.20	21.01	0.10	14	25.39	22.94	0.11
24	7	25.28	23.58	0.07	14	26.07	24.00	0.09
32	7	27.25	23.22	0.17	14	24.25	21.87	0.11
35	7	25.72	22.21	0.16	14	28.88	24.82	0.16
41	7	25.68	23.46	0.09	14	27.46	25.00	0.10
6	7	31.31	29.87	0.05	14	31.60	30.30	0.04
20	7	24.71	22.21	0.11	14	27.07	24.63	0.10
24	7	26	23.94	0.09	14	29.40	27.25	0.08
32	7	28.42	24.07	0.18	14	28.72	25.04	0.15
35	7	31.41	27.05	0.16	14	27.25	24.21	0.13
41	7	27.65	25.25	0.10	14	25.32	23.44	0.08

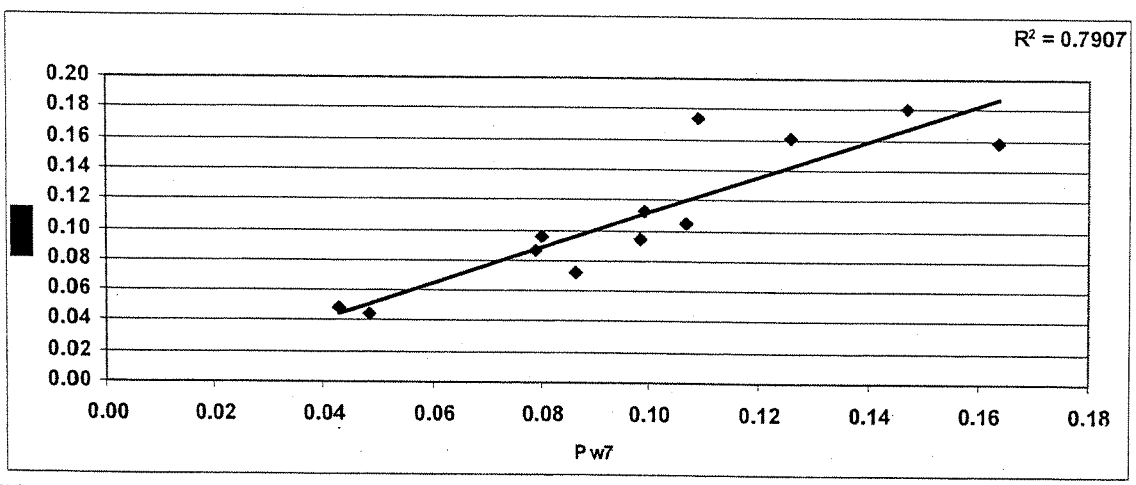

Figure 44. Moisture retention of sample soils at -15 bars left on the pressure plate for 7 days vs. samples left on for 14 days.

Table 15. Moisture retention at -15 bars for sample soils for periods of 10 and 14 days.

ID #	Days	Wet Weight	Dry Weight	Moisture Content	Days	Wet Weight	Dry Weight	Moisture Content
8	10	21.82	21.14	0.03	14	26.51	25.63	0.03
12	10	24.01	23.06	0.04	14	22.33	21.45	0.04
23	10	23.13	21.15	0.09	14	23.59	21.92	0.08
34	10	20.41	18.43	0.11	14	34.72	30.25	0.15
36	10	25.93	21.97	0.18	14	30.33	26.44	0.15
44	10	31.53	26.11	0.21	14	29.61	24.72	0.20
8	10	27.93	26.98	0.04	14	29.61	28.68	0.03
12	10	5.72	5.55	0.03	14	25.82	24.83	0.04
23	10	21.68	19.75	0.10	14	27.37	25.31	0.08
34	10	24.82	22.52	0.10	14	25.17	23.00	0.09
36	10	29.76	25.31	0.18	14	30.85	26.95	0.14
44	10	31.21	26.03	0.20	14	28.07	23.86	0.18

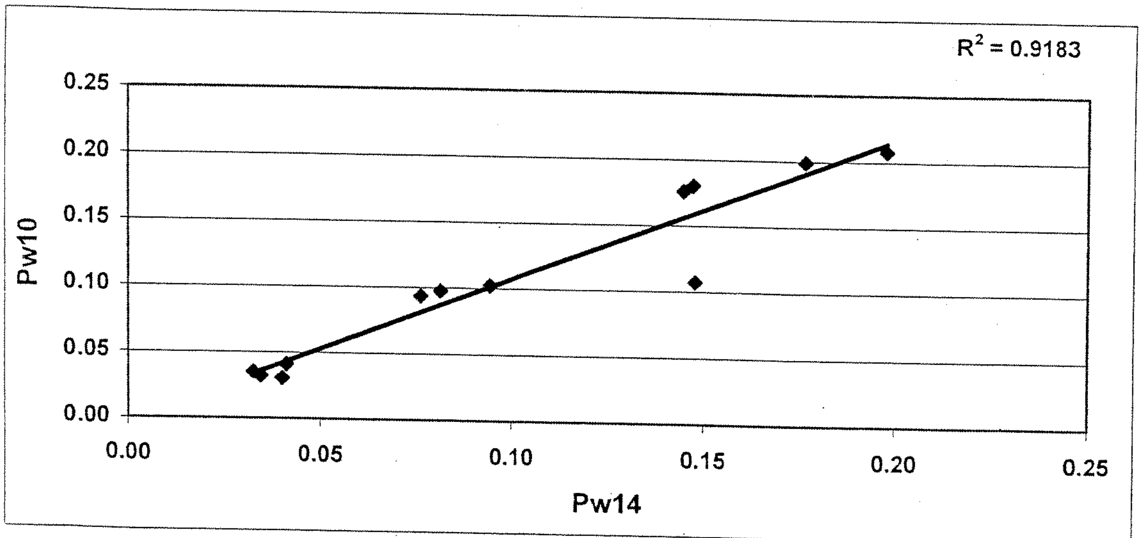

Figure 45. Moisture retention of sample soils at -15 bars left on the pressure plate for 10 days vs. samples left on for 14 days.

APPENDIX B

XRD FIGURES

Figure 46. XRD analysis for sample #1 (ID-SiCL 31) studied to determine the predominant clay type.

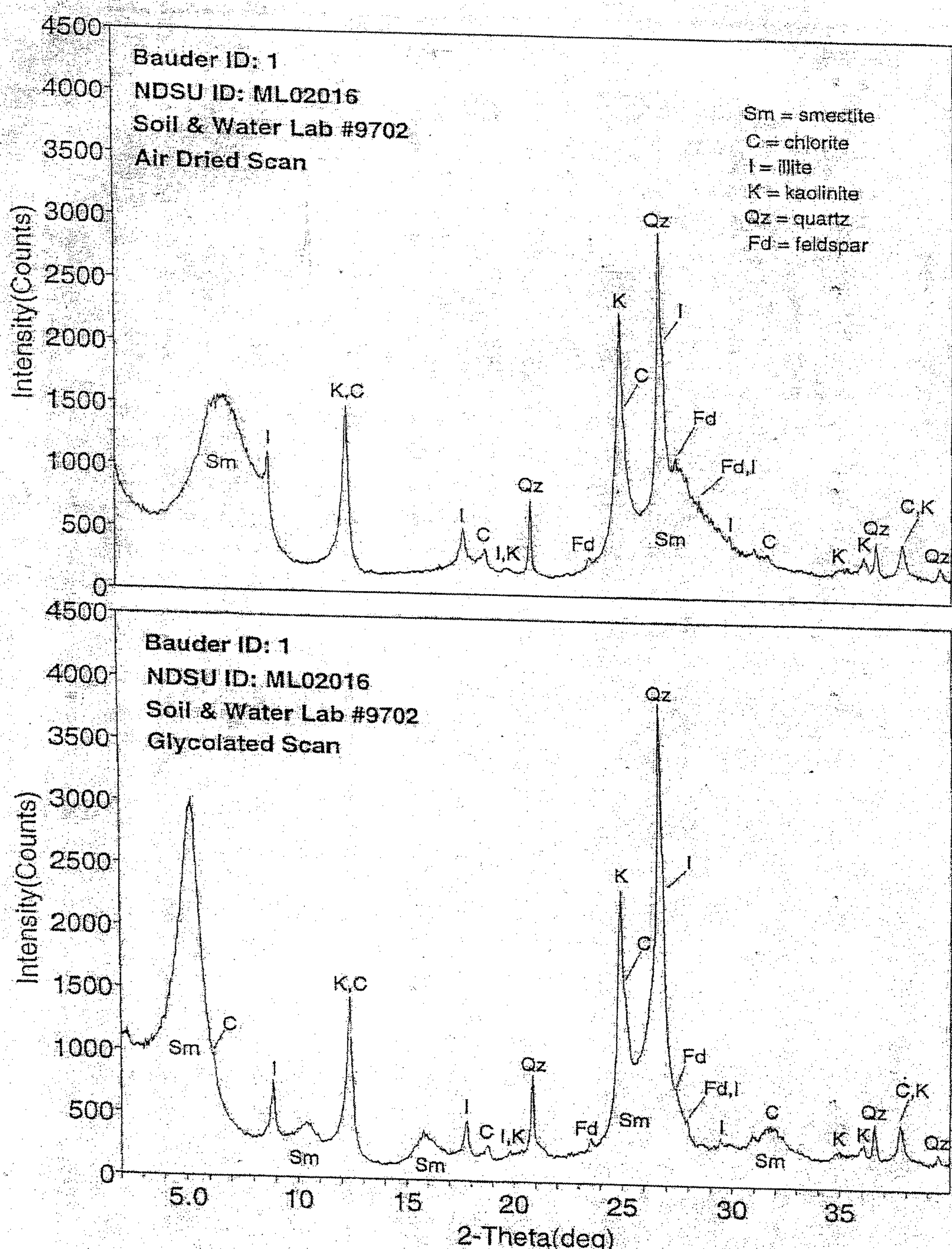

Figure 47. XRD analysis for sample #2 (ID-SiCL 28) studied to determine the predominant clay type.

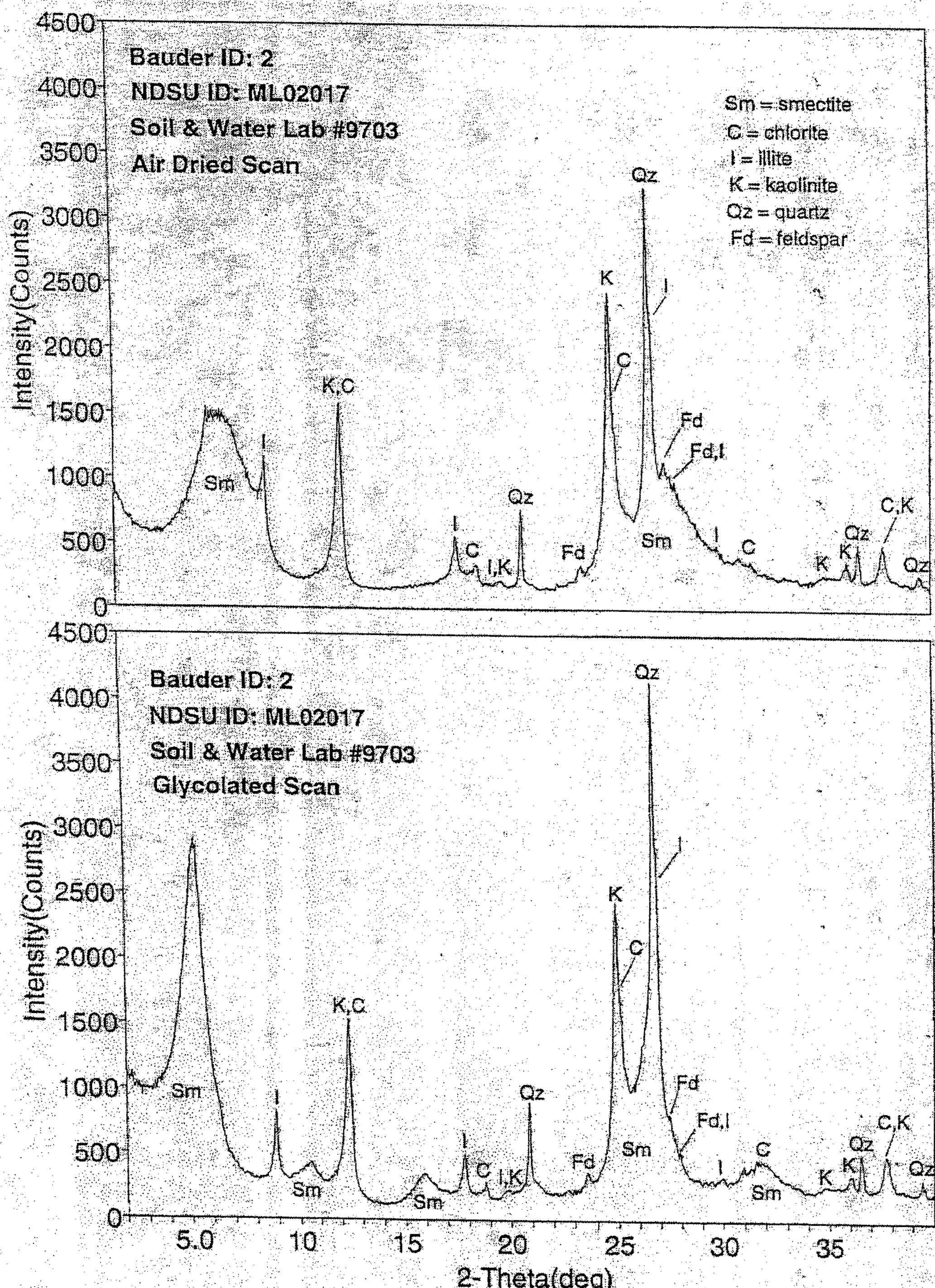

Figure 48. XRD analysis for sample #3 (ID-SiC 50) studied to determine the predominant clay type.

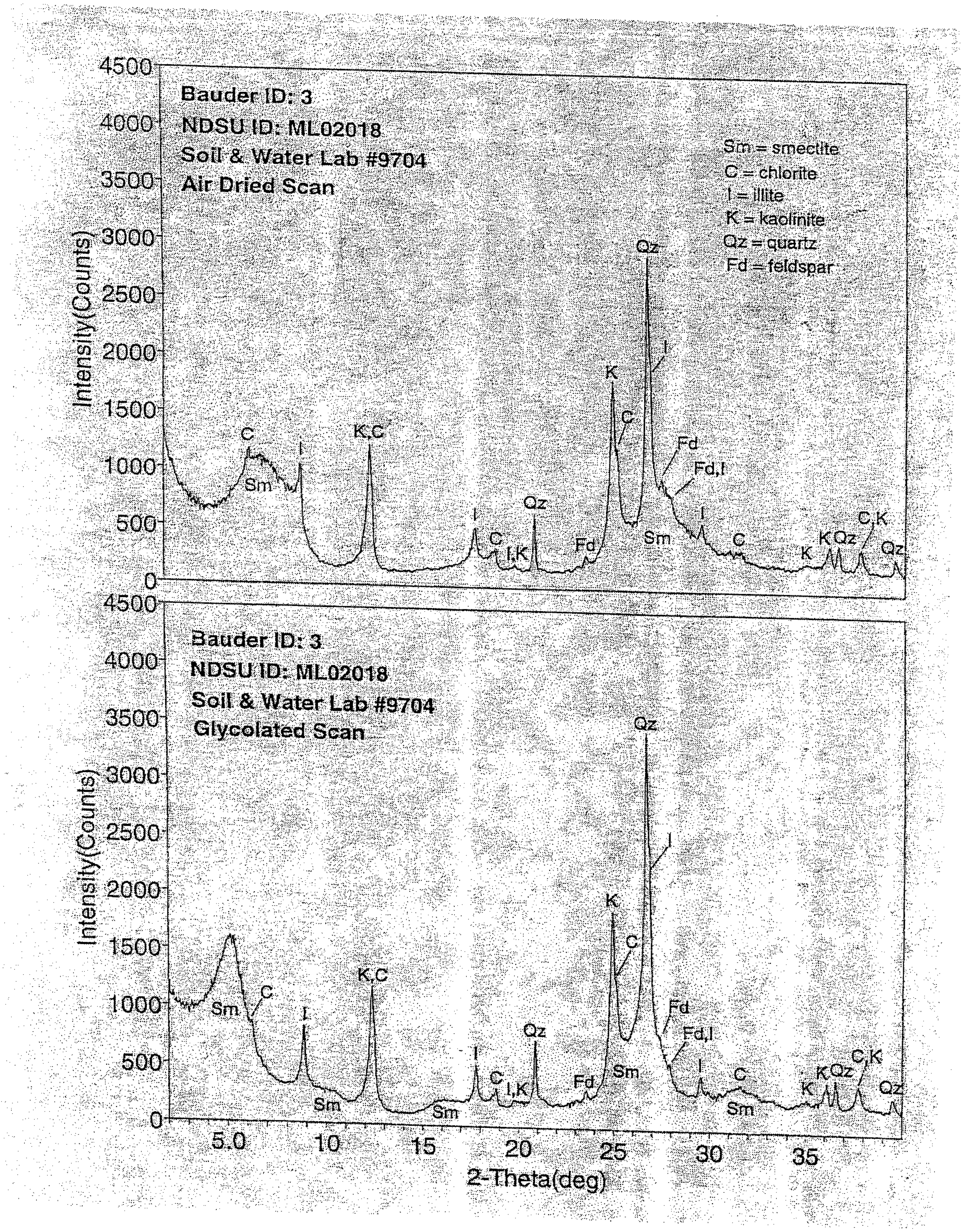

Figure 49. XRD analysis for sample #4 (ID-SiC 48) studied to determine the predominant clay type.

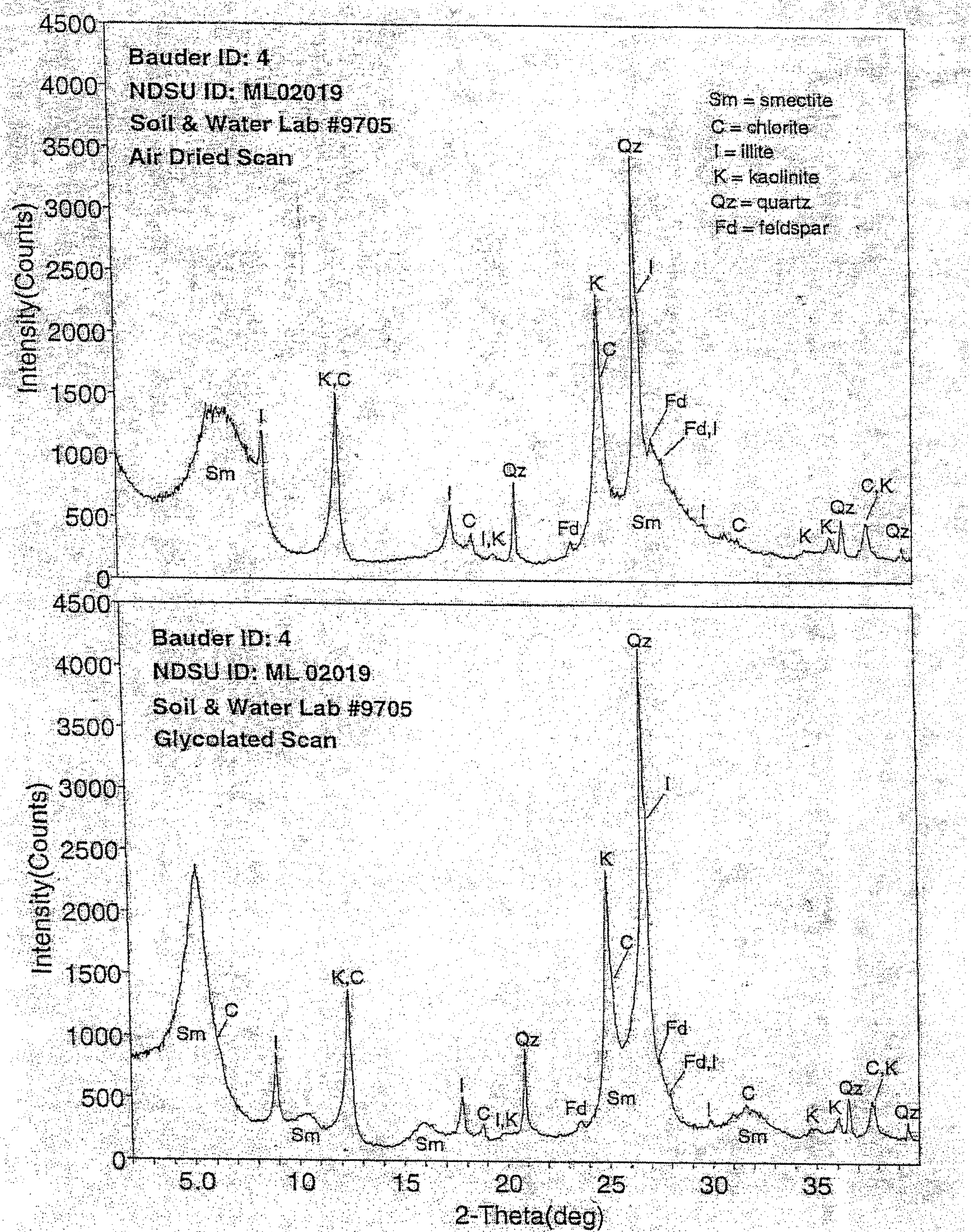

Figure 50. XRD analysis for sample #5 (ID-SiC 47) studied to determine the predominant clay type.

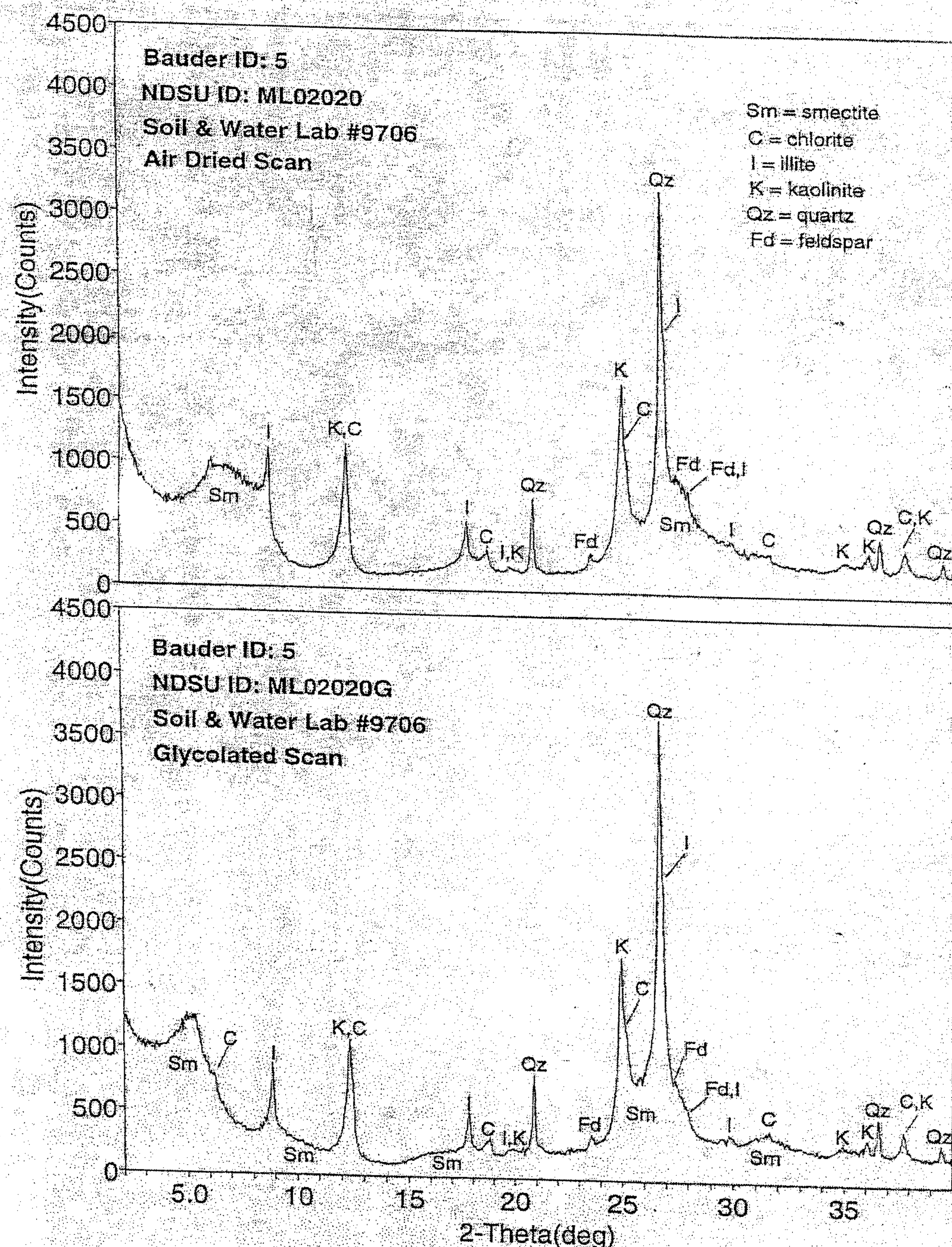

Figure 51. XRD analysis for sample #6 (ID-SiC 44) studied to determine the predominant clay type.