

Hydraulic property modification of saline-sodic soils by addition of calcium chloride
by Bryan Lee Woodbury

A thesis submitted in partial fulfillment of requirements for the degree of Master of Science in Soils
Montana State University
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Abstract:
Saline-sodic soils have developed in some irrigated areas of eastern Montana, due in part to increasing total dissolved solids of irrigation water and sodium accumulation in these irrigated soils. This accumulation has resulted in reduced yields, prompting farmers to consider application of amendments without evaluating the potential impact on irrigation return flow quality and/or soil physical properties other than sodium displacement.

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The second study utilized the remaining undisturbed soil columns to evaluate the effect of calcium chloride application on soil hydraulic properties. Calcium chloride was applied at a rate of 6.42 kg m-2 to soil columns. Following calcium chloride application, a 5 cm irrigation was applied and allowed to drain below soil surface. Intact cores were taken from surface and placed in Tempe cells to determine effect of treatments on soil hydraulic properties.

Irrigation of the soils with present and projected future water qualities resulted in decreased macro-porosity and reduced soil hydraulic conductivity. Addition of calcium chloride increased the macro-porosity but resulted in significantly elevated sodium concentration in drainage water. This elevated sodium concentration would likely have deleterious effects on groundwater quality.

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 13 May 1993

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LIST OF SYMBOLS

Symbol	Meaning
EPSR	Effective pore size radius
PAW	Plant available water
n	Number of hydrogen bonded molecules in polymer
σ	Surface tension of water (dynes cm^{-2})
r	Radius of pore (cm), radius of curvature
P_e	Pressure greater than atmospheric
g	Acceleration due to gravity (980 cm sec^{-1})
ρ	Temperature dependent density of water (g cm^{-3})
γ	Contact or wetting angle
h	Height of water rise in capillary tube (cm)
V_{max}	Terminal velocity
υ	Coefficient of velocity
F	Tangential force exerted on massless plate
A	Cross-sectional area of capillary tube
W	Distance between plates
F_s	Shear force
dV/dy	Velocity gradient perpendicular to stationary plate
C	Ion concentration at a specific distance from a charged surface
C_o	Ion concentration of bulk solution
Z	Ion valence
q	Electrostatic unit charge

LIST OF SYMBOLS- Continued

Symbol	Meaning
ψ_e	Distance dependent colloid electrical potential
k	Boltzmann constant
F_{ic}	Force of ion-clay interaction
D	Dielectric constant of solution
$q^{+/-}$	Electrostatic unit of cation/anion
d	Distance
ψ_z	Gravitational potential
ψ_m	Matric potential
ψ_p	Pressure potential
ψ_S	Solute potential
ψ_h	Hydraulic potential
F_p	Force between two points in a capillary tube
P_a	Pressure at point a
P_b	Pressure at point b
ΔP	Change in ψ_h between two points
R	Radius of capillary tube
L	Length of capillary tube (cm)
τ	Tangential force per unit area
v	Velocity of fluid flow
dv/dR	Change in velocity perpendicular to tube wall
T	Absolute temperature

LIST OF SYMBOLS-Continued

Symbols	Meaning
Q	Quantity of water
J_w	Water flux
K_i	Intrinsic permeability
HC	Hydraulic conductivity
ϵ	Water-filled porosity
f	Fluidity
η	Viscosity of water (poise)
HC_s	Saturated hydraulic conductivity
EC	Electrical conductivity
ESP	Exchangeable sodium percentage
SAR	Sodium adsorption ratio
MRC	Moisture release curve
PDTP	Percent of total porosity
TDS	Total dissolved solids
θ_v	Volumetric water content
θ_m	Mass water content
h_m	Matric head

ABSTRACT

Saline-sodic soils have developed in some irrigated areas of eastern Montana, due in part to increasing total dissolved solids of irrigation water and sodium accumulation in these irrigated soils. This accumulation has resulted in reduced yields, prompting farmers to consider application of amendments without evaluating the potential impact on irrigation return flow quality and/or soil physical properties other than sodium displacement.

Previous greenhouse experiments have been conducted with intact soil columns of loam, silt loam, and silty clay loam textures. Medicago sativa L. was grown in soil columns irrigated with an accelerated salt-loading schedule using past, present and projected future irrigation water qualities from the Powder River. Following the final harvest, two studies were conducted. One study utilized undisturbed soil cores from two of the five replicated soil columns to characterize long-term irrigation and subsequent calcium chloride application effects on soil hydraulic properties and drainage water quality. Identical cores were treated with two rates of calcium chloride, 6.42 kg m^{-2} and 7.73 kg m^{-2}. Calcium chloride solution was applied to the cores and passed through with a pressure head of 33.0 kPa to simulate free drainage. Leachate was collected and analyzed for sodium concentration. Following amendment application and leaching, replicated Tempe cell measurements in the pressure range 0-100 kPa were made to determine the effect of calcium chloride on soil hydraulic properties. Water outflow data were used to prepare moisture release curves and calculate pore size distribution.

The second study utilized the remaining undisturbed soil columns to evaluate the effect of calcium chloride application on soil hydraulic properties. Calcium chloride was applied at a rate of 6.42 kg m^{-2} to soil columns. Following calcium chloride application, a 5 cm irrigation was applied and allowed to drain below soil surface. Intact cores were taken from surface and placed in Tempe cells to determine effect of treatments on soil hydraulic properties.

Irrigation of the soils with present and projected future water qualities resulted in decreased macro-porosity and reduced soil hydraulic conductivity. Addition of calcium chloride increased the macro-porosity but resulted in significantly elevated sodium concentration in drainage water. This elevated sodium concentration would likely have deleterious effects on groundwater quality.

CHAPTER 1

INTRODUCTION

Many ancient civilizations came into power by forming an agricultural-based economy through extensive use of irrigation. These same civilizations experienced difficulty when their soils became too salty to sustain continued crop production (Schafer, 1982). Salinization of irrigated cropland not only has a serious impact on the economy of a nation but can influence quality of the environment.

It is generally assumed there is a direct relationship between irrigation of arid and semiarid soils and crop yield. About one-third of the earth's land is arid or semiarid (James et al., 1982). With the earth's population expanding exponentially, there is increasing need to bring this land under production. Irrigation is the key for enabling these regions to produce food necessary to feed this expanding population.

For the most part, all soil parent materials contain some salts (Schafer, 1982). Natural weathering processes release these salts, and water moving through this material solubilizes these salts (Rhoades, 1968a). Irrigation water containing excessive salts can have a deleterious effect on structure and physical properties of soil.

Fine-textured soils are adversely affected when sodium becomes the predominant cation on the exchange sites of clay minerals. Shrinking and swelling of the clay double layer in response to decreases and increases in soil water content weaken soil aggregates (Abu-Sharar et al., 1987 and Barnes, 1980). This weakening decreases overall effective pore size radius (EPSR). Soils with relatively smaller EPSR retain soil water at more negative potential than soils with larger EPSR for a given volumetric water content. Since plants are limited in the potentials they are able to generate for extracting soil water, this decrease in EPSR reduces the amount of plant available water (PAW) in soil.

The Montana Department of Natural Resources and Conservation is concerned about sodium accumulation in soils irrigated with Powder River water. This accumulation has resulted in reduction of irrigated crop yields over the past two decades (Gallagher, 1986). These yield reductions have prompted irrigators to consider various land management alternatives, including the use of surface-applied soil amendments.

Numerous studies have evaluated the effect of surface-applied amendments on crop yield, performance, and soil properties (Richards, 1969; Brock, 1991; Anderson et al., 1972). Farmers along the Powder River have considered application of amendments without evaluating the potential impact on irrigation return flow quality and/or soil

physical properties other than sodium displacement. Previous studies in this area have shown limited benefit from addition of either calcium sulfate ($CaSO_4$) or elemental sulfur (S) (Brock, 1991). The lack of consistent response to these amendments is due in part to the fact that many of the soils along the Powder River are saturated with respect to calcium carbonate ($CaCO_3$), and S is a common constituent of the irrigation water. Calcium chloride and/or $MgCl_2$ have been considered as alternative amendments (Bond et al., 1984). However, little is known about the effect of either of these amendments on soil hydraulic property modification or the effect on irrigation return flow qualities. Excessive Mg^{2+} cations on clay exchange sites can have a more deleterious effect than sodium on soil structure.

Objectives

The objective of this study was to evaluate the effect of reclaiming sodium-damaged soils from along the Powder River on water quality of irrigation return flows and shallow groundwater. This thesis provides baseline data for predictive modeling of irrigation leachate quality and return flow of sodium by soil type into the Powder River water table. Also, an attempt was made to quantify the potential impact of future irrigation and reclamation efforts on vadose zone salt loading.

Specific objectives were:

1. To determine the impact of $CaCl_2$ on the physical and hydraulic properties of three soils irrigated with simulated past, present, and expected future irrigation water qualities of the Powder River;
2. Evaluate the effect of $CaCl_2$ addition on quality of irrigation return flow.

CHAPTER 2

LITERATURE REVIEW

Much work has been done to examine effects of surface-applied amendments on soil physical properties, but little work has been done to assess the impact amendment rates have on the quality of groundwater and irrigation return flow. Sodium, the cation usually targeted for displacement by amendments, though not commonly considered a hazardous chemical, is deleterious to freshwater aquatic systems at high concentrations (Rhoades et al., 1973).

Soil water retention curves are used in models predicting non-saturated flow through soil, since fluid movement takes place only in those areas occupied by water. This approach is partially incorrect since part of the total soil water content is located in isolated pockets or dead-end pores not contributing to the overall hydraulic conductivity. Current methods for predicting solute transport rates have come under much scrutiny recently with the detection of hazardous chemicals in groundwater ahead of prediction.

It is necessary to understand concepts of water and its movement through soils before understanding amendment rate effects on groundwater quality and irrigation return flow.

Properties of Water

Molecular Properties

A water molecule consists of two hydrogen and one oxygen atoms, with a H-O bond length 9.7 x 10^{-11} m (Figure 1). The valence shell of the oxygen atom in the water molecule has two bonding and two nonbonding pairs of electrons. The four electron pairs are arranged in a tetrahedral shape with a bond angle of 105°, which gives the molecule an angular configuration. This configuration places the hydrogen atoms approximately 1.54 x 10^{-10} m apart (Figure 1).

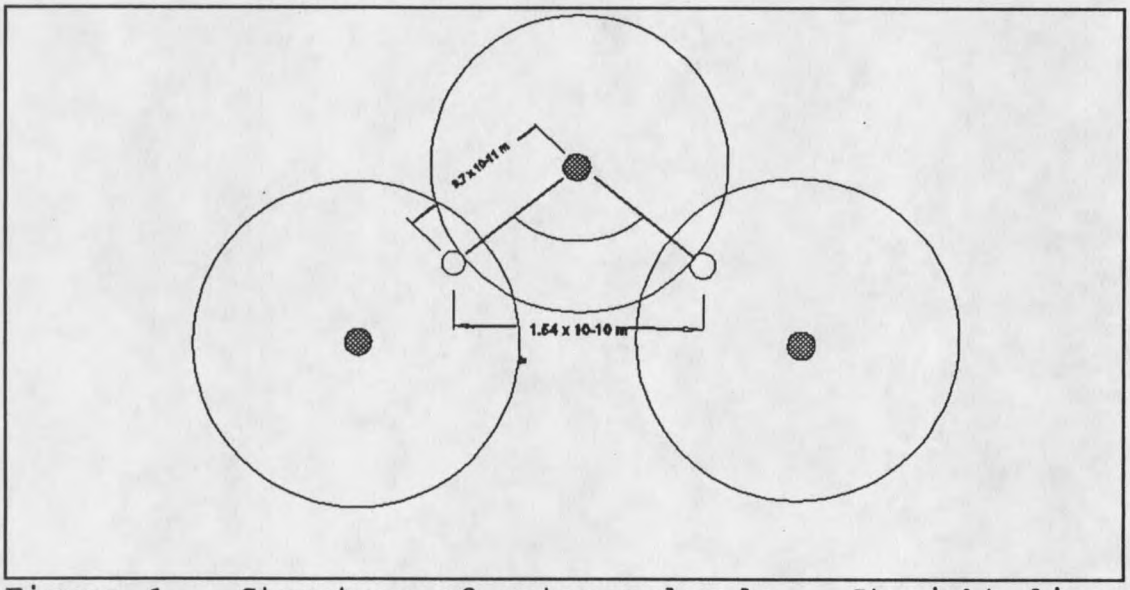

Figure 1. Structure of water molecule. Straight lines represent bonds, shaded circles are oxygen molecules, small open circles are hydrogen, and large open circles are electron cloud orbitals.

Water molecules exhibit distinct intermolecular forces

called hydrogen bonding (Mortimer, 1986). Hydrogen bonding occurs when hydrogen is covalently bonded to the small, strongly electronegative oxygen atom. The oxygen atom pulls the center of the electron cloud from the hydrogen, resulting in a significant partial positive charge on the almost exposed hydrogen proton. The electropositive hydrogen atom of water is attracted to unshared electrons of an electronegative atom, resulting in an electrostatic bonding force. Hydrogen bonds are relatively weak in comparison to covalent and ionic bonds. These bonds are, however, crucial to many important properties of water.

States of Water

Water molecules in vapor phase have a structure that is independent of other water molecules; although dimers and trimers structures are possible, they are very rare (Hillel, 1980). Water molecules in the solid phase have a rigid lattice structure with a tetrahedral configuration (Figure 2).

Liquid phase (state) water is somewhere between these two structures. When ice melts, the rigid lattice structure does not totally disappear. Hydrogen bonds between liquid water molecules hold the molecules in small, transient crystal configurations called "flickering ice crystals"

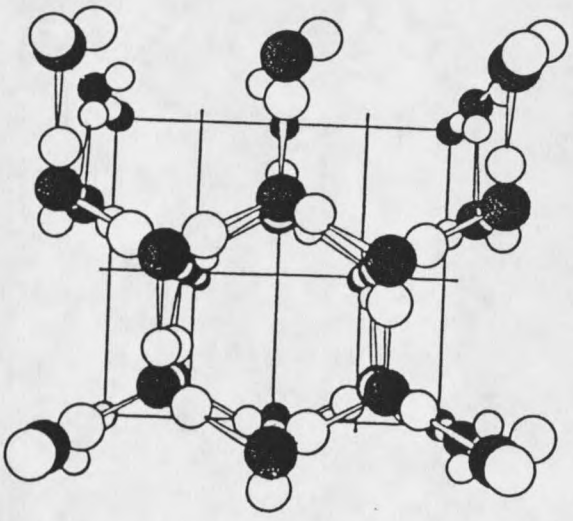

Figure 2. Schematic structure of an ice crystal. Oxygen atoms are shown in black and hydrogen atoms in white. Pegs linking adjacent molecules represent hydrogen bonds (from Hillel, 1980).

(Hillel, 1980). Molecules of water form and separate hydrogen-bonded polymers repeatedly in a random and transitory pattern designated as $(H_2O)_n$, where n is the number of hydrogen-bonded water molecules in a polymer at any one particular moment in time. These polymers have a quasi-crystalline structure with an average n of about 40; however, these polymers associate and dissociate so rapidly that liquid water behaves as a homogenous liquid (Hillel, 1980). The average n size is dependent on temperature, since n decreases as temperature increases.

Fluid Properties of Water

Water has many unusual properties including: density

greater as a liquid than a solid; high heat of fusion; high heat of vaporization; high specific heat; high dielectric constant (Table 1). These unusual fluid properties for water are best explained by the frequency of hydrogen bonding taking place between individual molecules.

Table 1. Selected physical properties of pure water (from Jury et al., 1991)

Properties	Value	Units	Temperature (^{o}C)
Density			
(liquid)	0.998	g cm^{-3}	20
(solid)	0.910	g cm^{-3}	0
(vapor)	1.73×10^{-5}	g cm^{-3}	20
Heat of fusion	3.34×10^{8}	erg g^{-1}	0
Heat of vapor.	2.45×10^{9}	erg g^{-1}	20
Specific heat	0.999	erg g^{-1} $^{o}C^{-1}$	20
Dielectric con.	80		20
Thermal cond.	6.03×10^{3}	erg cm^{-1} s^{-1} $^{o}C^{-1}$	20
Viscosity	1.00×10^{-2}	g cm^{-1} s^{-1}	20
Surface tension	72.7	erg cm^{-2}	20

Fluid Properties

Surface Tension

When water has an interface with another fluid like air, molecules near the interface are subject to many forces. Molecules of water in the bulk fluid are hydrogen bonded to adjacent molecules in all directions. There is no net tension pulling bulk fluid molecules in any particular

direction. The molecules exposed to an air-water interface do not have tension in all directions since no hydrogen bonding exists between the molecules of the air and the molecules of water at the water surface. The water molecules at the interface have a net tension pulling them toward the bulk fluid, thereby forming a crystalline-like structure at the surface. The density of water at the air-water interface is greater than that of the bulk fluid. Since the arrangement of the molecules at the surface has greater order, the molecules at the surface have more energy per unit area than molecules in the bulk fluid. This force exhibited on the surface molecules is referred to as surface tension (σ).

Surface tension is the reason water will form a dome at the top of an over-filled glass. This curved surface at the air-water-solid interface is the basis for another important property of water--pressure gradient across a curved interface. The pressure is greater on the convex side of a curved fluid interface than on the concave side (Kirkham and Powers, 1972). This pressure difference is the result of tension created by stretching of the hydrogen bonds in the surface layer, changing the surface area on the opposing sides of this layer. The pressure at the surface at equilibrium can be described by Equation 1.

$$\frac{2\pi r\sigma}{g\rho} = \pi r^2 P_e \qquad [1]$$

where r is the radius of curvature, and P_e is the pressure greater than atmospheric, σ is surface tension, ρ is fluid density, and g is the acceleration due to gravity (see Figure 2). Rearranging and solving Equation 1 for pressure yields Equation 2.

$$P_e = \frac{2\sigma}{rg\rho} \qquad [2]$$

Contact Angle

When water is present in a three phase system, the angle measured from the water-solid interface to the water-air interface is called the contact angle (γ). When water is preferentially attracted to a solid phase with more force than the cohesive attraction to adjacent water molecules, the solid phase is considered "wettable" (Figure 3).

When the cohesive force between adjacent water molecules is greater than the attractive force between water molecules and the liquid phase, the solid is considered "non-wettable" (Figure 4).

Capillary Rise

When a small, glass capillary tube is placed in a reservoir of water exposed to atmospheric pressure, the adhesive force between the liquid and solid phase causes the water to move up the sides of the glass tube, forming a curved surface at the interface (Figure 5).

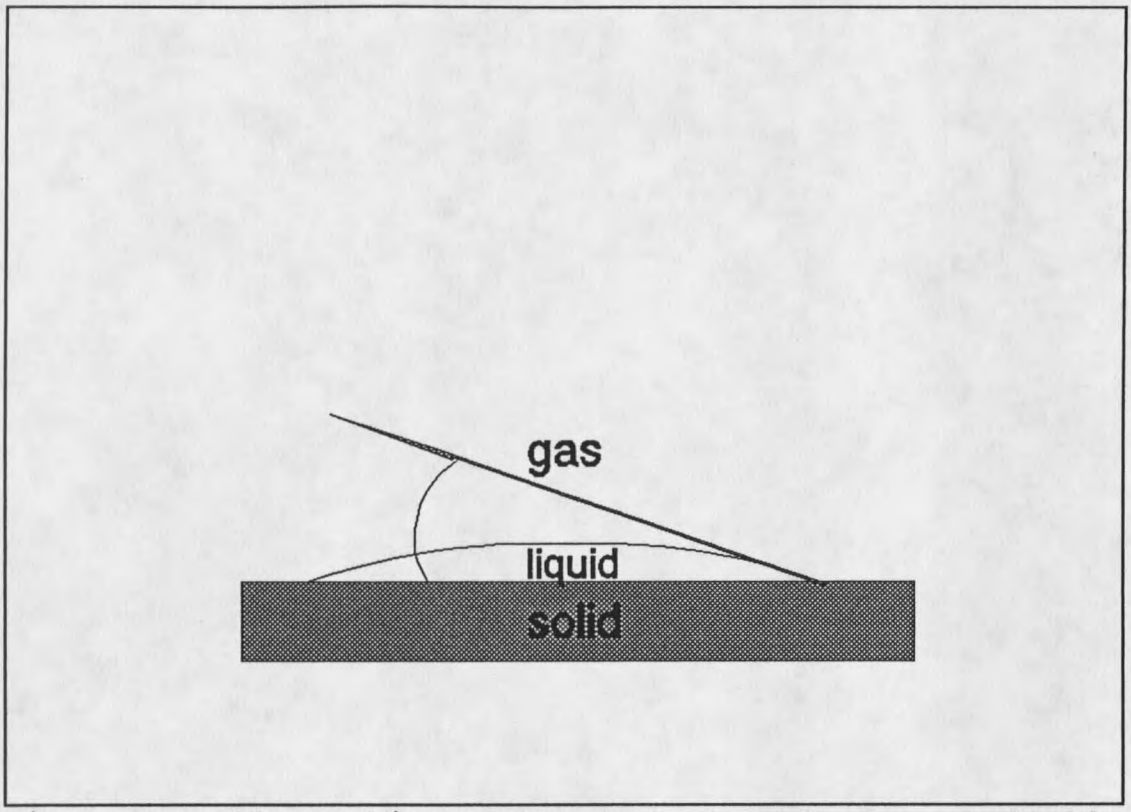

Figure 3. Illustration of the contact angle for a wettable solid.

This curved surface results in a pressure gradient, and atmospheric pressure pushes water up the tube. Water will rise up the capillary tube until the weight of the column of water equals the pressure gradient across the curved surface. Magnitude of the rise is dependent on the radius of the capillary tube and is described by Equation 3.

$$h=\frac{2\sigma\cos\gamma}{rg\rho} \qquad [3]$$

where h is height of water rise in capillary tube, σ is surface tension of water, γ is the wetting angle, r is the radius of the tube, g is acceleration due to gravity, ρ is

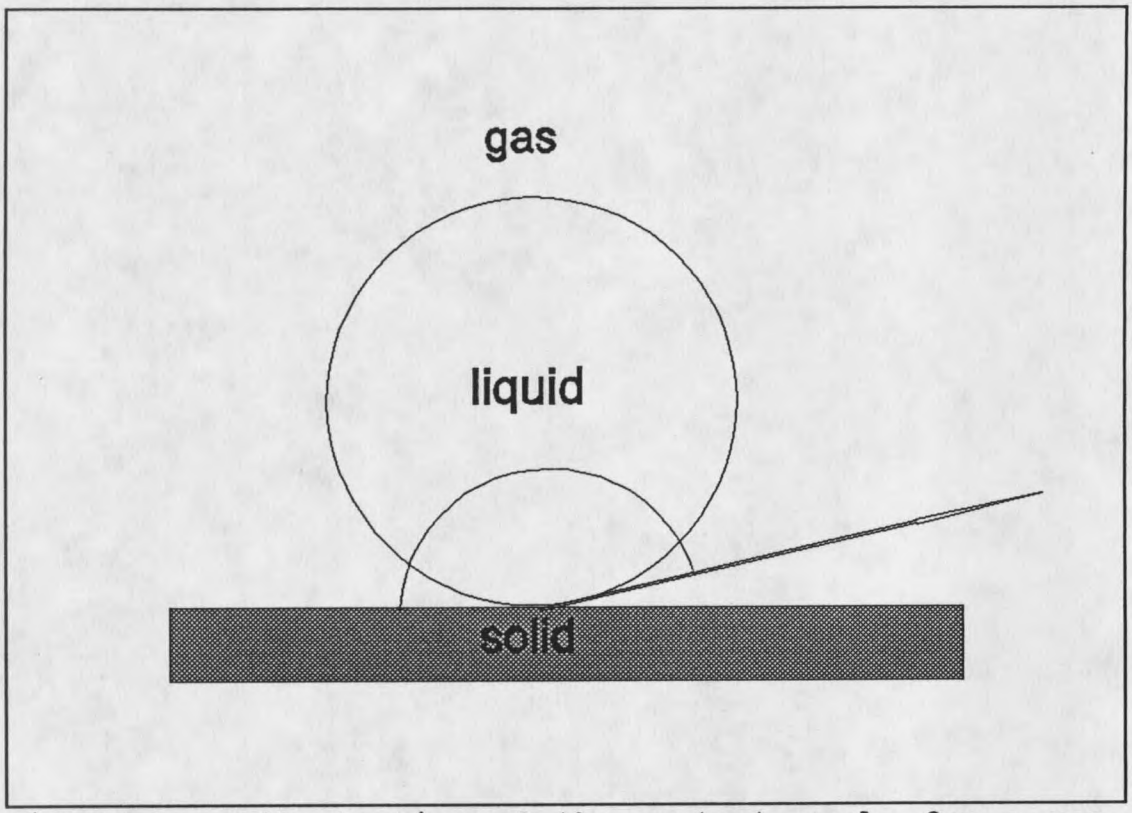

Figure 4. Illustration of the contact angle for a non-wettable solid.

the temperature dependent density of water.

Viscosity

Flickering ice crystals cause water to have quasi-liquid properties which restrict water molecules from movement within the bulk fluid. This resistant force is called drag or shear force and is best illustrated by example.

Consider a large massless plate placed on top of water and pushed in the x direction at a constant force. The plate will reach some terminal velocity (V_{max}). The water molecules attached to the moving plate will also be

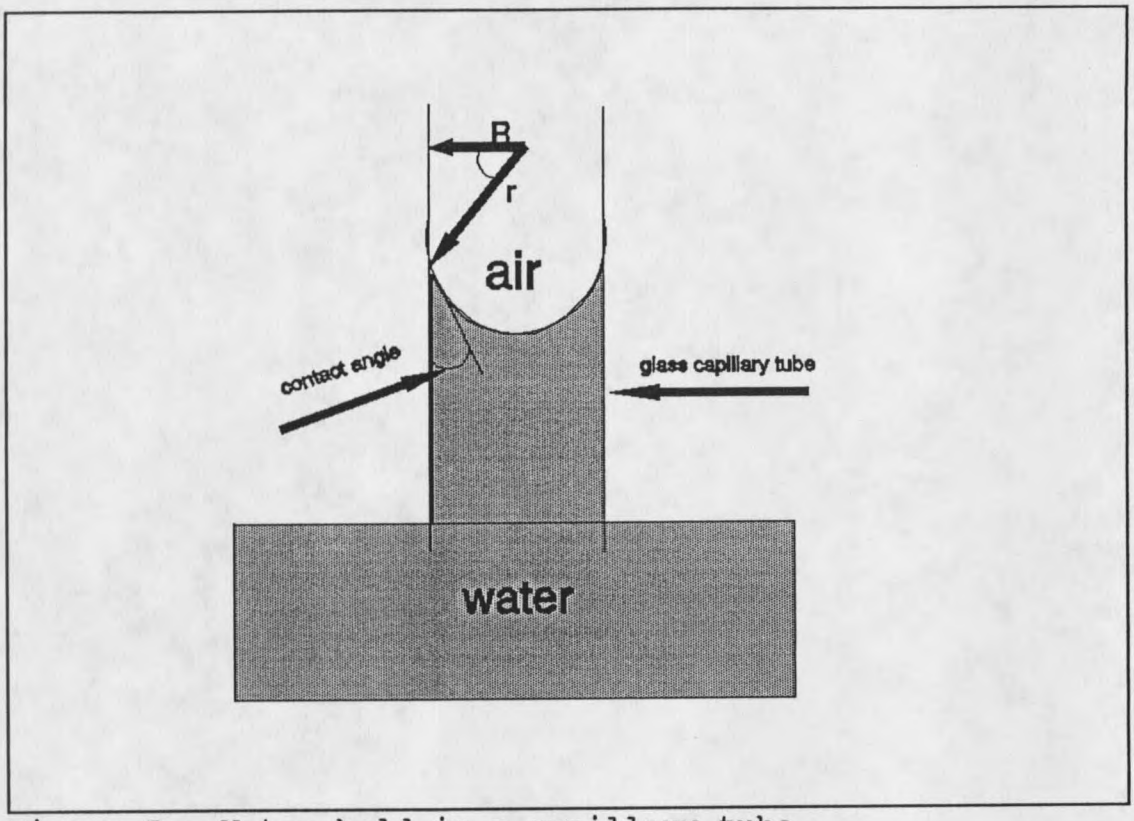

Figure 5. Water held in a capillary tube.

traveling at V_{max}, while the molecules attached to the stationary bottom will not move. This results in a velocity gradient perpendicular to the two plates. The tangential force per unit area on the plate and the velocity gradient perpendicular to the direction of movement is called the coefficent of velocity (ν) (Jury et al., 1991).

$$\nu = \frac{FW}{AV_{max}} \qquad [4]$$

The relationship between shear force and the velocity gradient is called Newton's law of viscosity (see Equation

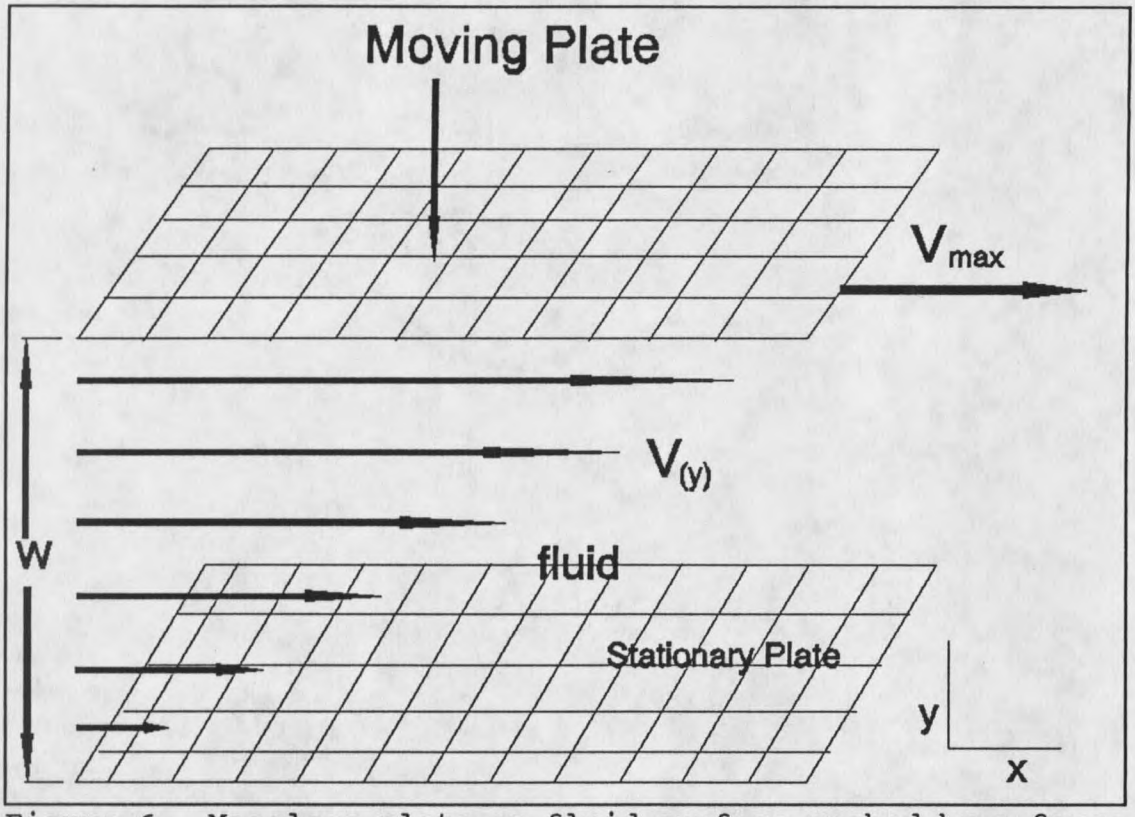

Figure 6. Massless plate on fluid surface pushed by a force in the x direction to a velocity of V_{max}. Velocity increases linearly in the y direction.

5) and is illustrated by Figure 6, where τ is shear force.

$$\tau = -\nu \frac{dV}{dy} \qquad [5]$$

Water Flow Near Particle Surfaces

Water flowing between soil particles has properties which are similar to the properties of water flowing in a pipe. The velocity of water decreases as the molecules get closer to the stationary particle surface. Water molecules adjacent to the soil particles are held in a rigid crystalline structure in a low energy state (Stumm and

Morgan, 1981). This water contributes very little to the overall flow process since it is essentially fixed.

Another phenomenom affecting flow of water near particle surfaces is the electrostatic attraction water has for ions held in the clay double layer. Water molecules that surround charged ions impede ion transport, and the attractive force between water molecules and ions increases the force with which water is held in solution. Water is likewise attracted to charged ions held in the double layer, resulting in properties similar to a semi-permeable membrane.

Diffuse Double Layer

Sand and silt soil particles are essentially electrostatically neutral and do not take part in the majority of physical, chemical, and biological reactions within most soil systems. Clay particles are electrostatically negative and play a vital role in water and solute transport. The net negative charge of clay particles attracts cations from the soil solution and repels anions away from clay particle surfaces. Under dry conditions, these cations are held tightly to the clay surface. This arrangement is called Helmholtz double layer (Figure 7). As water content of the soil increases, ion diffusion tends to dilute the concentration of cations with increasing distances from the clay surface. This results in

a diffuse double layer (Figure 8).

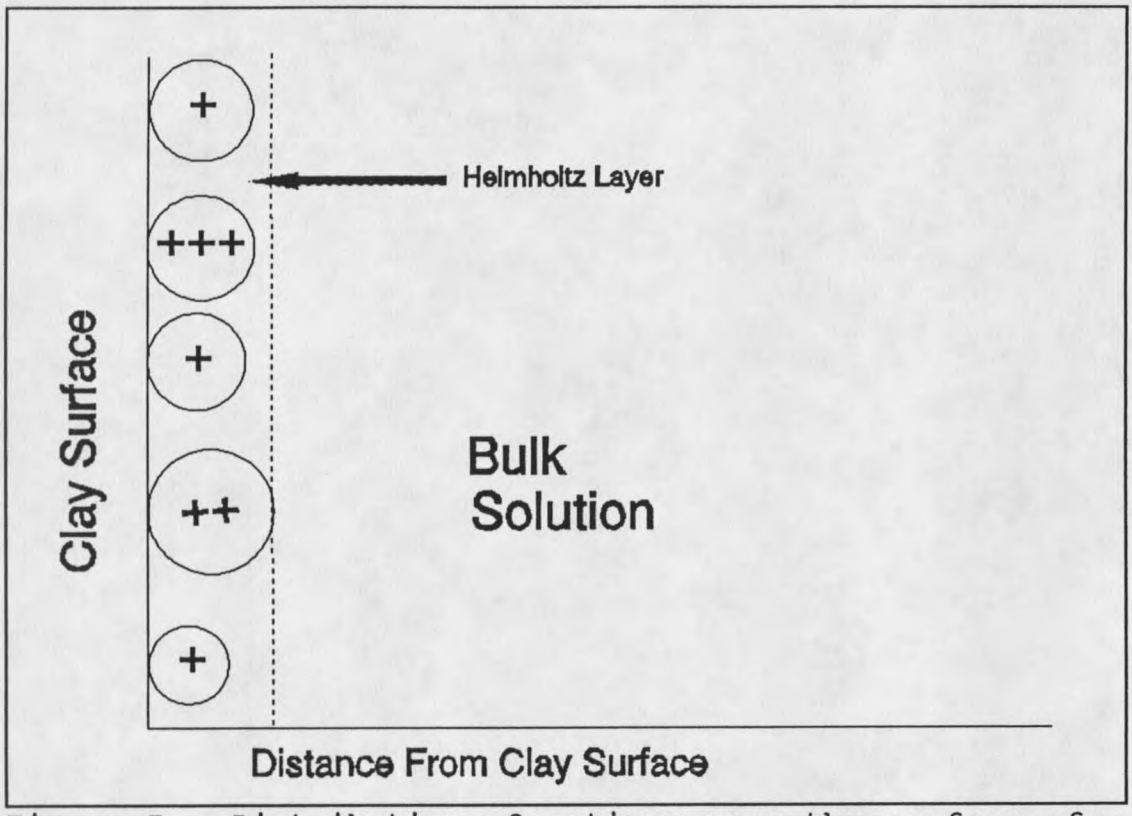

Figure 7. Distribution of cations near the surface of a clay particle, according to the Helmholtz model.

The fundamental theory of the diffuse double layer was developed independently by Gouy and Chapman (Barnes, 1980). The Gouy-Chapman theory of the diffuse double layer has three basic assumptions: (1) exchangeable cations are point charges, (2) colloid surfaces are planar and essentially infinite in magnitude, and (3) surface charge is distributed uniformly over the entire colloid surface (Bohn et al., 1985). These assumptions are inherently flawed but tend to cancel one another (Bolt, 1955).

Two forces controlling size of the diffuse layer are: (1) ion concentration-dependent gradient away from the clay

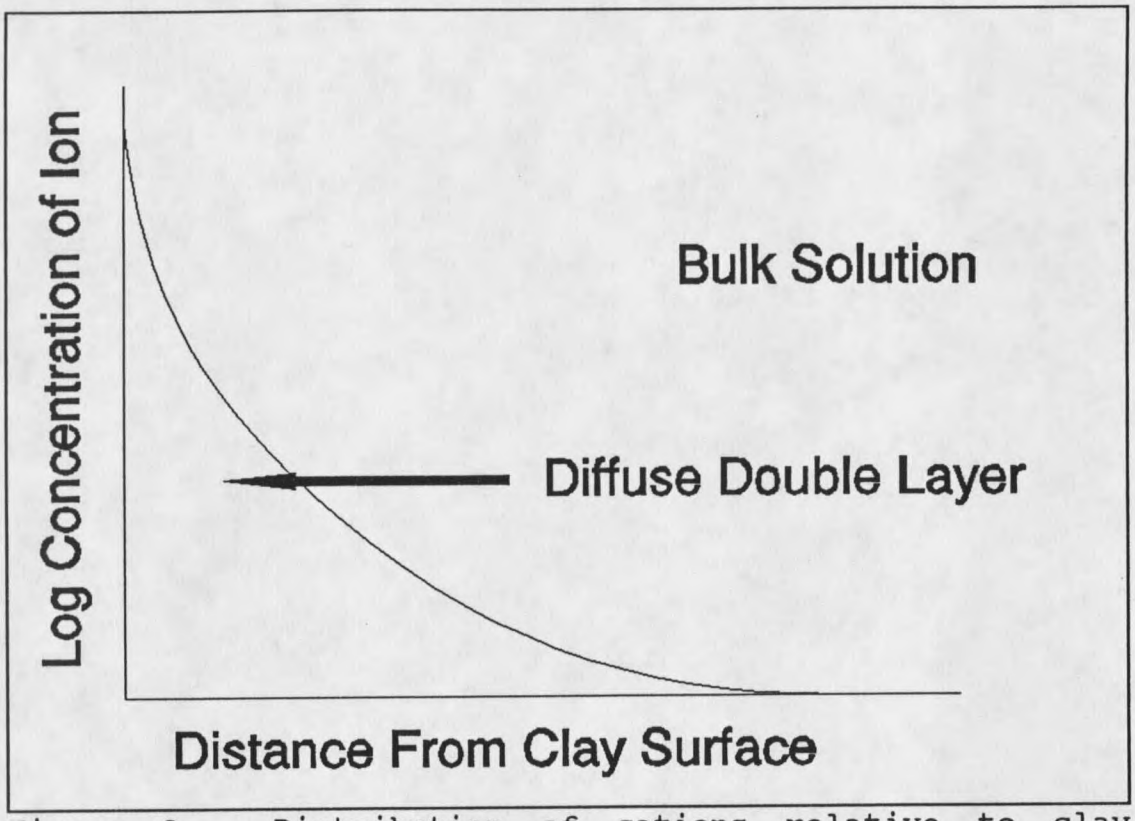

Figure 8. Distribution of cations relative to clay surfaces, according to the Gouy-Chapman model.

surface, and (2) Coulombic attraction of the electrostatic particles. Boltzmann combined equations describing these two forces and derived an equation with a particular solution of:

$$C=C_o*\exp\frac{-Zq\Psi_e}{kT} \qquad [7]$$

where C is the ion concentration at a specific distance from the charged surface, C_0 is the ion concentration in the bulk solution, Z is the valence of the ion, e is the eletrostatic unit charge, ψ is the distance-dependent electrical

potential of the colloid, k is the Boltzmann constant, T is absolute temperature.

Force of ion-clay interactions (F_{ic}) is governed by Coulomb's law (Equation 6):

$$F_{ic}=\frac{1}{D}\frac{e^{-}e^{+}}{d^{2}} \qquad [6]$$

where D is the dielectric constant of the solution, e^{-} is the electrostatic unit of the anion, e^{+} is the electrostatic unit of the cation, and d is distance between the point charge of the ion and point charge of the clay particle.

Force of ion attraction or repulsion increases with charge of the ion and with the clay surface charge density. Also, force of attraction or repulsion is inversely proportional to distance between the clay surface and the ion charge source.

Diffuse double layer is treated quantitatively either as: (1) the clay particle has a constant surface charge density; or (2) the clay particle has constant potential but varying surface charge density. The former is the traditional approach while the latter is more common for soil systems with pH-dependent charges (Bohn et al., 1985).

Stern improved on the Gouy-Chapman theory by assuming some ions are so tightly held on the colloid that they are stripped of their hydration sphere and adsorbed onto the

surface (Bohn et al., 1985). Distribution of ions in this layer is constant, with diffusion taking place beyond this layer. This adsorption of weakly hydrated ions offsets the negative surface charge density of clay, resulting in a smaller diffusion layer (Figure 9).

Water Movement in Soil

Water movement in soil takes place only in pores containing water. Size of pores, their interconnectedness (tortuosity), and potential gradient driving force dramatically influence the rate at which water moves through soil. Much work has been done trying to quantitatively

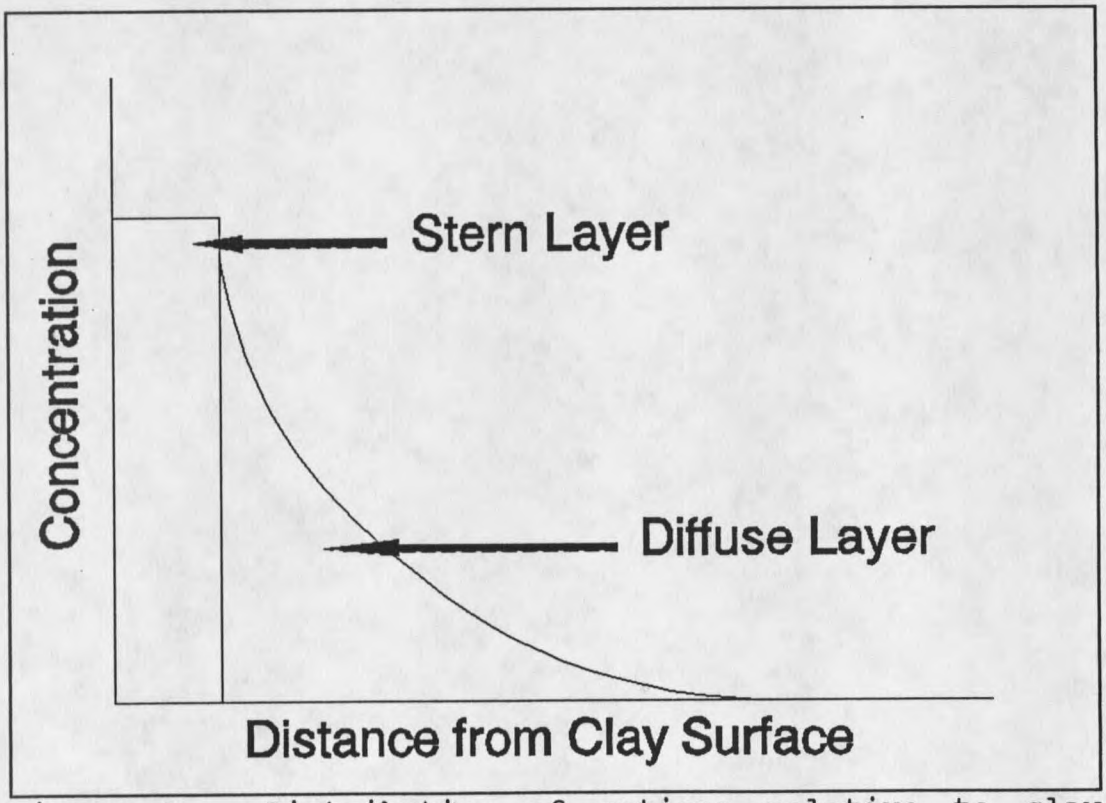

Figure 9. Distribution of cations relative to clay surfaces, according to the Stern model.

model soil pore size distribution and tortuosity. Due to the complexity of non-homogenous soils, models containing all the necessary parameters would be too complicated for practical use for predicting water movement in soil.

Energy State of Water in Soil

Water moves in response to a potential gradient between two points. Water flow in soil is dependent on several component potentials, including gravitational (ψ_z), matric (ψ_m), and pressure (ψ_p) potential. This combination of potentials is commonly referred to as hydraulic potential (ψ_h). For flow of liquid water in the absence of a semi-permeable membrane (e.g. root membranes, air-water interfaces), solute potential (ψ_s) is irrelevant.

Water Flow in a Capillary Tube

A simple system for describing water flow through porous media such as soil is the water-filled capillary tube. A round capillary tube of radius R and length L has water flowing through it in accordance with the potential difference between the two ends of the tube (Figure 10). Assuming no acceleration, the net force applied to the water is opposed by the viscous force of the fluid as described by Newton's law of viscosity. Accordingly, the net force of the water must be equal to zero. The ends of the capillary

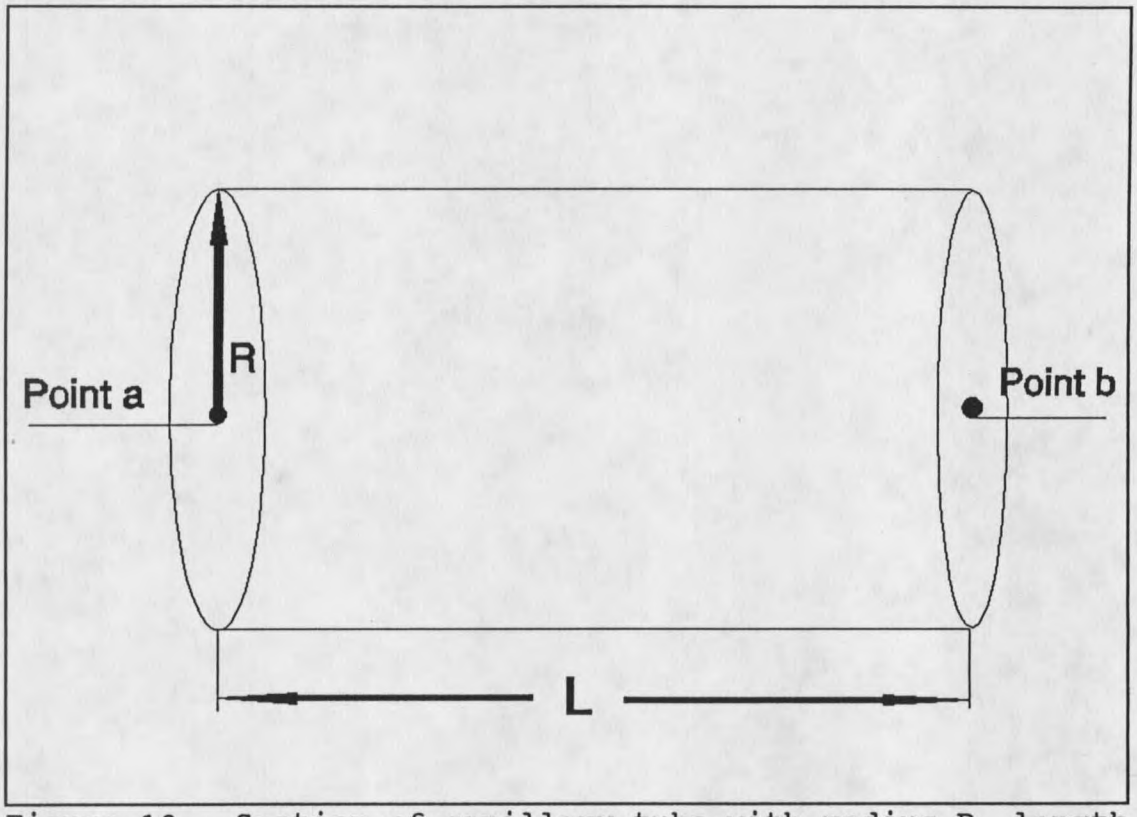

Figure 10. Section of capillary tube with radius R, length L, and pressure difference between point a and point b.

tube have force exerted on them equal to the hydrostatic pressure (P) times the cross-sectional surface area (A) (F=PA), such that there is a force gradient (F_p) from point A to point B. This force gradient is described by the equation:

$$F_p=P_a\pi R^2-P_b\pi R^2=\Delta P\pi R^2 \qquad [9]$$

where ΔP is the pressure difference from point A to B and R is the radius of the capillary tube. This pressure force is nullified by the shear force of the water attached to the capillary wall,

$$F_s=\tau(2\pi RL) \qquad [10]$$

where τ is the tangential force per unit area of the water. With acceleration of zero, $F_p=F_s$, which gives

$$\tau=\frac{\Delta PR}{2L} \qquad [11]$$

Relating τ to the rate of change of velocity V perpendicular to direction of fluid flow with Newton's law of viscosity gives

$$\tau=\frac{\Delta PR}{2L}=-v\frac{dv}{dR}, \qquad [12]$$

Separation of variables and integration of Equation [12] gives

$$v(r)=\Delta\frac{P}{4L_v}(R^2-r^2), \qquad [13]$$

Equation 13 describes the parabolic velocity profile of water flow through a capillary tube.

Poiseuille's Law

Once velocity of flow is determined, calculation of the quantity of water (Q) per unit area per unit time, or water flux (J_W), is possible since water is flowing at different

rates dependent on position in the capillary tube. The cylindrical shape of the capillary tube makes it possible to convert Equation 13 into a polar coordinate system and integrate across the tube cross-sectional area. Doing this yields

$$Q=\frac{\pi R^4 \Delta P}{8L}, \qquad [14]$$

which is referred to as Poiseuille's law. For a given length of tube with radius R, having a pressure gradient ΔP across the tube ends, a volume quantity (Q) of water will flow per unit time.

Dividing both sides of Equation 14 by the cross-sectional area of the capillary tube yields Equation [15]

$$J_w=\frac{R^2 \Delta P}{8L}, \qquad [15]$$

where J_W is the average volumetric water flux. Water flux is commonly used to describe the quantity of water flowing through a porous media per cross-sectional unit area per unit time.

Effect of Porosity on Hydraulic Conductivity

Knowledge of pore size distribution is useful when interpreting changes in soil physical properties caused by management practices (Bathke et al., 1991). Commonly used

techniques to evaluate pore size distribution of a soil include moisture release curves, non-polar liquid desorption, and mercury intrusion porosimetry (Diamond, 1970).

Klute and Dirksen (1986) have proposed a number of hydraulic models for laminar flow using the Hagen-Poiseuille equation. One of the simplest models describing porosity effects on water flow in soil is

$$K_i = \frac{\epsilon r^2}{8}, \qquad [16]$$

where K_i is intrinsic permeability, ϵ is the water-filled porosity, and r is the radius of pore spaces (Marshall and Holmes, 1988). Equation 16 shows the importance of pore radius and water-filled porosity in controlling intrinsic permeability.

Even though K_i is dependent only on the properties of the soil, properties of the fluid can be added to describe hydraulic conductivity (HC).

$$HC = K_i f \qquad [17]$$

where K_i is intrinsic permeability, and f is the fluidity. Fluidity is defined by

$$f = \frac{\rho g}{\eta} \qquad [18]$$

where ρ is the density of the fluid, g is the acceleration

due to gravity, and η is the dynamic viscosity of the fluid.

Effective pore size radius can be determined by evaluating the soil moisture release curve using Equation 3 (Childs and Collis-George, 1950). This is possible assuming there is no pressure potential, there is no semi-permeable membrane, and the gravitational potential is negligible. When these assumptions hold true, matric potential (ψ_m) can be equated to h in Equation 3.

Amendment Effects on Porosity

Salt retention is prevalent in many medium and fine textured irrigated soils because of a large irrigation water salt concentration and a limited leaching fraction (LF) (Anderson et al., 1972). Salt retention is aggravated in many arid regions by limited dilution from rainfall (Bernstein and Francois, 1973). Over a period of time, Na^+ will dominate the cation exchange sites of clays, resulting in dispersion of soil aggregates. Large pores will be sacrificed for smaller pores, causing substantially decreased hydraulic conductivity (Yousaf et al., 1987).

In accordance with Equation 3, small pores hold water at more negative ψ_m than large pores exposed to the same negative ψ_m. For plants to extract water, the potential within plant roots must be lower than the potential with which water is held in soil, thus creating a gradient driving force. Plant roots are limited in the potentials

they are able to create. This limitation reduces the gradient force with which roots can extract water.

Amendments have been used effectively to replace Na^+ on clay exchange sites saturated with divalent cations. This substitution results in soil flocculation, reversing the dispersive effect Na^+ has on soil aggregates. Flocculation leads to creation of additional larger pores, thereby reducing the potential roots need to exert for extracting soil water.

The two specific cations which are primarily used for replacement of sodium are calcium and magnesium. Many formulations of these cations are available as amendments; however, use of most amendments is prohibited by cost. Gypsum ($CaSO_4$) is the most commonly used amendment. Since the solubility of gypsum is relatively low, cation replacement is slow and high application rates of gypsum are necessary (Brock, 1991). Calcium chloride ($CaCl_2$) is much more soluble than $CaSO_4$, which causes faster replacement of Na^+ on clay exchange sites than $CaSO_4$, and can be applied at lower rates than $CaSO_4$.

Alternatively, magnesium chloride ($MgCl_2$) is a viable, cost-effective substitute for gypsum. Magnesium is preffered over Ca^{2+} on exchange sites (Bohn et at., 1985), and also increases the Mg/Ca ratio. Large Mg/Ca ratios increase the exchangeable Na or K (Rhoades, 1968b),

particularly in montmorillonitic soils.

Saturated Water Flow

Most soil contains a wide distribution of pore sizes. The largest pores in soil have the most significant impact on saturated HC, as described by Equation 12. However, since the exact geometry of all pores in the soil is unknown and interconnected pores of many different sizes are present, direct calculation of flow rates using Equation 12 is impossible. Average flow rates through many pores are used to define macroscopic flow equations of movement of water through soil. The first person to use this method was Henry Darcy (Jury et al., 1991).

Darcy's Law

Even though differences exist between the complex geometry of soil systems and the uniformity of a straight capillary tube, Darcy was able to use principles of flow through a tube to generate Equation 19,

$$\frac{Q}{A} = HC_s \frac{\Delta P}{L}, \qquad [19]$$

where HC_S is saturated hydraulic conductivity. Equation 19 (similar to Equation 15) describes water flow through a saturated, packed sand column. Saturated hydraulic conductivity is dependent on properties of the porous media

and properties of the fluid, but is constant for a given system. Rate of flow is dependent on length of the packed column and the hydraulic gradient across the ends of the column. Saturated hydraulic conductivity is independent of relative position within the column or column orientation.

Methods of Determining Hydraulic Conductivity

There are many different methods to estimate soil HC (Klute and Dirksen, 1986; Reynolds and Elrick, 1991; Ankeny et al., 1991; Campbell, 1974; van Genuchten, 1980; Schuh and Bauder, 1986, and Mualem, 1976b). Each method has advantages and disadvantages, dependent on application of the method, required input data, and reliability of the data.

Solution of unsaturated flow problems usually requires predetermination of soil hydraulic properties, such as: 1) the relationship between matric potential and soil water content, and 2) dependence of HC_s on θ (Mualem, 1986). These parameters are often difficult to determine because of cost, hysteresis, and soil heterogeneity. The impact of hysteresis is reduced in many models by utilizing the $HC(\theta)$ relationship instead of the $HC(\psi_m)$ relationship, since the hysteresis loop for the $HC(\theta)$ relationship is less significant than the hysteresis loop associated with the $HC(\psi_m)$ relationship (Klute and Dirksen, 1986).

Research effort has been undertaken to develop

numerical models describing fluid flow and mass transport in the unsaturated zone of soil using soil moisture release curves (van Genuchten, 1980). Moisture release curves on disturbed soils are relatively easy to obtain and have been used extensively in models for calculating unsaturated flow. Many models (Mualem, 1976a; Millington and Quirk, 1961; Brooks and Corey, 1966; Campbell, 1974) have been proposed for predicting HC from knowledge of the soil moisture release curve and HC_s. Mualem (1976a) proposed a simple integral equation for predicting the unsaturated HC. This approach enables a closed-form analytical expression (van Genuchten, 1980).

Complexity of soil-water systems limits the utility of these models for predicting HC over a wide variety of applications. Diversity and variability of required input parameters and variability of HC predictions limit the comparison of these predictive models and their output to each other, particularly under field conditions. Current use of HC models is not primarily directed at determining the precise value of HC, but at computing a comparative value of HC for evaluation of causal effects of treatments on HC.

CHAPTER 3

METHODS

Two different studies were conducted. One study utilized intact soil cores to characterize long-term irrigation and subsequent amendment application effects on soil physical and chemical properties and outflow water quality. Soil used in this study was obtained from two of the five replicated soil columns of a previously conducted greenhouse study (Thompson, 1991). The second study, a greenhouse investigation, utilized intact soil columns to evaluate subsequent amendment application effects on soil physical properties.

Laboratory Core Study

After approximately 18 months of an accelerated salt loading and crop consumptive use study, intact soil cores were collected from two of the five replications of intact soil columns (Thompson, 1991) by driving bevelled 0.09 m long by 0.054 m diameter aluminum rings into the soil at the surface, at 0.4 m, and at 0.8 m depths in the columns. Soil was then excavated around the bevelled rings to facilitate core removal. Excavated cores were transferred to 0.03 m long by 0.054 m diameter aluminum rings which could be

fitted inside Tempe pressure cells. The top and bottom portion of soil in the rings was removed to minimize physical property alteration resulting from the coring procedure. The aluminum rings with soil cores were wrapped in aluminum foil and placed in plastic containers along with bulk soil from the same depth as each respective core. The plastic containers were placed in a cold, wet storage room until chemical and physical analyses were completed.

Soil Selection and Site Location

Alfalfa (Medicago sativa var. Ladak 65) was grown in the greenhouse in replicated, intact columns of three soil series (Figure 11). The alfalfa crop was irrigated for approximately 18 months with an accelerated salt-loading irrigation schedule to represent past (WQ A), present (WQ B), and predicted future (WQ C) water qualities of the Powder River (Thompson, 1991) (see Table 2). Ion constituent concentrations for the irrigation water qualities are listed in Table 3. Criteria for soil selection and site location were described by Thompson (1991).

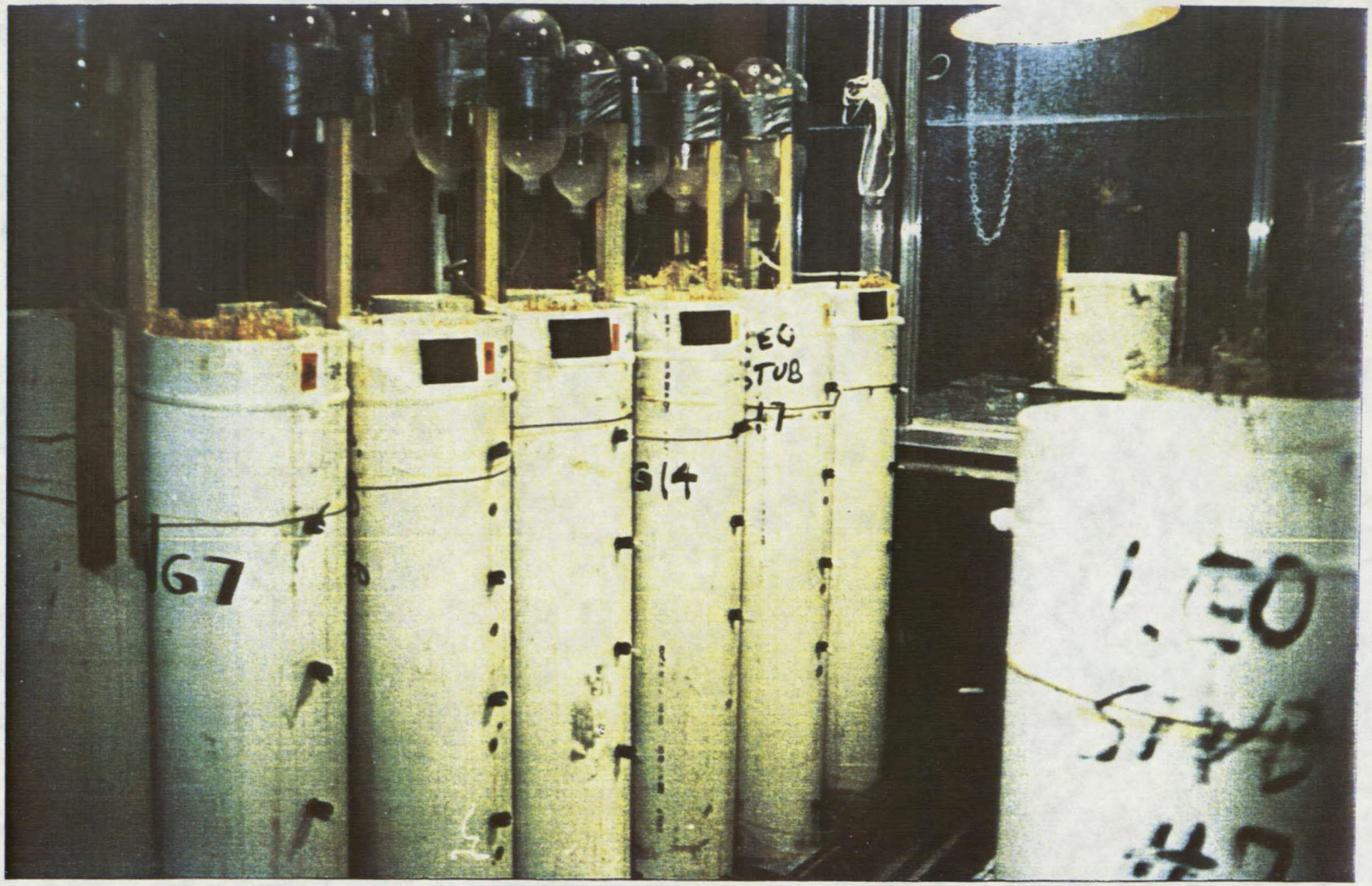

Figure 11. Intact soil columns in greenhouse.

Table 2. Irrigation water quality treatments (Thompson, 1991).

Treatment	TDS ($mg\ L^{-1}$)	EC ($dS\ m^{-1}$)	SAR	SAR_{adj}
A Past	750	1.0	1.1	2.3
B Present	1150	1.5	5.1	10.7
C Future	1650	2.4	9.6	19.7

Table 3. Ion constituent concentrations of water quality treatments (Thompson, 1991).

TDS	K^+	Ca^{2+}	Mg^{2+}	Na^+	Cl^-	SO_4^{2-}	HCO_3^-
$mg\ L^{-1}$	$mg\ L^{-1}$						
750	10	100	40	54	30	370	143
1150	10	75	40	220	85	510	220
1650	10	75	30	400	190	707	230

Soil Characterization

Particle Size Analysis

Samples from each of the soil replications were combined into a composite sample. Approximately 400 grams of ground, sieved 0.002 m soil from each composite sample were placed in Tempe cells. Distilled, deionized water was passed through each soil-filled cell at a pressure head of 33.0 kPa to remove soluble salts. Each cell was leached until the leachate had an electrical conductivity (EC) less than 0.750 $dS\ m^{-1}$. Following soluble salt removal, organic matter and carbonates were removed from each soil sample by oxidizing to completion the soil with 30% hydrogen peroxide.

The oxidized soil samples were dried, ground, and quantitatively passed through a 0.002 m sieve.

Particle size distribution was determined by the hydrometer method (Gee and Bauder, 1986). Sedimentation measurements were made at 0.5, 1.0, 3.0, 10.0, 30.0, 60.0, 90.0, 120.0, 1440 minutes after agitation. Summation percentage of particles in solution was calculated for each reading time interval. An equation was generated using TableCurve (release 3.11, Jandel Scientific, 1991) software. TableCurve uses Gauss-Jordan non-linear curve fitting procedures to generate an equation describing summation percentage data as a function of mean particle diameter for each soil sample. USDA particle size limit classification criteria were entered in the equation to determine percentages for sand, silt, and clay.

Sand size summation percentages were determined by quantitatively transferring the sedimentation sample through a 5.3×10^{-5} m sieve, retaining only sand-size particles on the sieve. All material passing through the sieve was discarded. Sand fraction samples were dried, weighed, and placed in a weighed nest of sieves with 2.00, 1.00, 0.50, 0.250, 0.106, 0.053 mm openings. Sieves were shaken for approximately 10 minutes and weighed to determine gravimetric percentage of sand for each of the different USDA sand size classes. Summaries of results are listed in Appendix B.

Organic Matter

Organic matter was determined using a simplified colorimetric procedure (Sims and Haby, 1970) for each soil, depth, and water quality treatment. Organic matter determination was averaged for all replications of the same treatment (Appendix B).

Cation Exchange Capacity

A 1 g sample from each soil, depth, and water quality treatment combination was treated with a 2.0 N NaCl solution to saturate exchange sites with sodium. The soil and sodium solution was shaken and centrifuged. The supernatant was decanted and discarded. The soil was then washed, shaken, centrifuged, and decanted 4 times with a 95% ethanol solution. A 1.0 N solution of ammonium acetate was added to the soil to remove the Na from the soil exchange sites. Sodium concentration of the decanted 1.0 N ammonium acetate supernatant was determined by atomic adsorption.

Chemical Sampling

Saturated paste extracts were prepared from samples of bulk soil for each replication of soil, depth, and WQ combination, according to methods described by Rhoades (1982). Solution extracts were analyzed for pH, EC, and concentration of Na^{+}, Ca^{2+}, and Mg^{2+} by atomic absorption.

Physical Sampling

θ_m - h_m Determination

Intact soil cores from each replication of each soil, depth, and WQ combination were placed in Tempe pressure cells. To prevent physical alteration, cores were then saturated with water of quality equal to that previously used to irrigate the columns. A pressure head simulating a matric potential of 2.00 kPa was applied to each saturated soil core to equilibrate all cores at a comparative starting point. After start point was established, matric head (h_m) was incrementally increased and allowed to equilibrate at 10.0, 33.0, 50.0, and 100.0 kPa, respectively. Time was allowed between each increase in matric head for the soil cores to reach a steady state mass water content (θ_m). Gravimetric measurements of the Tempe cell were made when cores reached equilibrium at each matric head to determine water outflow by weight loss.

When equilibrium was achieved at 100 kPa, the Tempe cell chambers were weighed and dismantled. Soil was removed from the aluminum rings, weighed and placed in a convective drying oven at 105° C. The dry soils were weighed to determine 100 kPa θ_m. Mass water content for the other matric head increments was back-calculated using gravimetric water outflow data.

Hydraulic Property Determination

Outflow data were fitted to Equation 20

$$\ln \Psi_m = \ln a - b \ln \Theta_m \quad [20]$$

which is a linear form of an equation proposed by Gardner et al. (1970), describing ψ_m as a function of gravimetric (mass) water content. The b-coefficients (slopes) for each moisture release curve were used for statistical comparisons to determine significant differences in the $\Theta_m - h_m$ relationship among main treatments and interactive effects. Allowing for sign difference, matric head (h_m) was substituted for ψ_m in Equation 20 by using short cores (3 cm), thereby reducing $\Delta\psi_z$ to negligible levels and allowing ψ_m to remain the primary driving force. Since the magnitude of ψ_m is dependent upon the radius of the pore, a direct substitution of h for ψ_m was done, using Equation 3.

Amendment Rate

Exchangeable sodium percentage (ESP) of each bulk soil from each soil series by water quality treatment by depth combination was determined by the difference between total and soluble sodium. Total sodium percentages were determined by procedures described by Knudsen et al. (1985) and Rhoades (1982). Soluble sodium percentage was determined by procedures similar to CEC determination.

Amendment rates 1 and 2 were determined by estimating

the amount of amendment required to reduce the average ESP of soils irrigated with WQ B to an ESP of 15% and 7.5%, respectively. The average ESP of all surface soil following accelerated salt loading was 52%, with a standard deviation of 19.34%. Therefore, amendment rate 1 was 6.42 kg m^{-2} and rate 2 was 7.73 kg m^{-2}. The rates were based on the assumption of replacing 1 meq Na /100 g soil with each 0.348 kg m^{-1} $CaCl_2$ for the upper 0.15 m of soil (Richards et al., 1969). The $CaCl_2$ was applied in a solution.

All soil cores were saturated with water of the quality with which they have been previously irrigated, after which a pressure of 2.00 kPa was applied to each soil core to establish a uniform starting point. Ring extensions were added to each Tempe cell to facilitate addition of 60 ml of amendment water to each soil core. Once the amendment was added, a matric head of 33.0 kPa was imposed to simulate free drainage. The soil cores were allowed to achieve equilibrium. The drainage water was collected and analyzed for sodium concentration.

To determine the effect of amendment and rate on hydraulic properties modification, the soil cores were re-saturated using WQ B. Incremental matric head was applied and outflow data were collected as described in the previous section describing θ_m vs. h_m determination.

Greenhouse Study

Amendment Rate

Three of the five undisturbed soil columns previously irrigated on an accelerated salt loading schedule (Thompson, 1991) were treated with $CaCl_2$ at a rate equivalent to rate 1 of the laboratory core study. The $CaCl_2$ was dissolved in 250 ml of water and sprinkled on the surface of each column. A subsequent 5.0 cm irrigation was drip applied to each soil column. The irrigation water was allowed to freely drain past the surface and drain freely from the bottom of the columns. No suction was applied to the bottom of columns.

Intact cores were removed from the surface of each column once the soils reached approximate container capacity. The θ_m vs h_m relationship was determined for each core of each treatment, as previously described. The outflow vs. pressure head data were compared statistically. Bulk soil from the surface of each column was placed in plastic containers and stored in a cold, wet storage room until chemical analyis could be completed.

Statistical Analysis

Significance of differences in hydraulic properties due to main treatments and interactions was determined from ANOVA of the b-coefficients derived with Equation 20 for each replication of each treatment. Analysis was completed

as a repeated measure of θ_m as a function of h_m. The study design was a randomized, complete block, three-factor experiment. Main treatment factors were water quality x soil series x amendment rate.

CHAPTER 4

RESULTS

Laboratory Core Study

All main treatments caused significant differences (α = 0.05 level) in calculated slopes of the θ_m vs. h_m curves (Table 4). Calculated b-coefficients (slopes) and r^2 values for all replications of all treatment combinations are presented in Table 5. Main treatment effects on b-coefficients and means separation are shown in Figure 12.

Table 4. Results of analysis of variance for b-coefficients from Equation 20.

Source	DF	S.S.	M.S.	F-Value	P-Value
WQ	2	4619.7	2309.9	194.92	0.0000
Soil	2	2928.4	1464.2	123.56	0.0000
Amend	2	418.9	209.45	17.67	0.0000
WQ*Soil	4	2556.0	638.99	53.92	0.0000
WQ*Amend	4	878.75	219.69	18.54	0.0000
Soil*Amend	4	366.89	91.72	7.74	0.0003
WQ*Soil*Amend	8	1237.7	154.71	13.06	0.0000
Error	27	319.96	11.85		
n = 54 observations					

Table 5. Calculated b-coefficients and r^2 values for all main treatments.

WQ	Rep	Soil	Amend.	b-coef.	r^2
A	1	B	0	-8.01	0.94
A	2	B	0	-15.84	0.92
A	1	H	0	-12.00	0.96
A	2	H	0	-7.92	0.94
A	1	T	0	-15.18	0.97
A	2	T	0	-13.98	0.99
B	1	B	0	-13.77	0.99
B	2	B	0	-13.74	0.74
B	1	H	0	-9.55	0.99
B	2	H	0	-14.75	0.99
B	1	T	0	-19.3	0.98
B	2	T	0	-19.63	0.99
C	1	B	0	-13.85	0.96
C	2	B	0	-15.23	0.95
C	1	H	0	-33.89	0.98
C	2	H	0	-32.85	0.93
C	1	T	0	-71.97	0.91
C	2	T	0	-70.61	0.96
A	1	B	1	-8.01	0.94
A	2	B	1	-20.56	0.93
A	1	H	1	-11.4	0.96
A	2	H	1	-7.64	0.93
A	1	T	1	-16.69	0.97
A	2	T	1	-15.16	0.99
B	1	B	1	-12.49	0.99
B	2	B	1	-12.38	0.74
B	1	H	1	-10.22	0.99
B	2	H	1	-16.48	0.99
B	1	T	1	-20.59	0.98

Table 5. continued

B	2	T	1	-19.08	0.99
C	1	B	1	-14.09	0.96
C	2	B	1	-12.08	0.97
C	1	H	1	-34.79	0.98
C	2	H	1	-32.83	0.93
C	1	T	1	-69.09	0.89
C	2	T	1	-68.41	0.57
A	1	B	2	-10.82	0.99
A	2	B	2	-5.29	0.93
A	1	H	2	-6.07	0.98
A	2	H	2	-6.49	0.97
A	1	T	2	-16.82	0.99
A	2	T	2	-17.30	0.97
B	1	B	2	-10.68	0.99
B	2	B	2	-20.62	0.98
B	1	H	2	-11.45	0.98
B	2	H	2	-16.81	0.99
B	1	T	2	-26.73	0.99
B	2	T	2	-17.85	0.99
C	1	B	2	-13.94	0.98
C	2	B	2	-13.75	0.97
C	1	H	2	-29.95	0.96
C	2	H	2	-21.85	0.99
C	1	T	2	-24.12	0.88
C	2	T	2	-25.44	0.98

Note: WQ A, B, C, = WQ A, WQ B, WQ C, respectively;
Soil B, H, T = Busby, Haverson, Thurlow, respectively;
Amend 0, 1, 2, = Control, Rate 1, Rate 2, respectively.

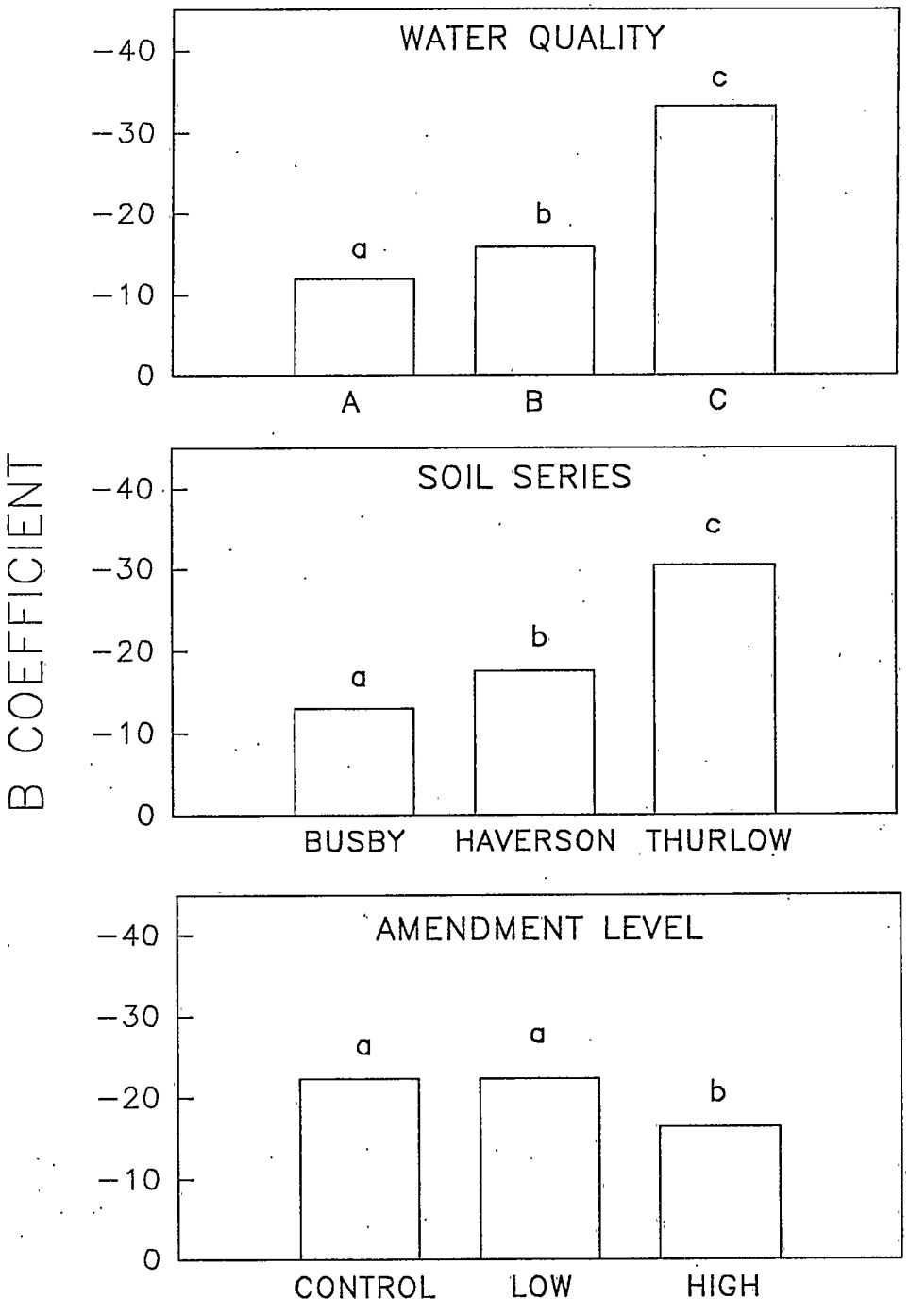

Figure 12. Average b-coefficients for WQ, soil series, and amendment rate effects. The b-coefficients within main treatments having the same letter designation did not differ significantly at $\alpha = 0.05$ level, according to Student's t test. (n = 18).

Similarly, all treatment interactions caused significant differences in b-coefficients (α = 0.05 level). Because of significance of effects of all main and interactive treatment combinations, only main treatments will be discussed.

Water Quality Effect on Hydraulic Properties

Although average b-coefficients were significantly different due to water quality treatments, the coefficients by themselves do not clearly illustrate the water quality treatment effects on soil hydraulic properties. Consequently, bar plots of mass water content (θ_m) with treatment mean separation were prepared for each h_m equilibration by averaging θ_m data over soil series, amendment rate, and replication for each water quality treatment (Figure 13, top). Effect of water quality treatment on pore size distribution was determined by calculating the percentage distribution of total porosity (PDTP) for each diameter class indicated in Figure 13 (bottom). Gravimetric outflow data between each sequential h_m was divided by total porosity to determine PDTP. The effective pore diameter was determined by re-arranging Equation 3 and solving for radius. Moisture release curves (MRC) were prepared by averaging h_m vs. θ_m data over soil series, amendment rate and replication for each water quality treatment (Figure 14).

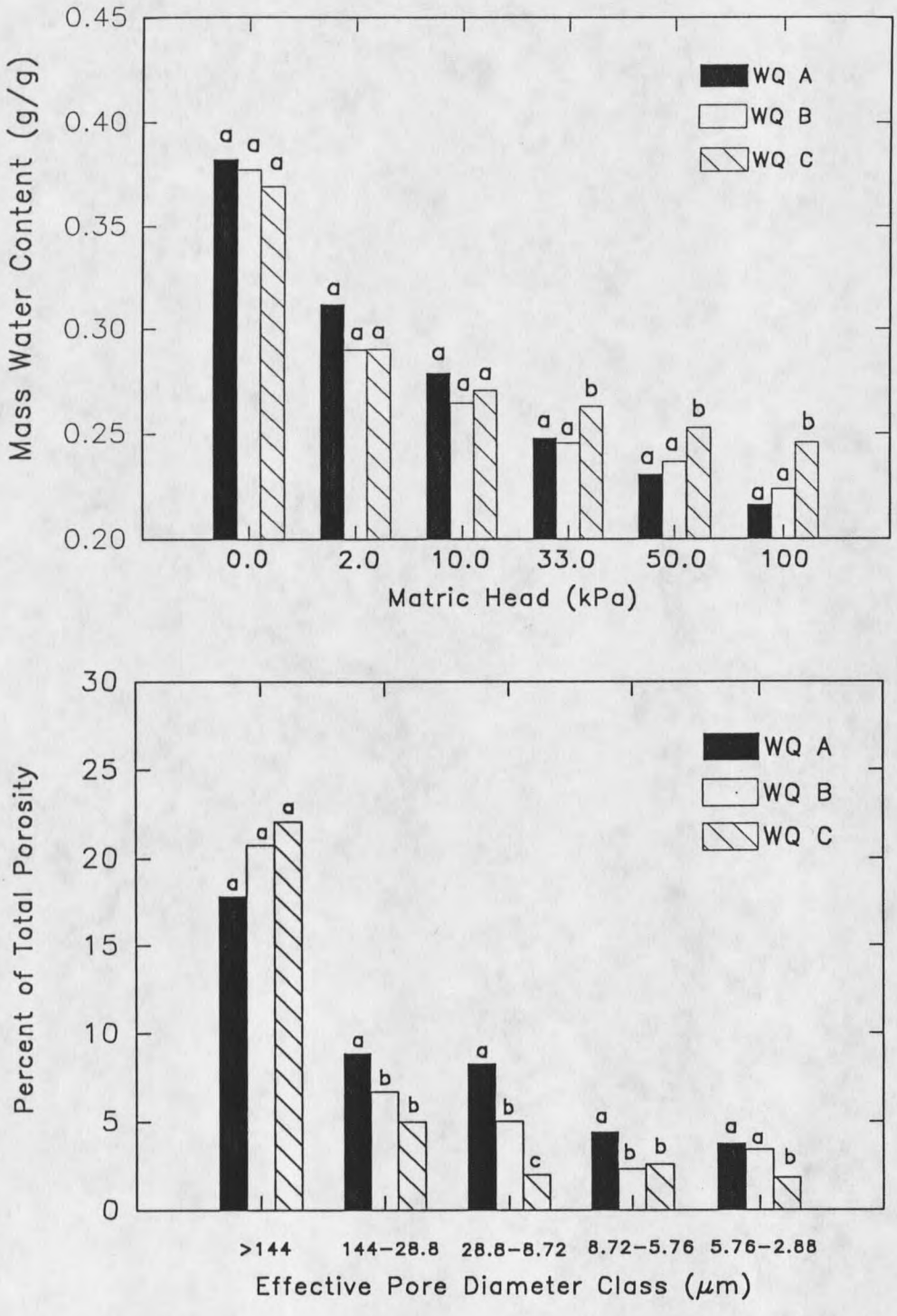

Figure 13. Average mass water content for each water quality and resulting percentage distribution of total porosity for each matric head increment.

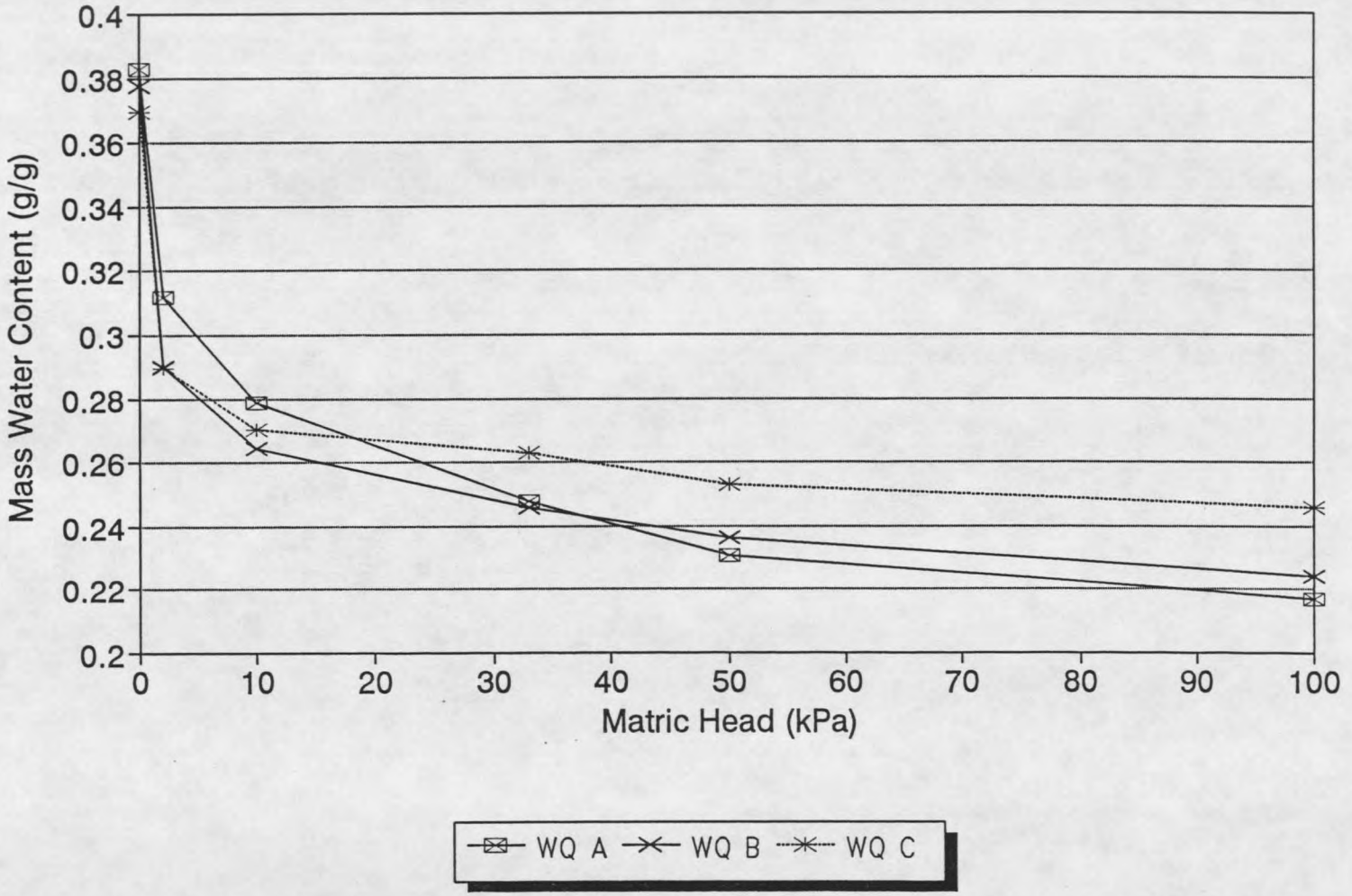

Figure 14. Average moisture release curve for each water quality treatment.

Differences in MRCs among the three water quality treatments are illustrated in the b-coefficients (Figure 12) and the treatment average θ_m, PDTP, and MRCs (Figure 13, top and bottom, and Figure 14). Mass water content and PDTP within matric head equilibrations having the same letter designation did not differ significantly at $\alpha = 0.05$ level, according to Student's t test.

Soils treated with WQ A had the most uniform PDTP across the measured pore diameter classes following accelerated salt loading and intensive cropping (Figure 13, bottom). Soils treated with water qualities B and C exhibited a substantial decrease in θ_m between 0 to 2.00 kPa matric head. Columns treated with water quality C retained more water at all matric heads >20.0 kPa than columns treated with water quality A or B and equilibrated at the same matric heads (Figure 14). The net result of this redistribution of pore sizes was the b-coefficient for cores treated with water quality C were substantially more negative than the b-coefficients for cores treated with water quality A or B(i.e., -11.95 vs. -15.90 and -33.25, respectively, Table 6).

Only 17.9% of the total porosity of soils treated with WQ A was >144 μm diameter; 25.4% of the total porosity ranged in diameter from 144 to 2.88 μm. Soils treated with WQ B had approximately equal distribution of pore percentages in the measured diameter classes, with 20.7% of

the total porosity in the >144 μm diameter range, and 17.4% of the total porosity in the 144 to 2.88 μm diameter range. Soils treated with WQ C had 22.0% and 11.4% of the total porosity in the same two diameter classes, respectively.

Increasing the salt concentration in the soil by means of irrigation seemed to cause an alteration in the soil hydraulic properties. The majority of the pores of columns treated with water quality B or C drained at less than 2.00 kPa matric head. This drainage at low matric head resulted in relatively few pores being drained at subsequently greater matric heads. This relatively rapid drainage with minimal applied pressure is best illustrated by Figure 13 (top) and Figure 14.

Soils treated with WQ C had greater θ_m at all matric heads >20.0 kPa than soils subjected to the same matric head equilibrations and treated with either WQ A or WQ B. A greater percentage of total porosity of the soils treated with WQ A drained when the matric head exceeded 20.0 kPa than did pores of soils treated with WQ B or WQ C.

The θ_m of the soils equilibrated at 100 kPa matric head also illustrates the effect of irrigation water quality on soil hydraulic properties. Increasing the salt concentration of irrigation water increased the percentage of pores with a diameter less than 2.88 μm (Table 6).

Soils treated with water quality A or B had the lower θ_m (0.217 and 0.224, respectively), while the soils treated

with WQ C had higher θ_m (0.246) at 100 kPa matric head. Significant difference in θ_m was detected at 33.0 kPa and all subsequent matric head equilibrations (Figure 13 top).

Table 6. Average b-coefficients for θ_m vs. h_m for all water quality treatments and resulting percentage distribution of total porosity. (n=18).

WQ	b-coef.	Matric Head	θ_m	Pore Diameter Class	PDTP
		kPa	g/g	μm	%
A	-11.95	0	0.384		
		2.00	0.329	>144	17.9
		10.0	0.279	144-28.8	8.9
		33.0	0.248	28.8-8.72	8.3
		50.0	0.231	8.72-5.76	4.4
		100	0.217	5.76-2.88	3.8
		% of total porosity >2.88 μm			43.3
B	-15.90	0	0.378		
		2.00	0.290	>144	20.7
		10.0	0.264	144-28.8	6.7
		33.0	0.246	28.8-8.72	5.0
		50.0	0.237	8.72-5.76	2.3
		100	0.224	5.76-2.88	3.4
		% of total porosity >2.88 μm			38.1
C	-33.25	0	0.370		
		2.00	0.290	>144	22.0
		10.0	0.270	144-28.8	5.0
		33.0	0.263	28.8-8.72	2.0
		50.0	0.253	8.72-5.76	2.6
		100	0.246	5.76-2.88	1.8
		% of total porosity >2.88 μm			33.4

Soil Series Effects on Hydraulic Properties

The procedures used to evaluate and illustrate the effect of soil series on soil hydraulic properties were the same as those used to evaluate water quality treatment effects. Differences in the b-coefficients for the three soil series are illustrated in Figure 12. Average Θ_m, PDTP and MRCs for all three soil series are illustrated in Figure 15 (top and bottom) and Figure 16.

Significant differences in Θ_m were found among all soil series for 0.0, 33.0, 50.0, and 100 kPa matric heads (Figure 15, top). No difference in Θ_m was found among soil series at 2.0 kPa, and only Thurlow was different from Busby and Haverson at the 10.0 kPa matric head.

Approximately 47% of the total porosity of the Busby soil had a diameter >2.88 μm; while 37.6% of total porosity of the Haverson soil and only 30.6% of total porosity of the Thurlow soil had diameters >2.88 μm (Table 7).

Busby's PDTP for pores with diameters >144 μm was significantly different than the PDTP for Haverson and Thurlow in the same diameter class. Significant differences in PDTP among all soil series were detected for pores in the 144-28.8 μm diameter class. Busby's PDTP was significantly different than Thurlow's PDTP in the 8.72-5.76 μm diameter class; however, Haverson's PDTP was not significantly different than Busby or Thurlow in the same diameter class.

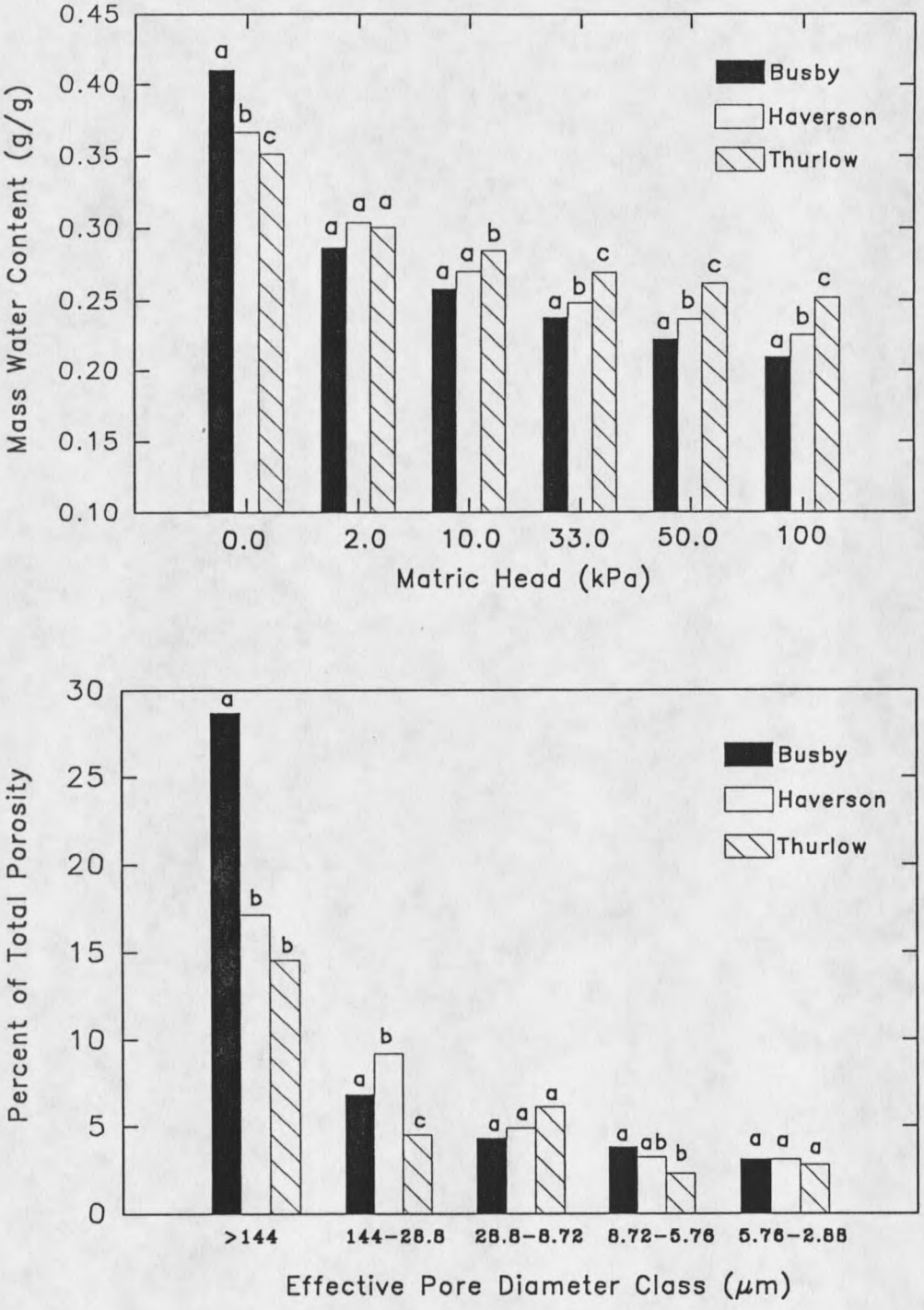

Figure 15. Average mass water content for each soil series and resulting percentage distribution of total porosity for each matric head increment.

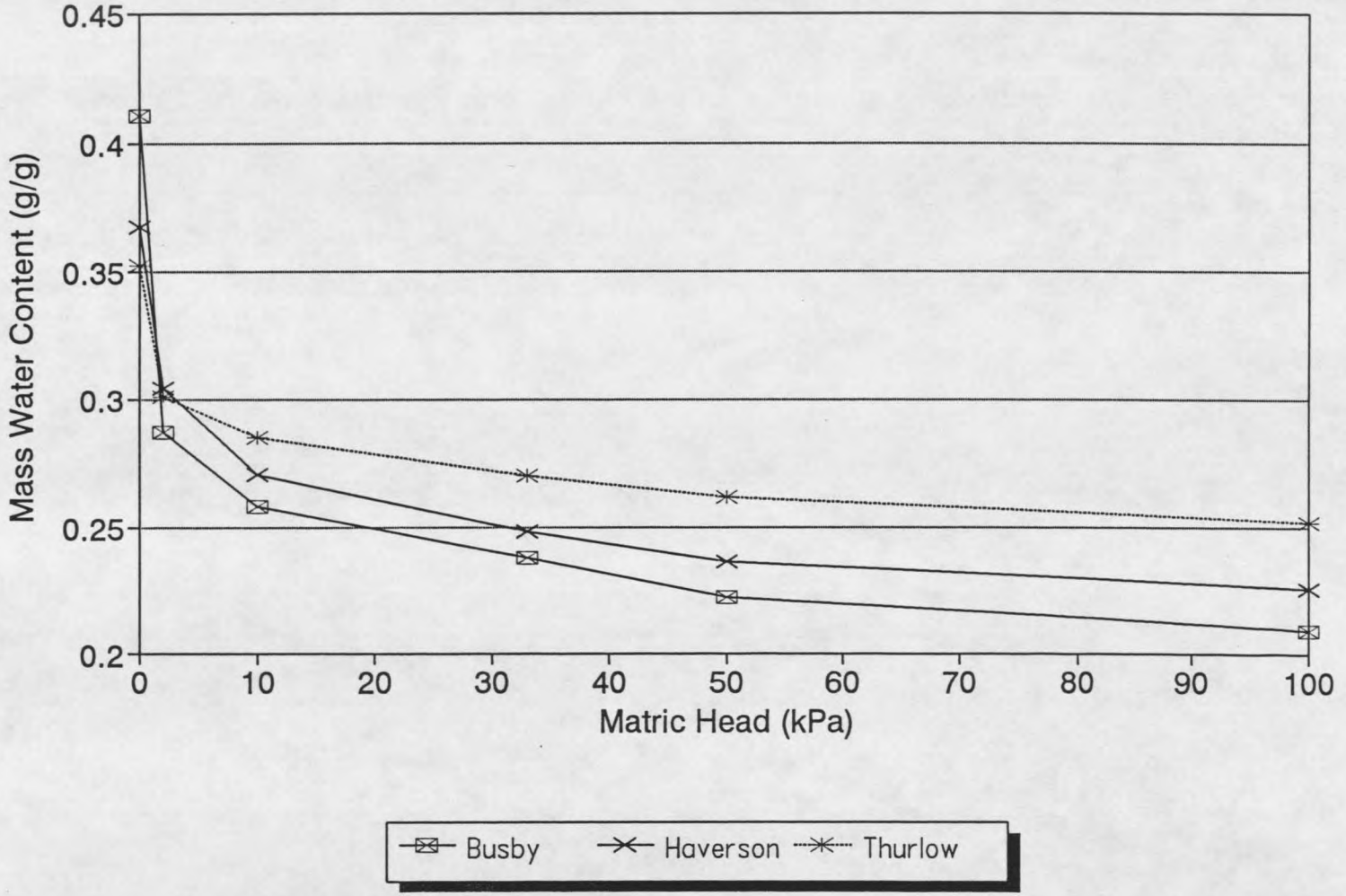

Figure 16. Average moisture release curve for each soil series.

Table 7. Average b-coefficients for θ_m vs. h_m for all soil series and resulting percentage distribution of total porosity. (n=18).

Soil Series	b-coef.	Matric Head	θ_m	Pore Diameter Class	PDTP
		kPa	g/g	μm	%
Busby	-13.05	0	0.415		
		2.00	0.277	>144	28.9
		10.0	0.258	144-28.8	6.8
		33.0	0.238	28.8-8.72	4.3
		50.0	0.222	8.72-5.76	3.8
		100	0.209	5.76-2.88	3.1
		% of total porosity >2.88 μm			46.9
Haverson	-17.61	0	0.367		
		2.00	0.304	144	17.2
		10.0	0.270	144-28.8	9.2
		33.0	0.248	28.8-8.72	4.9
		50.0	0.237	8.72-5.76	3.2
		100	0.225	5.76-2.88	3.1
		% of total porosity >2.88 μm			37.6
Thurlow	-30.44	0	0.352		
		2.00	0.301	144	14.6
		10.0	0.285	144-28.8	4.5
		33.0	0.270	28.8-8.72	6.1
		50.0	0.262	8.72-5.76	2.3
		100	0.252	5.76-2.88	2.8
		% of total porosity >2.88 μm			30.6

Amendment Rate Effect on Hydraulic Properties

The procedures used to evaluate and illustrate the effect of amendment rates on soil hydraulic properties were the same as water quality and soil series treatment effects. Differences in the b-coefficients due to amendment rates are illustrated in Figure 12. Average θ_ms, PDTP, and MRCs for all three amendment rates are illustrated in Figure 17 (top and bottom) and Figure 18.

There was no statistically significant difference between b-coefficients for the control treatment and amendment rate 1 (Figure 12). The averaged b-coefficients for the control treatment and amendment rate 1 were -22.34 and -22.33, respectively. The b-coefficient for the MRC due to amendment rate 2 was significantly different from the b-coefficient of either the control or amendment rate 1. The b-coefficient for the MRC due to amendment rate 2 was -16.43.

Significant increases in PDTP were in the >144 μm and the 144-28.8 μm diameter classes; PDTP increased nearly 4% in each of these diameter classes (Figure 17 and Table 8).

The θ_m of cores treated with amendment rate 2 was significantly greater at saturation than the θ_m of the cores treated with amendment rate 1. Similarly, θ_m of the cores treated with amendment rate 2 was less than θ_m of amendment rate 1 cores at all matric heads >12 kPa.

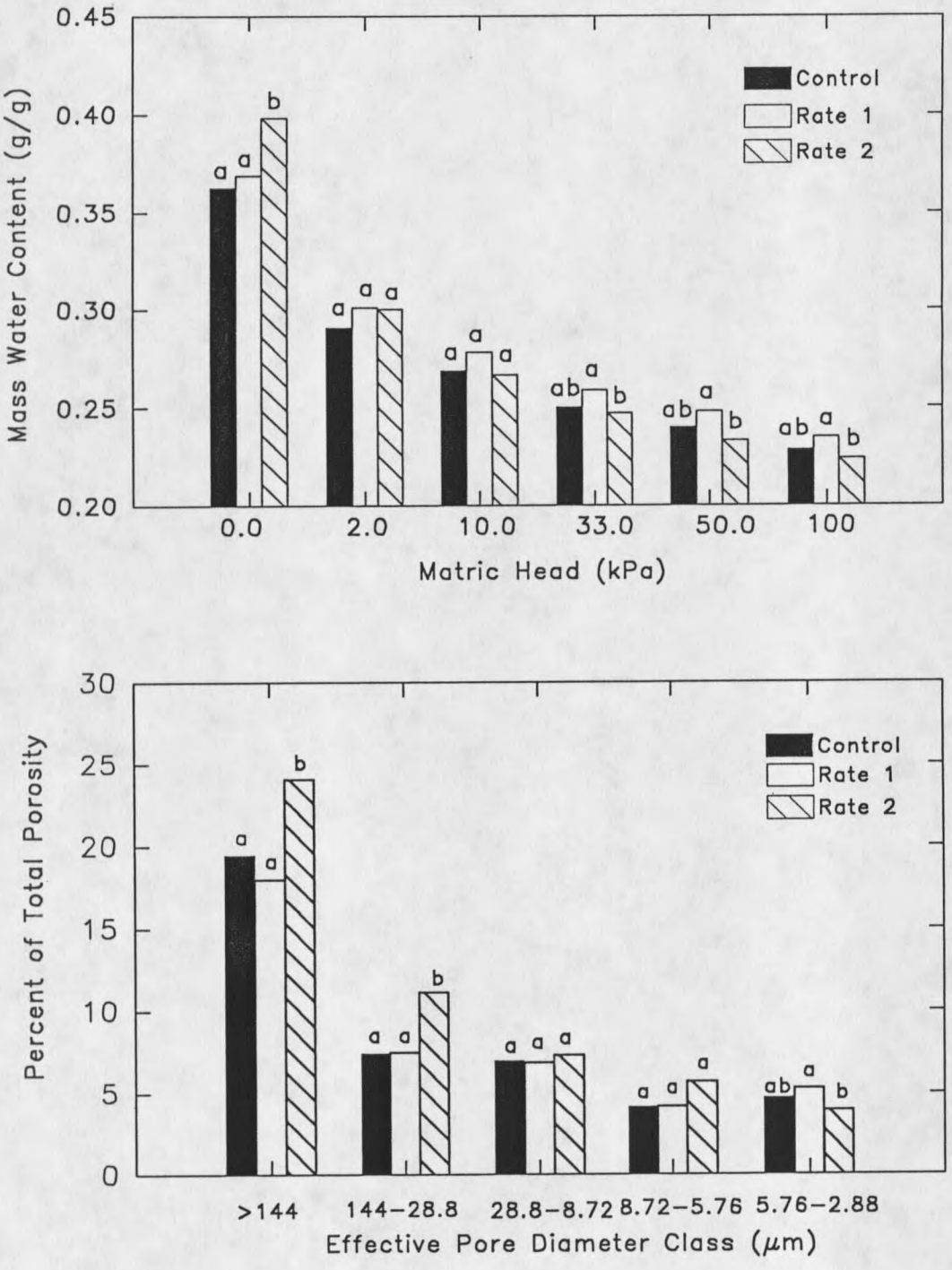

Figure 17. Average mass water content for each amendment rate and resulting effective pore size distribution percentage for each matric head increment.

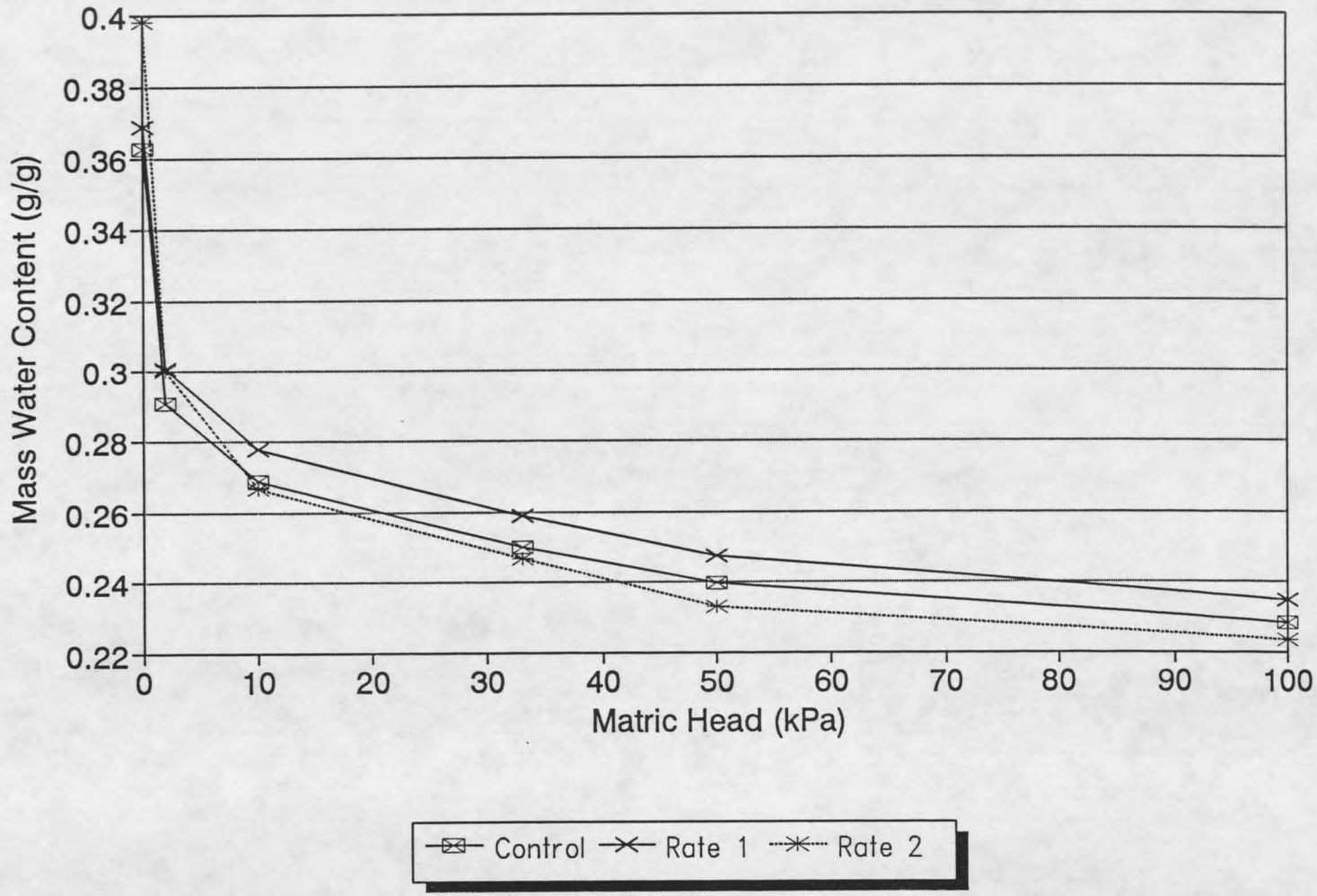

Figure 18. Average moisture release curve for each amendment rate treatment.

Table 8. Average b-coefficients for θ_m vs. h_m for all amendment rate treatments and resulting percentage distribution of total porosity. (n=18).

Amendment Rate	b-coef.	Matric Head	θ_m	Pore Diameter Class	PDTP
		kPa	g/g	μm	%
Control	-22.34	0	0.362		
		2.0	0.290	>144	19.1
		10.0	0.269	144-28.8	5.9
		33.0	0.250	28.8-8.72	5.1
		50.0	0.239	8.72-5.76	2.9
		100	0.228	5.76-2.88	3.1
		% of total porosity >2.88 μm			36.1
1	-22.33	0	0.368		
		2.0	0.301	>144	17.6
		10.0	0.278	144-28.8	6.1
		33.0	0.259	28.8-8.72	5.2
		50.0	0.248	8.72-5.76	2.9
		100	0.235	5.76-2.88	3.6
		% of total porosity >2.88 μm			35.4
2	-16.43	0	0.398		
		2.0	0.300	>144	24.0
		10.0	0.267	144-28.8	8.6
		33.0	0.247	28.8-8.72	5.0
		50.0	0.233	8.72-5.76	3.6
		100	0.224	5.76-2.88	2.4
		% of total porosity >2.88 μm			43.6

Drainage Water Results

All main treatments caused significant differences (α = 0.05 level) in drainage water sodium concentrations (Table 9). Sodium concentrations for all replications of all treatment combinations are presented in Table 10. Main treatment effects on sodium concentrations and means separation are shown in Figure 19.

Table 9. Analysis of variance for drainage water sodium concentrations.

Source	DF	S.S.	M.S.	F-Value	P-Value
WQ	2	1.06E7	5.3E6	147.98	0.0000
Soil	2	2.97E5	1.48E5	4.14	0.0269
Amend	2	8.64E6	4.32E6	120.46	0.0000
WQ*Soil	4	3.55E5	88719	2.47	0.0682
WQ*Amend	4	3.02E6	7.55E5	21.07	0.0000
Soil*Amend	4	2.70E5	67416	1.88	0.1428
WQ*Soil*Amend	8	8.52E5	1.06E5	2.97	0.016
Error	27	9.68E5	35848		
n = 54 observation					

Similarly, all interactions except WQ*Soil and Soil*Amend caused significant differences in drainage water sodium concentration (α = 0.05 level). This lack of significances suggests that the main treatment effects on drainage water sodium concentration were not necessarily additive.

Table 10. Average drainage water sodium concentrations for all treatment combinations.

WQ	Rep	Soil	Amend.	[Na] mg/L
A	1	B	0	54
A	2	B	0	54
A	1	H	0	54
A	2	H	0	54
A	1	T	0	54
A	2	T	0	54
B	1	B	0	220
B	2	B	0	220
B	1	H	0	220
B	2	H	0	220
B	1	T	0	220
B	2	T	0	220
C	1	B	0	400
C	2	B	0	400
C	1	H	0	400
C	2	H	0	400
C	1	T	0	400
C	2	T	0	400
A	1	B	1	390
A	2	B	1	400
A	1	H	1	230
A	2	H	1	280
A	1	T	1	250
A	2	T	1	260
B	1	B	1	1020
B	2	B	1	1330
B	1	H	1	750
B	2	H	1	960

Table 10. continue

B	1	T	1	1010
B	2	T	1	900
C	1	B	1	1850
C	2	B	1	1840
C	1	H	1	2650
C	2	H	1	1830
C	1	T	1	1100
C	2	T	1	1640
A	1	B	2	250
A	2	B	2	260
A	1	H	2	290
A	2	H	2	300
A	1	T	2	270
A	2	T	2	290
B	1	B	2	1300
B	2	B	2	1500
B	1	H	2	1720
B	2	H	2	1000
B	1	T	2	1490
B	2	T	2	1330
C	1	B	2	2380
C	2	B	2	1990
C	1	H	2	1300
C	2	H	2	1500
C	1	T	2	1250
C	2	T	2	1450

Note: WQ A, B, C, = WQ A, WQ B, WQ C, respectively;
Soil B, H, T = Busby, Haverson, Thurlow, respectively;
Amend 0, 1, 2, = Control, Rate 1, Rate 2, respectively.

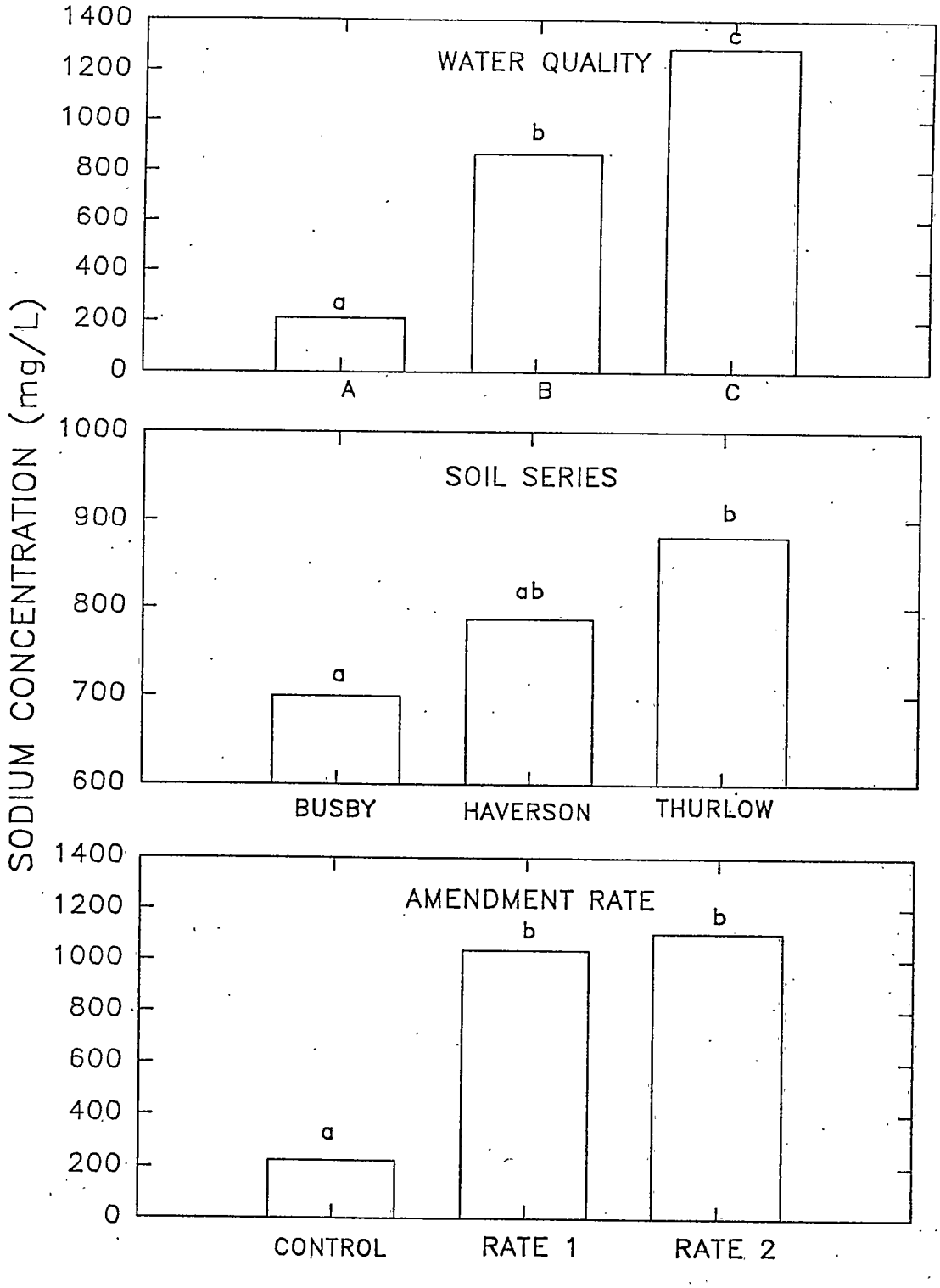

Figure 19. Average sodium concentrations of drainage water for WQ, soil series, and amendment rate treatments. Sodium concentrations within main treatments having the same letter designation did not differ significantly at $\alpha = 0.05$ level, according to Student's t test. (n = 18).

Mean separation of average drainage water sodium concentration indicated significant differences in sodium concentrations due to water quality treatments. Mean separation of average drainage water sodium concentration for each soil series indicated significant differences in drainage water concentration between Busby and Thurlow. Drainage water sodium concentration did not differ significantly between Busby and Haverson or Haverson and Thulow soil series. Means separation of average drainage water sodium concentration indicated no significant differences in sodium concentrations between amendment rates 1 or 2; however, the difference in effect between the control treatment and the two amendment rates was significant.

Greenhouse Study

All main treatments caused significant differences (α = 0.05 level) in calculated slopes of the θ_m vs. h_m curves (Table 11). Calculated b-coefficients (slopes) and r^2 values for all replications of all treatment combinations are presented in Table 12. Main treatment effects on b-coefficients and means separation are shown in Figure 17.

Similarly, all treatment interactions caused significant differences in b-coefficients (α = 0.05 level). This significance of interactive effects suggests that main treatment effects on soil hydraulic properties are additive,

rather than nullifying. Because of significance of effects for all main and interactive treatments, only main treatments will be discussed.

Table 11. Analysis of variance of b-coefficients from Equation 20 for samples from greenhouse study.

Source	DF	S.S.	M.S.	F-Value	P-Value
WQ	2	1516.6	758.29	87.85	0.000
Soil	2	1144.2	572.08	66.28	0.000
Amend	1	2286.3	2286.3	264.87	0.000
WQ*Soil	4	1223.3	305.82	35.43	0.000
WQ*Amend	2	1242.2	621.1	71.96	0.000
Soil*Amend	2	474.96	237.48	27.51	0.000
WQ*Soil*Amend	4	694.59	173.65	20.12	0.000
Error	18	155.37	8.6317		
n = 36 observations					

Table 12. Calculated b-coefficients and r^2 values for all main treatments for greenhouse study.

WQ	Rep	Soil	Amend.	b-coef.	r^2
A	1	B	0	-8.01	0.94
A	2	B	0	-15.84	0.92
A	1	H	0	-12.00	0.96
A	2	H	0	-7.92	0.94
A	1	T	0	-15.18	0.97
A	2	T	0	-13.98	0.99
B	1	B	0	-13.77	0.99
B	2	B	0	-13.74	0.74
B	1	H	0	-9.55	0.99
B	2	H	0	-14.75	0.99
B	1	T	0	-19.30	0.98
B	2	T	0	-19.63	0.99

Table 12. continued

C	1	B	0	-13.85	0.96
C	2	B	0	-15.23	0.95
C	1	H	0	-33.89	0.98
C	2	H	0	-32.85	0.93
C	1	T	0	-71.97	0.91
C	2	T	0	-70.61	0.96
A	1	B	1	-5.07	0.97
A	2	B	1	-4.98	0.89
A	1	H	1	-7.06	0.99
A	2	H	1	-3.61	0.88
A	1	T	1	-12.56	0.99
A	2	T	1	-3.98	0.81
B	1	B	1	-5.39	0.99
B	2	B	1	-6.68	0.99
B	1	H	1	-3.43	0.96
B	2	H	1	-7.08	0.99
B	1	T	1	-7.03	0.90
B	2	T	1	-5.74	0.80
C	1	B	1	-3.77	0.98
C	2	B	1	-1.86	0.91
C	1	H	1	-2.91	0.97
C	2	H	1	-8.07	0.99
C	1	T	1	-9.33	0.98
C	2	T	1	-16.63	0.99

Note: WQ A, B, C, = WQ A, WQ B, WQ C, respectively;
Soil B, H, T, = Busby, Haverson, Thurlow, respectively;
Amend 0, 1, 2, = Control, Rate 1, Rate 2, respectively.

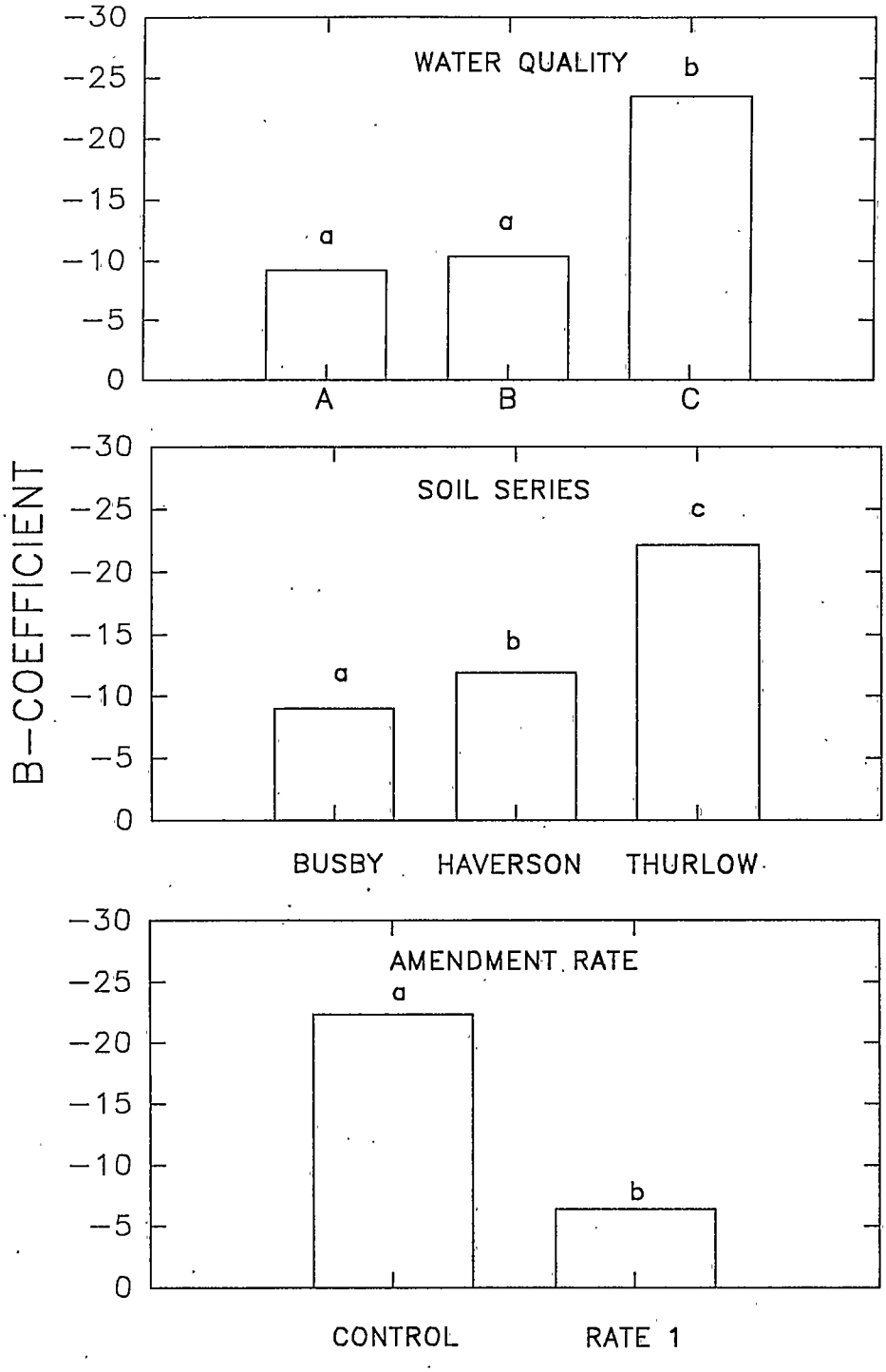

Figure 20. Average b-coefficients for WQ, soil series, and amendment rate treatments in greenhouse study. The b-coefficients within main treatments having the same letter designation did not differ significantly at $\alpha = 0.05$ level, according to Student's t test. (n = 18, 18, and 12, respectively).

Water Quality Effect on Hydraulic Properties

Although average b-coefficients were significantly different due to water quality treatments, the coefficients by themselves do not clearly illustrate the water quality treatment effects on soil hydraulic properties. Consequently, bar plots of mean θ_m values were prepared for each h_m equilibration by averaging θ_m data over soil series, amendment rate, and replication for each water quality treatment (Figure 21, top). Effect of water quality treatment on pore size distribution was determined by calculating the PDTP for each of five diameter classes (Figure 21, bottom). Moisture release curves were prepared by averaging h_m vs. θ_m data over soil series, amendment rate, and replication for each water quality treatment (Figure 22).

As illustrated in Figure 20, b-coefficients calculated from the MRCs resulting from treatments WQ A and WQ B did not differ significantly; however, the b-coefficient from the MRC resulting from treatment with WQ C did differ significantly from the other b-coefficients. The b-coefficient for soils treated with WQ C was -23.52, while the b-coefficients for soils treated with WQ A or WQ B were -9.21 and -10.37, respectively (Table 13).

Percentage of total porosity in the measured pore diameter classes was approximately equal for all cores, irrespective of water quality treatment. Columns treated

with water quality A had about 3.5% more pore volume in the 28.8-8.72 μm diameter class than soils treated with either of the other two water qualities.

Table 13. Average b-coefficients for θ_m vs. h_m for each water quality treatment and resulting percentage distribution of total porosity in greenhouse study. (n=12)

WQ	b-coef.	Matric Head	θ_m	Pore Diameter Class	PDTP
		kPa	g/g	μm	%
A	-9.21	0	0.456		
		2.00	0.324	>144	31.7
		10.00	0.288	144-28.8	8.6
		33.00	0.242	28.8-8.72	11.2
		50.00	0.223	8.72-5.76	4.6
		100.0	0.195	5.76-2.88	6.5
		% of total porosity >2.88 μm			62.2
B	-10.37	0	0.445		
		2.00	0.308	>144	32.9
		10.00	0.267	144-28.8	10.7
		33.00	0.236	28.8-8.72	7.9
		50.00	0.221	8.72-5.76	4.2
		100.0	0.199	5.76-2.88	6.8
		% of total porosity >2.88 μm			62.5
C	-23.52	0	0.448		
		2.00	0.306	>144	34.2
		10.00	0.261	144-28.8	11.5
		33.00	0.230	28.8-8.72	7.0
		50.00	0.213	8.72-5.76	3.4
		100.0	0.202	5.76-2.88	2.6
		% of total porosity >2.88 μm			58.7

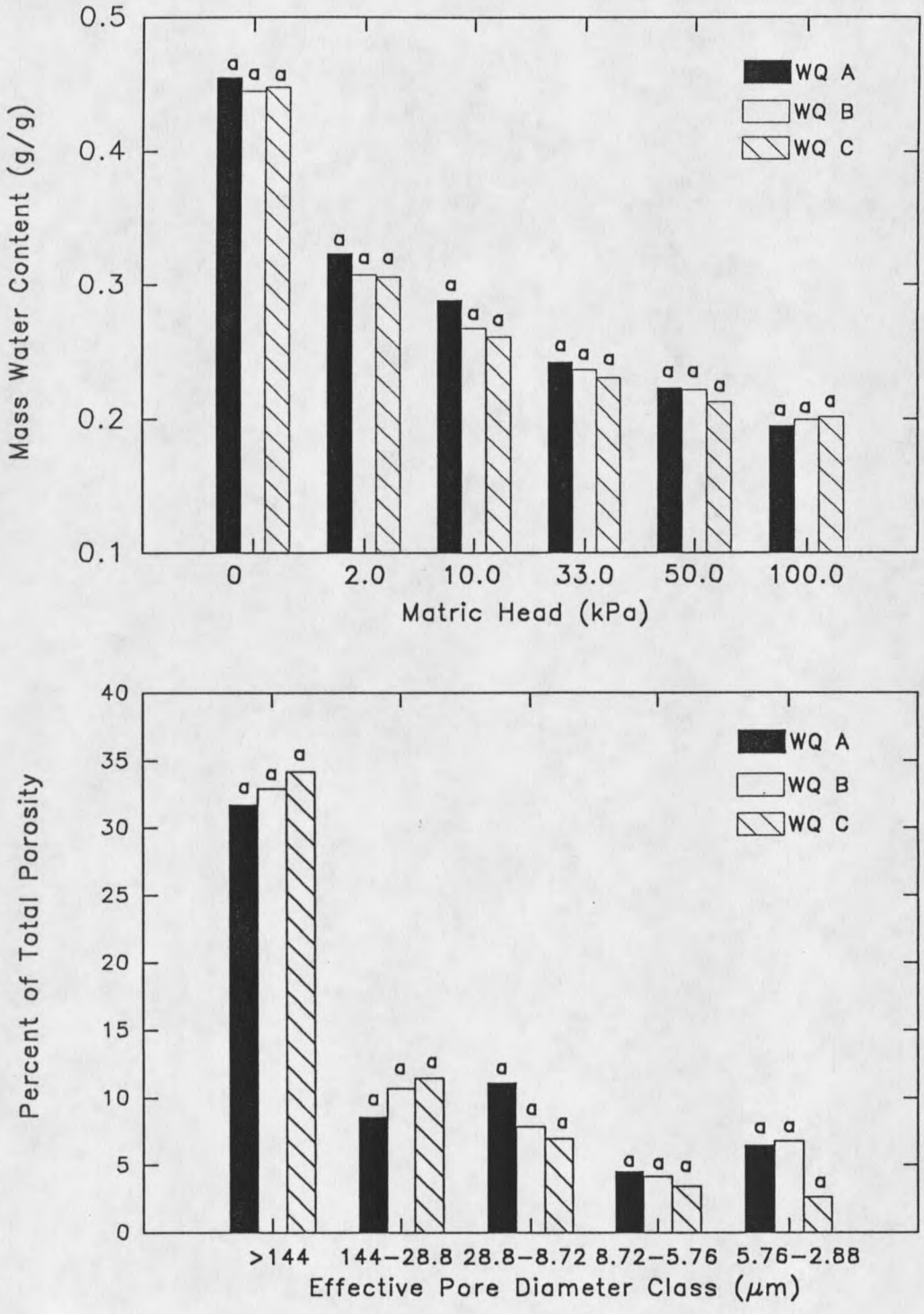

Figure 21. Average mass water content for each water quality and resulting percentage distribution of total porosity for each matric head increment in greenhouse study.

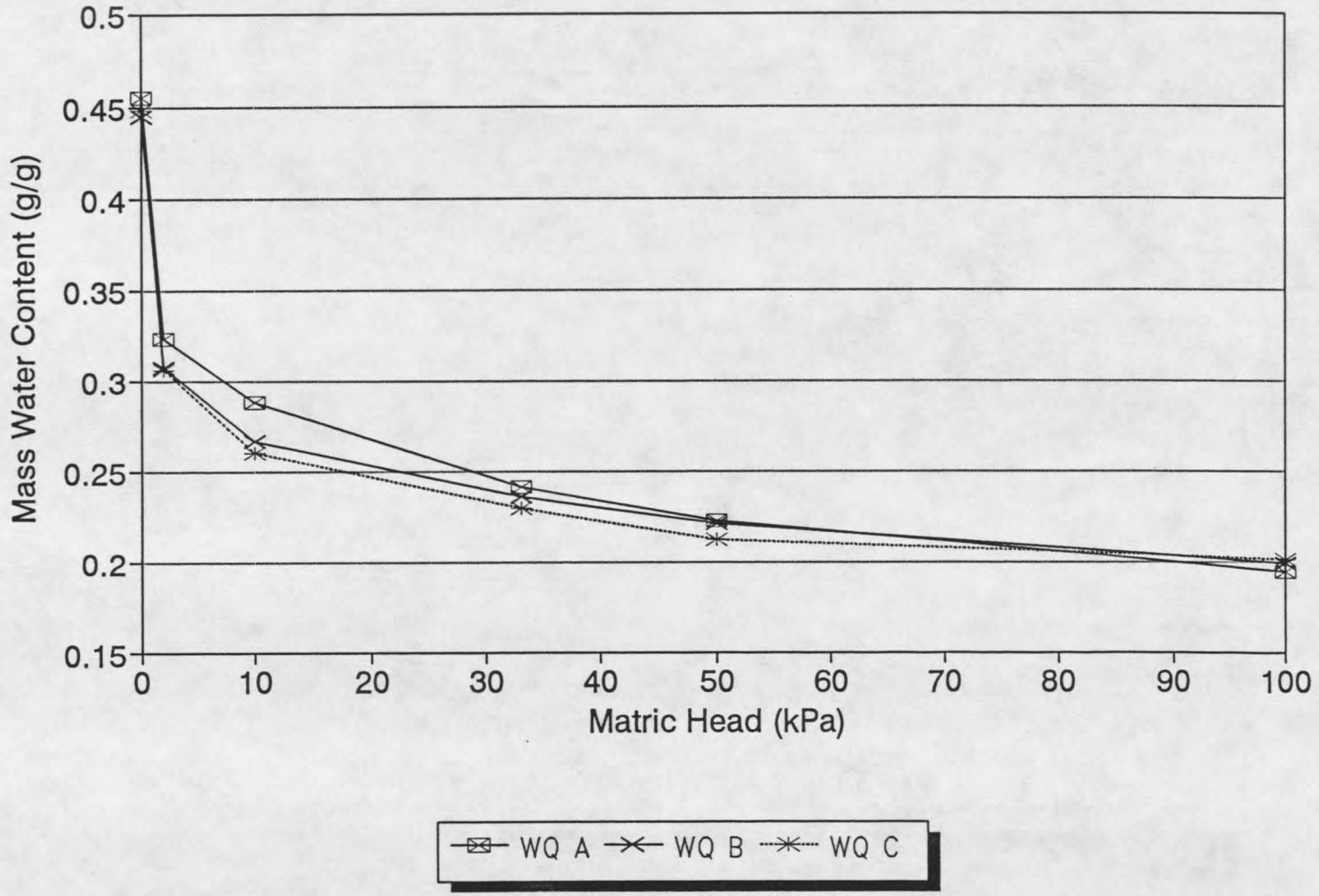

Figure 22. Average moisture release curve for each water quality treatment in greenhouse study.

Soil Series Effect on Hydraulic Properties

Effects of soil series on hydraulic properties in the greenhouse study were assessed the same way the effects of water quality treatments were evaluated. Differences in the b-coefficients for the MRCs for the three soil series are illustrated in Figure 20. Average θ_m, PDTP and MRCs for all three soil series are illustrated in Figure 23 (top and bottom) and Figure 24.

As illustrated in Figure 20, the b-coefficients for the MRCs differed significantly at $\alpha = 0.05$ level among all soil series. The b-coefficients for Busby and Haverson soils, although significantly different, ranged from only -9.02 to -11.93, respectively. The b-coefficient for the Thurlow soil was -22.16.

Significant differences in θ_m were found between the Busby soil and the Haverson or Thurlow soil at 2.0 and 10.0 kPa matric head equilibration (Figure 23, top). Significant differences in θ_m among all soils were detected at the 33.0, 50.0, and 100 kPa matric head equilibration.

Significant differences in PDTP were detected between the Busby soil and the Haverson or Thurlow soil series at the >144 μm diameter. No significant difference in PDTP among soils was detected in any other diameter class. Busby had 71.7% of total porosity with diameters >2.88 μm, while 54.4% and 44.5% of the total porosity of the Haverson and Thurlow, respectively, had a diameter >2.88 μm (Table 14).

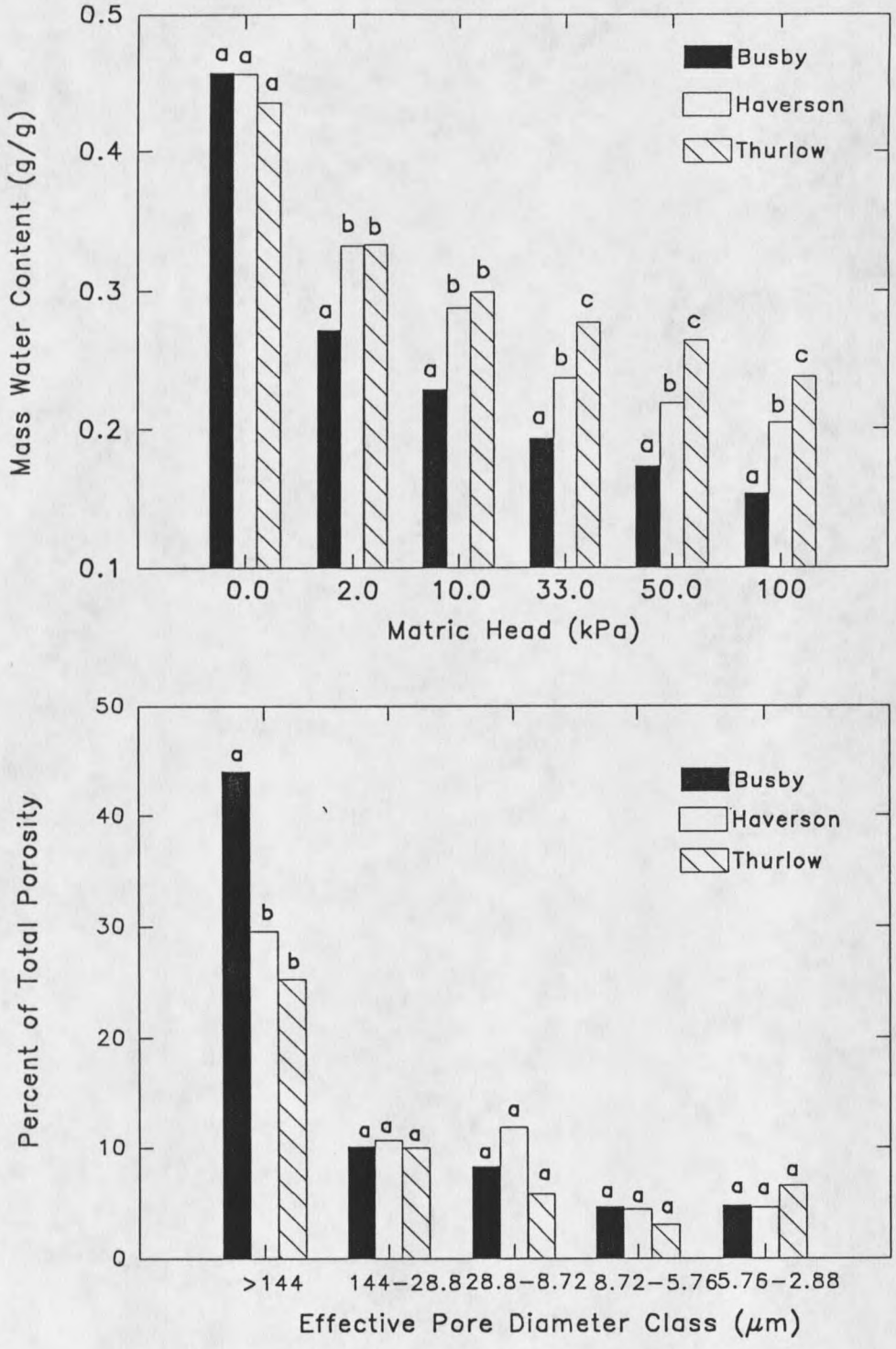

Figure 23. Average mass water content for each soil series and resulting percentage distribution of total porosity for each matric head increment in greenhouse study.

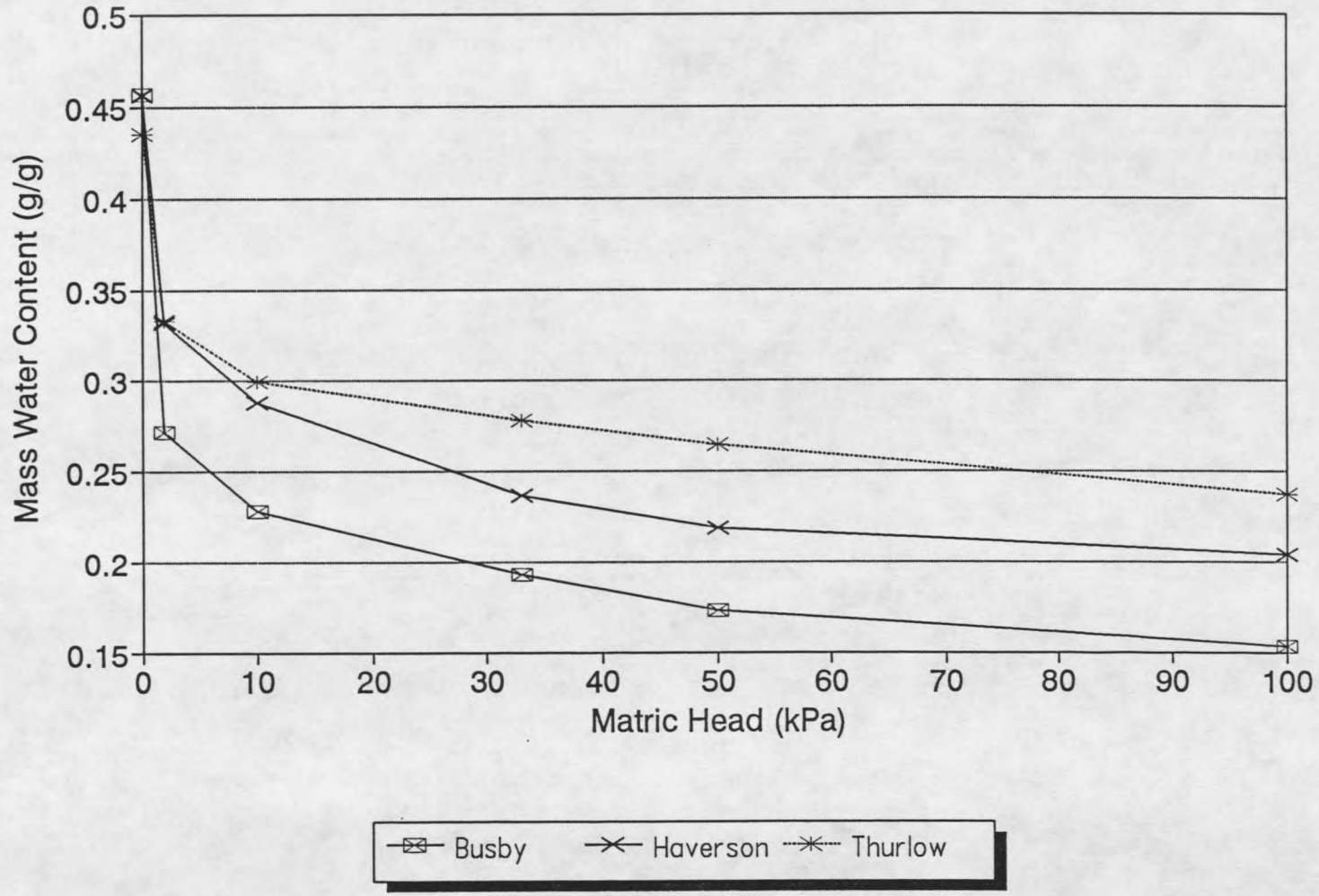

Figure 24. Average moisture release curve for each soil series in greenhouse study.

Table 14. Average b-coefficients for θ_m vs. h_m for all soil series and resulting percentage distribution of total porosity in greenhouse study. (n = 12).

Soil Series	b-coef.	Matric Head	θ_m	Pore Diameter Class	PDTP
		kPa	g/g	μm	%
Busby	-9.02	0	0.457		
		2.00	0.272	>144	44.0
		10.00	0.229	144-28.8	10.1
		33.00	0.193	28.8-8.72	8.2
		50.00	0.173	8.72-5.76	4.6
		100.0	0.153	5.76-2.88	4.8
		% of total porosity >2.88 μm			71.7
Haverson	-11.93	0	0.456		
		2.00	0.332	>144	29.6
		10.00	0.288	144-28.8	10.7
		33.00	0.237	28.8-8.72	11.9
		50.00	0.219	8.72-5.76	4.4
		100.0	0.205	5.76-2.88	4.6
		% of total porosity >2.88 μm			61.2
Thurlow	-22.16	0	0.436		
		2.00	0.333	>144	25.3
		10.00	0.299	144-28.8	10.0
		33.00	0.278	28.8-8.72	5.8
		50.00	0.265	8.72-5.76	3.1
		100.0	0.238	5.76-2.88	6.6
		% of total porosity >2.88 μm			50.8

Amendment Rate Effect on Hydraulic Properties

Effects of amendment rate on hydraulic properties of the soils in the greenhouse study were assessed the same way the effects of water quality treatments were evaluated. Differences in the b-coefficients of the MRCs due to the amendment rates are illustrated in Figure 20. Average Θ_m, PDTP and MRCs for both amendment rates are illustrated in Figure 25 (top and bottom) and Figure 26.

Addition of $CaCl_2$ caused the b-coefficient to be significantly different from the b-coefficient of the control treatment at the $\alpha = 0.05$ level. With regard to pore size distribution, the control treatment had only 36.1% of total porosity greater than 2.88 μm diameter, while the columns treated with amendment rate 1 had 86.3% of total porosity with diameter >2.88 μm.

Statistically significant differences in Θ_m between the control and addition of $CaCl_2$ were detected for all matric head equilibrations, with the exception of 10.0 kPa matric head. The $CaCl_2$ amended soil had greater Θ_m for 0.0 and 2.0 kPa matric head and then had lower Θ_m for subsequent matric heads >33.0 kPa (Figure 25, top). The control soils had a mass water content of 0.228 at 100 kPa matric head, while soils treated with $CaCl_2$ had a mass water content of only 0.169 for the same matric head equilibration.

Significant differences in PDTP between the control and $CaCl_2$ amended soils were detected for all pore diameter

classes. Addition of $CaCl_2$ resulted in large increases in percentage of total porosity with pore diameters >144, 144-28.8, and 28.8-8.72 μm. The control treatment had 19.1%, 5.9%, and 5.1% of the total porosity in these diameter classes, while the soil treated with $CaCl_2$ had 46.8%, 14.6%, and 12.2% of total porosity in these same diameter classes, respectively. Diameter classes 8.72-5.76 and 5.76-2.88 μm had significantly more PDTP. The addition of $CaCl_2$ caused a decrease in the percent porosity of pores with a diameter less than 2.88 μm. The control soil had 63.9% of the total porosity <2.88 μm, while the $CaCl_2$ amended soil had only 13.7% of the total porosity in the same diameter class.

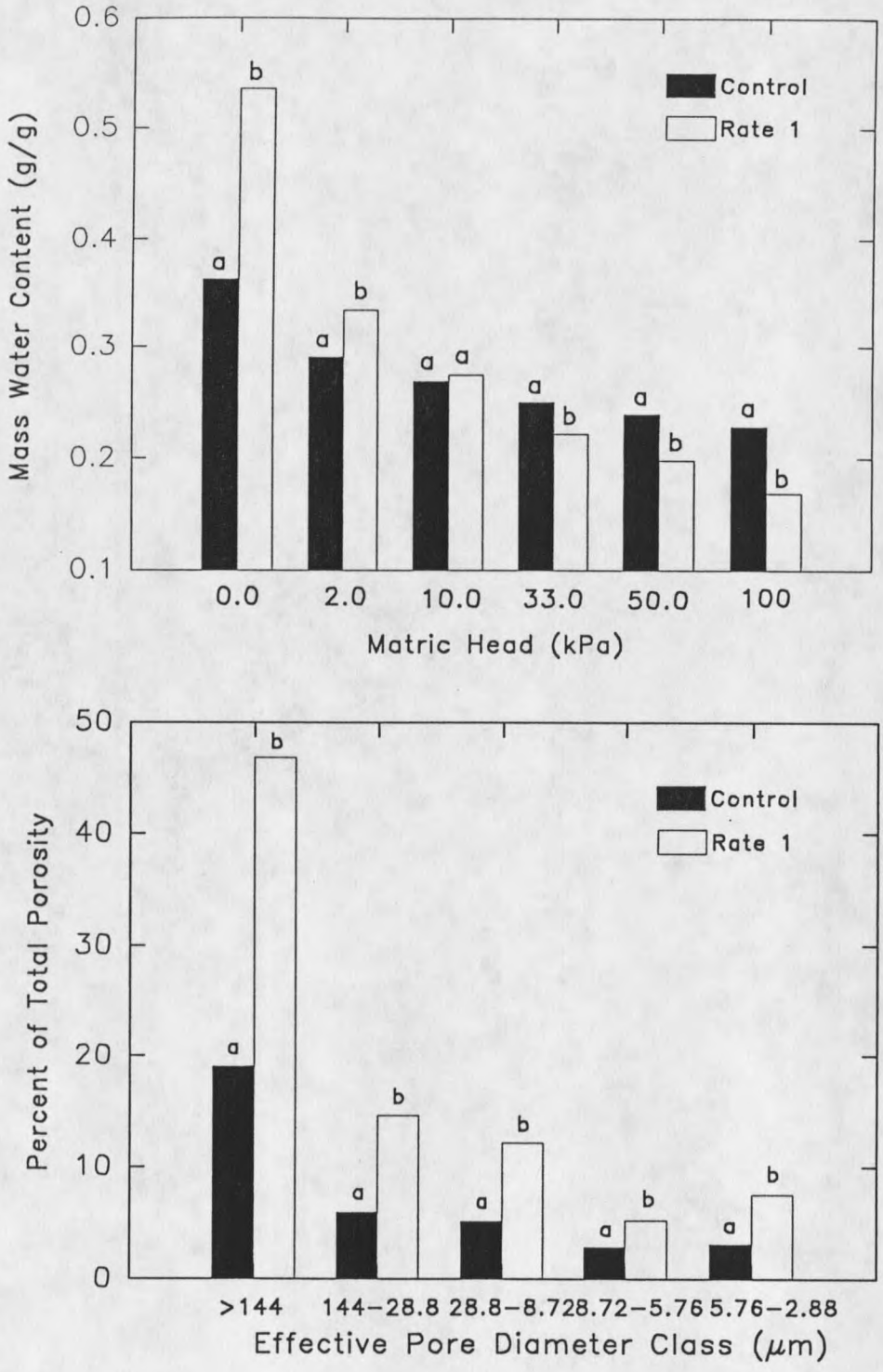

Figure 25. Average mass water content for each amendment rate and resulting percentage distribution of total porosity for each matric head increment in greenhouse study.

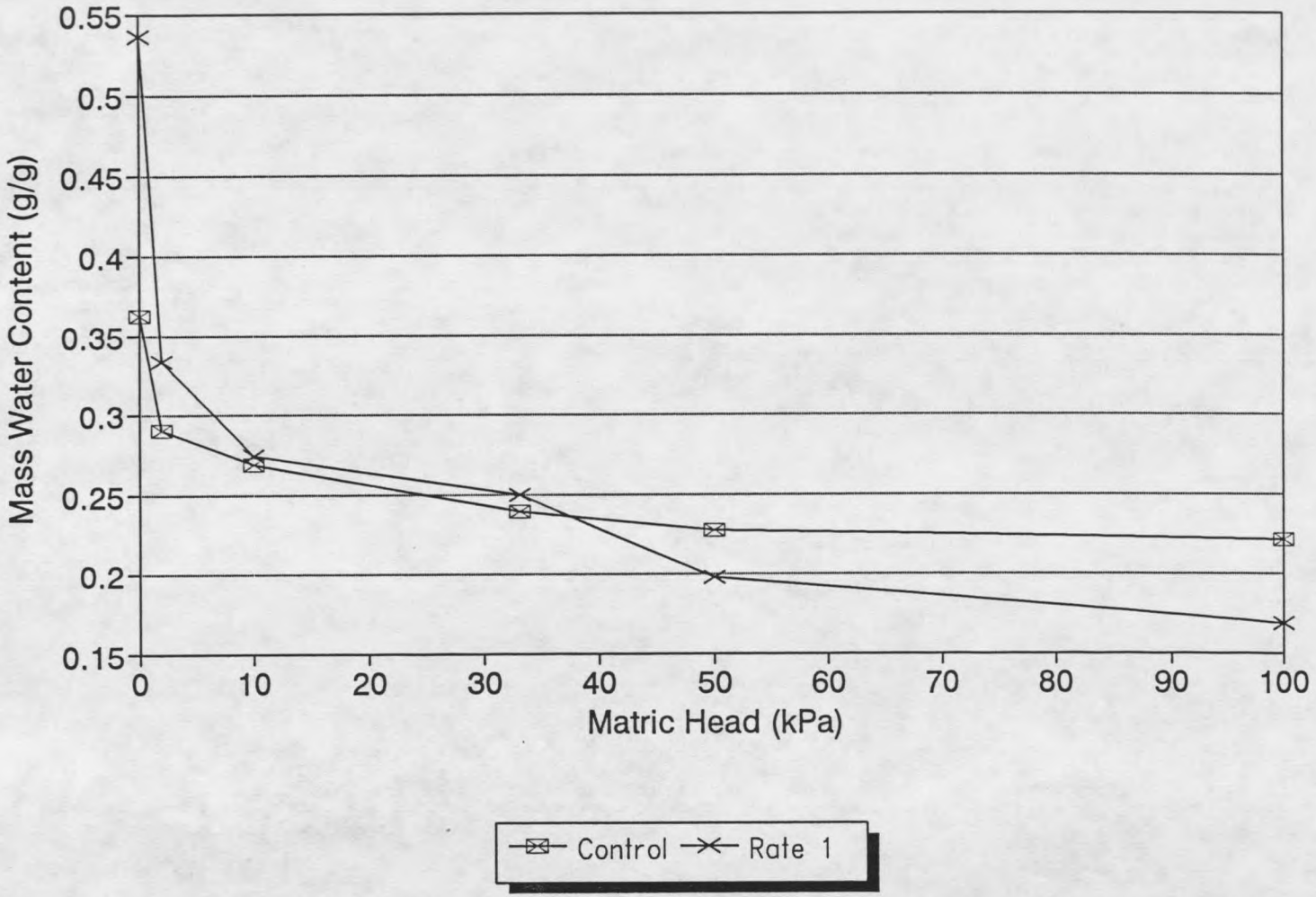

Figure 26. Average moisture release curve for each amendment rate treatment in greenhouse study.

Table 15. Average b-coefficients for θ_m vs. h_m for each amendment rate treatment and resulting percentage distribution of total porosity in greenhouse study. (n = 18).

Amend. Rate	b-coef.	Matric Head	θ_m	Pore Diameter Class	PDTP
		kPa	g/g	μm	%
Control	-22.34	0	0.363		
		2.00	0.291	>144	19.1
		10.00	0.269	144-28.8	5.9
		33.00	0.240	28.8-8.72	5.1
		50.00	0.228	8.72-5.76	2.9
		100.0	0.222	5.76-2.88	3.1
		% of total porosity >2.88 μm			36.1
1	-6.40	0	0.536		
		2.00	0.334	>144	46.8
		10.00	0.275	144-28.8	14.6
		33.00	0.250	28.8-8.72	12.2
		50.00	0.198	8.72-5.76	5.2
		100.0	0.169	5.76-2.88	7.5
		% of total porosity >2.88 μm			86.3

CHAPTER 5

DISCUSSION

Laboratory Core Study

Water Quality Effect on Hydraulic Properties

Differences in irrigation water quality caused significant differences in percent porosity and pore size distribution of the three soils included in this study. Increasing SAR of the irrigation water from 1.1 to 5.1 to 9.6 caused an increase in percent of total porosity occupied by pores with diameter <2.88 μm. Increasing SAR level (WQ B or WQ C) of irrigation water caused decreases in percentage of total porosity for pores with a diameter >144 μm. However, the remaining pore diameter classes showed disproportionate decreases in percentage of total porosity.

This shift in the pore size distribution may result in substantial decreases in soil hydraulic conductivity, particularly for montmorillonitic soils. Montmorillonitic soils generally have a dynamic pore diameter distribution, dependent on water content. As water content increases, the clay double layer swells, dispersing soil aggregates and shifting the pore distribution towards smaller pore diameters.

Very little water moves through small pores because of

the lack of sufficient potential gradient to cause substantial flow.

In soils which have a substantial percentage of their pore size distribution occupied by relatively small diameter pores, plants are required to decrease root potentials to extract water prior to salt loading from irrigation water.

Soil Series Effects on Hydraulic Properties

The effect of soil series on hydraulic properties was consistent with previously reported observations of the relationship between soil texture and soil water characteristics. Busby fine sandy loam, with its relatively coarse, single-grained texture, sustained a relatively large number of large pores with increasing irrigation water SAR levels, while Haverson and Thurlow responded accordingly with their increasing clay content.

Soils, like Thurlow, and to a lesser degree Haverson, dominated by montmorillonitic clay might present significant problems if the exchangeable sodium percentage is allowed to get sufficiently high to swell the double layer, disrupting soil aggregates and structure. The soil could then become sufficiently impermeable that reclamation with soil amendments would be impeded because of difficulty getting the amendment into the soil to displace sodium on the soil exchange sites. Reclamation via sodium displacement could be additionally hampered by inadequate leaching of sodium and drainage of dispersed soils.

Saline-sodic soils are dominated by small pores. Consequently, the exchange of sodium for calcium on the exchange site can become a diffusion-dependent process. In such situations, relatively low rates and frequent additions of amendments, coupled with slower irrigation rates, might allow adequate time for the exchange of calcium for sodium to take place in smaller, somewhat isolated pores. Even though this study did not look at the influence of irrigation rate on amendment effect, care was taken to allow adequate time for cation exchange between irrigation events.

Amendment Rate Effect on Hydraulic Properties

Application of $CaCl_2$ at a rate of 7.73 kg m^{-2} increased large pore percentages, particularly in the 5.76 to 144 μm diameter class, relative to the control treatment. This increase in the percentage of large pores would be beneficial to plants since pores in this range of diameters contain the largest volume of plant available water. Plants can extract water from much smaller pores; however, the available volume of water and rate of extraction is usually insufficient to meet plant transpirational demand.

A high rate of application of $CaCl_2$ was necessary because of the unusually high ESP of the salt-loaded soils (Appendix B). The rate used in this study might be unrealistic under field conditions. The plates on the bottom of the soil columns in the greenhouse study acted as

barriers to water flow. Drainage at the bottom of the columns took place only at or near saturated conditions. The barrier could have elevated the ESP of the soils to unrealistic levels.

Drainage Water Results

The addition of $CaCl_2$ significantly increased sodium concentration of the drainage water. Even though no significant differences in drainage water sodium concentration were detected between the low and high rate of $CaCl_2$ addition, the addition of the amendment increased the sodium concentration to a level nearly five times greater than the sodium concentration of the drainage water of the control treatment.

This increase of drainage water sodium concentration is cause for alarm due to the deleterious effect of high sodium concentration on fresh water groundwater supplies. However, the complexity of nonsaturated groundwater flow and the lack of data below the tested horizon makes quantifying the environmental impact of this high sodium concentration impractical. Again, these sodium concentrations may not be indicative of actual field levels because of the elevated ESP levels in the soil columns. However, if the exchange sites of fine-textured soils are saturated with sodium to the point a large amendment rate is necessary, deleterious effects on groundwater quality might result.

Greenhouse Study

Water Quality Effect on Hydraulic Properties

The b-coefficient associated with the MRC of columns irrigated with WQ C differed significantly from the b-coefficients for the MRCs of the columns irrigated with the other two water quality treatments. However, the distribution of pores within the various pore diameter classes of the soils associated with each water quality treatment did not appear dissimilar. Irrigation with water quality C increased the percentage of total porosity in the 28.8-8.72 μm diameter class, significantly affecting the calculated b-coefficients.

Soil Series Effect on Hydraulic Properties

The average b-coefficients from the MRCs for all soil series differed significantly. This difference is best illustrated by the percent of total porosity in the various diameter classes. The percent of total porosity in the measured diameter classes decreased as the texture became increasingly more fine. As previously stated, the swelling of the clay double layer may have disrupted the soil aggregates and structure, resulting in more of a total porosity in the diameter class <2.88 μm. This could limit the effectiveness of amendments because of the inability to achieve adequate drainage.

Amendment Rate Effect on Hydraulic Properties

The addition of $CaCl_2$ at a rate of 6.42 kg m^{-2} altered the soil hydraulic properties significantly. The b-coefficient associated with the MRC of the control columns differed significantly from the b-coefficient from the MRC of the columns treated with $CaCl_2$. Columns treated with $CaCl_2$ had significant increases in percentage of total porosity in the measured diameter classes, particularly for pore diameters greater than 8.72 μm. These changes in pore size distribution for the measured diameter classes resulted in large increases in percent of total porosity in the measured diameter classes.

CHAPTER 6

CONCLUSIONS

An accelerated irrigation and salt-loading study with undisturbed soil columns led to salt and sodium accumulation in all soils prior to this study. Conditions of the accelerated irrigation and salt-loading study were not truly representative of actual field conditions because a support plate on the bottom of each soil column inhibited drainage below the root zone. Under field conditions of adequate drainage, drainage water would leach excess salts below the root zone. Once below the root zone, the salts would either continue to move to the groundwater if the soils were well drained or concentrate in the perched water table, eventually migrating laterally or towards the surface.

Irrigation of the soils of this study with water comparable to either present or anticipated future water qualities of the Powder River resulted in the soils becoming saline or saline/sodic (Thompson, 1991). The current investigation revealed that this sodium accumulation in the soil profile resulted in greatly decreased macro-porosity, reducing soil hydraulic conductivity. Deleterious effects of water quality treatments on soil physical properties demonstrate the need for improved irrigation management in

the future, provided the calcium concentration of the Powder River does not increase proportionally with the sodium concentration of the water. This is especially true for soils such as Haverson and Thurlow which have relatively high montmorillinitic clay content.

A wide array of management schemes are available for well-drained soil; however, only a limited number of management options apply to poorly drained soils. Prevention of sodium accumulation might be the most cost-effective solution to the deleterious effects of sodium saturation and dispersion resulting from irrigation with water containing high sodium concentrations. Excess irrigation early in the spring or late in the fall with water containing relatively low levels of TDS could leach seasonal sodium accumulations below the root zone.

Monitoring SAR and TDS levels of irrigation water could offer insight into when the most advantageous seasonal irrigation could be accomplished (Rhoades et al., 1973). When SAR and TDS levels of irrigation water are low, excess irrigation could remove accumulated sodium and recharge the soil profile with soil water. This would provide crops with the water they need and limit the amount of irrigation water needed to sustain production through drier periods when irrigation water may have higher TDS levels.

However, should the water quality of the Powder River approach that of WQ C, gypsum could be used in conjunction

with calcium chloride to displace sodium accumulated in the soil. The high dissolution rate of calcium chloride might have short-term remedial effects on soil physical properties because it passes through the soil profile rapidly (Brock, 1992). Calcium chloride could be used to quickly improve soil physical properties. If the calcium chloride application was followed by a large rate of application of gypsum, which has a slower dissolution rate than calcium chloride, the gypsum would compensate for the high sodium concentration of the irrigation water. This would reduce the deleterious effects of sodium on soil physical properties over a longer period of time.

The use of crop rotations might help improve soil physical properties. Brock (1991) suggested that a rotation of barley, sordan, and then alfalfa might improve soil physical and chemical properties of these sodium-affected soils.

The use of proper cropping systems and irrigation management could abate or greatly reduce the need for amendments to remediate irrigation-induced saline and saline/sodic soils. These techniques could impact groundwater with small loads of salt over a much longer period of time, reducing stress to the ecosystem caused by the adverse effects of irrigation.

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APPENDICES

APPENDIX A

Charaterization of Soil Series

Table 16. Charaterization of all soil series profiles.

WILSON-GLEN BERG/BUSBY - IRRIGATED ALFALFA 10/6/87 Jerry Setera, Jim Bauder, Steve Van Fossen

Horizon	Depth	Color		Texture	Structure	Consistence			Reaction	Boundary	ROOTS	PORES
		Dry	Moist			Dry	Moist	Wet				
Ap	0-6"	10yr 5/3	10yr 4/3	l	mabk-mgr	sh	vfr	ss,ps	e	a,s	3vf	2vf
Bw1	6-A	10yr 5/3	10yr 3/4	vfsl	2cpr-2mabk	sh	vfr	so,po	es	a,s	3vf	3vf
Bw2	14-20	10yr 6/4	10yr 5/3	fsl	2msbk	sh	vfr	ss,ps	e s	a,s	3vf	2vf
Bk	20-22	10yr 6/4	10yr 5/3	vfsl	2msbk	sh	vfr	ss,ps	ev	a,s	3vf	2vf
C1	22-32	10yr 6/4	10yr 5/3	vfsl	m	so	vfr	ss,ps	es	a,s	2vf	3vf
C2	32-33	10yr 6/4 mottles	10yr 5/3	lfs	m	so	vfr	so,po	es	a,s	1vf	3vf
C3	33-42	10yr 6/4	10yr 5/3	fsl	m	so	vfr	so,po	es	a,s	1vf	3vf
C4	42-48	10yr 6/4	10yr 5/3	stratified fsl sicl lfs								

FULTON-HAVERSON-IRRIGATED 10/7/88 Jerry Setera, Jim Bauder and Steve Van fossen

Horizon	Depth	Color		Texture	Structure	Consistence			Reaction	Boundary	ROOTS	PORES	LIME
		Dry	Moist			Dry	Moist	Wet					
Ap1	0-2"	10YR 6/4	10YR 5/3	sicl	2fpl	sh	vfr	s,p	e	a,s	2vf	3vf, 1co	dissem-inated
Ap2	2-5	10YR 6/4	10YR 5/3	sicl	2mstk, 2csbk	vh	vfr	s,p	e	a,s	2vf	3vf, 1co	"
C1	5-15	10YR 6/4	10YR 5/3	Heavy sil	2msbk, 2csbk	h	fi	ss,ps	e	g,s	2vf	3vf, 1co	"
C2	15-23	10YR 5/3 Lignite	10YR 3/3	fsl	m	so	vfr	so,po	very e	g,s	1vf	3vf, 1co	"
C3	23-32	10YR 6/4	10YR 4/3	Heavy sil	m	h	fi	ss,ps	e	g,s	1vf, 1f	2vf, 1co	"
C4	32-41	10YR 6/4 Mottles	10YR 4/3	Heavy sil	m	so	vfr	ss,ps	e	a,s	2vf, 1f	2vf, 1co	"
C5	41-45	10YR 6/4 lignite & mottles	10YR 4/4	g,sil	m	lo	lo	so,po	very e	a,s	--	2vf, 1co	"
C6	45-60	10YR 6/4 lignite & Mottles	7.5YR 6/2	Heavy sil	m	h	fi	ss,ps	e	--	1vf	1vf	"
		No visible salts in profile											

Leo Jurica - Thurlow - Irrigated 10/07/87 Jerry Setera, Jim Bauder, Steve VanFossen

Horizon	Depth	Color		Texture	Structure	Consistence			Reaction	Boundary	ROOTS	PORES	LIME
		Dry	Moist			Dry	Moist	Wet			plowed		
Ap	0-5"	10YR 6/2	10YR 4/2	sicl	2msbk -2mgr	sh	slight fi	s,p	---	g,s	2vf, 2f	1vfv	
Bt	5-11"	10YR 5/3	10YR 3/3	Heavy sicl	2mpr -2msbk, 2fsbk	h	slight fi	s,p	---	g,w	2f, 2vf	2vft	
Btk	11-18"	10YR 6/3	10YR 4/3	sicl	2mpr -2msbk	h	fr	s,p	e	g,w	1f, 1vf	2vft	2m threads
Bk	18-25"	10YR 6/4	10YR 4/4	sicl	2cpr -2msbk	h	fr	s,p	es*	g,s	1vf	3vft	3mf threads
BC	25-42"	10YR 6/2	10YR 4/2	sic	2cpr	vh	fi	vs,p	e	g,w	TRACE	3vft	
C	42+"	10YR 6/4	10YR 5/3	sicl	m	h	fr	s,p	e	---	---	2vft	

*THIN SILT LOAM LAYER ABOUT 2" THICK THAT IS VIOLENTLY EFFERVESCENT.

APPENDIX B

Data Files

Table 17. Outflow data for all water quality, soil series, amendment rate, and replications from laboratory core study.

Water Quality	Soil Series	Amend Rate	Rep	Pres. kPa	Outflow ml	PDTP %	Pore Vol cm3	Porosity %	BD g/cm3	Θm g/g
A	Busby	0	1	0.00	30.43	24.02	33.20	48.30	1.37	0.353
A	Busby	0	1	2.00	22.45	5.80	33.20	48.30	1.37	0.260
A	Busby	0	1	10.00	20.53	9.38	33.20	48.30	1.37	0.238
A	Busby	0	1	33.00	17.41	4.69	33.20	48.30	1.37	0.202
A	Busby	0	1	50.00	15.85	4.97	33.20	48.30	1.37	0.184
A	Busby	0	1	100.00	14.21	42.78	33.20	48.30	1.37	0.165
A	Busby	0	2	0.00	36.94	50.49	36.83	53.58	1.23	0.436
A	Busby	0	2	2.00	18.34	1.91	36.83	53.58	1.23	0.216
A	Busby	0	2	10.00	17.64	4.08	36.83	53.58	1.23	0.208
A	Busby	0	2	33.00	16.14	1.36	36.83	53.58	1.23	0.190
A	Busby	0	2	50.00	15.64	3.00	36.83	53.58	1.23	0.184
A	Busby	0	2	100.00	14.53	39.46	36.83	53.58	1.23	0.171
A	Haverson	0	1	0.00	28.57	7.10	30.87	44.91	1.46	0.308
A	Haverson	0	1	2.00	26.38	7.50	30.87	44.91	1.46	0.284
A	Haverson	0	1	10.00	24.07	6.60	30.87	44.91	1.46	0.259
A	Haverson	0	1	33.00	22.03	3.90	30.87	44.91	1.46	0.237
A	Haverson	0	1	50.00	20.83	5.70	30.87	44.91	1.46	0.224
A	Haverson	0	1	100.00	19.07	61.78	30.87	44.91	1.46	0.205
A	Haverson	0	2	0.00	35.43	2.12	34.24	49.81	1.33	0.375
A	Haverson	0	2	2.00	34.71	6.95	34.24	49.81	1.33	0.367
A	Haverson	0	2	10.00	32.33	16.62	34.24	49.81	1.33	0.342
A	Haverson	0	2	33.00	26.64	6.35	34.24	49.81	1.33	0.282
A	Haverson	0	2	50.00	24.46	6.65	34.24	49.81	1.33	0.259
A	Haverson	0	2	100.00	22.19	64.79	34.24	49.81	1.33	0.235
A	Thurlow	0	1	0.00	34.17	14.54	33.20	48.30	1.37	0.353
A	Thurlow	0	1	2.00	29.34	5.58	33.20	48.30	1.37	0.303
A	Thurlow	0	1	10.00	27.48	6.82	33.20	48.30	1.37	0.284
A	Thurlow	0	1	33.00	25.22	3.72	33.20	48.30	1.37	0.260
A	Thurlow	0	1	50.00	23.99	3.10	33.20	48.30	1.37	0.248
A	Thurlow	0	1	100.00	22.96	69.14	33.20	48.30	1.37	0.237
A	Thurlow	0	2	0.00	37.76	17.68	35.80	52.08	1.27	0.410
A	Thurlow	0	2	2.00	31.44	7.37	35.80	52.08	1.27	0.341
A	Thurlow	0	2	10.00	28.80	7.37	35.80	52.08	1.27	0.313
A	Thurlow	0	2	33.00	26.16	2.95	35.80	52.08	1.27	0.284
A	Thurlow	0	2	50.00	25.11	3.24	35.80	52.08	1.27	0.273
A	Thurlow	0	2	100.00	23.95	66.89	35.80	52.08	1.27	0.260
B	Busby	0	1	0.00	34.41	18.79	34.50	50.19	1.32	0.380
B	Busby	0	1	2.00	27.93	8.38	34.50	50.19	1.32	0.309
B	Busby	0	1	10.00	25.03	5.78	34.50	50.19	1.32	0.277
B	Busby	0	1	33.00	23.04	3.18	34.50	50.19	1.32	0.255
B	Busby	0	1	50.00	21.94	2.31	34.50	50.19	1.32	0.242
B	Busby	0	1	100.00	21.14	61.29	34.50	50.19	1.32	0.234
B	Busby	0	2	0.00	31.27	21.57	33.20	48.30	1.37	0.353
B	Busby	0	2	2.00	24.11	0.85	33.20	48.30	1.37	0.272
B	Busby	0	2	10.00	23.83	3.69	33.20	48.30	1.37	0.269

Table 17. (Cont'd).

B	Busby	0	2	33.00	22.61	3.40	33.20	48.30	1.37	0.255
B	Busby	0	2	50.00	21.48	7.38	33.20	48.30	1.37	0.242
B	Busby	0	2	100.00	19.03	57.30	33.20	48.30	1.37	0.215
B	Haverson	0	1	0.00	39.78	21.33	36.57	53.21	1.24	0.429
B	Haverson	0	1	2.00	31.97	15.16	36.57	53.21	1.24	0.345
B	Haverson	0	1	10.00	26.43	8.33	36.57	53.21	1.24	0.285
B	Haverson	0	1	33.00	23.38	1.49	36.57	53.21	1.24	0.252
B	Haverson	0	1	50.00	22.84	4.46	36.57	53.21	1.24	0.246
B	Haverson	0	1	100.00	21.21	57.98	36.57	53.21	1.24	0.229
B	Haverson	0	2	0.00	32.96	21.67	33.46	48.68	1.36	0.358
B	Haverson	0	2	2.00	25.71	8.24	33.46	48.68	1.36	0.279
B	Haverson	0	2	10.00	22.95	5.30	33.46	48.68	1.36	0.249
B	Haverson	0	2	33.00	21.18	1.47	33.46	48.68	1.36	0.230
B	Haverson	0	2	50.00	20.69	2.94	33.46	48.68	1.36	0.225
B	Haverson	0	2	100.00	19.70	58.88	33.46	48.68	1.36	0.214
B	Thurlow	0	1	0.00	32.56	16.88	32.17	46.79	1.41	0.332
B	Thurlow	0	1	2.00	27.13	4.72	32.17	46.79	1.41	0.277
B	Thurlow	0	1	10.00	25.61	5.35	32.17	46.79	1.41	0.261
B	Thurlow	0	1	33.00	23.89	2.20	32.17	46.79	1.41	0.243
B	Thurlow	0	1	50.00	23.18	2.83	32.17	46.79	1.41	0.236
B	Thurlow	0	1	100.00	22.27	69.23	32.17	46.79	1.41	0.227
B	Thurlow	0	2	0.00	32.33	13.67	31.91	46.42	1.42	0.327
B	Thurlow	0	2	2.00	27.96	5.72	31.91	46.42	1.42	0.283
B	Thurlow	0	2	10.00	26.14	5.40	31.91	46.42	1.42	0.264
B	Thurlow	0	2	33.00	24.42	1.91	31.91	46.42	1.42	0.247
B	Thurlow	0	2	50.00	23.81	2.54	31.91	46.42	1.42	0.241
B	Thurlow	0	2	100.00	23.00	72.09	31.91	46.42	1.42	0.233
C	Busby	0	1	0.00	29.92	18.60	33.46	48.68	1.36	0.358
C	Busby	0	1	2.00	23.70	10.42	33.46	48.68	1.36	0.283
C	Busby	0	1	10.00	20.21	1.87	33.46	48.68	1.36	0.242
C	Busby	0	1	33.00	19.58	3.47	33.46	48.68	1.36	0.234
C	Busby	0	1	50.00	18.42	1.34	33.46	48.68	1.36	0.220
C	Busby	0	1	100.00	17.97	53.71	33.46	48.68	1.36	0.215
C	Busby	0	2	0.00	29.14	23.08	32.42	47.17	1.4	0.337
C	Busby	0	2	2.00	21.66	6.93	32.42	47.17	1.4	0.250
C	Busby	0	2	10.00	19.41	1.39	32.42	47.17	1.4	0.224
C	Busby	0	2	33.00	18.96	4.44	32.42	47.17	1.4	0.219
C	Busby	0	2	50.00	17.53	2.22	32.42	47.17	1.4	0.203
C	Busby	0	2	100.00	16.81	51.84	32.42	47.17	1.4	0.194
C	Haverson	0	1	0.00	34.31	24.60	33.98	49.43	1.34	0.369
C	Haverson	0	1	2.00	25.95	3.57	33.98	49.43	1.34	0.279
C	Haverson	0	1	10.00	24.74	1.78	33.98	49.43	1.34	0.266
C	Haverson	0	1	33.00	24.13	2.08	33.98	49.43	1.34	0.259
C	Haverson	0	1	50.00	23.42	0.59	33.98	49.43	1.34	0.252
C	Haverson	0	1	100.00	23.22	68.34	33.98	49.43	1.34	0.250
C	Haverson	0	2	0.00	35.55	25.69	34.50	50.19	1.32	0.380
C	Haverson	0	2	2.00	26.69	4.78	34.50	50.19	1.32	0.285

Table 17. (Cont'd).

C	Haverson	0	2	10.00	25.04	0.60	34.50	50.19	1.32	0.268
C	Haverson	0	2	33.00	24.83	2.69	34.50	50.19	1.32	0.266
C	Haverson	0	2	50.00	23.91	0.00	34.50	50.19	1.32	0.256
C	Haverson	0	2	100.00	23.91	69.29	34.50	50.19	1.32	0.256
C	Thurlow	0	1	0.00	32.34	8.69	32.42	47.17	1.4	0.337
C	Thurlow	0	1	2.00	29.53	0.92	32.42	47.17	1.4	0.308
C	Thurlow	0	1	10.00	29.23	1.23	32.42	47.17	1.4	0.304
C	Thurlow	0	1	33.00	28.83	0.92	32.42	47.17	1.4	0.300
C	Thurlow	0	1	50.00	28.53	1.54	32.42	47.17	1.4	0.297
C	Thurlow	0	1	100.00	28.03	86.45	32.42	47.17	1.4	0.292
C	Thurlow	0	2	0.00	32.31	12.68	32.42	47.17	1.4	0.337
C	Thurlow	0	2	2.00	28.20	1.54	32.42	47.17	1.4	0.294
C	Thurlow	0	2	10.00	27.70	0.92	32.42	47.17	1.4	0.289
C	Thurlow	0	2	33.00	27.40	1.23	32.42	47.17	1.4	0.286
C	Thurlow	0	2	50.00	27.00	0.92	32.42	47.17	1.4	0.282
C	Thurlow	0	2	100.00	26.71	82.36	32.42	47.17	1.4	0.278
A	Busby	1	1	0.00	36.83	34.20	36.06	52.45	1.26	0.427
A	Busby	1	1	2.00	24.50	5.81	36.06	52.45	1.26	0.284
A	Busby	1	1	10.00	22.40	9.44	36.06	52.45	1.26	0.260
A	Busby	1	1	33.00	19.00	4.71	36.06	52.45	1.26	0.220
A	Busby	1	1	50.00	17.30	4.99	36.06	52.45	1.26	0.200
A	Busby	1	1	100.00	15.50	42.99	36.06	52.45	1.26	0.180
A	Busby	1	2	0.00	37.61	39.41	36.83	53.58	1.23	0.444
A	Busby	1	2	2.00	23.10	1.88	36.83	53.58	1.23	0.272
A	Busby	1	2	10.00	22.40	4.09	36.83	53.58	1.23	0.264
A	Busby	1	2	33.00	20.90	1.34	36.83	53.58	1.23	0.246
A	Busby	1	2	50.00	20.40	2.99	36.83	53.58	1.23	0.241
A	Busby	1	2	100.00	19.30	52.40	36.83	53.58	1.23	0.228
A	Haverson	1	1	0.00	33.46	18.29	33.72	49.06	1.35	0.360
A	Haverson	1	1	2.00	27.30	7.40	33.72	49.06	1.35	0.294
A	Haverson	1	1	10.00	24.80	6.52	33.72	49.06	1.35	0.267
A	Haverson	1	1	33.00	22.60	3.85	33.72	49.06	1.35	0.243
A	Haverson	1	1	50.00	21.30	5.65	33.72	49.06	1.35	0.229
A	Haverson	1	1	100.00	19.40	57.53	33.72	49.06	1.35	0.209
A	Haverson	1	2	0.00	34.24	4.95	33.20	48.30	1.37	0.362
A	Haverson	1	2	2.00	32.60	6.91	33.20	48.30	1.37	0.345
A	Haverson	1	2	10.00	30.30	16.56	33.20	48.30	1.37	0.320
A	Haverson	1	2	33.00	24.80	6.34	33.20	48.30	1.37	0.262
A	Haverson	1	2	50.00	22.70	6.62	33.20	48.30	1.37	0.240
A	Haverson	1	2	100.00	20.50	61.74	33.20	48.30	1.37	0.217
A	Thurlow	1	1	0.00	33.19	6.68	32.94	47.92	1.38	0.343
A	Thurlow	1	1	2.00	31.00	5.47	32.94	47.92	1.38	0.320
A	Thurlow	1	1	10.00	29.19	6.68	32.94	47.92	1.38	0.301
A	Thurlow	1	1	33.00	27.00	3.65	32.94	47.92	1.38	0.279
A	Thurlow	1	1	50.00	25.79	3.02	32.94	47.92	1.38	0.266
A	Thurlow	1	1	100.00	24.80	75.27	32.94	47.92	1.38	0.256
A	Thurlow	1	2	0.00	34.24	6.65	33.72	49.06	1.35	0.372

Table 17. (Cont'd).

A	Thurlow	1	2	2.00	32.00	7.40	33.72	49.06	1.35	0.347
A	Thurlow	1	2	10.00	29.50	7.42	33.72	49.06	1.35	0.320
A	Thurlow	1	2	33.00	27.00	2.98	33.72	49.06	1.35	0.293
A	Thurlow	1	2	50.00	26.00	3.26	33.72	49.06	1.35	0.282
A	Thurlow	1	2	100.00	24.90	73.83	33.72	49.06	1.35	0.270
B	Busby	1	1	0.00	33.46	22.50	34.50	50.19	1.32	0.370
B	Busby	1	1	2.00	25.70	8.41	34.50	50.19	1.32	0.284
B	Busby	1	1	10.00	22.80	4.80	34.50	50.19	1.32	0.252
B	Busby	1	1	33.00	21.14	4.18	34.50	50.19	1.32	0.234
B	Busby	1	1	50.00	19.70	2.33	34.50	50.19	1.32	0.218
B	Busby	1	1	100.00	18.90	54.77	34.50	50.19	1.32	0.209
B	Busby	1	2	0.00	33.72	29.27	35.28	51.32	1.29	0.380
B	Busby	1	2	2.00	23.40	0.86	35.28	51.32	1.29	0.264
B	Busby	1	2	10.00	23.10	3.68	35.28	51.32	1.29	0.260
B	Busby	1	2	33.00	21.80	3.39	35.28	51.32	1.29	0.246
B	Busby	1	2	50.00	20.60	7.38	35.28	51.32	1.29	0.232
B	Busby	1	2	100.00	18.00	51.01	35.28	51.32	1.29	0.203
B	Haverson	1	1	0.00	32.42	3.93	33.72	49.06	1.35	0.350
B	Haverson	1	1	2.00	31.10	15.13	33.72	49.06	1.35	0.335
B	Haverson	1	1	10.00	26.00	8.30	33.72	49.06	1.35	0.280
B	Haverson	1	1	33.00	23.20	1.49	33.72	49.06	1.35	0.250
B	Haverson	1	1	50.00	22.70	4.44	33.72	49.06	1.35	0.245
B	Haverson	1	1	100.00	21.20	62.87	33.72	49.06	1.35	0.229
B	Haverson	1	2	0.00	31.91	9.14	33.98	49.43	1.34	0.346
B	Haverson	1	2	2.00	28.80	8.25	33.98	49.43	1.34	0.313
B	Haverson	1	2	10.00	26.00	5.30	33.98	49.43	1.34	0.282
B	Haverson	1	2	33.00	24.20	1.46	33.98	49.43	1.34	0.263
B	Haverson	1	2	50.00	23.70	2.95	33.98	49.43	1.34	0.257
B	Haverson	1	2	100.00	22.70	66.80	33.98	49.43	1.34	0.246
B	Thurlow	1	1	0.00	31.65	10.30	31.65	46.04	1.43	0.323
B	Thurlow	1	1	2.00	28.39	4.76	31.65	46.04	1.43	0.289
B	Thurlow	1	1	10.00	26.88	5.37	31.65	46.04	1.43	0.274
B	Thurlow	1	1	33.00	25.19	2.19	31.65	46.04	1.43	0.257
B	Thurlow	1	1	50.00	24.49	2.85	31.65	46.04	1.43	0.250
B	Thurlow	1	1	100.00	23.59	74.55	31.65	46.04	1.43	0.240
B	Thurlow	1	2	0.00	32.15	16.77	31.39	45.66	1.44	0.325
B	Thurlow	1	2	2.00	26.89	5.74	31.39	45.66	1.44	0.272
B	Thurlow	1	2	10.00	25.09	5.41	31.39	45.66	1.44	0.254
B	Thurlow	1	2	33.00	23.39	1.90	31.39	45.66	1.44	0.237
B	Thurlow	1	2	50.00	22.79	2.56	31.39	45.66	1.44	0.230
B	Thurlow	1	2	100.00	21.99	70.06	31.39	45.66	1.44	0.222
C	Busby	1	1	0.00	34.93	22.27	36.06	52.45	1.26	0.418
C	Busby	1	1	2.00	26.90	10.81	36.06	52.45	1.26	0.322
C	Busby	1	1	10.00	23.00	1.94	36.06	52.45	1.26	0.275
C	Busby	1	1	33.00	22.30	3.60	36.06	52.45	1.26	0.267
C	Busby	1	1	50.00	21.00	1.39	36.06	52.45	1.26	0.251
C	Busby	1	1	100.00	20.50	56.85	36.06	52.45	1.26	0.245

Table 17. (Cont'd).

C	Busby	1	2	0.00	35.28	21.18	37.09	53.96	1.22	0.408
C	Busby	1	2	2.00	27.42	10.92	37.09	53.96	1.22	0.317
C	Busby	1	2	10.00	23.37	2.78	37.09	53.96	1.22	0.270
C	Busby	1	2	33.00	22.34	4.65	37.09	53.96	1.22	0.258
C	Busby	1	2	50.00	20.62	1.89	37.09	53.96	1.22	0.238
C	Busby	1	2	100.00	19.91	53.69	37.09	53.96	1.22	0.230
C	Haverson	1	1	0.00	34.00	22.60	33.72	49.06	1.35	0.366
C	Haverson	1	1	2.00	26.38	3.57	33.72	49.06	1.35	0.284
C	Haverson	1	1	10.00	25.17	1.77	33.72	49.06	1.35	0.271
C	Haverson	1	1	33.00	24.57	2.08	33.72	49.06	1.35	0.264
C	Haverson	1	1	50.00	23.87	0.59	33.72	49.06	1.35	0.257
C	Haverson	1	1	100.00	23.67	70.20	33.72	49.06	1.35	0.255
C	Haverson	1	2	0.00	34.50	25.70	33.46	48.68	1.36	0.369
C	Haverson	1	2	2.00	25.90	4.79	33.46	48.68	1.36	0.277
C	Haverson	1	2	10.00	24.30	0.60	33.46	48.68	1.36	0.260
C	Haverson	1	2	33.00	24.10	2.69	33.46	48.68	1.36	0.258
C	Haverson	1	2	50.00	23.20	0.00	33.46	48.68	1.36	0.248
C	Haverson	1	2	100.00	23.20	69.33	33.46	48.68	1.36	0.248
C	Thurlow	1	1	0.00	32.42	8.71	32.42	47.17	1.4	0.338
C	Thurlow	1	1	2.00	29.60	0.61	32.42	47.17	1.4	0.308
C	Thurlow	1	1	10.00	29.40	1.55	32.42	47.17	1.4	0.306
C	Thurlow	1	1	33.00	28.90	0.93	32.42	47.17	1.4	0.301
C	Thurlow	1	1	50.00	28.60	1.53	32.42	47.17	1.4	0.298
C	Thurlow	1	1	100.00	28.10	86.67	32.42	47.17	1.4	0.293
C	Thurlow	1	2	0.00	32.42	14.27	32.42	47.17	1.4	0.338
C	Thurlow	1	2	2.00	27.80	0.93	32.42	47.17	1.4	0.290
C	Thurlow	1	2	10.00	27.50	1.53	32.42	47.17	1.4	0.287
C	Thurlow	1	2	33.00	27.00	1.23	32.42	47.17	1.4	0.282
C	Thurlow	1	2	50.00	26.60	9.88	32.42	47.17	1.4	0.277
C	Thurlow	1	2	100.00	23.40	72.17	32.42	47.17	1.4	0.244
A	Busby	2	1	0.00	38.92	31.30	37.09	53.96	1.22	0.442
A	Busby	2	1	2.00	27.32	10.21	37.09	53.96	1.22	0.310
A	Busby	2	1	10.00	23.53	6.56	37.09	53.96	1.22	0.267
A	Busby	2	1	33.00	21.09	2.40	37.09	53.96	1.22	0.240
A	Busby	2	1	50.00	20.20	3.06	37.09	53.96	1.22	0.230
A	Busby	2	1	100.00	19.07	51.40	37.09	53.96	1.22	0.217
A	Busby	2	2	0.00	37.47	7.66	36.83	53.58	1.23	0.436
A	Busby	2	2	2.00	34.64	13.56	36.83	53.58	1.23	0.403
A	Busby	2	2	10.00	29.65	14.58	36.83	53.58	1.23	0.345
A	Busby	2	2	33.00	24.28	13.86	36.83	53.58	1.23	0.282
A	Busby	2	2	50.00	19.17	3.42	36.83	53.58	1.23	0.223
A	Busby	2	2	100.00	17.91	48.63	36.83	53.58	1.23	0.208
A	Haverson	2	1	0.00	34.31	9.63	33.98	49.43	1.34	0.369
A	Haverson	2	1	2.00	31.04	25.32	33.98	49.43	1.34	0.334
A	Haverson	2	1	10.00	22.43	8.02	33.98	49.43	1.34	0.241
A	Haverson	2	1	33.00	19.71	6.77	33.98	49.43	1.34	0.212
A	Haverson	2	1	50.00	17.41	2.47	33.98	49.43	1.34	0.187

Table 17. (Cont'd).

A	Haverson	2	1	100.00	16.57	48.76	33.98	49.43	1.34	0.178
A	Haverson	2	2	0.00	37.62	10.27	35.02	50.94	1.3	0.392
A	Haverson	2	2	2.00	34.02	27.15	35.02	50.94	1.3	0.354
A	Haverson	2	2	10.00	24.52	8.68	35.02	50.94	1.3	0.255
A	Haverson	2	2	33.00	21.48	4.60	35.02	50.94	1.3	0.224
A	Haverson	2	2	50.00	19.86	2.33	35.02	50.94	1.3	0.207
A	Haverson	2	2	100.00	19.05	54.39	35.02	50.94	1.3	0.198
A	Thurlow	2	1	0.00	34.90	21.14	33.46	48.68	1.36	0.358
A	Thurlow	2	1	2.00	27.82	8.57	33.46	48.68	1.36	0.285
A	Thurlow	2	1	10.00	24.96	4.46	33.46	48.68	1.36	0.256
A	Thurlow	2	1	33.00	23.47	2.49	33.46	48.68	1.36	0.241
A	Thurlow	2	1	50.00	22.63	1.22	33.46	48.68	1.36	0.232
A	Thurlow	2	1	100.00	22.22	66.42	33.46	48.68	1.36	0.228
A	Thurlow	2	2	0.00	33.17	15.26	32.94	47.92	1.38	0.347
A	Thurlow	2	2	2.00	28.14	4.92	32.94	47.92	1.38	0.295
A	Thurlow	2	2	10.00	26.52	5.26	32.94	47.92	1.38	0.278
A	Thurlow	2	2	33.00	24.79	4.00	32.94	47.92	1.38	0.260
A	Thurlow	2	2	50.00	23.47	2.23	32.94	47.92	1.38	0.246
A	Thurlow	2	2	100.00	22.73	69.00	32.94	47.92	1.38	0.238
B	Busby	2	1	0.00	39.24	46.37	39.17	56.98	1.14	0.500
B	Busby	2	1	2.00	21.08	7.01	39.17	56.98	1.14	0.269
B	Busby	2	1	10.00	18.33	4.71	39.17	56.98	1.14	0.234
B	Busby	2	1	33.00	16.49	2.71	39.17	56.98	1.14	0.210
B	Busby	2	1	50.00	15.43	1.74	39.17	56.98	1.14	0.197
B	Busby	2	1	100.00	14.75	37.65	39.17	56.98	1.14	0.188
B	Busby	2	2	0.00	38.73	43.71	38.65	56.23	1.16	0.485
B	Busby	2	2	2.00	21.83	3.21	38.65	56.23	1.16	0.273
B	Busby	2	2	10.00	20.59	2.85	38.65	56.23	1.16	0.258
B	Busby	2	2	33.00	19.49	1.50	38.65	56.23	1.16	0.244
B	Busby	2	2	50.00	18.91	2.18	38.65	56.23	1.16	0.237
B	Busby	2	2	100.00	18.07	46.74	38.65	56.23	1.16	0.226
B	Haverson	2	1	0.00	34.52	26.77	34.50	50.19	1.32	0.380
B	Haverson	2	1	2.00	25.29	7.48	34.50	50.19	1.32	0.278
B	Haverson	2	1	10.00	22.71	5.86	34.50	50.19	1.32	0.250
B	Haverson	2	1	33.00	20.68	3.07	34.50	50.19	1.32	0.228
B	Haverson	2	1	50.00	19.62	4.93	34.50	50.19	1.32	0.216
B	Haverson	2	1	100.00	17.92	51.95	34.50	50.19	1.32	0.197
B	Haverson	2	2	0.00	33.65	33.77	33.72	49.06	1.35	0.363
B	Haverson	2	2	2.00	22.26	4.97	33.72	49.06	1.35	0.240
B	Haverson	2	2	10.00	20.59	3.85	33.72	49.06	1.35	0.222
B	Haverson	2	2	33.00	19.29	2.69	33.72	49.06	1.35	0.208
B	Haverson	2	2	50.00	18.38	1.92	33.72	49.06	1.35	0.198
B	Haverson	2	2	100.00	17.73	52.58	33.72	49.06	1.35	0.191
B	Thurlow	2	1	0.00	35.33	23.33	35.28	51.32	1.29	0.398
B	Thurlow	2	1	2.00	27.10	4.03	35.28	51.32	1.29	0.305
B	Thurlow	2	1	10.00	25.68	2.84	35.28	51.32	1.29	0.289
B	Thurlow	2	1	33.00	24.68	1.53	35.28	51.32	1.29	0.278

Table 17. (Cont'd).

B	Thurlow	2	1	50.00	24.14	2.16	35.28	51.32	1.29	0.272
B	Thurlow	2	1	100.00	23.37	66.26	35.28	51.32	1.29	0.263
B	Thurlow	2	2	0.00	35.37	17.22	35.28	51.32	1.29	0.398
B	Thurlow	2	2	2.00	29.30	7.22	35.28	51.32	1.29	0.330
B	Thurlow	2	2	10.00	26.75	3.81	35.28	51.32	1.29	0.301
B	Thurlow	2	2	33.00	25.41	2.27	35.28	51.32	1.29	0.286
B	Thurlow	2	2	50.00	24.60	3.41	35.28	51.32	1.29	0.277
B	Thurlow	2	2	100.00	23.40	66.33	35.28	51.32	1.29	0.263
C	Busby	2	1	0.00	37.45	41.48	37.35	54.34	1.21	0.449
C	Busby	2	1	2.00	21.96	4.94	37.35	54.34	1.21	0.263
C	Busby	2	1	10.00	20.11	3.81	37.35	54.34	1.21	0.241
C	Busby	2	1	33.00	18.69	3.22	37.35	54.34	1.21	0.224
C	Busby	2	1	50.00	17.49	2.04	37.35	54.34	1.21	0.210
C	Busby	2	1	100.00	16.72	44.77	37.35	54.34	1.21	0.201
C	Busby	2	2	0.00	36.09	24.81	36.06	52.45	1.26	0.416
C	Busby	2	2	2.00	27.15	11.11	36.06	52.45	1.26	0.313
C	Busby	2	2	10.00	23.14	3.05	36.06	52.45	1.26	0.267
C	Busby	2	2	33.00	22.04	2.72	36.06	52.45	1.26	0.254
C	Busby	2	2	50.00	21.06	1.33	36.06	52.45	1.26	0.243
C	Busby	2	2	100.00	20.58	57.08	36.06	52.45	1.26	0.237
C	Haverson	2	1	0.00	32.89	19.22	32.94	47.92	1.38	0.347
C	Haverson	2	1	2.00	26.56	3.15	32.94	47.92	1.38	0.280
C	Haverson	2	1	10.00	25.52	2.06	32.94	47.92	1.38	0.269
C	Haverson	2	1	33.00	24.84	2.61	32.94	47.92	1.38	0.262
C	Haverson	2	1	50.00	23.98	1.82	32.94	47.92	1.38	0.253
C	Haverson	2	1	100.00	23.38	70.97	32.94	47.92	1.38	0.247
C	Haverson	2	2	0.00	34.66	22.06	34.76	50.57	1.31	0.386
C	Haverson	2	2	2.00	26.99	5.16	34.76	50.57	1.31	0.301
C	Haverson	2	2	10.00	25.20	2.98	34.76	50.57	1.31	0.281
C	Haverson	2	2	33.00	24.16	2.58	34.76	50.57	1.31	0.269
C	Haverson	2	2	50.00	23.27	1.95	34.76	50.57	1.31	0.259
C	Haverson	2	2	100.00	22.59	64.98	34.76	50.57	1.31	0.252
C	Thurlow	2	1	0.00	33.21	23.75	33.20	48.30	1.37	0.353
C	Thurlow	2	1	2.00	25.33	1.21	33.20	48.30	1.37	0.269
C	Thurlow	2	1	10.00	24.93	3.56	33.20	48.30	1.37	0.265
C	Thurlow	2	1	33.00	23.75	2.95	33.20	48.30	1.37	0.252
C	Thurlow	2	1	50.00	22.77	2.41	33.20	48.30	1.37	0.242
C	Thurlow	2	1	100.00	21.97	66.16	33.20	48.30	1.37	0.233
C	Thurlow	2	2	0.00	32.89	14.01	32.94	47.92	1.38	0.347
C	Thurlow	2	2	2.00	28.27	4.67	32.94	47.92	1.38	0.299
C	Thurlow	2	2	10.00	26.73	2.91	32.94	47.92	1.38	0.282
C	Thurlow	2	2	33.00	25.78	2.73	32.94	47.92	1.38	0.272
C	Thurlow	2	2	50.00	24.88	1.76	32.94	47.92	1.38	0.263
C	Thurlow	2	2	100.00	24.30	73.76	32.94	47.92	1.38	0.257

Table 18. Drainage water sodium concentrations for water quality, soil series, amendment rate, and replications from laboratory core study.

Quality Water	Series Soil	Rate Amend	Rep	[Na] mg/L
A	Busby	0	1	54
A	Busby	0	2	54
A	Busby	1	1	390
A	Busby	1	2	400
A	Busby	2	1	250
A	Busby	2	2	260
A	Haverson	0	1	54
A	Haverson	0	2	54
A	Haverson	1	1	230
A	Haverson	1	2	280
A	Haverson	2	1	290
A	Haverson	2	2	300
A	Thurlow	0	1	54
A	Thurlow	0	2	54
A	Thurlow	1	1	250
A	Thurlow	1	2	260
A	Thurlow	2	1	270
A	Thurlow	2	2	290
B	Busby	0	1	220
B	Busby	0	2	220
B	Busby	1	1	1020
B	Busby	1	2	1330
B	Busby	2	1	1300
B	Busby	2	2	1500
B	Haverson	0	1	220
B	Haverson	0	2	220
B	Haverson	1	1	750
B	Haverson	1	2	960
B	Haverson	2	1	1720
B	Haverson	2	2	1000
B	Thurlow	0	1	220
B	Thurlow	0	2	220
B	Thurlow	1	1	1010
B	Thurlow	1	2	900
B	Thurlow	2	1	1490
B	Thurlow	2	2	1330
C	Busby	0	1	400
C	Busby	0	2	400
C	Busby	1	1	1850
C	Busby	1	2	1840
C	Busby	2	1	2380
C	Busby	2	2	1990
C	Haverson	0	1	400
C	Haverson	0	2	400
C	Haverson	1	1	2650

Table 18. (Cont'd).

C	Haverson	1	2	1830
C	Haverson	2	1	1300
C	Haverson	2	2	1500
C	Thurlow	0	1	400
C	Thurlow	0	2	400
C	Thurlow	1	1	1100
C	Thurlow	1	2	1640
C	Thurlow	2	1	1250
C	Thurlow	2	2	1450

Table 19. Outflow data for all water quality, soil series, amendment rate, and replications from greenhouse study.

Water Quality	Soil Series	Amend Rate	Rep	Pres. kPa	Outflow mL	PDTP %	Pore Vol. cm3	Porosity %	BD g/cm3	θm g/g
A	Busby	0	1	0.0	30.43	24.03	33.20	0.483019	1.37	0.353
A	Busby	0	1	2.0	22.45	5.78	33.20	0.483019	1.37	0.260
A	Busby	0	1	10.0	20.53	9.40	33.20	0.483019	1.37	0.238
A	Busby	0	1	33.0	17.41	4.70	33.20	0.483019	1.37	0.202
A	Busby	0	1	50.0	15.85	4.94	33.20	0.483019	1.37	0.184
A	Busby	0	1	100.0	14.21	42.80	33.20	0.483019	1.37	0.165
A	Busby	0	2	0.0	36.94	50.50	36.83	0.535849	1.23	0.436
A	Busby	0	2	2.0	18.34	1.90	36.83	0.535849	1.23	0.216
A	Busby	0	2	10.0	17.64	4.07	36.83	0.535849	1.23	0.208
A	Busby	0	2	33.0	16.14	1.36	36.83	0.535849	1.23	0.190
A	Busby	0	2	50.0	15.64	3.01	36.83	0.535849	1.23	0.184
A	Busby	0	2	100.0	14.53	39.45	36.83	0.535849	1.23	0.171
A	Busby	1	1	0.0	45.45	61.40	35.80	0.520755	1.27	0.522
A	Busby	1	1	2.0	23.47	11.51	35.80	0.520755	1.27	0.269
A	Busby	1	1	10.0	19.35	12.46	35.80	0.520755	1.27	0.222
A	Busby	1	1	33.0	14.89	3.77	35.80	0.520755	1.27	0.171
A	Busby	1	1	50.0	13.54	7.12	35.80	0.520755	1.27	0.155
A	Busby	1	1	100.0	10.99	30.70	35.80	0.520755	1.27	0.126
A	Busby	1	2	0.0	45.42	57.30	36.06	0.524528	1.26	0.525
A	Busby	1	2	2.0	24.76	11.45	36.06	0.524528	1.26	0.286
A	Busby	1	2	10.0	20.63	8.35	36.06	0.524528	1.26	0.239
A	Busby	1	2	33.0	17.62	4.77	36.06	0.524528	1.26	0.204
A	Busby	1	2	50.0	15.9	12.40	36.06	0.524528	1.26	0.184
A	Busby	1	2	100.0	11.43	31.70	36.06	0.524528	1.26	0.132
A	Haverson	0	1	0.0	28.57	7.09	30.87	0.449057	1.46	0.308
A	Haverson	0	1	2.0	26.38	7.48	30.87	0.449057	1.46	0.284
A	Haverson	0	1	10.0	24.07	6.61	30.87	0.449057	1.46	0.259
A	Haverson	0	1	33.0	22.03	3.89	30.87	0.449057	1.46	0.237
A	Haverson	0	1	50.0	20.83	5.70	30.87	0.449057	1.46	0.224
A	Haverson	0	1	100.0	19.07	61.78	30.87	0.449057	1.46	0.205
A	Haverson	0	2	0.0	35.43	2.10	34.24	0.498113	1.33	0.375
A	Haverson	0	2	2.0	34.71	6.95	34.24	0.498113	1.33	0.367
A	Haverson	0	2	10.0	32.33	16.62	34.24	0.498113	1.33	0.342
A	Haverson	0	2	33.0	26.64	6.37	34.24	0.498113	1.33	0.282
A	Haverson	0	2	50.0	24.46	6.63	34.24	0.498113	1.33	0.259
A	Haverson	0	2	100.0	22.19	64.81	34.24	0.498113	1.33	0.235
A	Haverson	1	1	0.0	45.03	46.18	36.32	0.528302	1.25	0.562
A	Haverson	1	1	2.0	28.26	16.63	36.32	0.528302	1.25	0.353
A	Haverson	1	1	10.0	22.22	8.23	36.32	0.528302	1.25	0.277
A	Haverson	1	1	33.0	19.23	3.52	36.32	0.528302	1.25	0.240
A	Haverson	1	1	50.0	17.95	5.09	36.32	0.528302	1.25	0.224
A	Haverson	1	1	100.0	16.1	44.33	36.32	0.528302	1.25	0.201
A	Haverson	1	2	0.0	44.82	20.19	37.35	0.543396	1.21	0.563
A	Haverson	1	2	2.0	37.28	3.11	37.35	0.543396	1.21	0.468
A	Haverson	1	2	10.0	36.12	39.81	37.35	0.543396	1.21	0.453

Table 19. (Cont'd).

A	Haverson	1	2	33.0	21.25	9.02	37.35	0.543396	1.21	0.267
A	Haverson	1	2	50.0	17.88	5.65	37.35	0.543396	1.21	0.224
A	Haverson	1	2	100.0	15.77	42.22	37.35	0.543396	1.21	0.198
A	Thurlow	0	1	0.0	34.17	14.55	33.20	0.483019	1.37	0.353
A	Thurlow	0	1	2.0	29.34	5.60	33.20	0.483019	1.37	0.303
A	Thurlow	0	1	10.0	27.48	6.81	33.20	0.483019	1.37	0.284
A	Thurlow	0	1	33.0	25.22	3.70	33.20	0.483019	1.37	0.260
A	Thurlow	0	1	50.0	23.99	3.10	33.20	0.483019	1.37	0.248
A	Thurlow	0	1	100.0	22.96	69.15	33.20	0.483019	1.37	0.237
A	Thurlow	0	2	0.0	37.76	17.66	35.80	0.520755	1.27	0.410
A	Thurlow	0	2	2.0	31.44	7.37	35.80	0.520755	1.27	0.341
A	Thurlow	0	2	10.0	28.8	7.37	35.80	0.520755	1.27	0.313
A	Thurlow	0	2	33.0	26.16	2.93	35.80	0.520755	1.27	0.284
A	Thurlow	0	2	50.0	25.11	3.24	35.80	0.520755	1.27	0.273
A	Thurlow	0	2	100.0	23.95	66.91	35.80	0.520755	1.27	0.260
A	Thurlow	1	1	0.0	45.7	41.58	35.02	0.509434	1.3	0.509
A	Thurlow	1	1	2.0	31.14	12.19	35.02	0.509434	1.3	0.358
A	Thurlow	1	1	10.0	26.87	5.43	35.02	0.509434	1.3	0.308
A	Thurlow	1	1	33.0	24.97	1.83	35.02	0.509434	1.3	0.287
A	Thurlow	1	1	50.0	24.33	3.08	35.02	0.509434	1.3	0.279
A	Thurlow	1	1	100.0	23.25	66.39	35.02	0.509434	1.3	0.259
A	Thurlow	1	2	0.0	45.48	38.13	37.87	0.550943	1.19	0.550
A	Thurlow	1	2	2.0	31.04	13.49	37.87	0.550943	1.19	0.379
A	Thurlow	1	2	10.0	25.93	8.69	37.87	0.550943	1.19	0.316
A	Thurlow	1	2	33.0	22.64	8.71	37.87	0.550943	1.19	0.276
A	Thurlow	1	2	50.0	19.34	18.27	37.87	0.550943	1.19	0.236
A	Thurlow	1	2	100.0	12.42	32.79	37.87	0.550943	1.19	0.151
B	Busby	0	1	0.0	34.41	18.78	34.50	0.501887	1.32	0.380
B	Busby	0	1	2.0	27.93	8.41	34.50	0.501887	1.32	0.309
B	Busby	0	1	10.0	25.03	5.77	34.50	0.501887	1.32	0.277
B	Busby	0	1	33.0	23.04	3.19	34.50	0.501887	1.32	0.255
B	Busby	0	1	50.0	21.94	2.32	34.50	0.501887	1.32	0.243
B	Busby	0	1	100.0	21.14	61.28	34.50	0.501887	1.32	0.234
B	Busby	0	2	0.0	31.27	21.56	33.20	0.483019	1.37	0.353
B	Busby	0	2	2.0	24.11	0.84	33.20	0.483019	1.37	0.272
B	Busby	0	2	10.0	23.83	3.67	33.20	0.483019	1.37	0.269
B	Busby	0	2	33.0	22.61	3.40	33.20	0.483019	1.37	0.255
B	Busby	0	2	50.0	21.48	7.38	33.20	0.483019	1.37	0.242
B	Busby	0	2	100.0	19.03	57.31	33.20	0.483019	1.37	0.215
B	Busby	1	1	0.0	48.75	78.86	37.61	0.54717	1.2	0.546
B	Busby	1	1	2.0	19.09	14.62	37.61	0.54717	1.2	0.231
B	Busby	1	1	10.0	13.59	5.56	37.61	0.54717	1.2	0.164
B	Busby	1	1	33.0	11.5	1.99	37.61	0.54717	1.2	0.139
B	Busby	1	1	50.0	10.75	4.65	37.61	0.54717	1.2	0.130
B	Busby	1	1	100.0	9	23.93	37.61	0.54717	1.2	0.109
B	Busby	1	2	0.0	45.63	68.49	36.57	0.532075	1.24	0.533
B	Busby	1	2	2.0	20.58	10.64	36.57	0.532075	1.24	0.240

Table 19. (Cont'd).

B	Busby	1	2	10.0	16.69	7.35	36.57	0.532075	1.24	0.195
B	Busby	1	2	33.0	14	2.79	36.57	0.532075	1.24	0.164
B	Busby	1	2	50.0	12.98	4.29	36.57	0.532075	1.24	0.152
B	Busby	1	2	100.0	11.41	31.20	36.57	0.532075	1.24	0.133
B	Haverson	0	1	0.0	39.78	21.35	36.57	0.532075	1.24	0.429
B	Haverson	0	1	2.0	31.97	15.15	36.57	0.532075	1.24	0.345
B	Haverson	0	1	10.0	26.43	8.34	36.57	0.532075	1.24	0.285
B	Haverson	0	1	33.0	23.38	1.48	36.57	0.532075	1.24	0.252
B	Haverson	0	1	50.0	22.84	4.46	36.57	0.532075	1.24	0.246
B	Haverson	0	1	100.0	21.21	57.99	36.57	0.532075	1.24	0.229
B	Haverson	0	2	0.0	32.96	21.67	33.46	0.486792	1.36	0.358
B	Haverson	0	2	2.0	25.71	8.25	33.46	0.486792	1.36	0.279
B	Haverson	0	2	10.0	22.95	5.29	33.46	0.486792	1.36	0.249
B	Haverson	0	2	33.0	21.18	1.46	33.46	0.486792	1.36	0.230
B	Haverson	0	2	50.0	20.69	2.96	33.46	0.486792	1.36	0.225
B	Haverson	0	2	100.0	19.7	58.87	33.46	0.486792	1.36	0.214
B	Haverson	1	1	0.0	44.42	24.20	37.35	0.543396	1.21	0.542
B	Haverson	1	1	2.0	35.38	19.94	37.35	0.543396	1.21	0.424
B	Haverson	1	1	10.0	27.93	26.34	37.35	0.543396	1.21	0.335
B	Haverson	1	1	33.0	18.09	9.02	37.35	0.543396	1.21	0.217
B	Haverson	1	1	50.0	14.72	6.26	37.35	0.543396	1.21	0.176
B	Haverson	1	1	100.0	12.38	33.14	37.35	0.543396	1.21	0.148
B	Haverson	1	2	0.0	45.44	64.23	36.06	0.524528	1.26	0.523
B	Haverson	1	2	2.0	22.28	6.66	36.06	0.524528	1.26	0.256
B	Haverson	1	2	10.0	19.88	2.00	36.06	0.524528	1.26	0.229
B	Haverson	1	2	33.0	19.16	4.49	36.06	0.524528	1.26	0.220
B	Haverson	1	2	50.0	17.54	9.37	36.06	0.524528	1.26	0.202
B	Haverson	1	2	100.0	14.16	39.27	36.06	0.524528	1.26	0.220
B	Thurlow	0	1	0.0	32.56	16.88	32.17	0.467925	1.41	0.332
B	Thurlow	0	1	2.0	27.13	4.73	32.17	0.467925	1.41	0.277
B	Thurlow	0	1	10.0	25.61	5.35	32.17	0.467925	1.41	0.261
B	Thurlow	0	1	33.0	23.89	2.21	32.17	0.467925	1.41	0.244
B	Thurlow	0	1	50.0	23.18	2.83	32.17	0.467925	1.41	0.236
B	Thurlow	0	1	100.0	22.27	69.24	32.17	0.467925	1.41	0.227
B	Thurlow	0	2	0.0	32.33	13.70	31.91	0.464151	1.42	0.327
B	Thurlow	0	2	2.0	27.96	5.70	31.91	0.464151	1.42	0.283
B	Thurlow	0	2	10.0	26.14	5.39	31.91	0.464151	1.42	0.264
B	Thurlow	0	2	33.0	24.42	1.91	31.91	0.464151	1.42	0.247
B	Thurlow	0	2	50.0	23.81	2.54	31.91	0.464151	1.42	0.241
B	Thurlow	0	2	100.0	23	72.09	31.91	0.464151	1.42	0.233
B	Thurlow	1	1	0.0	45.53	21.62	35.02	0.509434	1.3	0.510
B	Thurlow	1	1	2.0	37.96	26.90	35.02	0.509434	1.3	0.423
B	Thurlow	1	1	10.0	28.54	1.14	35.02	0.509434	1.3	0.320
B	Thurlow	1	1	33.0	28.14	1.57	35.02	0.509434	1.3	0.324
B	Thurlow	1	1	50.0	27.59	30.47	35.02	0.509434	1.3	0.307
B	Thurlow	1	1	100.0	16.92	48.32	35.02	0.509434	1.3	0.190
B	Thurlow	1	2	0.0	45.76	23.84	35.02	0.509434	1.3	0.509

Table 19. (Cont'd).

B	Thurlow	1	2	2.0	37.41	15.68	35.02	0.509434	1.3	0.352
B	Thurlow	1	2	10.0	31.92	17.96	35.02	0.509434	1.3	0.355
B	Thurlow	1	2	33.0	25.63	7.74	35.02	0.509434	1.3	0.287
B	Thurlow	1	2	50.0	22.92	3.86	35.02	0.509434	1.3	0.257
B	Thurlow	1	2	100.0	21.57	61.60	35.02	0.509434	1.3	0.240
C	Busby	0	1	0.0	29.92	18.59	33.46	0.486792	1.36	0.358
C	Busby	0	1	2.0	23.7	10.43	33.46	0.486792	1.36	0.284
C	Busby	0	1	10.0	20.21	1.88	33.46	0.486792	1.36	0.242
C	Busby	0	1	33.0	19.58	3.47	33.46	0.486792	1.36	0.234
C	Busby	0	1	50.0	18.42	1.34	33.46	0.486792	1.36	0.220
C	Busby	0	1	100.0	17.97	53.70	33.46	0.486792	1.36	0.215
C	Busby	0	2	0.0	29.14	23.07	32.42	0.471698	1.4	0.337
C	Busby	0	2	2.0	21.66	6.94	32.42	0.471698	1.4	0.250
C	Busby	0	2	10.0	19.41	1.39	32.42	0.471698	1.4	0.224
C	Busby	0	2	33.0	18.96	4.41	32.42	0.471698	1.4	0.219
C	Busby	0	2	50.0	17.53	2.22	32.42	0.471698	1.4	0.203
C	Busby	0	2	100.0	16.81	51.84	32.42	0.471698	1.4	0.194
C	Busby	1	1	0.0	44.56	74.71	36.83	0.535849	1.23	0.573
C	Busby	1	1	2.0	17.04	12.54	36.83	0.535849	1.23	0.219
C	Busby	1	1	10.0	12.42	8.82	36.83	0.535849	1.23	0.160
C	Busby	1	1	33.0	9.17	4.07	36.83	0.535849	1.23	0.118
C	Busby	1	1	50.0	7.67	4.26	36.83	0.535849	1.23	0.099
C	Busby	1	1	100.0	6.1	16.56	36.83	0.535849	1.23	0.078
C	Busby	1	2	0.0	44.71	30.54	36.32	0.528302	1.25	0.568
C	Busby	1	2	2.0	33.62	26.08	36.32	0.528302	1.25	0.427
C	Busby	1	2	10.0	24.15	30.18	36.32	0.528302	1.25	0.307
C	Busby	1	2	33.0	13.19	17.87	36.32	0.528302	1.25	0.167
C	Busby	1	2	50.0	6.7	3.44	36.32	0.528302	1.25	0.085
C	Busby	1	2	100.0	5.45	15.01	36.32	0.528302	1.25	0.069
C	Haverson	0	1	0.0	34.31	24.60	33.98	0.49434	1.34	0.369
C	Haverson	0	1	2.0	25.95	3.56	33.98	0.49434	1.34	0.279
C	Haverson	0	1	10.0	24.74	1.80	33.98	0.49434	1.34	0.266
C	Haverson	0	1	33.0	24.13	2.09	33.98	0.49434	1.34	0.260
C	Haverson	0	1	50.0	23.42	0.59	33.98	0.49434	1.34	0.252
C	Haverson	0	1	100.0	23.22	68.33	33.98	0.49434	1.34	0.250
C	Haverson	0	2	0.0	35.55	25.68	34.50	0.501887	1.32	0.380
C	Haverson	0	2	2.0	26.69	4.78	34.50	0.501887	1.32	0.285
C	Haverson	0	2	10.0	25.04	0.61	34.50	0.501887	1.32	0.268
C	Haverson	0	2	33.0	24.83	2.67	34.50	0.501887	1.32	0.266
C	Haverson	0	2	50.0	23.91	0.00	34.50	0.501887	1.32	0.256
C	Haverson	0	2	100.0	23.91	69.30	34.50	0.501887	1.32	0.256
C	Haverson	1	1	0.0	45.32	53.59	36.83	0.535849	1.23	0.534
C	Haverson	1	1	2.0	25.58	19.60	36.83	0.535849	1.23	0.301
C	Haverson	1	1	10.0	18.36	17.32	36.83	0.535849	1.23	0.216
C	Haverson	1	1	33.0	11.98	7.17	36.83	0.535849	1.23	0.141
C	Haverson	1	1	50.0	9.34	6.43	36.83	0.535849	1.23	0.110
C	Haverson	1	1	100.0	6.97	18.92	36.83	0.535849	1.23	0.082

Table 19. (Cont'd).

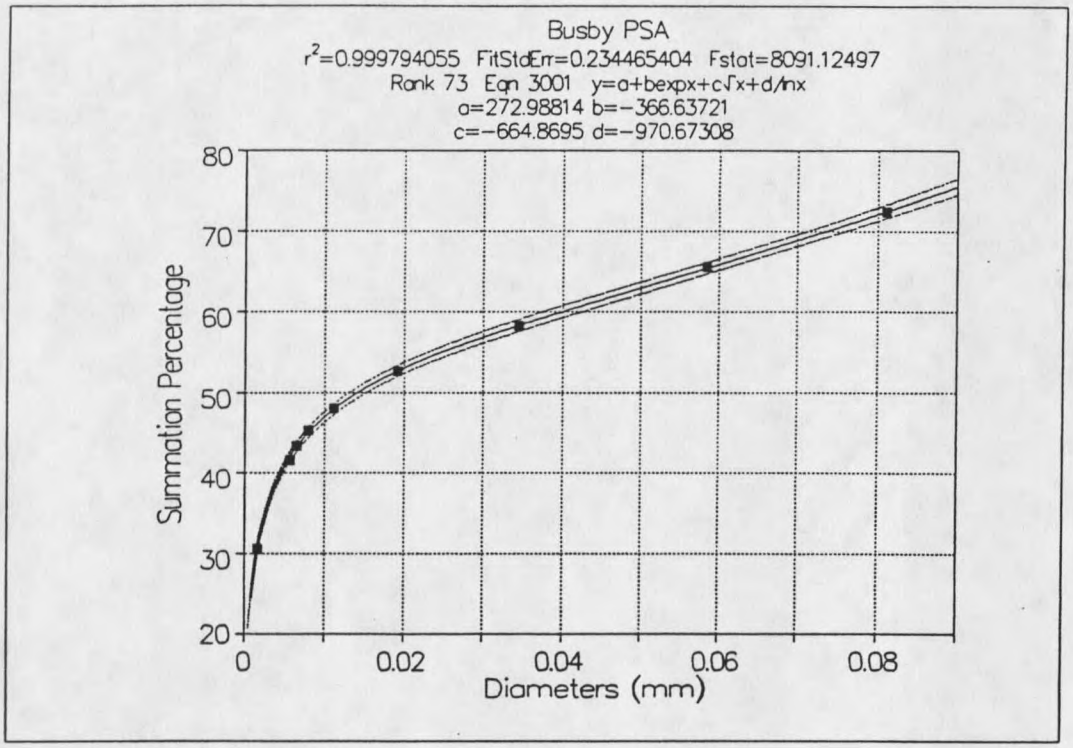
C	Haverson	1	2	0.0	45.46	43.99	36.57	0.532075	1.24	0.533
C	Haverson	1	2	2.0	29.37	15.91	36.57	0.532075	1.24	0.344
C	Haverson	1	2	10.0	23.55	9.49	36.57	0.532075	1.24	0.276
C	Haverson	1	2	33.0	20.08	2.11	36.57	0.532075	1.24	0.235
C	Haverson	1	2	50.0	19.31	2.24	36.57	0.532075	1.24	0.226
C	Haverson	1	2	100.0	18.49	50.55	36.57	0.532075	1.24	0.217
C	Thurlow	0	1	0.0	32.34	8.67	32.42	0.471698	1.4	0.337
C	Thurlow	0	1	2.0	29.53	0.93	32.42	0.471698	1.4	0.308
C	Thurlow	0	1	10.0	29.23	1.23	32.42	0.471698	1.4	0.304
C	Thurlow	0	1	33.0	28.83	0.93	32.42	0.471698	1.4	0.300
C	Thurlow	0	1	50.0	28.53	1.54	32.42	0.471698	1.4	0.297
C	Thurlow	0	1	100.0	28.03	86.45	32.42	0.471698	1.4	0.292
C	Thurlow	0	2	0.0	32.31	12.68	32.42	0.471698	1.4	0.337
C	Thurlow	0	2	2.0	28.2	1.54	32.42	0.471698	1.4	0.294
C	Thurlow	0	2	10.0	27.7	0.93	32.42	0.471698	1.4	0.289
C	Thurlow	0	2	33.0	27.4	1.23	32.42	0.471698	1.4	0.286
C	Thurlow	0	2	50.0	27	0.89	32.42	0.471698	1.4	0.282
C	Thurlow	0	2	100.0	26.71	82.38	32.42	0.471698	1.4	0.279
C	Thurlow	1	1	0.0	44.65	47.17	33.98	0.49434	1.34	0.570
C	Thurlow	1	1	2.0	28.62	16.98	33.98	0.49434	1.34	0.365
C	Thurlow	1	1	10.0	22.85	5.71	33.98	0.49434	1.34	0.291
C	Thurlow	1	1	33.0	20.91	2.30	33.98	0.49434	1.34	0.267
C	Thurlow	1	1	50.0	20.13	4.09	33.98	0.49434	1.34	0.257
C	Thurlow	1	1	100.0	18.74	55.15	33.98	0.49434	1.34	0.239
C	Thurlow	1	2	0.0	45.48	46.92	33.20	0.483019	1.37	0.482
C	Thurlow	1	2	2.0	29.9	9.10	33.20	0.483019	1.37	0.317
C	Thurlow	1	2	10.0	26.88	4.10	33.20	0.483019	1.37	0.285
C	Thurlow	1	2	33.0	25.52	1.72	33.20	0.483019	1.37	0.271
C	Thurlow	1	2	50.0	24.95	4.67	33.20	0.483019	1.37	0.265
C	Thurlow	1	2	100.0	23.4	70.48	33.20	0.483019	1.37	0.248

Table 20. Organic matter, exchangeable sodium percentage, and cation exchange capacity data for each soil.

Water Quality	Soil Series	Column No.	Organic Matter g/100g	ESP %	CEC meq/100g
A	Busby	1	2.15	27.78	14.99
A	Busby	2	3.09	29.75	19.58
A	Haverson	1	2.67	30.77	19.73
A	Haverson	2	2.67	30.15	19.97
A	Thurlow	1	1.9	43.94	26.37
A	Thurlow	2	2.12	41.02	25.64
B	Busby	1	3.7	26.78	22.27
B	Busby	2	3.72	42.8	18.84
B	Haverson	1	2.08	41.21	21.31
B	Haverson	2	2.26	52.7	21.83
B	Thurlow	1	1.77	69.56	26.86
B	Thurlow	2	1.49	78.93	26.65
C	Busby	1	4.17	51.25	19.9
C	Busby	2	4.13	66.17	22.67
C	Haverson	1	2.5	56.56	19.73
C	Haverson	2	2.46	45.58	19.47
C	Thurlow	1	1.9	82.36	26.53
C	Thurlow	2	2.12	95.05	26.98

Table 21. Particle size analysis data for each soil.

Soil Series	Summation Percentage %	Particle Diameter mm
Busby	72.4	0.0811
Busby	65.5	0.0585
Busby	58.2	0.0345
Busby	52.6	0.01917
Busby	48	0.0112
Busby	45.2	0.00796
Busby	43.3	0.00654
Busby	41.5	0.00569
Busby	30.5	0.00169
Haverson	82	0.0686
Haverson	76.5	0.0492
Haverson	67.2	0.0292
Haverson	56.6	0.0165
Haverson	47	0.00978
Haverson	41.8	0.00701
Haverson	37.7	0.00578
Haverson	36.5	0.00502
Haverson	26.6	0.00148
Thurlow	83.1	0.0642
Thurlow	81.2	0.0456
Thurlow	77.9	0.0266
Thurlow	71.3	0.0149
Thurlow	64	0.00878
Thurlow	59.6	0.00629
Thurlow	56.3	0.00518
Thurlow	54.4	0.00464
Thurlow	39.3	0.00136



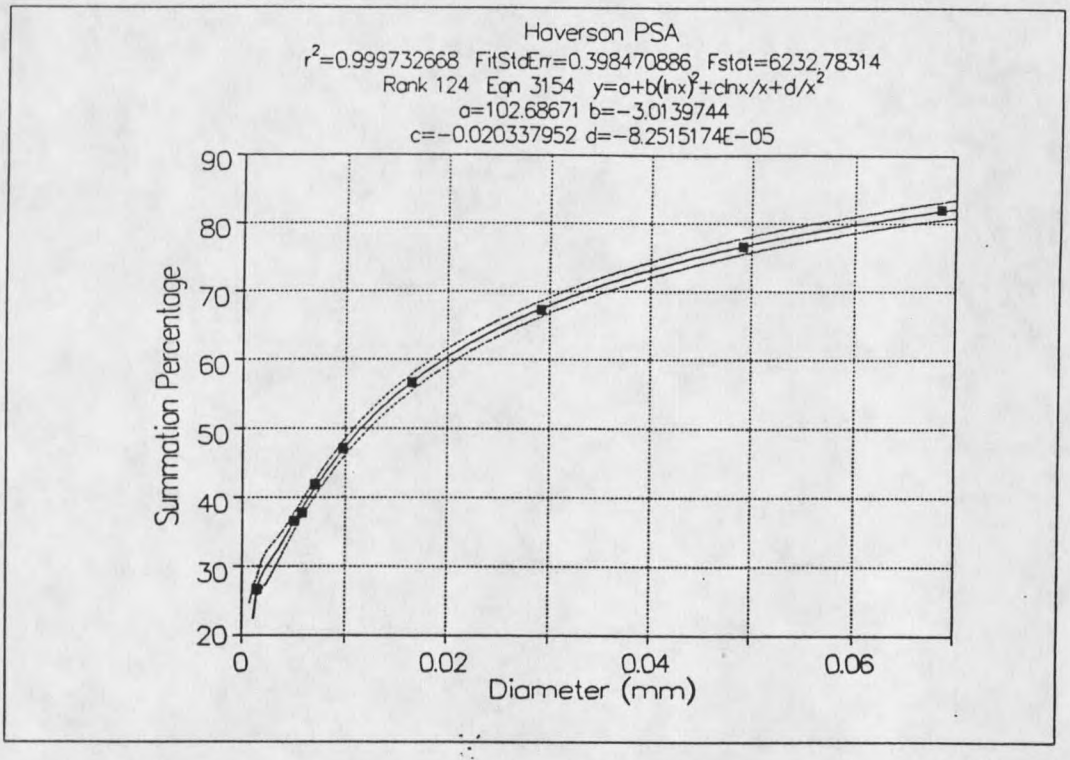
Busby PSA May 17,1993 4:33 AM
9 Active X-Y Points
X: Diameters (mm) Mean: 0.02515 SD: 0.0276841602
Y: Summation Percentage Mean: 50.8 SD: 12.916462364
File Source: BUSBYPSA.PRN

Rank 73 Eqn 3001 y=a+bexpx+cSQRTx+d/lnx

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9997940554	0.9995881108	0.2344654035	8091.1249689

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	272.9881396	14.29184056	19.10097853	236.1138215	309.8624578
b	-366.637206	14.94514391	-24.5321964	-405.197109	-328.077302
c	-664.8695	45.90385601	-14.4839575	-783.305847	-546.433153
d	-970.673076	48.25271544	-20.1164446	-1095.16971	-846.176447

Figure 27. Busby particle size analysis equation generated using Table Curve (release 3.11, Jandel Scientific, 1991).



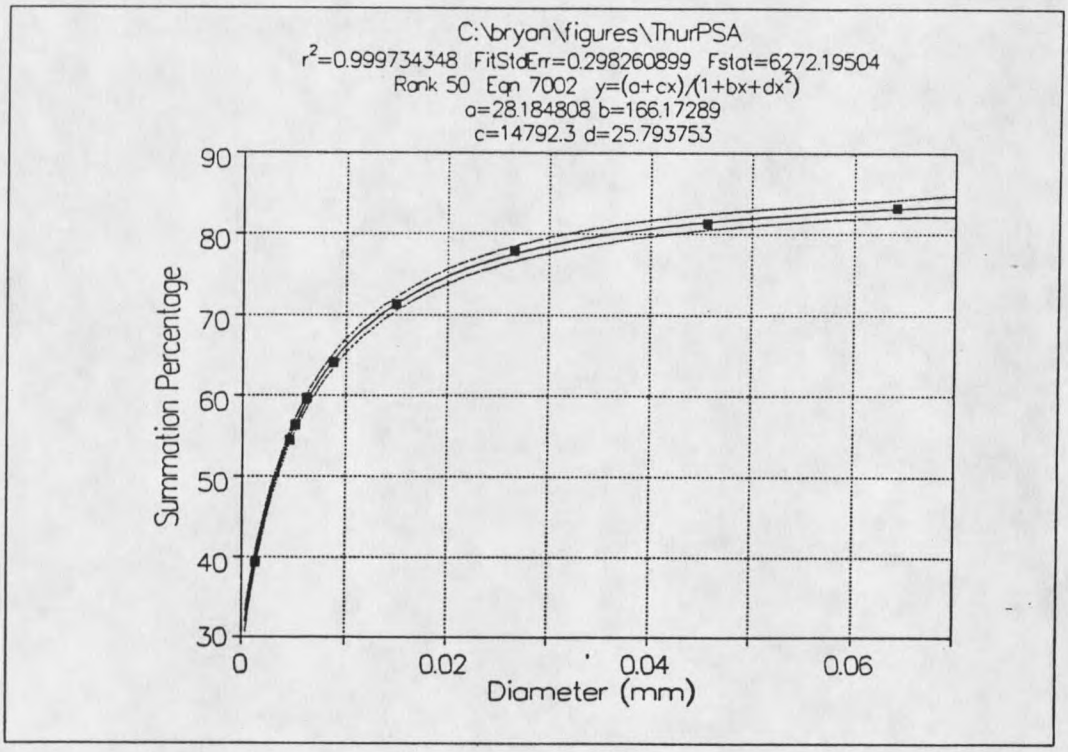
Haverson PSA May 17,1993 4:40 AM
9 Active X-Y Points
X: Diameter (mm) Mean: 0.0213966667 SD: 0.0232828306
Y: Summation Percentage Mean: 52.433333333 SD: 19.26687572
File Source: C:\BRYAN\FIGURES\HAVPSA.PRN

Rank 124 Eqn 3154 y=a+blnx2+clnx/x+d/x2

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9997326682	0.9994653364	0.3984708861	6232.7831447

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	102.6867138	0.79654665	128.9148775	100.6315471	104.7418805
b	-3.01397442	0.088674679	-33.9891214	-3.24276358	-2.78518525
c	-0.02033795	0.002469956	-8.23413585	-0.02671068	-0.01396523
d	-8.2515e-05	1.7428e-05	-4.73463635	-0.00012748	-3.7549e-05

Figure 28. Haverson particle size analysis equation generated using Table Curve (release 3.11, Jandel Scientific, 1991).



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9 Active X-Y Points
X: Diameter (mm) Mean: 0.0197277778 SD: 0.0217794833
Y: Summation Percentage Mean: 65.233333333 SD: 14.467031485
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Rank 50 Eqn 7002 y=(a+cx)/(1+bx+dx2)

r2 Coef Det	DF Adj r2	Fit Std Err	F-value
0.9997343476	0.9994686951	0.2982608986	6272.1950421

Parm	Value	Std Error	t-value	95% Confidence Limits	
a	28.18480795	0.474102188	59.44880378	26.96157888	29.40803703
b	166.1728905	3.979109417	41.76132724	155.9064069	176.4393741
c	14792.30042	314.8419884	46.98325181	13979.97792	15604.62292
d	25.79375339	5.706894524	4.519752955	11.06941865	40.51808812

Figure 29. Thurlow particle size analysis equation generated using Table Curve (release 3.11, Jandel Scientific, 1991).

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