STUDIES ON THE GENESIS
OF SELECTED SOILS
OF OKLAHOMA

BY

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PREFACE

The dissertation has three chapters. Each chapter is a manuscript, set in dissertation format, written for submission to a peer-reviewed journal for publication. Chapter 1 and 2 summarize the results and interpretations of a 3-year study of dispersed soils in Oklahoma. Chapter 3 is a summary of one study in a series of studies concerning the hydrology, pedology, and geology of an unconfined aquifer in terrace sediments along Boomer Creek in Stillwater, OK. Chapter 1, *Dispersion of Soils in Semiarid to Subhumid Areas of Oklahoma*, is written for the Journal of the Soil Science Society of America, Chapter 2, *Selected Amendments for Reducing Soil Dispersion*, is written for the journal Soil Science, and Chapter 3, *Fluctuations in Temperature and Chemistry of Water in an Unconfined Aquifer*, is written for the Vadose Zone Journal.

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CHAPTER 1 – DISPERSION IN SOILS OF SEMIARID TO SUBHUMID AREAS OF OKLAHOMA

Mechanics of Soil Dispersion

Dispersion of soil is a global phenomena affecting use and management of many parcels of land. Dispersion of soils impedes establishment and maintenance of vegetative covers, infiltration and percolation of water into and through the soil, and results in excessive hardening of soils upon drying. Roadways and dams built using dispersed soil tend to erode, degrade, pipe, and tunnel more frequently than similar structures built on non-dispersed soil.

Sumner (1995) used the term dispersive to describe soils of Australia with abundant sodium ions on cation exchange complexes of clays in the soil and in soil water. Soils classified as sodic in the U. S. resemble the dispersed soils of Australia described by Sumner (1995). Sumner (1995) preferred the term dispersive versus sodic to describe the phenomena of dispersion in soil because sodium is only partly responsible for dispersion of soil. Dispersion in soil is a function of the types and amounts of clay, kinds and amounts of exchangeable cations on cation exchange sites of clays, concentrations of electrolytes in soil water, mineralogy (minerals as sands, silts, clays, and cementing agents), particle size distribution, and amounts of organic matter in the soil (Oster et al., 1980; Curtin et al., 1994b). Curtin et al., (1994b) observed the effects of mechanical and physical stresses like impact of rain droplets, cultivation, treading of animals, and heavy equipment traffic affecting soil dispersion. The term dispersed rather than sodic describes soils affected by dispersion discussed in this paper following the recommendation of Sumner (1995).

The amount of sodium adsorbed to cation exchange sites of soil clays and the concentration of electrolytes in water held by soil control the process of soil dispersion.

The net negative charge of soil clay attracts exchangeable sodium ions. Exchangeable cations, held by net negative charges of soil clays, attract electrolytes in soil water between clay particles. Sodium ions adsorb less tightly to cation exchange sites of clays than more-densely charged ions of calcium and magnesium commonly more abundant in non-dispersed soils. Distances between individual clay particles in soils increase when sufficient numbers of sodium ions adsorb to cation exchange sites of soil clays and electrolyte concentrations of soil waters are not large enough to minimize repulsion between individual clay particles. The potential for dispersion in soils containing clays with sufficient numbers of sodium ions adsorbed to cation exchange sites increases because inter-particle (van der Waal's) forces responsible for aggregating individual clay particles may not extend across wider spaces between clay particles caused by an abundance of exchangeable sodium ions (Curtin et al., 1994c). The adsorbed sodium ions in dispersed soils surround individual clay particles and disable aggregation of affected particles.

Dispersion can occur with increases in soil SAR and decreases in concentration of electrolytes in water held by soils (Curtin et al., 1994c; 1995). Sufficient concentrations of electrolytes in soil waters deter increases in distances between clays caused by abundant numbers of adsorbed sodium ions (Rengasamy and Olsson, 1991; Shainberg et al., 1992; Lebron et al., 1994). Clays require a minimum concentration of electrolytes in soil water for aggregation. The potential for dispersion of soil increases when electrolyte concentration in soil water is less than the minimum required for aggregation.

Properties of Soil and Soil Dispersion

The concentrations of electrolytes in soil water necessary for aggregation of soil vary in response to other properties of soils (Rengasamy and Olsson, 1991; Lebron et al., 1994; Curtin et al., 1994c; 1995; Morshedi and Sameni, 2000). Soil properties associated with dispersion of soil include bulk density (Curtin et al., 1994a), % clay-sized particles (Curtin et al., 1994c; Morshedi and Sameni, pH (saturated paste extract) (Curtin et al., 1994c), EC (saturated paste extract) (Curtin et al., 1995), SAR (Curtin et al., 1994a), % organic carbon (Barzegar et al., 1997), total charge of ions in soil water (Lebron et al., 1994), ratio of charge of calcium ions to charge of magnesium ions in soil water (Curtin et al., 1994c; Seelig et al., 1990), ratio of charge of chloride ions to charge of sulfate ions in soil water (Frenkel and Meiri, 1985), ratio of charge of sodium ions to sum of charges of sodium and calcium ions in soil water (Rengasamy, 1984) , liquid limit (Lebron et al., 1994), and plasticity index (Lebron et al., 1994). Soils with abundant exchangeable sodium or large amounts of clay require more electrolytes in soil water to maintain aggregation than soils with less clay or soils with mostly exchangeable calcium and/or magnesium ions. Soils containing large amounts of soluble sodium salts need more electrolytes in soil water to aggregate. Concentration of electrolytes needed in soil water to maintain aggregation decreases in soil containing abundant soluble calcium and /or magnesium salts. Ligands in soil water of soils containing abundant organic matter and hydrogen ions in acidic soils maintain aggregation of soils by displacing adsorbed sodium from exchange sites of soil clays.

Soils display unique sensitivities to dispersion because of the multitude of possible conditions resulting from interactions of different soil properties. Conditions associated with dispersion in some soils do not affect other soils (Curtin et al., 1994c). Minimum concentrations of electrolytes in soil water needed for aggregation are smaller for soils containing large amounts of gypsum or calcite compared to soils containing large amounts of halite. Clayey soils with abundant gypsum require smaller concentrations of electrolytes in soil water to maintain aggregation than clayey, kaolinitic soils. Dispersion increases with amounts of clay in some soils (Curtin et al., 1994c; Morshedi and Sameni, 2000). Velasco-Molina et al. (1971) measured, under weakly saline, dispersive conditions, more dispersion in soils having smectite and mica as primary components of the clay fraction compared to soils with clay fractions containing mostly kaolinite. Frenkel et al. (1978) observed, under dispersive, non-saline conditions, dispersion in soils with mostly kaolinite in the clay fraction and less dispersion in such soils with acid pH compared to such soils with neutral pH. McNeal and Coleman (1966) measured more dispersion in soils containing mostly 2:1 clays compared to soils with clays of mostly kaolinite and abundant oxides of iron and aluminum. Rhoades and Ingverson (1969) observed more dispersion in smectite compared to vermiculite. Felhendler et al., (1974) measured less dispersion in soils with large SAR values (~20) and mainly smectite in the clay fraction when concentrations of electrolytes in soil water were at least 10 mmol_c/l. Soils with abundant magnesium ions on cation exchange complexes disperse more easily than soils with mostly calcium ions on exchange complexes because sodium ions compete more successfully with magnesium ions for exchange sites (Curtin et al., 1994b; Dontsova and Norton, 2002). This process is most prevalent in soils with clays of mixed (Yousaf et al., 1987), kaolinitic (Emerson and Smith, 1970), and illitic mineralogy (Rengasamy et al., 1984).

In calcium-magnesium systems, ratios of 1:2 exchangeable calcium to exchangeable magnesium on exchange complexes of clays produce similar amounts of dispersion as clays with exchange complexes holding nearly all calcium ions indicating the presence of any calcium ions lessens the potential for soil to disperse (Curtin et al., 1994b; Dontsova and Norton, 2002). Magnesium ions, however, can promote the dissolution of calcium carbonate when present, causing the release of calcium ions into soil water, raising the number of calcium ions available for adsorption to exchange sites, and decreasing the potential for soil dispersion. The presence of gypsum promotes aggregation in soil because dissolution of gypsum releases calcium and sulfate ions into soil water (Morshedi and Sameni, 2000).

Addition of organic matter in the form of plant residues increases the stability of dispersed soil (Barzegar et al., 1997). The most stable soil structure occurs in soils with small SAR values, abundant organic matter, and clays of mixed mineralogy (Barzegar et al., 1997). Barzegar et al. (1997) observed increased stability without removal of sodium ions in soils with potential for dispersion in fields under minimum tillage.

Engineering properties of soils, like moisture content at wilting point and field capacity, plastic limit, liquid limit (moisture content at which soil begins to flow like liquid), coefficient of linear extensibility, and dispersion index reflect physical and chemical conditions in soils at different ratios of soil to water (Lebron et al., 1994). Lebron et al., (1994) observed increased potential for erosion in soils with liquid limits <0.3 and plasticity indexes of <0.1. Lebron et al., (1994) suggested the best diagnostic tool for evaluating remediation of dispersed soil is ratio of liquid limit to moisture content at field capacity (0.03 MPa matric potential). Dispersion is likely in soils with liquid limits less than the moisture at field capacity (Lebron et al., 1994).

Raising the pH of some soils increased dispersion in the soils (Arora and

Coleman, 1979; Curtin et al., 1994a). Soils susceptible to increased dispersion with increased pH contain significant amounts of variable charge from minerals or organic matter (Suarez et al., 1984).

Differing amounts of dispersion between soils with similar concentrations of exchangeable sodium and electrolytes in soil water make establishment of uniform guidelines for identification and management of dispersed soils difficult (Curtin et al., 1994a; 1994c). Soil conditions responsible for dispersion vary from region to region because properties of soils vary from region to region. The best guidelines for identification and management of dispersed soils in a region result from analyses of dispersed soils of the region (Curtin et al., 1994c).

The objectives of this study are: 1) quantification of dispersion occurring in some potentially dispersed subsoil horizons from soils of Oklahoma, 2) identification of soil properties associated with dispersion in the horizons, and 3) establishment of diagnostic SAR and EC values for recognition and management of dispersed soils in Oklahoma and similar areas based on properties of the tested horizons. Quantification of dispersion and identification of properties of soil associated with dispersion for a number of soil horizons affected by a range of soil and environmental conditions increases the understanding of and ability to identify and manage dispersed soils in semiarid to subhumid parts of Oklahoma and other similar areas. Measurements of percent dispersion, SAR, EC, pH, types and amounts of clay, types and concentration of ions in soil water, organic matter content, and special features of soil like the presence of gypsum, calcium carbonate, and/or sesquioxides for more than 100 potentially dispersed subsoil horizons increases amount of available data concerning dispersed soils in semiarid and subhumid regions. Determination of diagnostic SAR and EC values based on measurements of soils of the region and identification of soil properties associated with dispersion in soils of Oklahoma promotes improved identification, delineation, and management of dispersed soils in Oklahoma and other semi-arid to sub-humid areas.

Materials and Methods

The process of selection of soil pedons for sampling and analysis included examination of U. S. Department of Agriculture (USDA)-Natural Resource Conservation Service (NRCS) county soil surveys for soil series affected by dispersion and areas of potentially dispersed soil, recommendations from Oklahoma Department of Transportation (ODOT) personnel and NRCS soil scientists, and preliminary investigation of more than 70 prospective locations. The preliminary study included sampling of soils with a Giddings soil probe and/or hand augers, brief field descriptions of sampled profiles, and laboratory analyses of saturated paste extracts from soil samples for pH, EC, and SAR.

Sites selected for sampling for the primary study represent the ranges in pH, EC, and SAR of extracts from soils sampled for the preliminary study. The 23 soil pedons sampled and analyzed represent a large area of Oklahoma containing dispersed soils (Fig. 1). The selected pedons are from 19 different counties. Three counties contain more than one sampled pedon. The sampling locations are native range and improved or unimproved pastures and most are on intermediate or high stream terraces. Other locations are either floodplains or uplands. Slopes at sampling locations are primarily 0 to 1 percent and range to 7 percent.

Soil pits, ~2 m deep and 2 m wide excavated with backhoes, provided access to

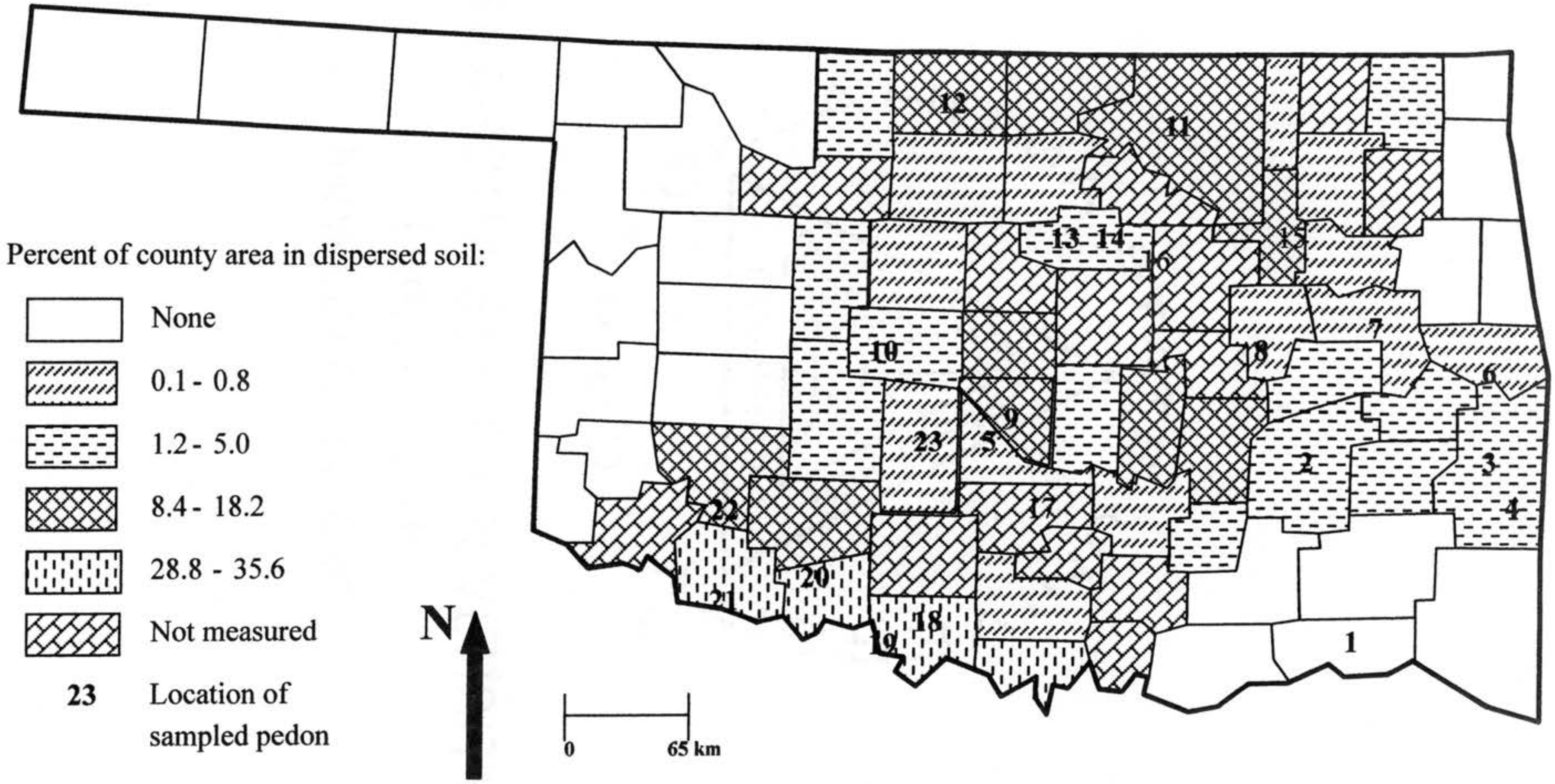

Figure 1. Locations of sampled pedons and areas of dispersed soils within Oklahoma according to soil surveys.

the soil pedons selected for sampling. The sampling procedure included a detailed description of the soil profile (Soil Survey Division Staff, 1993) (Table 1) and retrieval of samples of each of the individual horizons described in the profile for laboratory analyses. Processing of samples for analyses included air-drying and grinding to pass a No. 10 soil sieve (2 mm diameter sieve openings). Paper, 4 L cartons with lids held dried and ground samples available for testing and free of contamination. Table 2 contains a list of the laboratory analyses performed on the samples.

Division of sampled horizons into dispersion groups followed the scheme established by Knodel (1991). Soils <30% dispersed show no to weak dispersion, soils 30 to 65% dispersed display moderate dispersion, and soils >65% dispersed have strong dispersion (Knodel, 1991). Student's t-tests comparing means of properties of soils for the different dispersion groups identified properties associated with dispersion in the soils.

Derivation of diagnostic SAR values for dispersed soils in Oklahoma and semi-arid and sub-humid areas with soils and climates similar to Oklahoma (mean annual soil temperature of 16° C) included assessments of relationships of SAR, EC, and percent dispersion for the tested horizons. Thirty percent or more dispersion by the Double Hydrometer method indicated a horizon as adversely affected by dispersion following recommendations of Knodel (1991) and Crouch et al., (1991). Diagnostic SAR values determined in this study from properties of soil horizons of the study are solutions to equations resulting from linear regressions of SAR versus % dispersion values of analyzed horizons. Derived diagnostic SAR values yield a value of 30% for dispersion by the regression equations. Soils less than 30% dispersed typically do not show

Table 1. Field descriptions of soil horizons sampled for the study

Sample No.	Horizon	Depth[*]	Texture[#]	Color	Structure[+]	Special features[%]
Site No. 1 – Bosville soil series, Choctaw Co., (Fine, mixed, thermic Albaquic Paleudalf)						
3	Bt1	28-53	CL	7.5YR 6/6	3fSBK	Fe-Mn soft bodies; siltans
4	Bt2	53-76	SiCL	2.5Y 6/4, 2.5YR 4/8	3cPR / 1cSBK	Siltans
5	Bty3	76-130	C	10YR 6/6	3cSBK	Masses of gypsum; siltans
6	Bty4	130-168	SiCL	10YR 6/6	2cPR / 1cSBK	Masses of gypsums; Fe-Mn soft bodies; siltans
7	BC	168-200	L	10YR 6/6	2cPR / 1cSBK	Fe-Mn soft bodies; siltans
Site No. 2 – Dwight soil series, Pittsburg Co., (Fine, smectitic, mesic Typic Natrustoll)						
9	Bn1	17-36	SiCL	10YR 4/2	3mPR	Ft. redox depl.
10	Bn2	36-64	CL	10YR 5/2	3mPR	Dt. redox depl.; siltans
11	Bt3	64-110	SiCL	10YR 3/2	1mSBK	Ft. redox depl.; siltans
12	Bt4	110-140	SiCL	10YR 6/2	1mSBK	Dt. redox depl. and accum.
13	BC	140-170	SiC	10YR 6/2	massive	Dt. redox depl.; krotovinas; siltans
Site No. 3 – Wing soil series, LeFlore Co., (Fine, mixed, thermic Aquic Natrustalf)						
15	Bt1	20-41	C	10YR 4/4	2mPR / 3mSBK	Dt. redox accum.
16	Bty2	41-72	SiC	2.5Y 5/4	2mSBK	Pt. redox accum.; masses of gypsum
17	2Btk3	72-115	SICL	10YR 5/4	1cSBK	Pt. redox depl; dt. redox depl.; $CaCO_3$ nodules; Fe-Mn concretions and soft bodies; rounded sandstone gravels, krotovinass
18	2BCk	115-170	SiCL	7.5YR 6/8, N 5/0	1cSBK	Varigated (2 matrix colors); $CaCO_3$ nodules; rounded sandstone gravels; krotovinas
Site No. 4 – Wister soil series, LeFlore Co., (Fine, mixed, thermic Vertic Natrudalf)						
21	Bt1	25-55	SiCL	10YR 4/3	2mSBK	Ft. redox accum.
22	Bt2	55-78	SiC	2.5Y 5/3	2mSBK	Pt. redox accum.
23	Bt3	78-105	SiC	2.5Y 5/2, 5YR 4/6	1mSBK	Varigated (2 matrix colors); slickensides; rock fragments;

Table 1. Field descriptions of soil horizons sampled for the study (cont.).

Sample No.	Horizon	Depth*	Texture#	Color	Structure+	Special features%
		Site No. 5 - Pawhuska soil series, McClain Co., (Fine, mixed, thermic Mollic Natrustalf)				
28	Bn1	23-55	CL	10YR 5/3	3cPL	Siltans
29	Bty2	55-81	CL	10YR 4/3	1cPR	Ft. redon depl.; masses of gypsum
30	Btk3	81-120	SiC	10YR-2.5Y 4/4	1mPR	CaCO$_3$ nodules; Fe-Mn nodules
31	Bt4	120-150	SiC	10YR 4/4	1cPR / 1mSBK	Ft. redox depl.; CaCO$_3$ nodule; Fe-Mn nodules
32	BC	150-210	SiC	5YR 5/8	1cPR / 1mSBK	Pt. redox depl.
		Site No. 6 – Lafe soil series, Sequoyah Co., (Fine-silty, mixed, thermic Glossic Natrudalf)				
34	Btn1	12-30	SiC	10YR 6/4	2cSBK	Dt. redox depl and accum.; Fe-Mn nodules
35	Bty2	30-55	SiC	2.5Y 5/6	1cPR / 2mSBK	Dt. redox depl and accum; masses of gypsum; Fe-Mn nodules
36	Btky3	55-95	C	10YR 6/6	2cPR	Dt. redox accum.; masses of gypsum; CaCO$_3$ nodules; Fe-Mn nodules
37	BCk	95-140	C	7.5YR 6/8, 10 YR 6/1	massive	Green sandstone fragments; CaCO$_3$ nodules; varigated (2 matrix colors)
		Site No. 7 – Carytown soil series, Muskogee Co., (Fine, mixed, thermic Albic Natraqualf)				
40	E	6-22	VFSL	10 YR 5/3	1fG	
41	Btn1	22-49	C	7.5YR 3/2	2mSBK	Siltans
42	Bt2	49-89	SiCL	10YR 4/4	2mPR	Dt. redox depl.; pt.redox accum.; masses of gypsum
43	Bty3	89-119	SiC	7.5YR 6/8	2cPR	Pt. redox depl.; masses of gypsum
44	Bty4	119-150	SiC	10YR 6/8	2cPR	Pt. redox depl.; masses of gypsum
		Site No. 8 – Dwight soil series, Okmulgee Co., (Fine, smectitic, mesic Typic Natrustoll)				
47	Bn1	19-61	SiCL	10YR 3/1	1mPR / 2mSBK	Siltans; krotorvinas
48	Btk2	61-105	CL	7.5YR 5/6	1cPR / 1cSBK	Pt. redox depl.; CaCO$_3$ concretions; krotovinas

Table 1. Field descriptions of soil horizons sampled for the study (cont.).

Sample No.	Horizon	Depth*	Texture#	Color	Structure+	Special features%
Site No. 8 – Dwight soil series, Okmulgee Co. (cont.)						
49	Btk3	105-152	SiC	10YR 5/3	1cPR / 1mSBK	Pt. redox accum.; $CaCO_3$ concretions; Fe-Mn nodules; krotovinas
50	BCk	152-193	SiCL	10YR 4/6	1cPR	Ft redox accum.; $CaCO_3$ concretions
Site No. 9 – Doolin soil series, Cleveland Co., (Fine, smectitic, thermic Typic Natrustoll)						
52	Btn1	23-56	CL	10YR 2/2	2cPR / 1mSBK	Dt. Redox accum.; siltans; Fe-Mn nodules
53	Btk2	56-81	SiC	10YR 3/4	1mSBK	Masses of gypsum; Fe-Mn nodules
54	Btky3	81-107	CL	10YR 4/3	1mSBK	Masses of gypsum; $CaCO_3$ nodules; Fe-Mn nodules
55	Btk4	107—160	CL	5YR 5/8	1cPR	Dt. redox depl.; $CaCO_3$ nodules; Fe-Mn nodules; krotovinas
56	2BCk	160-210	SiC	2.5YR 4/6	1mSBK	Pt. redox depl.; $CaCO_3$ nodules; Fe-Mn nodules; krotovinas
Site No. 10 – Drummond soil series, Canadian Co., (Fine, mixed, thermic Mollic Natrustalf)						
58	Btk1	26-54	SiCL	10YR 3/1	2fSBK	Ft. redox depl.; $CaCO_3$ soft bodies; siltanss
59	Btss2	54-91	SiCL	10YR 3/1	1mSBK	Dt. redox accum.; slickensides
60	Btss3	91-117	SiC	2.5Y 4/2	1mSBK	Ft. redox depl.
61	2Bt4	117-164	SCL	2.5Y 6/3	1cPR / 1cSBK	Dt. redox depl.; standing water at 164 cm
Site No. 11 – Dwight soil series, Osage Co., (Fine, smectitic, mesic Typic Natrustoll)						
63	Btn1	13-38	CL	10YR 3/1	3mCO / 2fSBK	Ft. redox accum.; $CaCO_3$ soft bodies; siltans
64	Btn2	38-67	C	10YR 4/1	1cCO / 2mSBK	Ft. redox accum.; limestone fragments; siltans
65	Bt3	67-95	SiC	2.5Y 4/3	1mSBK	Dt. redoc depl.; limestone fragments
Site No. 12 – Drummond soil series, Grant Co., (Fine, mixed, thermic Mollic Natrustalf)						
70	Ap2	19-40	L	7.5YR 4/2	1cSBK	Siltans
71	A1, b	40-56	SiCL	7.5YR 3/2	1cPR / 1mSBK	-

Table 1. Field descriptions of soil horizons sampled for the study (cont.).

Sample No.	Horizon	Depth[*]	Texture[#]	Color	Structure[+]	Special features[%]
			Site No. 12 – Drummond soil series, Grant Co. (cont.)			
72	Bty1, b	56-79	SiC	5YR 4/3	1cPR / 1mSBK	Masses of gypsum
73	Btk2, b	79-117	SiCL	5YR 4/6	1cPR	$CaCO_3$ nodules; standing water at 112 cm
74	Btk3, b	117-148	SiCL	5YR 5/4	1cPR	$CaCO_3$ nodules
			Site No. 13 – Huska soil series, Payne Co., (Fine, mixed, thermic Mollic Natrustalf)			
77	Bn1	27-52	L	7.5YR 4/4	1cPR / 1mSBK	Fe-Mn softt bodies and nodules
78	Bn2	52-84	CL	7.5YR 5/3	1cPR / 2mSBK	Pt. redox accum.; Fe-Mn soft bodies and nodules
79	Bt3	84-113	CL	5YR 5/4	1cPR / 1mSBK	Pt. redox accum.; Fe-Mn soft bodies and nodules
			Site No. 14 – Doolin soil series, Payne Co., (Fine, smectitic, thermic Typic Natrustoll)			
83	Btn1	24-49	SiCL	7.5YR 3/2	1mPR	Fe-Mn soft bodies and nodules
84	Btn2	49-69	CL	10YR 5/4	2mSBK	Ft redox accum.; Fe-Mn soft bodies and nodules
85	Btkn3	69-92	SiC	10YR 5/4	1cPR / 2mSBK	Ft redox accum.; Fe-Mn soft bodies; $CaCO_3$ nodules and soft bodies
86	Btnyq4	92-136	SiCL	7.5YR 5/8	1cPR / 1cSBK	Pt .redox accum.; masses of gypsum; Fe-Mn soft bodies; silica soft bodies
87	Btnq5	136-166	SCL	7.5YR 5/6	1mSBK	Pt. redox depl.; silica soft bodies; sandstone gravels
			Site No. 15 – Carytown soil series, Tulsa Co. (Fine, mixed, thermic Albic Natraqualf)			
90	Btn1	19-37	CL	10YR 3/1	2mPR	Ft redox accum.; Fe-Mn soft bodies; sandstone fragments
91	Btn2	37-76	C	2.5Y 4/3	2mSBK	Fe-Mn soft bodies
92	Btny3	76-100	C	5Y 4/4	2mSBK	Masses of gypsum; $CaCO_3$ nodules

Table 1. Field descriptions of soil horizons sampled for the study (cont.).

Sample No.	Horizon	Depth*	Texture#	Color	Structure+	Special features%
Site No. 15 – Carytown soil series, Tulsa Co. (cont.)						
93	Btn4	100-138	SiCL	5Y 5/6	2mSBK	Pt redox depl.; Fe-Mn nodules and soft bodies; sandstone gravels
94	Btnk5	138-172	SiCL	10YR 5/6	2mSBK	Pt redox depl.; Fe-Mn nodules and soft bodies; sandstone gravels
Site No. 16 – Seminole soil series, Payne Co., (Fine, mixed, thermic Typic Natrustoll)						
97	Ban	21-34	VFSL	10YR 3/3	1mPR / 1mSBK	-
98	Btn1	34-57	CL	10YR 4/4	2mPR	Dt. redox accum.
99	Btn2	57-97	SC	7.5YR 4/4	2cSBK	Dt redox accum; Fe-Mn nodules
100	Btnky3	97-137	SCL	7.5YR 3/6	1cSBK	Pt redox accum., masses of gypsum, Fe-Mn nodules, $CaCO_3$ nodules
Site No. 17 – Healdton soil series, Carter Co., (Fine, mixed, thermic Vertic Natraqualf)						
104	Btn1	13-39	SiC	10YR 2/2	3cCO	Siltans
105	Btn2	39-56	SiC	10YR 3/2	2mSBK	Siltans
106	Btk3	56-91	SiCL	10YR 4/3	2mSBK	$CaCO_3$ nodules
107	Btk4	91-123	SiCL	10YR 4/3	1mPR	Pt. redox accum.; $CaCO_3$ nodules
108	Akss, b	123-151	SiCL	10YR 3/3	2mPR	Pt. redox accum.; $CaCO_3$ nodules
109	Btkss1, b	151-186	SiC	10YR 3/3	2cPR / 2mSBK	Dt. redox accum.; $CaCO_3$ nodules; slickensides
110	Btkss2, b	186-202	SiC	10YR 3/3	2cPR / 2mSBK	Dt. redox accum.; $CaCO_3$ nodules; slickensides
Site No. 18 – Wing soil series, Jefferson Co., (Fine, mixed, thermic Aquic Natrustalf)						
113	Btn1	27-53	SCL	7.5YR 3/2	1mPR / 2mSBK	Ft. redox depl.; siltans
114	Btn2	53-77	SCL	10YR 4/4	1mSBK	Ft. redox accum.; siltans; Fe-Mn nodules

Table 1. Field descriptions of soil horizons sampled for the study (cont.).

Sample No.	Horizon	Depth[*]	Texture[#]	Color	Structure[+]	Special features[%]
Site No. 18 – Wing soil series, Jefferson Co. (cont.)						
115	Btkn3	77-97	SCL	10YR 5/3	1cSBK	Pt. redox depl. and accum.; $CaCO_3$ soft bodies; Fe-Mn nodules
116	BCkg	97-137	FSL	5GY 6/1	1cSBK	Pt. redox accum.; $CaCO_3$ soft bodies; Fe-Mn nodules
Site No. 19 – Oscar soil series, Jefferson Co., (Fine-silty, mixed, thermic Typic Natrustalf)						
120	Btnky1	15-38	SiCL	7.5YR 4/4	1cPR / 2mSBK	Masses of gypsum; $CaCO_3$ soft bodies; siltans
121	Btnky2	38-78	SiC	5YR 4/3	1cPR / 2mSBK	Masses of gypsum; $CaCO_3$ soft bodies and nodules; Fe-Mn nodules; siltans
122	Btn3	78-110	SiCL	5YR 4/4	SmPR / 2mSBK	Fe-Mn nodules; siltans
123	Btc4	110-173	SiCL	5YR 4/4	1cSBK	Ft. redox depl.; Fe-Mn nodules
Site No. 20 – Foard soil series, Comanche Co., (Fine, smectitic, thermic Vertic Natrustoll)						
126	Btn1	10-32	CL	7.5YR 3/1	2cCO	Siltans
127	Btnky2	32-60	CL	7.5YR 4/1	2mSBK	Masses of gypsum; $CaCO_3$ soft bodies and nodules; siltans
128	Btnky3	60-90	CL	7.5YR 4/3	2mPR	Masses of gypsum; $CaCO_3$ soft bodies and nodules; siltans
129	Btnky4	90-122	C	7.5YR 4/2	1mPR	Ft. redox accum.; Masses of gypsum; $CaCO_3$ soft bodies and nodules; siltans
130	2BCk	122-169	CL	2.5YR 4/2	2cSBK	Pt. redox accum; $CaCO_3$ soft bodies and nodules; siltans; Fe-Mn soft bodies and nodules
Site No. 21 – Oscar soil series, Tillman Co., (Fine, smectitic, thermic Vertic Natrustoll)						
133	Btkyn1	9-25	CL	7.5YR 3/2	1cCO	Masses of gypsum; $CaCO_3$ nodules; siltans
134	Btkyn2	25-37	CL	10YR 3/1	2mSBK	Masses of gypsum; $CaCO_3$ nodules
135	Btkn3	37-57	CL	7.5YR 3/2	2mSBK	$CaCO_3$ nodules; siltans; krotovinas
136	Btkn4	57-87	SCL	7.5YR 4/4	1cSBK	$CaCO_3$ nodules; krotovinas

Table 1. Field descriptions of soil horizons sampled for the study (cont.).

Texture#	Color	Depth*	Texture#	Color	Structure+	Special features%
Site No. 21 – Oscar soil series, Tillman Co. (cont.)						
137	Btkn5	87-118	SiCL	7.5YR 4/4	1cPR / 1cSBK	CaCO$_3$ nodules; krotovinas; Fe-Mn soft bodies
138	BCk	118-144	L	10YR 4/3	1cSBK	Ft. redox accum.; CaCO$_3$ nodules; Fe-Mn soft bodies and nodules
Site No. 22 – Hinkle soil series, Kiowa Co., (Fine, smectitic, thermic Vertic Natrustalf)						
141	Btkn1	18-41	CL	7.5YR 3/3	2mPR / 3mSBK	Fe-Mn soft bodies; CaCO$_3$ soft bodies and nodules; siltans
142	Btkyn2	41-58	CL	7.5YR 3/2	2mPR / 2mSBK	Masses of gypsum; Fe-Mn nodules; CaCO$_3$ soft bodies and nodules; shale fragments
143	Btkn3	58-77	C	7.5TR 332	2mPR / 2mSBK	Pt. redox accum.; CaCO$_3$ nodules; Fe-Mn nodules
144	Btkn4	77-107	SiCL	7.5YR 3/4	2cPR / 2mSBK	Pt. redox accum; CaCO$_3$ nodules; Fe-Mn soft bodies; krotovinas
145	Btkn5	107-157	CL	7.5 YR 4/6	1cPR / 2cSBK	Fe-Mn soft bodies; CaCO$_3$ soft bodies and nodules; krotovinas
146	BCk	157-200	SiCL	2.5YR 4/6	1cPR / 2mSBK	Fe-Mn soft bodies; CaCO$_3$ nodules; stratified; grains of rounded quartzite
Site No. 23 – Hinkle soil series, Grady Co., (Fine, smectitic, thermic Vertic Natrustalf)						
148	Btnss1	18-48	SiCL	2.5YR 4/6	1mPR / 2mSBK	Fe-Mn soft bodies; siltans; slickensides
149	Btk2	48-74	SiCL	2.5YR 4/6	1cPR / 1cSBK	Fe-Mn soft bodies; siltans; CaCO$_3$ soft bodies; caliche gravels at base;
150	Ck1	74-104	SiL	2.5YR 4/6	Massive (shale)	CaCO$_3$ soft bodies in fissures

* cm; # SiL – silt loam, SiCL – silty clay loam, CL – clay loam, C – clay, L – loam, SiC – silty clay, SCL – sandy clay loam, FSL – fine sandy loam, VFSL – very fine sandy loam, SC – sandy clay; + 1 – weak, 2 – moderate, 3 – strong; f – fine, m – medium, c – coarse; PR – prismatic, SBK – subangular blocky, CO – columnar, G – granular, PL – platy, / - parting to; % Ft – faint, Dt – distinct, Pt - prominent

Table 2. Laboratory methods used to measure properties of soil horizons analyzed in this study

Soil Property	Method
Soil profile description	Soil Survey Division Staff, 1993. Soil Survey Manual, United States Department of Agriculture (USDA) Handbook No. 18. USDA.
pH (saturated Paste)	USDA-Natural Resources Conservation Service (NRCS) -National Soil Survey Center (NSSC), 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Method 8C1b-Reaction (pH)-Saturated Paste, p. 411.
pH (1:1 soil-water by weight)	USDA-NRCS-NSSC, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Method 8C1a- Reaction (pH)-Water dilution, p.671.
Electrical conductivity (Saturated Paste Extract)	USDA-NRCS-NSSC, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Method 8A1a- Conductivity of Saturation Extract, p. 669.
Sodium adsorption ratio	USDA-NRCS-NSSC, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Method 5E- Sodium-Adsorption Ratio, p. 215-216.
Bulk density	USDA-NRCS-NSSC, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Method 4A1b-Saran-Coated Clods-Air-Dry, p.591-594.
Organic carbon	Yeomans, J. C., and Bremner, J. M., 1988. A Rapid and Precise Method for Routine Determination of Organic Carbon in Soil, Communications in Soil Science and Plant Analysis, 19:1467-1476.
Total carbon	USDA-NRCS-NSSC, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Method 6A2c-CO_2 Evolution III, p.607.
Carbonates	By difference of Total carbon and Organic carbon.

Table 2. Laboratory methods used to measure properties of soil horizons analyzed in this study (cont.)

Soil Property	Method
Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}	USDA-NRCS-NSSC, 1996, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Methods 6N1b, 6O1b, 6P1b, 6Q1b-Saturation Extraction, Atomic Absorption, p. 299-304.
F^{-}, Cl^{-}, Br^{-}, NO_3^{-}, SO_4^{2}	USDA-NRCS-NSSC, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Methods 6U1b, 6K1d, 6M1d,6L1d,- Saturation Extract, Chromatograph (Anion Suppressor), p. 287-292.
Liquid limit, Plasticity index	American Society for Testing and Materials (ASTM), 1995. Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (Designation D 4318 – 93), 1995 Annual Book of ASTM Standards, Section 4-Construction, Volume 4.08, p. 554-564.
Dispersion	ASTM, 1995. Standard Test Method for Dispersive Characteristics of Clay Soil by Double Hydrometer (Designation: D 4221 – 90), 1995 Annual Book of ASTM Standards, Section 4-Construction, Volume 4.08, p. 526-528.
Particle size distribution	USDA-NRCS-NSSC, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Method 3A-Particles <2mm (Pipet Method), p. 588-590.
Exchangeable sodium percentage	USDA-NRCS-NSSC, 1996. Soil Survey Laboratory Methods Manual, Soil Investigations Report No. 42, Version 3. Method 5D- Exchangeable Sodium Percentage, p. 215-216.
Cation exchange capacity	Sumner, M. E. and Miller, W. P., 1996. Cation Exchange Capacity of Soils Containing Salts, Carbonates or Zeolites. Methods of Soil Analysis, Part 3. Chemical Methods- SSSA Book Series 5, Chapter 40, p. 1213-1214.

Table 2. Laboratory methods used to measure properties of soil horizons analyzed in this study (cont.)

Soil Property	Method
Clay mineralogy	Whittig, I. D., and Allardice, W. R., 1986. X-Ray Diffraction Techniques. Methods of Soil Analysis, Part Physical and Mineralogical Methods- Agronomy Monograph No. 9 (2nd Edition), Chapter 12, p. 331-362.

characteristics commonly attributed to dispersed soils (Knodel, 1991).

Results and Discussion

Properties of Dispersed Soils of Oklahoma

Measured dispersion in the analyzed horizons ranges from 0 to >95%, SAR ranges from <1 to >85, and EC ranges from <1 to 15 dS/m (decisiemens per meter) (Table 3). The group of soils with no to weak dispersion (>30% dispersion) contains 31 horizons, the moderately dispersed group of soils (30 to 65% dispersion) contains 30 horizons, and the strongly dispersed group of soils (<65% dispersion contains 42 horizons (Table 4).

Soil properties associated with dispersion in the horizons include bulk density, % clay-sized particles, pH, EC, SAR, % organic carbon, ratio of the charge of chloride ions to the charge of sulfate ions in soil water, and ratio of charge of sodium ions to the sum of the charges of sodium and calcium ions in soil water (Table 5). The group of horizons with no to weak dispersion has smaller mean pH, SAR, and ratio of charge of sodium ions to the sum of charges of sodium and calcium ions in soil water than the groups of horizons with moderate or strong dispersion (Table 5). The group of moderately dispersed horizons has smaller mean pH, SAR, ratio of charge of sodium ions to sum of charges of sodium and calcium ions in soil water, and EC than the group of strongly dispersed horizons (Table 5). The group of strongly dispersed horizons has greater mean bulk density and ratio of charge of chloride ions to charge of sulfate ions in soil water than the groups affected by less dispersion (Table 5). The mean % clay-sized particles and % organic carbon for the group of strongly dispersed horizons are smaller than for the group of horizons with no to weak dispersion (Table 5). The means of the 3 groups

Table 3. Laboratory measurements of soil properties tested for effect on dispersion of sampled soils

Sample No.	Site No.	Dispersion, %	B.D.	Clay, %	pH	EC	SAR	OC	Ions	Ca:Mg	Cl:SO4	$Na^+/(Na^+ + Ca^{2+})$	LL	PI
3	1	0.0	1.71	43.6	5.3	0.1	1.6	0.4	0.2	3.0	1.7	0.70	0.47	0.30
35	6	0.0	1.84	42.9	8.3	12.0	11.3	0.2	25.3	0.4	0.3	0.78	0.48	0.32
53	9	0.0	1.92	39.2	8.5	3.8	18.4	0.5	8.6	0.5	0.4	0.93	0.56	0.38
78	13	0.2	1.80	31.1	6.3	0.2	0.9	0.3	0.4	1.6	1.2	0.47	0.35	0.19
142	22	2.2	1.79	37.5	7.9	6.8	24.2	0.4	34.5	1.0	0.6	0.72	0.53	0.35
44	7	2.4	1.89	41.4	6.6	8.4	9.9	0.2	30.7	0.4	0.0	0.74	0.48	0.33
85	14	2.7	1.80	32.9	7.9	7.2	14.8	0.3	22.9	1.1	0.2	0.74	0.39	0.24
77	13	2.9	1.79	30.6	6.5	0.2	0.5	0.7	0.6	1.5	4.0	0.36	0.41	0.24
45	7	4.5	1.20	36.9	6.5	6.7	8.2	0.2	24.3	0.4	0.0	0.71	0.41	0.26
21	4	5.8	1.54	72.9	6.6	0.4	3.1	1.0	0.6	1.5	3.0	0.78	0.88	0.55
106	17	6.0	1.83	43.6	7.7	9.0	21.1	0.4	27.2	2.9	0.7	0.76	0.48	0.30
100	16	6.3	1.87	33.0	7.8	6.8	13.8	0.2	20.7	1.2	0.2	0.74	0.38	0.21
79	13	10.0	1.85	26.7	7.0	0.2	0.7	0.3	0.4	1.8	1.3	0.39	0.38	0.22
98	16	11.2	1.88	41.8	6.5	0.3	13.7	0.8	0.5	0.0	1.3	1.00	0.56	0.37
54	9	11.5	1.94	37.8	7.9	7.9	14.1	0.3	16.2	0.6	0.2	0.78	0.49	0.31
127	20	11.7	1.79	40.6	8.2	5.4	16.8	0.6	12.8	1.1	1.3	0.85	0.53	0.34
22	4	11.8	1.76	68.8	6.2	0.1	4.6	0.7	0.3	0.0	1.8	0.92	0.83	0.55
29	5	15.3	1.69	37.8	8.4	5.2	11.6	0.6	18.5	1.3	0.1	0.70	0.53	0.35
41	7	18.7	1.53	43.9	6.4	4.4	10.0	0.9	13.4	0.2	0.0	0.88	0.53	0.33
134	21	19.4	1.89	41.1	9.6	18.5	47.0	0.8	59.3	1.4	1.5	0.80	0.61	0.41
128	20	19.6	1.78	44.9	8.1	5.8	14.9	0.5	15.9	1.0	0.9	0.82	0.56	0.36
34	6	19.8	1.92	38.5	8.0	13.0	12.6	0.5	35.4	0.3	0.5	0.82	0.47	0.31
70	12	21.9	1.62	10.3	7.7	5.5	15.0	0.5	13.6	1.1	0.8	0.82	0.27	0.70
23	4	22.2	1.88	51.0	6.5	0.7	32.1	0.6	1.6	1.5	0.1	0.98	0.78	0.54
130	20	22.6	1.65	45.1	8.3	11.0	30.1	0.3	27.2	1.2	2.6	0.89	0.62	0.43
97	16	23.4	1.61	20.3	6.5	0.4	4.0	0.9	0.6	1.3	1.0	0.86	0.28	0.11
42	7	24.6	1.79	42.5	6.7	8.2	9.9	0.7	38.1	0.3	0.0	0.76	0.45	0.29
129	20	24.8	1.74	45.0	8.0	5.6	17.3	0.4	15.4	1.2	1.2	0.84	0.58	0.38
55	9	27.1	2.00	40.6	8.1	5.2	2.6	0.2	14.5	1.6	0.4	0.61	0.54	0.37
28	5	27.2	1.51	38.4	8.4	1.0	12.2	0.6	2.3	1.3	0.4	0.93	0.60	0.42

Table 3. Laboratory measurements of soil properties tested for effect on dispersion of sampled soils (cont.)

Sample No.	Site No.	Dispersion, %	B.D.	Clay, %	pH	EC	SAR	OC	Ions	Ca:Mg	Cl:SO4	$Na^+/(Na^+ + Ca^{2+})$	LL	PI
4	1	27.3	1.80	43.5	5.7	0.3	5.1	0.3	0.7	1.0	4.3	0.91	0.59	0.41
43	7	30.6	1.52	41.0	6.4	8.6	10.0	0.4	64.4	0.9	0.0	0.78	0.49	0.34
73	12	31.7	1.88	29.3	8.0	8.4	22.2	0.4	29.3	1.1	0.3	0.82	0.43	0.25
50	8	31.8	0.86	28.8	8.8	0.8	18.6	0.1	1.5	2.0	1.4	0.98	0.44	0.28
126	20	33.6	1.78	42.9	8.4	2.7	13.7	0.8	5.4	1.2	6.3	0.89	0.63	0.42
5	1	35.0	1.88	32.0	5.7	0.4	4.6	0.2	0.7	1.3	4.6	0.88	0.42	0.28
47	8	35.5	1.51	26.8	7.8	1.4	10.7	0.6	2.6	2.1	0.5	0.88	0.38	0.23
52	9	38.0	1.71	42.1	8.0	1.7	17.4	0.7	4.0	0.8	1.2	0.99	0.63	0.45
63	11	39.0	1.41	44.2	8.0	3.0	20.0	1.6	7.2	1.5	0.6	0.92	0.65	0.42
30	5	39.6	1.58	37.3	8.3	3.9	18.0	0.4	12.0	0.9	0.1	0.88	0.54	0.37
32	5	41.3	1.53	46.0	8.1	2.9	19.8	0.2	7.4	1.4	1.0	0.92	0.56	0.38
56	9	41.8	1.85	41.3	8.3	2.8	14.2	0.1	6.3	1.1	0.7	0.88	0.53	0.37
72	12	43.6	1.72	40.2	7.7	8.5	23.2	0.5	31.5	1.1	0.2	0.83	0.56	0.37
87	14	44.6	1.78	27.2	8.1	2.6	19.1	0.2	5.0	1.2	0.9	0.94	0.30	0.13
48	8	46.2	1.15	33.6	8.6	2.0	22.8	0.3	4.3	1.7	0.4	0.95	0.51	0.36
49	8	48.9	1.24	33.8	8.9	1.2	23.4	0.1	2.4	1.5	0.9	0.97	0.52	0.38
9	2	49.3	1.73	32.6	7.5	0.5	4.9	0.6	1.1	2.2	2.0	0.80	0.39	0.23
7	1	50.2	1.79	32.5	5.4	2.4	11.8	0.2	4.9	0.8	2.0	0.89	0.36	0.23
141	22	51.0	1.78	43.0	8.4	5.9	25.0	0.6	15.6	0.6	1.7	0.93	0.60	0.42
133	21	52.1	1.73	37.0	7.9	15.0	51.7	0.7	40.9	1.3	3.1	0.93	0.57	0.39
105	17	52.4	1.89	49.5	7.4	5.0	24.6	0.7	12.0	2.2	5.1	0.90	0.54	0.36
15	3	52.8	1.92	42.0	5.6	1.1	23.4	0.8	2.1	1.0	0.1	0.98	0.71	0.52
104	17	53.4	1.82	47.6	7.4	5.6	19.5	0.9	5.4	2.8	2.8	0.92	0.51	0.34
37	6	53.5	1.75	39.5	8.9	3.2	35.2	0.1	8.0	0.3	0.0	0.99	0.45	0.28
90	15	55.9	1.79	37.2	6.4	1.5	19.2	1.1	2.9	1.5	0.4	0.96	0.54	0.33
36	6	58.0	1.93	43.4	8.7	5.4	17.3	0.1	16.7	0.2	0.0	0.94	0.51	0.35
149	23	58.2	1.94	28.2	9.1	9.6	37.2	0.2	31.8	0.3	1.2	0.96	0.35	0.20
99	16	61.4	1.85	40.3	7.9	1.5	15.4	0.4	3.1	1.0	0.4	0.94	0.63	0.44
84	14	63.9	1.91	35.1	7.9	3.2	18.9	0.5	7.1	1.2	0.7	0.91	0.49	0.33
144	22	64.1	1.84	30.8	8.5	8.4	31.2	0.2	21.2	0.5	2.7	0.94	0.44	0.28

Table 3. Laboratory measurements of soil properties tested for effect on dispersion of sampled soils (cont.)

Sample No.	Site No.	Dispersion, %	B.D.	Clay, %	pH	EC	SAR	OC	Ions	Ca:Mg	Cl:SO4	$Na^+/(Na^+ + Ca^{2+})$	LL	PI
31	5	64.7	1.72	38.2	8.2	3.8	20.8	0.2	11.5	1.0	0.3	0.88	0.54	0.38
150	23	66.1	2.08	22.4	9.3	6.8	40.2	0.1	19.0	0.6	5.7	0.96	0.33	0.18
86	14	66.7	1.52	37.6	7.9	4.0	20.3	0.3	8.9	1.0	0.6	0.92	0.47	0.30
145	22	66.7	1.62	23.6	8.8	8.6	30.8	0.1	19.2	0.7	4.4	0.93	0.36	0.20
91	15	67.0	1.94	43.0	6.5	3.1	11.9	0.8	12.0	1.6	1.5	0.82	0.70	0.49
107	17	67.2	2.06	43.9	7.9	5.2	26.5	0.4	11.9	3.5	2.8	0.90	0.50	0.33
71	12	70.3	1.63	30.0	7.9	7.2	26.4	0.8	19.2	0.9	0.6	0.91	0.42	0.26
61	10	71.2	NA	23.3	9.4	1.8	33.5	0.3	4.1	1.3	0.6	0.98	0.47	0.29
74	12	71.4	1.62	32.7	8.4	8.5	31.5	0.3	8.8	1.0	0.9	0.95	0.56	0.40
143	22	72.6	1.74	34.7	8.3	8.4	29.3	0.4	24.1	0.5	2.1	0.93	0.52	0.36
83	14	73.7	1.78	42.6	7.4	1.6	16.3	0.8	3.2	1.0	2.1	0.95	0.54	0.37
64	11	74.3	NA	55.5	8.1	3.8	28.4	1.0	10.2	1.0	0.4	0.94	0.77	0.54
93	15	74.3	1.85	40.1	8.4	4.3	31.0	0.3	10.2	1.4	0.1	0.95	0.53	0.35
10	2	75.3	1.83	32.7	6.5	0.7	8.7	0.6	1.3	3.5	0.3	0.89	0.40	0.25
120	19	75.8	1.86	23.9	9.3	9.8	62.6	0.3	25.0	0.5	1.7	0.98	0.34	0.21
6	1	76.4	1.84	30.1	5.4	0.6	7.7	0.2	1.1	1.7	6.0	0.91	0.33	0.21
146	22	77.3	1.73	23.0	8.9	6.8	29.9	0.1	15.7	0.5	6.4	0.95	0.33	0.16
94	15	78.3	1.86	27.3	8.5	3.3	41.6	0.3	6.1	1.2	0.2	0.98	0.44	0.24
18	3	78.9	1.83	43.6	8.6	1.9	26.2	0.1	4.1	0.7	0.1	0.98	0.54	0.36
16	3	79.3	1.95	47.9	6.6	4.0	12.2	0.7	11.7	0.7	0.0	0.82	0.66	0.47
65	11	80.7	NA	51.9	8.3	3.9	32.5	0.5	8.8	1.1	0.9	0.96	0.93	0.71
122	19	80.7	1.99	22.2	9.6	9.6	50.9	0.1	4.7	1.0	8.7	0.99	0.35	0.22
121	19	81.4	1.60	22.1	9.6	9.6	74.4	0.2	11.1	0.6	3.2	0.99	0.44	0.30
13	2	81.7	1.71	46.7	7.3	0.8	12.1	0.3	1.5	2.0	2.7	0.94	0.59	0.41
59	10	82.5	1.82	55.8	8.9	5.2	59.4	1.0	13.5	1.7	0.5	0.98	0.15	0.13
148	23	82.8	1.90	35.3	8.7	8.4	32.2	0.2	24.4	0.3	0.4	0.95	0.40	0.25
116	18	83.1	1.86	26.4	8.7	4.5	37.0	0.1	8.5	1.0	2.5	0.97	0.33	0.16
123	19	83.1	1.92	24.4	9.4	9.4	15.8	0.2	1.7	3.0	2.4	0.96	0.31	0.18
113	18	83.6	1.92	34.0	8.2	7.0	39.8	0.5	14.6	0.6	1.9	0.97	0.40	0.25
137	21	84.6	1.86	25.8	9.1	5.8	85.4	0.2	12.7	0.3	10.7	1.00	0.60	0.41

Table 3. Laboratory measurements of soil properties tested for effect on dispersion of sampled soils (cont.)

Sample No.	Site No.	Dispersion, %	B.D.	Clay, %	pH	EC	SAR	OC	Ions	Ca:Mg	Cl:SO4	$Na^+/(Na^+ + Ca^{2+})$	LL	PI
114	18	84.7	1.97	28.1	8.5	6.8	51.1	0.2	16.5	0.6	1.4	0.98	0.43	0.29
138	21	85.0	1.83	25.6	9.5	2.5	56.2	0.2	5.0	1.0	5.9	0.99	0.64	0.46
17	3	85.6	1.77	45.6	7.5	3.7	30.5	0.2	8.1	0.6	0.0	0.97	0.60	0.40
115	18	85.7	1.99	29.9	8.8	9.8	56.6	0.1	27.3	0.5	1.5	0.97	0.45	0.30
58	10	86.2	1.79	46.6	8.8	10.2	85.4	0.9	32.0	0.8	0.4	0.98	0.11	0.09
60	10	86.6	1.82	55.4	9.1	2.9	34.1	0.6	6.1	2.0	0.7	0.97	0.16	0.13
11	2	87.2	1.82	37.0	6.4	0.8	11.4	0.7	1.6	2.0	0.6	0.93	0.49	0.35
109	17	88.1	1.94	42.6	7.9	4.6	26.9	0.3	10.3	2.4	3.6	0.92	0.50	0.34
92	15	88.9	1.91	48.0	7.3	7.2	19.4	0.5	21.6	2.3	0.0	0.80	0.63	0.43
136	21	91.2	1.83	27.9	8.7	10.0	68.1	0.3	23.0	0.6	8.8	0.98	0.47	0.31
12	2	91.3	1.71	41.1	7.2	0.8	10.8	0.3	1.5	1.7	3.3	0.93	0.51	0.34
108	17	91.4	1.94	42.1	7.9	4.9	27.0	0.4	10.9	2.5	3.4	0.91	0.48	0.31
135	21	95.5	1.77	27.7	8.4	14.0	72.9	0.6	38.0	0.9	5.1	0.97	0.64	0.44

[*] B.D. - bulk density (g/cc), EC - electrical conductivity (dS/m), SAR - sodium adsorption ratio, OC - organic carbon (%), Ions - sum of charge of major ions in solution (cmolc/L), Ca:Mg - ratio of charge of calcium ions to charge of magnesium ions in solution, Cl:SO4 - ratio of charge of chloride ions to charge of sulfate ions in solution, Na/(Na+Ca) - ratio of the charge of sodium ions to the sum of the charge of the sodium and calcium ions in solution, LL - liquid limit, PI - plasticity index

Table 4. Means and standard deviations (s.d.) of soil properties tested for effect on dispersion for the soils of the dispersion groups of the study.

Dispersion Group		B.D.	Clay, %	pH	EC	SAR	OC	Ions	Ca:Mg	Cl:SO4	Na/(Na + Ca)	LL	PI
Weak to no	mean	1.76	40.1	7.4	5.2	13.0	0.5	15.6	1.1	1.0	0.77	0.52	0.35
	s. d.	0.16	11.4	1.0	4.6	10.2	0.2	14.6	0.7	1.1	0.15	0.14	0.12
Moderate	mean	1.69	37.4	7.8	4.1	20.5	0.5	12.3	1.2	1.4	0.91	0.51	0.34
	s. d.	0.25	6.3	1.0	3.4	9.4	0.3	14.4	0.6	1.6	0.05	0.10	0.08
Strong	mean	1.83	35.7	8.2	5.5	35.8	0.4	12.4	1.3	2.5	0.94	0.56	0.39
	s. d.	0.13	10.3	1.0	3.3	20.9	0.3	9.0	0.8	2.7	0.05	0.27	0.25

* B.D. - bulk density (g/cc), EC - electrical conductivity (dS/m), SAR - sodium adsorption ratio, OC - organic carbon (%), Ions - sum of charge of major ions in solution (cmolc/L), Ca:Mg - ratio of charge of calcium ions to charge of magnesium ions in solution, Cl:SO4 - ratio of charge of chloride ions to charge of sulfate ions in solution, Na/(Na+Ca) - ratio of the charge of sodium ions to the sum of the charges of the sodium and calcium ions in solution, LL - liquid limit, PI - plasticity index

Table 5. Probability values from Student's t-tests for comparison of means of the groups of soils of weak to no, moderate, and strong dispersion*

Comparison	B.D.	Clay, %	pH	EC	SAR	OC	Ions	Ca:Mg	Cl:SO4	Na/(Na+Ca)	LL	PI
None to weak and moderate	0.104	0.131	0.040*	0.152	0.002**	0.346	0.19	0.221	0.157	.000***	0.38	0.304
None to weak and strong	0.024*	0.045*	0.000***	0.345	0.002**	0.047*	0.125	0.192	0.003**	.000***	0.207	0.22
Moderate and strong	0.002**	0.209	0.037*	0.037*	0.002**	0.166	0.489	0.432	0.023*	0.005**	0.154	0.141

*B.D. - bulk density (g/cc); EC - electrical conductivity (dS/m); SAR - sodium adsorption ratio; OC - organic carbon (%); Ions - sum of charge of major ions in solution (cmolc/L); Ca:Mg - ratio of charge of calcium ions to charge of magnesium ions in solution; Cl:SO4 - ratio of charge of chloride ions in solution to charge of sulfate ions in solution; Na/(Na+Ca) - ratio of the charge of sodium ions to the sum of the charges of the sodium and calcium ions in solution, LL - liquid limit, PI - plasticity index of soils are not different for total charge of ions in soil water, ratio of charge of calcium ions to charge of magnesium ions in soil water, liquid limit, and plasticity index (Table 5).

Strong dispersion affects a majority of horizons with SAR values >25 (31 of 38; Fig. 2). Most of the tested horizons exceed the critical level for identifying dispersed soil suggested by Rengasamy (1984) of 0.8 for the ratio of charge of sodium ions to the sum of charges of sodium and calcium ions in soil water (Fig. 3). Fourteen of the 23 sampled pedons contain a horizon with no to weak dispersion (Table 3) and 10 of the sampled pedons with a horizon of no to weak dispersion contain multiple horizons with no to weak dispersion. Masses of gypsum occur within or in a horizon below 24 of the 31 horizons with no to weak dispersion (Table 1). Nodules of calcium carbonate are common within a horizon of no to weak dispersion not associated with any gypsum (Table 1). Two pedons contain no gypsum or calcium carbonate (Table 1) and multiple horizons of no to weak dispersion (Tables 1 and 3). Gypsum and calcium carbonate are recommended amendments for reducing dispersion in soil. Addition or presence of gypsum or calcium carbonate can reduce dispersion by increasing the number of calcium ions in the soil available to displace sodium ions from exchange sites on the cation exchange complexes of soil clays.

The soil horizons tested in this study are similar to dispersed soils in other parts of the world (Sumner, 1995; Morshedi and Sameni, 2000) (Table 6). In agreement with the findings of Sumner (1995), several soil properties contribute to the dispersion displayed by the horizons of this study. Soil properties associated with dispersed soil horizons from semiarid to subhumid parts of Oklahoma include SAR, EC, pH, bulk density, percent

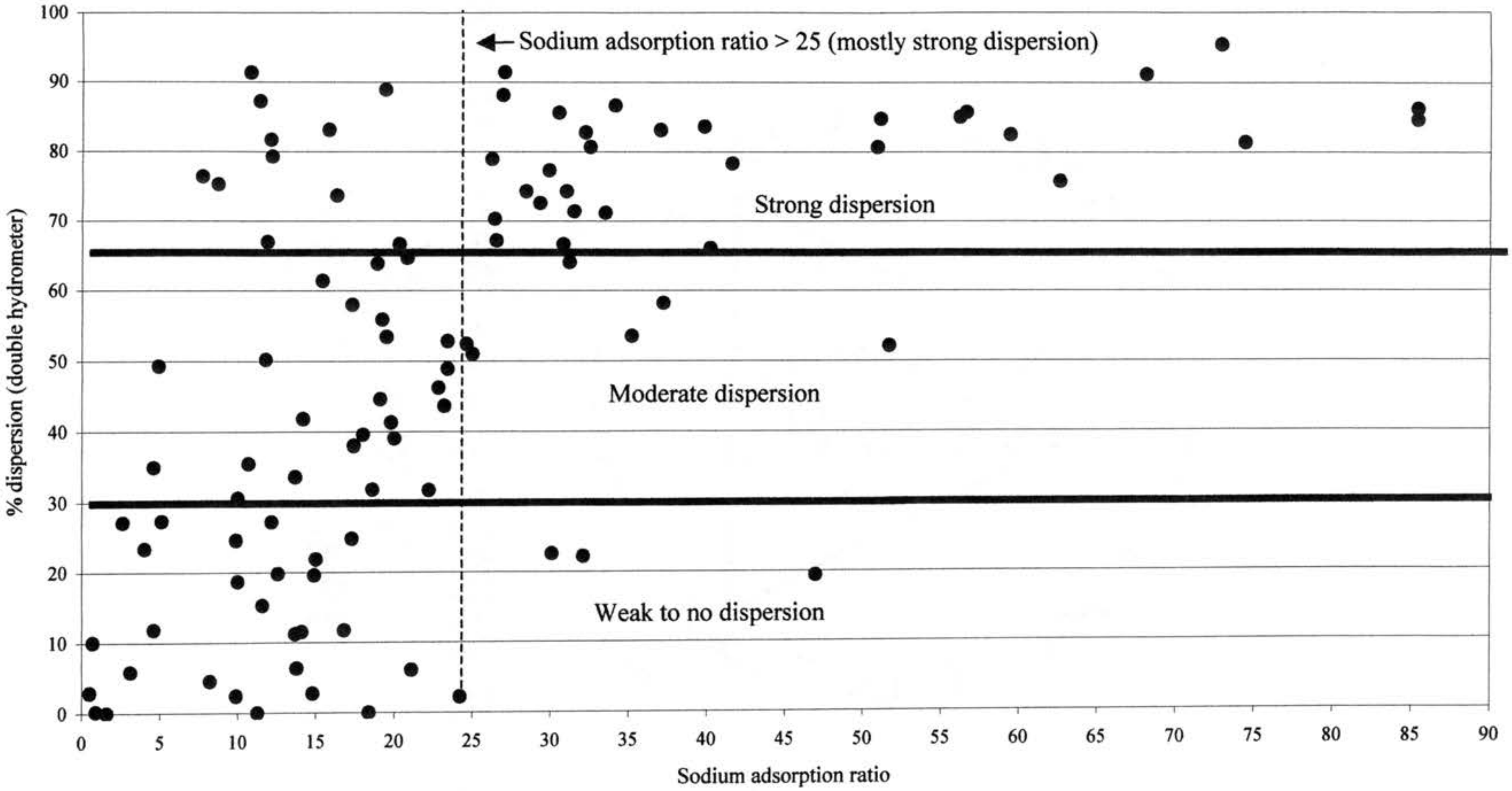

Figure 2. Dispersion in relation to sodium adsorption ratio for horizons of the study.

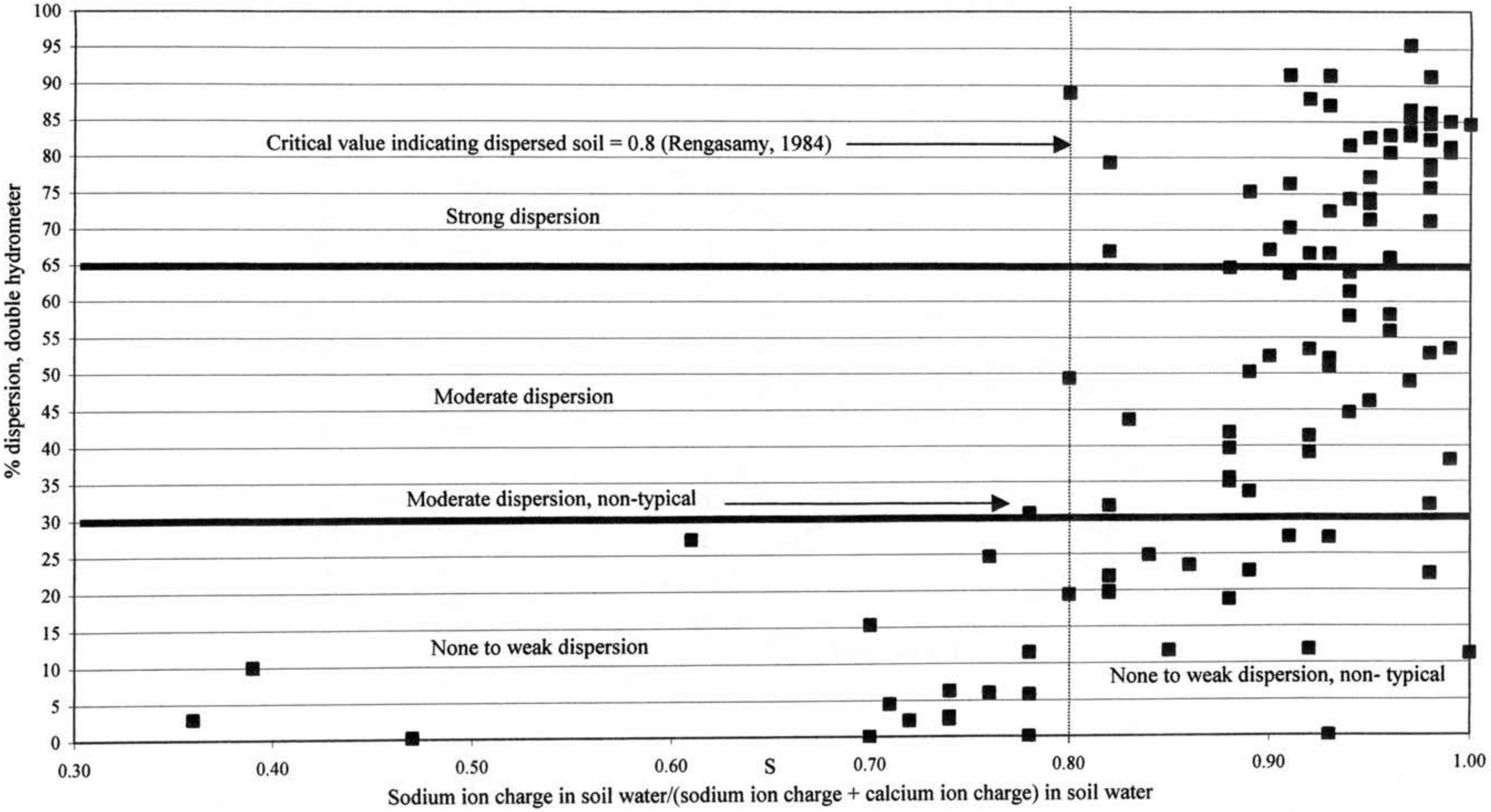

Figure 3. Dispersion in relation to ratio of charge of sodium ions to charge of (sodium +calcium ions) in soil water for horizons of the study

Table 6. Relationships of salinity, sodicity, and dispersion for soils from other parts of the world

Location	Description	Salinity	Sodicity	Classification
California (present general duidelines for U.S.; Richards, 1954)		EC<4	ESP<15 or SAR<12	Non-saline, non-sodic
		EC>4	ESP>15 or SAR>12	Saline-sodic
		EC<4	ESP>15 or SAR>12	sodic
California (Lebron et al., 1994)	Saline-sodic, fine, illitic, calcareous, xeric soil	EC<2	SAR – 2 to 5	dispersive
Saskatchewan, Canada (Curtin et al., 1994a)	Mollisols (prairie soils)	Dissolved salts (mmol$_c$/L) – 5 to 30 increases as % clay increases	SAR>20	dispersive
Saskatchewan, Canada (Curtin et al., 1994b)	Soils in Glacial till	Dissolved salts (mmol$_c$/L) <10	SAR>10	dispersive
		Dissolved salts (mmol$_c$/L) <20	SAR>20	dispersive
Iran (Morshedi and Sameni, 2000)	Calcareous soil	Dissolved salts (mmol$_c$/L) <10	SAR>20	dispersive
Australia (Rengasamy and Olsson, 1991)	Salty ground water, clayey	EC>TEC (threshold electrolyte concentration)	SAR>3	Saline-sodic
		EC<TEC	SAR>3	Alkaline, neutral , or acidic sodic depending on pH

clay-sized particles, percent organic carbon, concentrations of ions in soil water, and types of minerals in the soils.

Dispersion and Clay Mineralogy

Variation exists in the types and relative amounts of clay minerals in the clay fractions of several horizons of the study (Table 7). The set of horizons analyzed for clay mineralogy includes 9 horizons with no to weak dispersion, 6 moderately dispersed horizons, and 21 strongly dispersed horizons (Table 7).

The amount of dispersion measured in the soils analyzed for clay mineralogy increased as the amount of illite in the clays increased (Table 7). Interstratified illite-smectite, smectite, and/or vermiculite are abundant in most of the strongly dispersed horizons (Table 7). With a few exceptions, kaolinite in the clay fraction of tested horizons decreased as % dispersion increased. Greater amounts of kaolinite in soils with abundant vermiculite resulted in less dispersion (Table 7). Smectite mostly occurred interstratified with illite (Table 7). Elevated amounts of illite, smectite, and vermiculite also occur in moderately and strongly dispersed soil horizons in other parts of the world (McNeal and Coleman, 1966; Rhoades and Ingverson, 1969; Morshedi and Sameni, 2000).

Derivation of Diagnostic Sodium Adsorption Ratios

Percent dispersion, pH, EC, and SAR values of moderately and strongly dispersed soil horizons analyzed in this study indicate an SAR >12 (USDA, 1954) does not adequately identify dispersed soils in semiarid to subhumid parts of Oklahoma. Many of the strongly dispersed soil horizons identified in this study have SAR values <12 (Table 3).

Table 7. Relationships of dispersion and clay mineralogy for soils of this study

					Identified Clay Minerals					
				Dispersion	Mixed*	Smectite	Vermiculite	Illite	Kaolinite	Quartz
Sample No.	Site No.	Series	Horizon	%	Relative %*					
Weak to no Dispersion										
21	4	Wister	Bt1	6	3	0	72	6	18	1
22	4	Wister	Bt2	12	0	3	46	9	40	2
23	4	Wister	Bt3	22	0	4	43	9	41	2
28	5	Pawhuska	Bn1	27	73	0	4	8	5	10
34	6	Lafe	Btn1	20	0	11	16	8	62	3
35	6	Lafe	Bty2	0	0	0	60	4	33	3
41	7	Carytown	Btn1	19	70	0	12	5	13	0
85	9	Doolin	Btkn3	3	74	0	14	4	7	1
142	22	Hinkle	Btnky2	2	7	85	0	4	3	1
Moderate Dispersion										
7	1	Bosville	BC	50	50	0	0	19	27	4
15	3	Wing	Bt1	53	0	0	43	10	44	3
36	6	Lafe	Btky3	58	0	14	30	16	38	2
37	6	Lafe	BCk	53	39	0	0	13	47	1
48	8	Dwight	Btk2	46	72	0	4	6	15	3
141	22	Hinkle	Btkn1	51	0	88	0	6	3	3
Strong Dispersion										
6	1	Bosville	Btn4	76	60	0	0	16	20	4
11	2	Dwight	Bt3	87	82	0	0	5	10	3
16	3	Wing	Bty2	80	0	3	33	6	54	3

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					Identified Clay Minerals					
				Dispersion	Mixed*	Smectite	Vermiculite	Illite	Kaolinite	Quartz
Sample No.	Site No.	Series	Horizon	%	Relative %*					
Weak to no Dispersion										
21	4	Wister	Bt1	6	3	0	72	6	18	1
22	4	Wister	Bt2	12	0	3	46	9	40	2
23	4	Wister	Bt3	22	0	4	43	9	41	2
28	5	Pawhuska	Bn1	27	73	0	4	8	5	10
34	6	Lafe	Btn1	20	0	11	16	8	62	3
35	6	Lafe	Bty2	0	0	0	60	4	33	3
41	7	Carytown	Btn1	19	70	0	12	5	13	0
85	9	Doolin	Btkn3	3	74	0	14	4	7	1
142	22	Hinkle	Btnky2	2	7	85	0	4	3	1
Moderate Dispersion										
7	1	Bosville	BC	50	50	0	0	19	27	4
15	3	Wing	Bt1	53	0	0	43	10	44	3
36	6	Lafe	Btky3	58	0	14	30	16	38	2
37	6	Lafe	BCk	53	39	0	0	13	47	1
48	8	Dwight	Btk2	46	72	0	4	6	15	3
141	22	Hinkle	Btkn1	51	0	88	0	6	3	3
Strong Dispersion										
6	1	Bosville	Btn4	76	60	0	0	16	20	4
11	2	Dwight	Bt3	87	82	0	0	5	10	3
16	3	Wing	Bty2	80	0	3	33	6	54	3

Dispersed soils in other areas of the U.S. and the world show considerable variation concerning critical levels of EC and SAR (Table 6). SAR and EC values established for diagnosis of dispersion in soils of an area reflect the properties of soils of the area. Values of EC and SAR for diagnosis of dispersion in soils of semiarid to subhumid parts of Oklahoma derived in this study reflect the nature of the properties identified in this study as associated with dispersion in the soils. Effects of pH, bulk density, types and amounts of clay and minerals, and concentrations of ions in soil water contribute to derivation of SAR and EC values for diagnosis of dispersion in the soils.

Derivation of diagnostic SAR values from study data included dividing horizons into groups based on EC values (Fig. 4). Weakly saline horizons have EC values <1.0 dS/m), moderately saline horizons have EC values from 1.0 to 9.0 dS/m, and strongly saline soils have EC values >9.0 dS/m (Fig. 4). Correlation coefficients for regression equations from linear regression of SAR and % dispersion measurements of tested horizons tested SAR and % dispersion data for resulted omission of data for several of the horizons from the regression analyses. Omission of data occurred for several horizons of moderate salinity, with large SAR values, and much dispersion (Fig. 4) because nearly all cations in soil water are sodium and these soils require special treatment for remediation. Excessive sodium in soil water affects horizons at Soil Sampling Locations No. 10 (Drummond soil series, Canadian Co.), No. 17 (Healdton soil series (Carter Co.), No. 18 (Wing soil series, Jefferson Co.), No. 19 (Oscar soil series, Jefferson Co.), and No. 21 (Oscar soil series, Tillman Co.). Omission of data also occurred for some horizons that contain gypsum. No to weak dispersion occurs in some horizons with large SAR values because dissolution of gypsum helps maintain

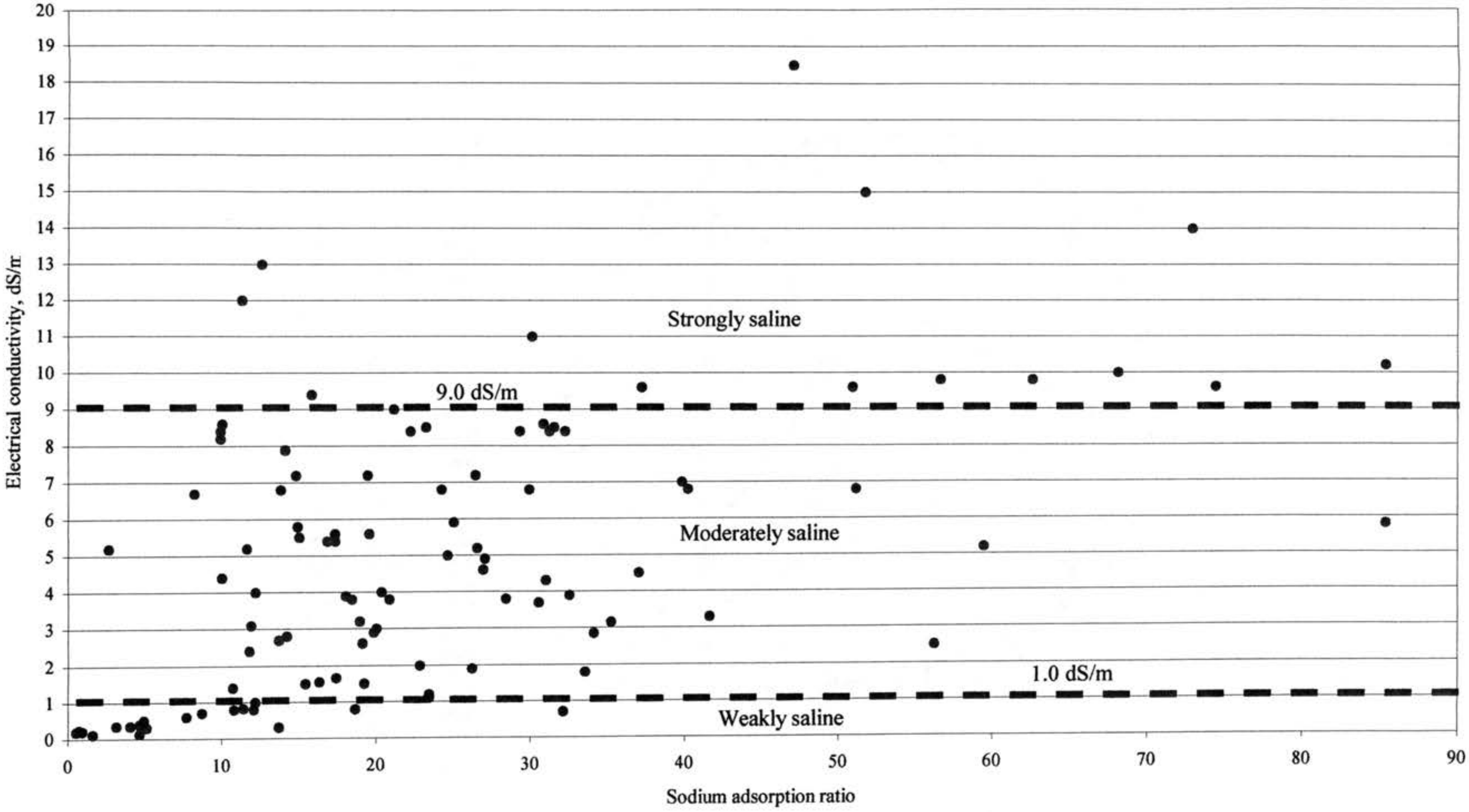

Figure 4. Electrical conductivity in relation to sodium adsorption ratio for horizons of the study.

aggregation of soil. Gypsum reduces dispersion in horizons at Soil Sampling Locations No. 6 (Lafe soil series, Sequoyah Co.), No. 7 (Carytown soil series, Muskogee Co.), No. 9 (Doolin soil series, Cleveland Co.), No. 12 (Drummond soil series, Grant Co.), No. 14 (Doolin soil series, Payne Co.), No. 16 (Seminole soil series, Payne Co., and No. 20 (Foard soil series, Comanche Co.).

Calculations of diagnostic SAR values for the different salinity groups utilized equations derived from linear regression of SAR versus % dispersion of horizons in the salinity groups. The diagnostic SAR values yield values of 30% dispersion from the regression equations (Figs. 5 and 6) (the minimum level of dispersion associated with adverse effects of dispersion on soil and the dividing point for soils of no to weak dispersion and moderately and strongly dispersed soils (Knodel, 1991)). Derived SAR values for identifying dispersed soils in semiarid to subhumid areas of Oklahoma are 7.1 to 8.8 and greater for moderately saline soils (Fig. 5) and 4.2 to 4.7 and greater for weakly saline soils (Fig. 6). No attempt at calculation or interpretation of a diagnostic SAR value for strongly saline soils occurred because the number of horizons of the study in the group is small and much variation is apparent in the relationships of SAR, EC, and % dispersion for the group of strongly saline horizons tested in this study (Fig. 4).

Improved Diagnosis and Management of Dispersive Soils

Dispersed soil horizons in Oklahoma have a wide range of physical and chemical characteristics and show much variation in measured dispersion percentages. Moderately and strongly dispersed horizons in Oklahoma (soil affected by >30% dispersion measured by the Double Hydrometer test) have greater pH, SAR, and ratios of charge of sodium ions to sum of charges of sodium and calcium ions in soil water compared to non-

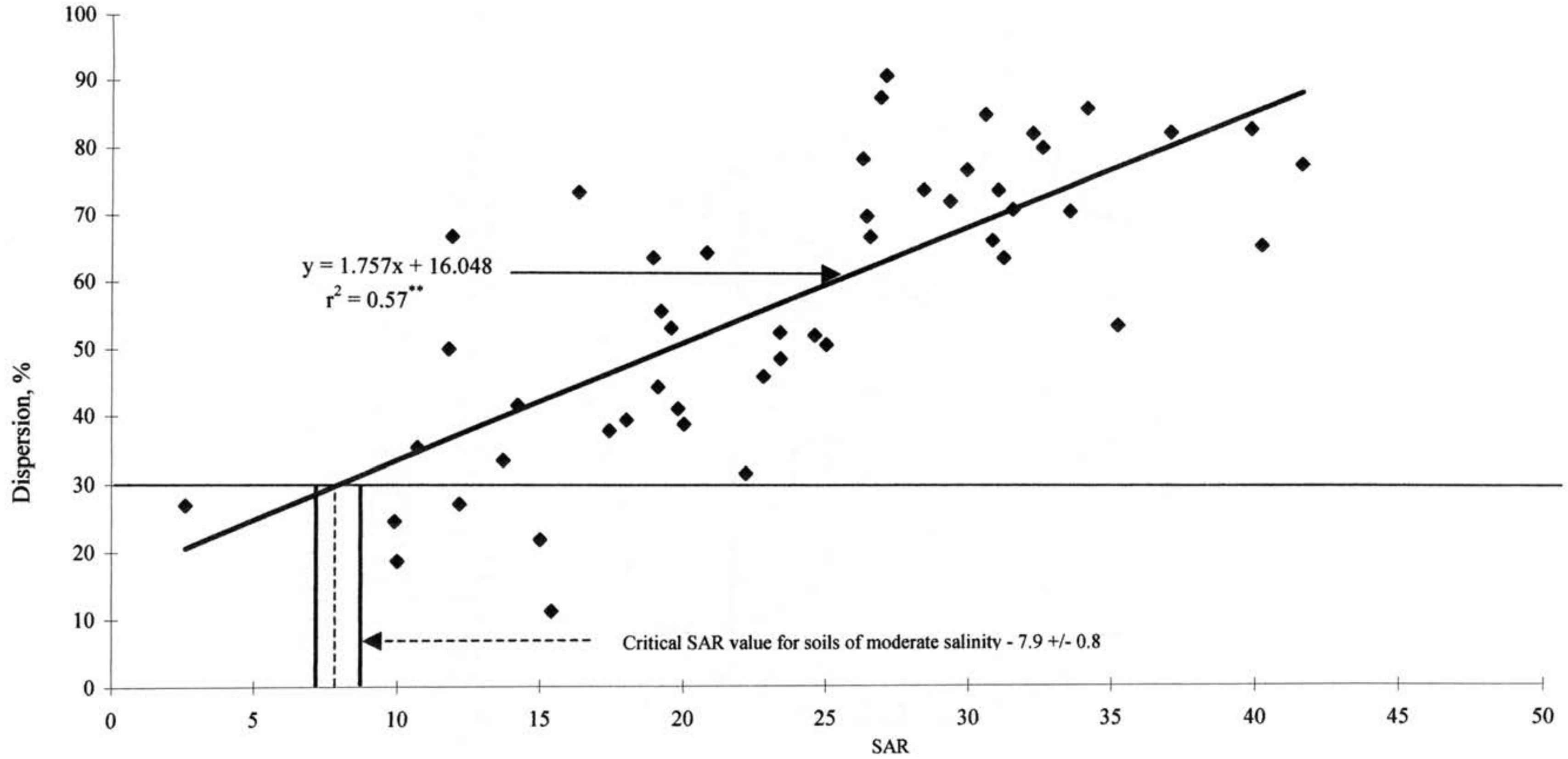

Figure 5. Linear regression of dispersion in relation to sodium adsorption ratio for moderately saline (electrical conductivity between 1 and 9 dS/m) horizons of the study and interpretation of critical SAR value.

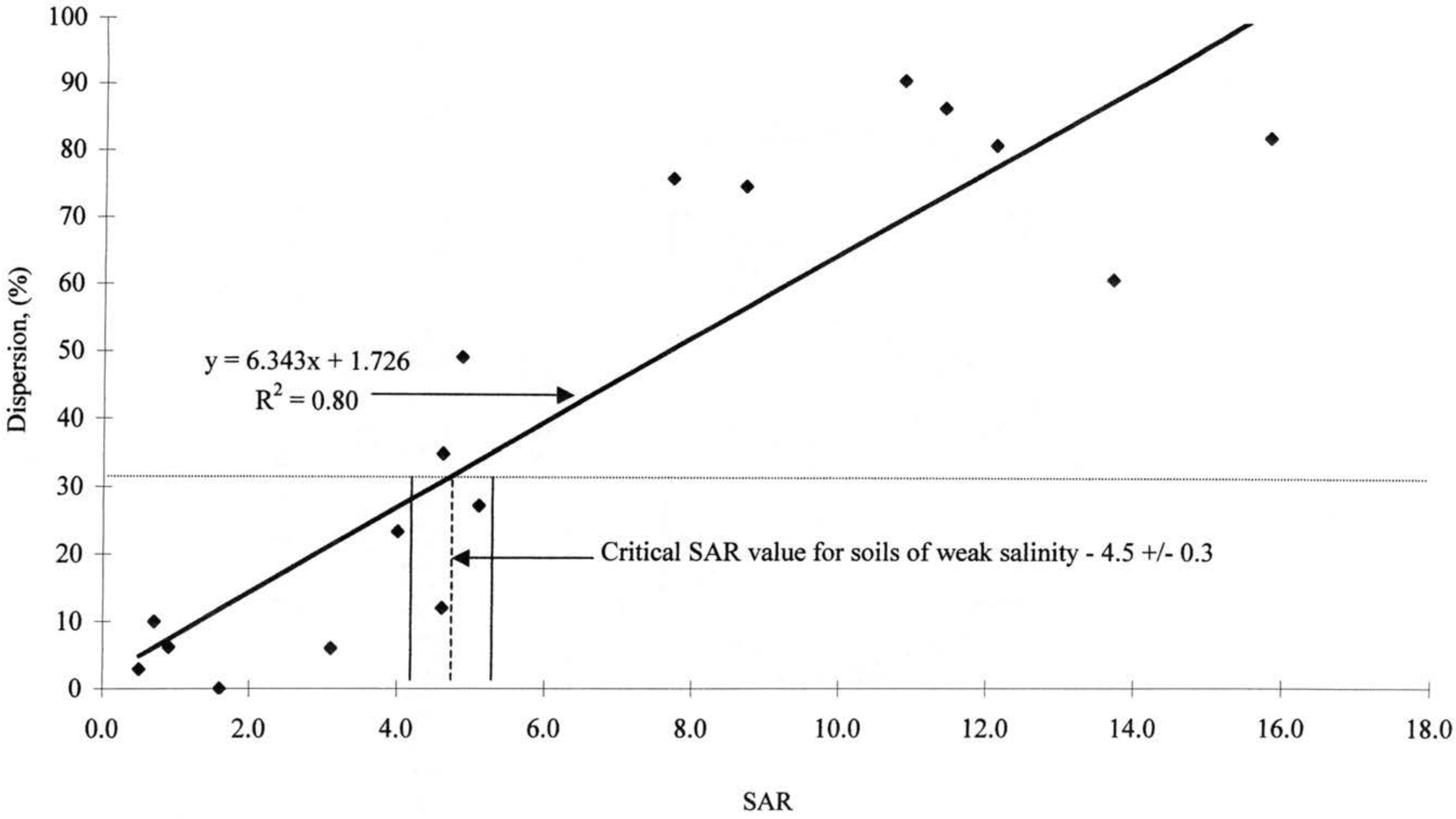

Figure 6. Linear regression of dispersion in relation to sodium adsorption ratio for weakly saline (electrical conductivity <1 dS/m) saline horizons of the study and interpretation of critical SAR value.

dispersed and weakly dispersed horizons (affected by <30% dispersion). Strongly dispersed horizons in Oklahoma (affected by >65 % dispersion) have greater bulk density, greater ratios of charge of chloride ions to charge of sulfate ions in soil water, and less clay and organic carbon than weakly dispersed and non-dispersed horizons. The presence of gypsum or calcium carbonate in horizons may affect amount of dispersion in the horizons. Amounts of dispersion observed in horizons from Oklahoma soils depends on or influences several soil properties and the term dispersed, in contrast to sodic, better describes horizons affected by dispersion in soils of Oklahoma.

Sodium adsorption ratios indicating possible problems with dispersion for soils of Oklahoma and areas with similar soils and climates as Oklahoma are 4.5 +/- 0.3 and greater for weakly saline soils (EC<1 dS/m) and 7.9 +/- 0.8 and greater for moderately saline soils (EC from 1 to 9 dS/m). Some minerals and compounds common to many soils of Oklahoma, like gypsum, calcium carbonate, and organic matter, alter dispersion and are important factors to consider in evaluating degrees of dispersion in the horizons. The SAR values determined in this study for recognition of dispersed soil differ from the value commonly used in the U. S. of 12 established for sodic soils almost a half century ago (USDA, 1954). Application of the diagnostic SAR values derived from properties of horizons tested in this study likely will indicate more areas of potentially dispersed soil. The diagnostic SAR values for identification of dispersed, weakly or moderately saline soils derived from the soils in this study are alternate references for recognition, management, and reclamation of dispersed soils in semiarid to subhumid regions of Oklahoma and areas of similar soils and climates elsewhere.

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The Oklahoma Department of Transportation provided funding and manpower for this project. ODOT personnel recognized the need for a better understanding of dispersive soils in Oklahoma in response to costly failures of roadways and structures in areas affected by dispersive soil. Laboratory personnel at the department measured the engineering characteristics of many of the sampled soils. Soil Scientists with the Natural Resources and Conservation Service assisted in locating sites for sampling, obtaining permission for use of the land at many sampling locations, describing, and sampling the soils.

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CHAPTER 2 – SELECTED AMENDMENTS FOR REDUCING SOIL DISPERSION

Introduction

Highways and secondary roads transect areas affected by dispersed soils in many parts of Oklahoma. Incorporating of dispersed soil in roadways and support structures (bridge approaches, underpasses, and overpasses, for example) often results in cracking, piping, erosion, and subsequent failure of affected features (Shainberg, 1984; Knodel, 1991; Bell and Maud, 1994). Physical properties of dispersed soils include slow infiltration and percolation of water, crusting and sealing of soil surfaces, and dense packing of subsoil (Oster et al., 1995; Sumner and Naidu, 1998). Dispersive soils retard or prevent growth of many types of native vegetation (Tisdall and Adem, 1988).

Dispersed soils occur in Oklahoma in areas irrigated with water containing large amounts of dissolved salt, used for disposal of oil field waste, and with soil parent materials containing large amounts of salt and sodium (Stiegler, 1986; Johnson, 1990). Areas of dispersed soil in Oklahoma are of irregular size and shape and at various topographic locations (Ryker, 1977). Parent materials of dispersed soil in Oklahoma are alluvium, residuum, or colluvium derived from salt-bearing Permian or Pennsylvanian sandstone and shale (Ryker, 1977).

Recognizing Dispersed Soils

Soil disperses when inter-particle forces primarily responsible for aggregation of soil, known as van der Waal's forces, cannot bind individual clay particles in a mass of soil. Cation exchange sites of soil clays hold sodium ions less tightly than calcium or magnesium ions. The positive charge of a sodium ion is weaker and not as dense as the positive charges of calcium or magnesium ions. Thickness of layers of ions adsorbed to soil clays increase if sufficient numbers of adsorbed ions are sodium ions. The increase in thickness of layers of ions surrounding soil clays in a sodium-affected or dispersed soil increases distances between individual particles beyond effective distances of van der Waal"s forces. Thickened layers of ions surrounding soil clays cause dispersion of soils by isolating and preventing aggregation of the particles. Sufficient amounts of dissolved salt in water within potentially dispersed soil maintain distances between clays within reach of van der Waal's forces and decrease dispersion.

Properties identifying dispersed soil include exchangeable sodium percentage (ESP) of the cation exchange capacity (CEC) of soils and electrical conductivity (EC) and sodium adsorption ratio (SAR) of water held by soils. Electrical conductivity is a measure of amount of salt dissolved in soil water. Sodium adsorption ratios indicate concentrations of sodium, calcium, and magnesium ions in soil water. Moderate to strong (>30%) dispersion occurs in soils with small ESP or SAR if EC of soil is also small.

U. S. Dept. of Agriculture (USDA) (1954) identified potentially dispersed soils (also known as sodic soils) as having, 1) EC values <4 dS/m and ESP values >15 or, 2) SAR values >12. The basis for these criteria, routinely in use in the U.S. at present and developed nearly half a century ago (USDA, 1954), is data from a group of California soils. Alternative SAR, ESP, and EC values, developed from research on dispersed soils from other parts of the world (Lebron et al., 1994; Curtin et al., 1994a; 1994b; Morshedi and Sameni, 2000; Rengasamy and Olsson, 1991), identify dispersed soils also.

Effective EC, ESP, and SAR criterion for identifying potentially dispersed soil in affected areas are products of research on dispersed soils in the areas of concern (Curtin et al., 1994a). EC and SAR values for identifying and managing dispersed soils identified in this study also differ from values presented in USDA (1954). SAR and percent dispersion data from soil horizons tested in this study indicate moderate to strong soil dispersion (>30% dispersion) occurs in soils with SAR values <12. SAR and EC criterion for identifying dispersed soils presented in this paper are from interpretations of relationships of percent dispersion (measured with the double hydrometer test (ASTM, 1995)), SAR, and EC for more than 100 subsoil horizons affected by large amounts of sodium, salts, and dispersion from soils within Oklahoma.

Amending Dispersed Soil

Ions released by dissolution of amendments applied to reduce soil dispersion displace sodium ions from exchange sites of soil clays in treated soils. Some materials, like gypsum, and hydrated lime, supply a large number of calcium ions to displace sodium ions from cation exchange sites of clays. Other materials, like sulfuric acid and acids in organic matter, dissolve calcium-containing minerals, such as calcium carbonate, in soils to provide calcium ions for displacing sodium ions from exchange sites of clays. Acidic amendments also supply hydronium ions for displacing sodium. Successful amendment of dispersed soil requires rainfall or irrigation to leach displaced sodium ions from treated soil. Some amendments, like gypsum, sulfuric acid, and organic matter, also increase the electrolyte concentrations and EC of soil water.

Effectiveness of amendments in reducing SAR values of soils also depends on rate of water movement into and through the soils, particle size distribution, ESP, and depth of dispersed soil horizons (Quirk and Schofield, 1955). Selection of effective amendments for improvement of dispersed soils depends on properties of soils needing amendment, availability and cost of amendments, number of ions (calcium, magnesium, and/or hydronium) produced or provided by amendment for displacement of sodium ions from exchange complexes of treated soils, and time allotted for soil reclamation (Oster and Frenkel, 1980).

The objectives of this study include: 1) identifying changes in SAR of selected dispersed soil horizons resulting from addition of amendments, 2) influences of properties of treated soils on effectiveness of treatments, and 3) application rates of amendments effectively reducing SAR values of treated soils. Criteria for evaluation of effectiveness of treatments is reduction of SAR values of treated soils to levels of SAR associated with soil not affected by excessive sodium or soils showing no to weak dispersion (<30% dispersion) according to present U. S. standards (SAR>12; Richards, 1954). Evaluation of effectiveness of amendments also includes comparisons with standards developed from the relationships of SAR, EC, and percent dispersion of soil horizons examined in this study (EC<1 dS/m – SAR>4.5 +/- 0.3 or EC from 1 to 9 dS/m – SAR>7.9 +/- 0.8).

Amending materials tested in this study contain varying amounts of calcium and magnesium ions for displacement of sodium ions from cation exchange complexes of clays in treated soils. Application of between 2 and 10 Mg/ha gypsum reduced surface crusting and erosion and increased infiltration of water (Emerson, 1984; Fitzpatrick, 1984). Recommended application rates for gypsum are 5 to 10 Mg/ha for dispersed soils in Oklahoma (Stiegler and Ward, 1986; Johnson, 1990). Hydrated lime ($Ca(OH)_2$) is a dry, white powder made by adding water (~24%) to quicklime (CaO). Addition of hydrated lime effectively reduced dispersion in soil and erosion of several dams on a small creek near Lawton, Oklahoma (Ryker, 1977). Fly ash is a residue created by coalfired electric generators. Application of fly ash at a rate of 20 Mg/ha to dispersed soil in India resulted in reduced bulk density and increased hydraulic conductivity (Tivari et al., 1991). Production of cement kiln dust requires mixing of limestone, clay, and sandstone and heating to a temperature of 1900 degrees Celsius. Application of cement kiln dust reduced plasticity and swelling of clays (Sayah, 1993) and increased compressive strength of some Pennsylvania soils (McCoy and Criner, 1971). Cement kiln dust and fly ash applied in this study are from the Holnam cement factory in Ada, OK, which produces ~972 Mg of cement kiln dust a day at full production. Humate is a by-product of the oil refining process. Addition of humate increased organic matter content and size of root mass in some dispersed soils (Haynes, 1986). Addition of calcium chloride ($CaCl_2$+$2H_2O$) supplies calcium ions more rapidly to soil than gypsum because calcium chloride is more soluble than gypsum. Sulfuric acid (H_2SO_4) dissolves limestone in soil causing the release of calcium ions, formation of gypsum, and removal of sodium ions from soils in the form of dissolved sodium sulfate. Application of sulfuric acid directly to the surface of a soil rapidly increased permeability and decreased ESP of near-surface dispersed horizons (Prater et al., 1978; Abrol et al., 1988). Leaching (transport in solution by percolation of water through soil profiles) of displaced sodium ions is an important part of the process of removing sodium ions from cation exchange complexes of dispersed soil horizons (Quirk and Schofield, 1955).

Materials and Methods

Selection of Soil Horizons for Treatment

The soil horizons selected for treatment are from a set of 151 horizons sampled for a reconnaissance of potentially dispersed soil in Oklahoma (Fig. 7 and Table 8). The

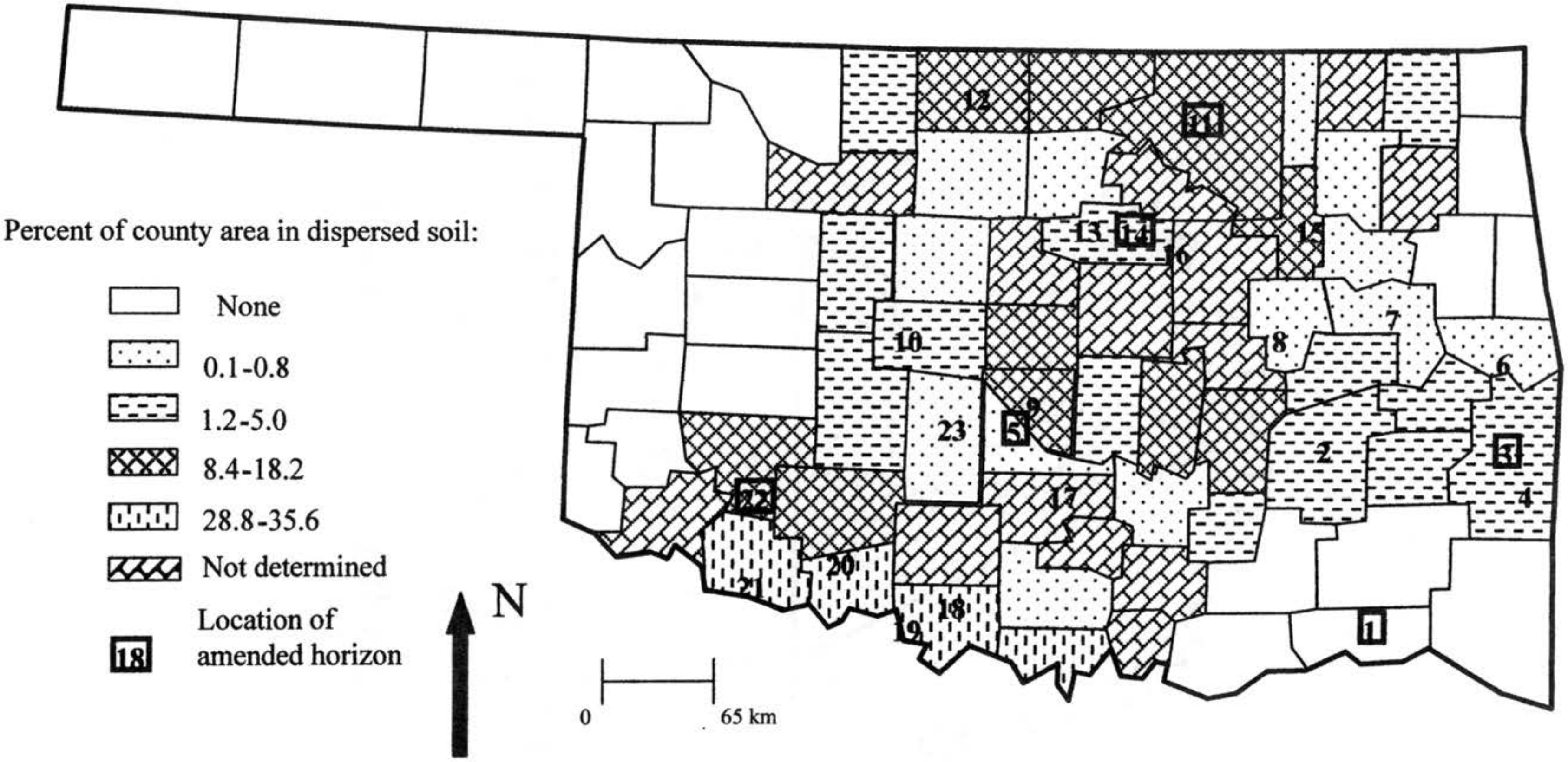

Fig 7. Locations of pedons containing amended horizons

Table 8. Site and field descriptions for amended soil horizons[†]

Horizon No.	7	15	28	64	65	85	86	146
Soil property								
Horizon	BC	Bt1	Bn1	Btn2	Bt3	Btkn3	Btnyq4	BCk
Depth (cm)	168-200	20-41	23-55	38-67	67-95	69-92	92-136	157-200
Color (moist	10YR6/6	10YR4/4	10YR5/3	10YR4/1	2.5Y4/3	10YR5/4	7.5YR5/8	2.5YR4/6
Texture	L	C	CL	C	SiC	SiC	SiCL	SiCL
Structure	2cPR	2mPR	3cPL	1cCO	1mSBK	1cPR	1cPR	1cPR
Special Features	siltans	Redox accum	siltans	Siltans; limestone fragments; Redox accum.	Redox depl; limestone fragments	Redox accum; limestone nodules	Redox accum; gypsum; siltans	Limestone nodules
Soil series	Bosville	Wing	Pawhuska	Dwight	Dwight	Doolin	Doolin	Hinkle
Soil classification	Fine, mixed, thermic Albaquic Paleudalf	Fine, mixed, thermic Aquic Natrustalf	Fine, mixed, thermic Mollic Natrustalf	Fine, smectitic, mesic Typic Natrustoll	Fine, smectitic, mesic Typic Natrustoll	Fine, smectitic, thermic Typic Natrustoll	Fine, smectitic, thermic Typic Natrustoll	Fine, smectitic, thermic Vertic Natrustalf

[†] L – loam, C – clay, CL – clay loam, SiC – silty clay, SiCL – silty clay loam; 1 – weak, 2 – moderate, 3- strong, m – medium, c – coarse, PR – prismatic, SBK – subangular blocky, PL – platy, CO – columnar, / - parting to; Ft. – faint, Dt. – distinct, Pt. – prominent, redox – redoximorphic, accum. – accumulations, depl. - depletions

study included pedons from several areas of Oklahoma affected by dispersed soils. Selection of pedons included identification and location of potentially dispersed soils from county soil surveys. Natural Resources Conservation Service (NRCS) soil scientists and research engineers for the Oklahoma Department of Transportation (ODOT) assisted in the selection process. The selected pedons are from a preliminary sampling of ~70 potential locations with a gas-powered soil probe or hand auger, and laboratory measurement of SAR, EC, and pH of saturated paste extracts from samples of soil horizons in the pedons.

Laboratory data collected on sampled horizons included measurements of pH, EC, SAR, Na^+, Ca^{2+}, Mg^{2+}, K^+, F^-, Cl^-, Br^-, NO_3^-, and SO_4^{2-} of saturated paste extracts (USDA-NRCS-NSSC, 1996), pH (1:1 soil to water, by weight; USDA-NRCS-NSSC, 1996), bulk density (USDA-NRCS-NSSC, 1996), organic carbon (Yeomans and Bremmer, 1988), total carbon (USDA-NRCS-NSSC, 1996), liquid limit (ASTM, 1995), plasticity index (ASTM, 1995), % dispersion (double hydrometer test; ASTM, 1995), pinhole test class (ASTM, 1995), crumb test class (ASTM, 1995), and particle size distribution (USDA-NRCS-NSSC, 1996). Additional characterization of horizons selected for amendment included cation exchange capacity (CEC) (USDA-NRCS-NSSC, 1996), ESP (USDA-NRCS-NSSC, 1996), and clay mineralogy (Whittig and Allardice, 1986).

The horizons selected for amending are from pedons across Oklahoma (Fig. 7 and Table 8). Redoximorphic features, siltans (pockets of illuviated sand grains, released from dispersed soil, in soil pore spaces), and secondary precipitates of lime and gypsum occur within the horizons (Table 8). Selected horizons (Table 9) are slightly alkaline to

Table 9. Dispersive characteristics of amended soil horizons[†]

Horizon No.	Horizon	Depth (cm)	Dispersion (%)	SAR	ESP	EC
7	BC	168-200	50.2	11.8	19.7	2.4
15	Bt1	20-41	52.8	23.4	35.0	1.0
28	Bn1	23-55	27.2	12.2	13.2	1.0
64	Btn2	38-67	74.3	28.4	42.1	3.8
65	Bt3	67-95	80.7	32.5	ND	3.9
85	Btkn3	69-92	2.7	14.8	ND	7.2
86	Btnyq4	92-136	66.7	21.3	ND	4.0
146	BCk	157-200	77.3	29.9	34.7	6.8

[†] SAR – sodium adsorption ratio; ESP – exchangeable sodium percentage; EC – electrical conductivity, decisiemens per meter

alkaline, moderately saline, and show moderate to strong dispersion (>30% dispersion by the double hydrometer test (except Horizon Nos. 28 and 85)). Selection of soils for amending occurred before the completion of percent dispersion measurements and Horizon Nos. 28 and 85, although selected for amending, are weakly dispersed.

Amendments for Reducing SAR in Soils

Amendments examined included gypsum, hydrated lime, fly ash, cement kiln dust, humate, calcium chloride, and sulfuric acid (Table 10). ODOT requested testing of samples of cement kiln dust, fly ash, and hydrated lime because abundant, inexpensive quantities of the materials are available for use by the department and the materials contain significant amounts of calcium (Table 10). Testing of gypsum, calcium chloride, humate, and sulfuric acid indicated these materials reduce soil SAR values and dispersion (Emerson, 1984; Haynes, 1986; Prater et al., 1978)

Procedure to Evaluate Ability of Amendments to Reduce SAR of Soils

The laboratory procedure followed to evaluate the ability of the amendments/treatments to reduce SAR values of dispersed soils included: 1) addition of correct quantity of amendment to ~250 g of soil, 2) preparation of saturated pastes from soil-amendment mixtures, 3) overnight equilibration of pastes, 4) extraction of soil water from pastes with a baroid press, 4) measurement of pH and EC of extracts, 5) measurements of concentrations of cations in extracts using an atomic absorption (AA) spectrophotometer, and 6) calculation of SAR from concentrations of cations in the extracts.

Calculation of soil-specific rates of application (Table 11) required measurement of CEC and ESP of the selected horizons. ESP measurements enabled calculations of

Table 10. Compositions of amendments tested for ability to lower SAR values of dispersed soils.

Element/Compound/ Property	CKD[†]	Fly ash	Gypsum	Hydrated lime	Humate	Calcium chloride	Sulfuric acid
					%		
Silica (SiO_2)	15.1	39.9	NA	NA	NA		NA
Aluminum oxide (Al_2O_3)	3.9	16.7	NA	NA	13.4	NA	NA
Iron oxide (Fe_2O_3)	2.0	5.8	NA	NA	NA	Trace	NA
Calcium oxide (CaO)	48.4	24.3	NA	NA	5.9	NA	NA
Hydrated lime ($Ca(OH)_2$)	NA	NA	NA	98.0	NA	NA	NA
Calcium chloride ($CaCl_2$)	NA	NA	NA	NA	NA	74.9	NA
Calcium sulfate ($CaSO_4$)	NA	NA	88.0	NA	NA	NA	NA
Magnesium oxide (MgO)	1.4	4.6	NA	0.1	1.5	Trace	NA
Sulfur oxide (SO_3)	4.5	3.3	NA	NA	3.0	NA	NA
Sulfate (SO_4^{21})	NA	NA	70.5	NA	NA	NA	98.0
Physical state	solid	solid	solid	solid	solid	solid	liquid
Mode of action	Provide Ca^{2+}	Provide Ca^{2+}	Provide Ca^{2+}	Provide Ca^{2+}	Dissolve Ca^{2+}-bearing minerals	Provide Ca^{2+}	Dissolve Ca^{2+}-bearing minerals
Supplier[=]	ODOT[+]	ODOT	Garden supply store	ODOT	Petroleum distributor	Chemical supply store	Chemical supply store

[⌜] CKD – cement kiln dust

[+] ODOT – Oklahoma Department of Transportation

Table 11. Effects of treatments on sodium adsorption ratio, electrical conductivity, and pH of amended horizons.

Treatment	Horizon No.[#]	SAR		EC (dS/m)		pH	
Gypsum		1st leaching*	5 leachings*	1st leaching*	5 leachings*	1st leaching*	5 leachings*
site specific[@]							
(4.9 Mg/ha-f-s)	28	16.8	ND	5.1	ND	7.8	ND
(2.2 Mg/ha-f-s)	64	26.4	ND	3.6	ND	8.9	ND
(7.4 Mg/ha-f-s)	85	14.4	ND	6.6	ND	7.9	ND
(7.7 Mg/ha-f-s)	146	21.1	ND	5.1	ND	7.8	ND
11.2 Mg/ha	7	10.2	6.4	4.2	3.2	7.3	6.7
	28	10.5	7.2	4.1	2.7	7.9	7.5
	64	24.8	16.5	6.0	3.8	7.9	7.5
	85	14.8	7.4	5.9	3.8	7.7	7.2
	146	25.1	8.9	8.0	3.8	7.7	7.2
22.4 Mg/ha	7	10.1	6.3	4.5	2.4	7.2	7.2
	28	9.8	6.2	4.1	3.4	7.7	7.2
	64	28.1	12.4	6.4	4.2	7.7	6.8
	85	13.9	8.0	6.4	3.8	7.8	7.3
	146	24.5	8.4	7.4	4.0	7.7	7.3
224 Mg/ha							
	7	9.9	3.2	4.1	2.8	7.8	8.4
	28	6.8	ND	4.5	ND	8.1	ND
	64	23.9	ND	12.0	ND	8.4	ND
	85	12.6	ND	6.6	ND	7.9	ND
	146	17.9	ND	7.8	ND	6.8	ND
11.2 Mg/ha+ H_2SO_4[+]							
	7	7.7	4.9	4.8	3.0	6.5	7.4

Table 11. Effects of treatments on sodium adsorption ratio, electrical conductivity, and pH of amended horizons (cont.).

Treatment	Horizon No.#	SAR		EC (dS/m)		pH	
Gypsum (cont.)		1st leaching*	5 leachings*	1st leaching*	5 leachings*	1st leaching*	5 leachings*
11.2 Mg/ha+ H_2SO_4+							
	15	11.8	6.0	4.8	1.8	7.4	6.5
Hydrated lime							
site-specific@							
(3.5 Mg/ha-f-s)	28	8.7	ND	1.0	ND	8.4	ND
(1.6 Mg/ha-f-s)	65	24.2	ND	3.5	ND	7.9	ND
(5.4 Mg/ha-f-s)	86	15.7	ND	4.8	ND	7.5	ND
(5.6 Mg/ha-f-s)	146	27.7	ND	6.0	ND	7.8	ND
11.2 Mg/ha							
	7	21.6	6.6	2.6	1.0	10.5	11.3
	28	25.3	6.1	1.0	0.9	7.9	7.2
	65	32.1	12.7	3.4	2.2	9.9	7.5
	86	51.6	11.7	3.5	1.6	10.0	7.2
	146	60.3	9.2	7.0	2.0	10.7	7.6
22.4 Mg/ha							
	7	18.2	3.4	3.1	2.2	11.7	7.5
	28	15.2	10.8	1.2	0.8	11.3	9.2
	65	35.9	23.0	2.2	1.8	10.8	8.4
	86	53.2	11.5	1.5	1.0	11.1	8.6
	146	80.4	11.5	2.5	1.0	10.7	9.8

Table 11. Effects of treatments on sodium adsorption ratio, electrical conductivity, and pH of amended horizons (cont.).

Treatment	Horizon No.	SAR		EC (dS/m)		pH	
		1st leaching*	5 leachings*	1st leaching*	5 leachings*	1st leaching*	5 leachings*
Hydrated lime (cont.)							
224 Mg/ha							
	7	12.9	5.3	6.4	5.1	12.3	12.8
	28	10.5	ND	6.8	ND	12.7	ND
	65	24.0	ND	10.8	ND	12.9	ND
	86	17.8	ND	9.8	ND	12.9	ND
	146	37.7	ND	11.0	ND	12.8	ND
11.2 Mg/ha+ $H_2SO_4^+$							
	7	11.1	9.6	3.0	0.8	10.4	7.7
	15	18.4	10.6	2.2	0.8	7.7	7.2
Fly ash							
site-specific@							
(11.0 Mg/ha-f-s)	28	9.3	ND	1.2	ND	7.2	ND
(5.1 Mg/ha-f-s)	65	19.9	ND	3.6	ND	7.5	ND
(16.8 Mg/ha-f-s)	86	14.4	ND	5.8	ND	7.8	ND
(17.5 Mg/ha-f-s)	146	21.8	ND	6.4	ND	7.9	ND
11.2 Mg/ha							
	7	12.0	13.1	3.1	1.2	7.8	8.7
	28	23.0	13.3	1.5	0.9	8.2	7.6
	65	27.4	25.0	3.0	2.3	8.1	8.3
	146	29.6	25.4	6.0	1.7	8.0	8.0

Table 11. Effects of treatments on sodium adsorption ratio, electrical conductivity, and pH of amended horizons (cont.).

Treatment	Horizon No.	SAR		EC (dS/m)		pH	
Fly ash (cont.)		1st leaching*	5 leachings*	1st leaching*	5 leachings*	1st leaching*	5 leachings*
22.4 Mg/ha							
	7	15.7	6.6	3.0	1.5	7.9	7.4
	28	14.6	15.5	1.2	1.0	7.4	7.7
	65	22.9	15.6	3.0	2.3	7.9	7.3
	86	11.8	10.5	3.6	2.0	7.5	7.4
	146	22.6	20.1	5.5	2.4	7.4	7.7
224 Mg/ha							
	7	19.3	12.1	3.0	1.2	10.2	10.2
	28	10.1	ND	2.3	ND	10.9	ND
	65	26.0	ND	4.3	ND	10.7	ND
	86	13.9	ND	4.2	ND	10.8	ND
	146	34.0	ND	6.4	ND	11.5	ND
11.2 Mg/ha+ H_2SO_4+							
	7	6.3	5.4	3.0	1.0	6.4	7.8
	15	15.7	11.3	2.2	1.1	8.0	7.1
22.4 Mg/ha+H_2SO_4+							
	7	8.8	6.7	3.2	1.0	6.7	8.1

Table 11. Effects of treatments on sodium adsorption ratio, electrical conductivity, and pH of amended horizons (cont.).

Treatment	Horizon No.	SAR		EC (dS/m)		pH	
		1st leaching[*]	5 leachings*	1st leaching[*]	5 leachings*	1st leaching[*]	5 leachings*
Cement kiln dust							
site-specific[@]							
(4.1 Mg/ha-f-s)	28	7.0	ND	2.6	ND	7.5	ND
(1.9 Mg/ha-f-s)	64	19.2	ND	4.1	ND	7.6	ND
(6.2 Mg/ha-f-s)	85	11.8	ND	5.8	ND	7.1	ND
(6.5 Mg/ha-f-s)	146	15.5	ND	6.8	ND	7.1	ND
11.2 Mg/ha							
	7	13.2	9.6	3.1	1.7	6.9	7.5
	28	12.1	16.8	2.6	1.4	8.8	9.3
	64	27.6	22.1	4.1	3.0	7.6	7.6
	85	13.9	9.2	5.8	2.6	7.7	7.1
	146	18.7	18.4	6.8	1.2	7.9	7.8
224 Mg/ha							
	7	9.8	6.1	4.5	1.8	12.6	12.0
	28	16.2	ND	4.2	ND	11.7	ND
	64	15.0	ND	5.0	ND	12.1	ND
	85	22.9	ND	5.0	ND	12.7	ND
	146	33.1	ND	6.5	ND	12.5	ND
11.2 Mg/ha+ H_2SO_4[+]							
	7	8.9	5.3	4.0	1.0	8.0	7.7
	15	11.1	7.4	3.5	1.4	8.0	7.4

Table 11. Effects of treatments on sodium adsorption ratio, electrical conductivity, and pH of amended horizons (cont.).

Treatment	Horizon No.	SAR		EC (dS/m)		pH	
Cement kiln dust (cont.)		1st leaching*	5 leachings*	1st leaching*	5 leachings*	1st leaching*	5 leachings*
22.4 Mg/ha+H_2SO_4[+]							
	7	8.6	5.8	4.2	1.0	6.8	7.5
Humate							
11.2 Mg/ha							
	7	17.0	15.3	2.0	1.2	6.5	7.6
	28	8.4	10.1	1.5	1.0	7.9	8.2
	65	33.2	20.7	3.2	2.5	8.3	8.0
	86	20.7	16.7	3.5	2.0	7.8	7.5
	146	30.1	27.2	6.0	2.3	8.1	8.0
22.4 Mg/ha							
	7	16.7	10.0	3.0	1.2	7.5	7.6
	28	15.8	9.9	4.1	2.6	8.9	8.2
	65	19.8	15.5	5.0	4.0	7.8	7.5
	86	13.7	10.9	6.6	4.0	8.0	7.6
	146	34.9	12.1	8.2	4.5	8.2	7.6
11.2 Mg/ha+ H_2SO_4[+]							
	7	12.2	8.3	2.5	1.0	7.7	7.4
	15	13.0	5.9	2.0	0.8	7.8	7.1
22.4 Mg/ha+H_2SO_4[+]							
	7	9.6	7.3	3.0	1.0	7.1	7.1

Table 11. Effects of treatments on sodium adsorption ratio, electrical conductivity, and pH of amended horizons (cont.).

Treatment	Horizon No.	SAR		EC (dS/m)		pH	
Humate		1st leaching*	5 leachings*	1st leaching*	5 leachings*	1st leaching*	5 leachings*
11.2 Mg/ha							
	7	17.0	15.3	2.0	1.2	6.5	7.6
	28	8.4	10.1	1.5	1.0	7.9	8.2
	65	33.2	20.7	3.2	2.5	8.3	8.0
	86	20.7	16.7	3.5	2.0	7.8	7.5
	146	30.1	27.2	6.0	2.3	8.1	8.0
22.4 Mg/ha							
	7	16.7	10.0	3.0	1.2	7.5	7.6
	28	15.8	9.9	4.1	2.6	8.9	8.2
	65	19.8	15.5	5.0	4.0	7.8	7.5
	86	13.7	10.9	6.6	4.0	8.0	7.6
	146	34.9	12.1	8.2	4.5	8.2	7.6
11.2 Mg/ha+ $H_2SO_4^+$							
	7	12.2	8.3	2.5	1.0	7.7	7.4
	15	13.0	5.9	2.0	0.8	7.8	7.1
22.4 Mg/ha+$H_2SO_4^+$							
	7	9.6	7.3	3.0	1.0	7.1	7.1
	15	28.2	10.3	3.5	1.4	8.0	7.4
Calcium chloride							
11.2 Mg/ha	7	13.2	3.5	15.0	2.0	6.8	6.6

Table 11. Effects of treatments on sodium adsorption ratio, electrical conductivity, and pH of amended horizons (cont.).

Treatment	Horizon No.	SAR		EC (dS/m)		pH	
		1st leaching*	5 leachings*	1st leaching*	5 leachings*	1st leaching*	5 leachings*
Calcium chloride (cont.)							
11.2 Mg/ha (cont.)							
	15	22.8	9.1	14.0	3.3	7.7	7.1
	28	11.9	6.4	14.0	4.0	7.8	7.2
	65	28.6	18.9	13.0	4.0	7.8	7.6
	86	14.7	9.8	13.0	1.6	7.2	7.0
	146	20.7	14.7	15.0	2.6	7.4	7.2
Sulfuric acid (~12M)							
125,000 L/ha							
	7	15.9	25.7	3.0	1.5	7.0	6.8
	15	74.9	20.0	2.5	1.0	7.2	6.6
	28	29.5	14.2	5.8	3.5	7.7	7.4
	65	71.4	66.3	4.0	2.7	8.8	8.3
	146	68.0	51.4	9.0	2.0	8.6	7.5

*After first and fifth saturation/extraction, respectively

#Untreated SAR, EC, and pH: Horizon No. 7 - 11.8, 2.4 dS/m, and 7.0; Horizon No. 15 - 23.4, 1.1 dS/m, and 6.1; Horizon 28 - 12.2, 1.0 dS/m, and 8.4; Horizon 64 - 28.4, 3.8 dS/m, and 8.2; Horizon 65 - 32.5, 3.9 dS/m, and 8.4; Horizon 85 - 14.8, 7.2 dS/m, and 7.5; Horizon 86 - 21.3, 4.0 dS/m, 7.6; Horizon 146 - 29.9, 6.8 dS/m, and 7.8

&also termed site-specific; addition of amendment required to supply equivalents of Ca^{2+} ions equal to equivalents of Na^+ ions measured on cation exchange complex of soil

+addition of amount of H_2SO_4 equivalent to ~25,000 L/ha and amendment numbers of equivalents of sodium on cation exchange complexes of clays in the horizons. Calculations of amounts of amendment to apply on a site-specific basis included amounts of calcium-supplying compounds in the amendments and the concentrations of calcium in the calcium-supplying compounds. Site-specific rates of application supplied the number of equivalents of calcium equal to the number of equivalents of sodium on cation exchange complexes of clays in the selected horizons.

Rates of application tested were soil-specific (gypsum, hydrated lime, fly ash, and cement kiln dust), 11.2 (gypsum, hydrated lime, fly ash, cement kiln dust, humate, and calcium chloride), 22.4 (gypsum, hydrated lime, fly ash, cement kiln dust, and humate), and 224 (gypsum, hydrated lime, fly ash, and cement kiln dust) Mg/ha. Other treatments tested were combinations of gypsum, (11.2 Mg/ha), hydrated lime (11.2 Mg/ha), fly ash (11.2 and 22.4 Mg/ha), cement kiln dust (11.2 and 22.4 Mg/ha), and humate (11.2 and 22.4 Mg/ha) with sulfuric acid (~130,000 liters acid/ha) and addition of sulfuric acid alone at a rate of 650,000 liters acid/ha. Evaluation of reduction in SAR of dispersed soils by amendment included 107 different soil/amendment treatments (Table 11) and more than 400 saturated paste saturation/equilibrations. Twenty-two treatments included addition of fly ash or a combination of fly ash and sulfuric acid (Table 11; 8 different horizons treated), 21 treatments included addition of gypsum or a combination of gypsum and sulfuric acid (Table 11; 6 different horizons treated), 21 treatments included addition of hydrated lime or a combination of hydrated lime and sulfuric acid (Table 11; 8 different horizons treated), 17 treatments included addition of cement kiln dust or a combination of cement kiln dust and sulfuric acid (Table 11; 8 different horizons treated), 14 treatments included addition of humate (Table 11; 6 different horizons treated), 6 treatments included addition of calcium chloride (Table 11; 6 different horizons treated), and 6 treatments included addition of sulfuric acid alone (Table 11; 6 different horizons treated).

Evaluations of effects of leaching on ability of treatments to reduce SAR values in amended horizons included repeated preparations of saturated pastes, equilibrations, extractions of soil water, and measurements of properties of extracts subsequent to initial amendment of the soils. No evaluations of leaching occurred on site-specific or 224 Mg/ha (except for Horizon 7) treatments. The other treatments received five successive saturation/extractions after addition of amendment for evaluation of the influence of leaching on the ability of amendments/treatments to lower SAR values. Seventy-five of the 105 treatments evaluated the influence of leaching on the ability of amendments to reduce SAR values of dispersed soils by multiple saturation/extractions after addition of amendments (Table 11).

Criteria for evaluation of the effectiveness of treatments are reduction of SAR values of amended horizons below values established for identifying dispersed soil (either the present U.S. standard (USDA, 1954) or the standards developed from the properties of the soil horizons tested for this study). Measurement of SAR is less time-consuming and less expensive compared to measurement of ESP. Correlation exists between SAR and ESP of selected horizons (Fig. 8).

Knodel (1991) identified 30% (measured by the double hydrometer test) as the upper limit for dispersion in soil with little or no expression of the adverse properties common to dispersed soil. In the U. S., an SAR of 12 identifies dispersed soil (USDA, 1954). Linear regression of SAR and percent dispersion data for the horizons sampled

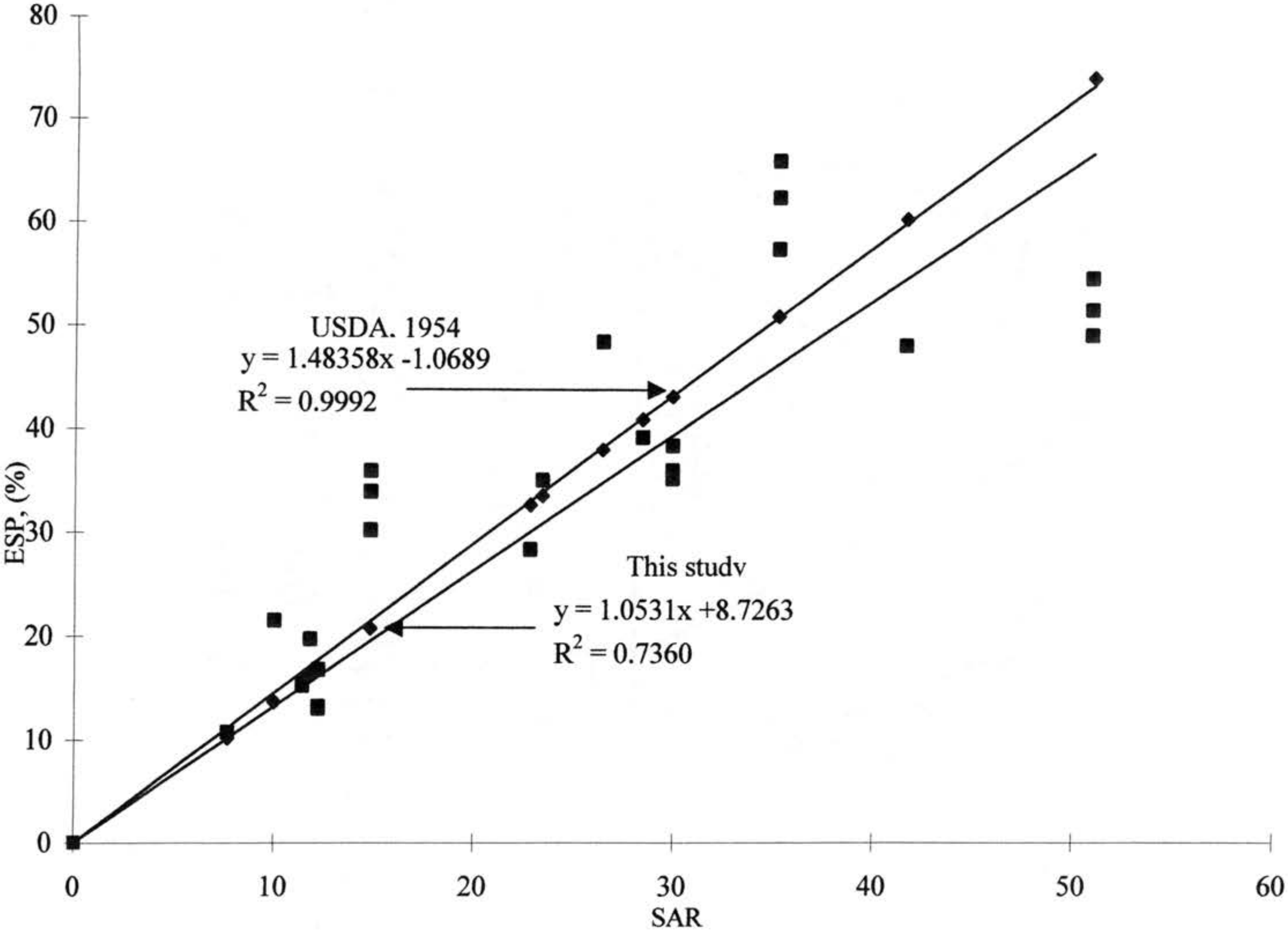

Figure 8. Relationships between SAR and ESP for selected soil horizons (diamonds, USDA, 1954; squares - this study)

for reconnaissance of potentially dispersed soil in Oklahoma enabled interpretation of critical SAR values associated with moderate and strong dispersion (>30% dispersion). Sodium adsorption ratios for identifying potentially dispersed soils in Oklahoma derived from regression data are 4.5 +/- 0.3 for weakly saline soils (EC<1 dS/m) and 7.9 +/- 0.8 for moderately saline soils (EC from 1 to 9 dS/m) (Figs. 9 and 10, respectively).

Results and Discussion

Effects of Amendments and Leaching on SAR of Dispersive Soils

Addition of amendment reduced SAR values of the first paste extract after treatment in 64% (68 of 107) of the treatments. Amendments lowered SAR values of initial paste extracts after treatments below 12 in 22% (24 of 107) and below 7.9 in <4% (4 of 107) of the treatments.

Addition of fly ash lowered SAR values of initial paste extracts after treatment below 12 in 5 treatments and below 7.9 in 1 treatment (Table 11). Addition of gypsum lowered SAR values of initial extracts below 12 in 8 treatments and below 7.9 in 2 treatments (Table 11). Addition of hydrated lime lowered SAR values of initial extracts below 12 in 3 treatments and below 7.9 in none of the treatments (Table 11). Addition of cement kiln dust lowered SAR values of initial extracts below 12 in 5 treatments and below 7.9 in 1 treatment (Table 11). Addition of humate lowered SAR values of initial extracts below 12 in 2 treatments and below 7.9 in none of the treatments (Table 11). Addition of calcium chloride lowered SAR values of initial extracts below 12 in 1 treatment and below 7.9 in none of the treatments (Table 11). Addition of sulfuric acid alone did not lower SAR values of initial extracts below 12 or 7.9 in any of the treatments (Table 11).

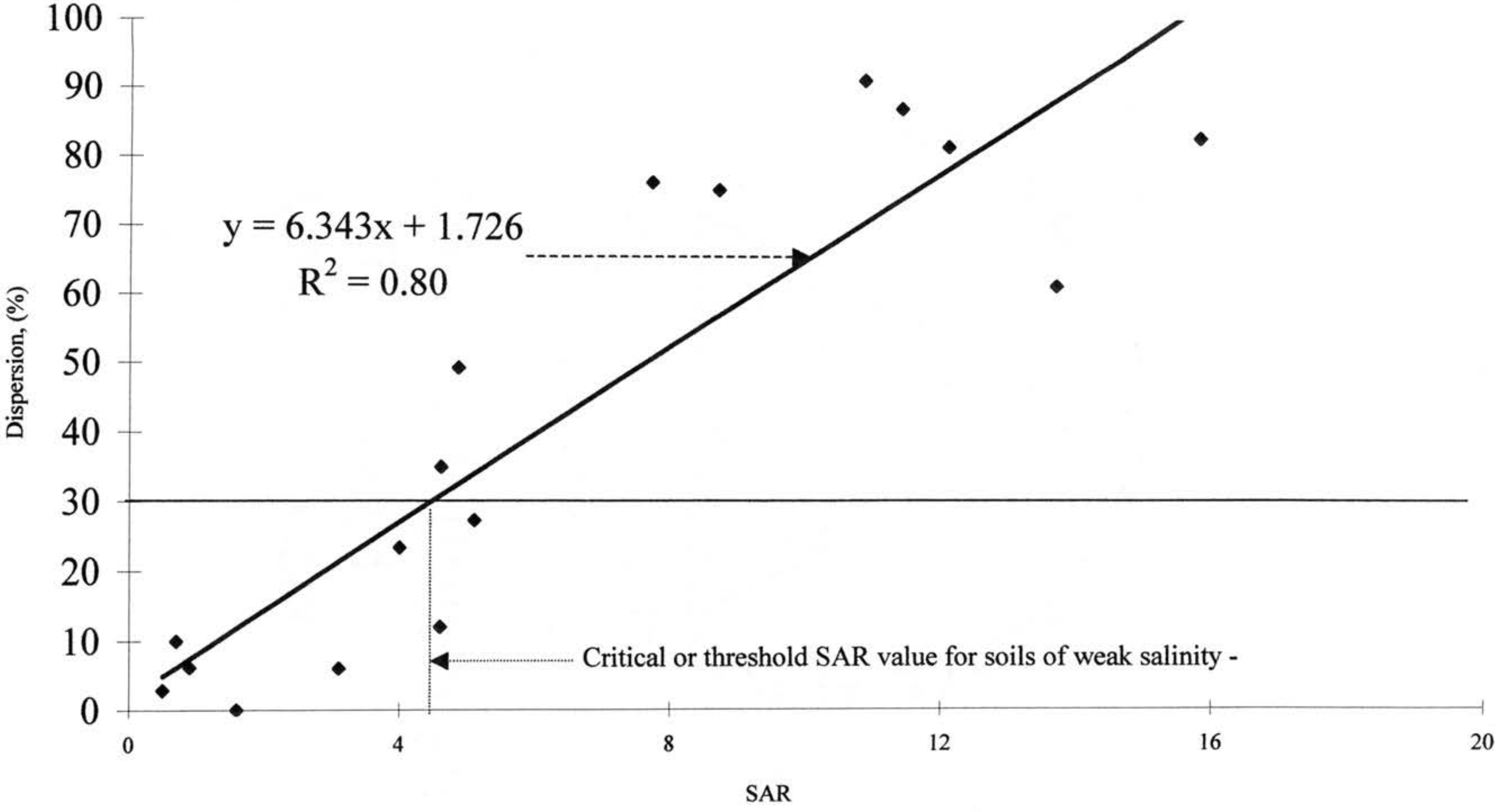

Figure 9. Linear relationship of sodium adsorption ratio and dispersion for soils of the study of weak salinity (<1.0 dS/m)

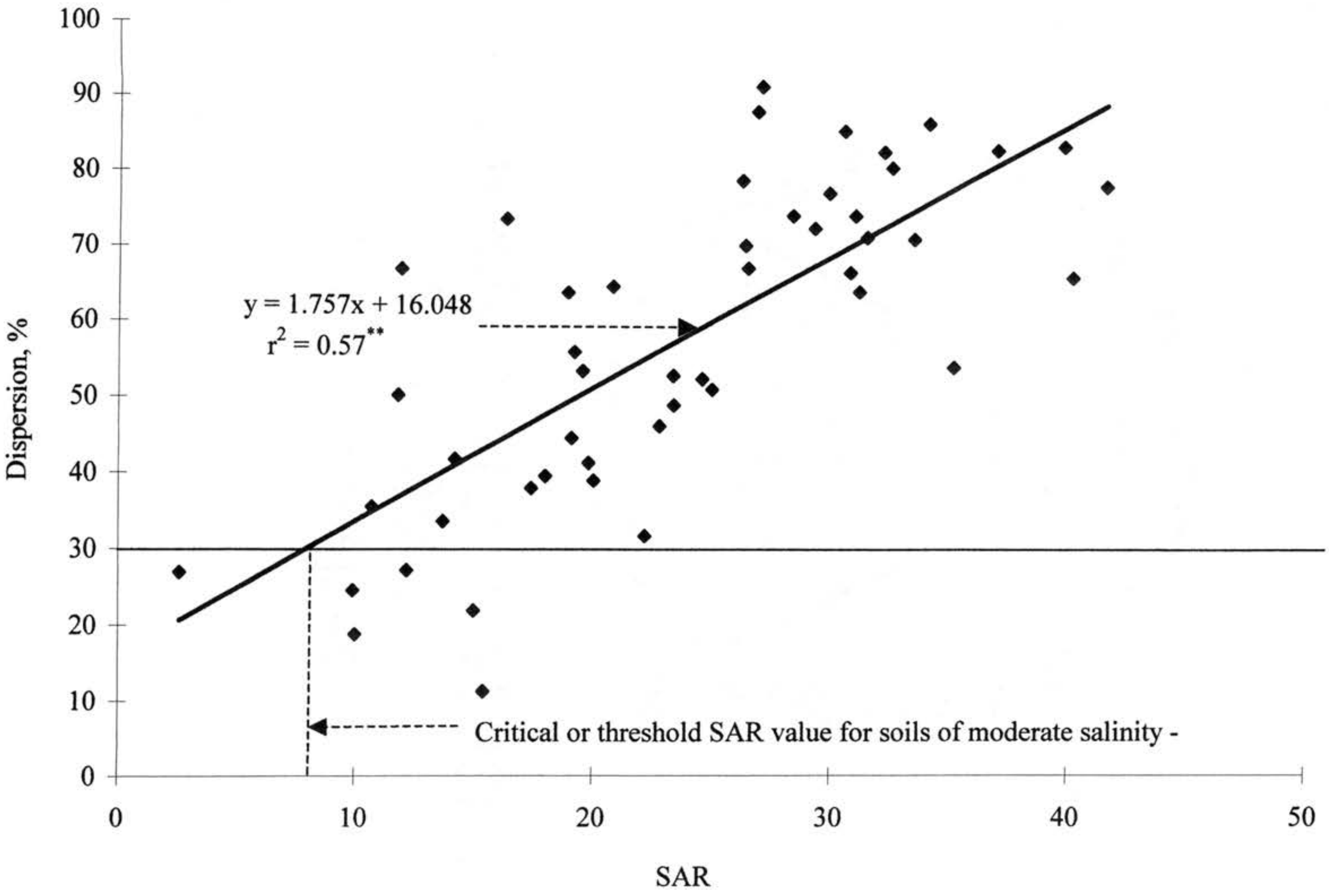

Figure 10 - Linear relationship of sodium adsorption ratio and dispersion for soils of the study of moderate salinity (1-9 dS/m).

Addition of amendments followed by leaching lowered SAR values after treatment in 87% (65 of 75) of the treatments (Table 11). Addition of amendments followed by leaching reduced SAR values below 12 in 61% (46 of 75) and below 7.9 in 31% (23 of 75) of the treatments (Table 11). Reduced SAR values in the leaching experiments indicate removal of sodium ions from the soil by leaching (Figs. 11 through 17 and Table 11).

Effects of Amendments and Leaching on EC and pH of Dispersed Soils

Addition of amendments increased EC values of initial paste extracts after treatment above untreated values for the soils in 68% (73 of 107) of the experiments (Table 11). Addition of amendments with leaching resulted in increased EC values of extracts from the fifth saturation/equilibration after treatment above untreated values for the soils in 23% (17 of 75) of the leached experiments (Table 11). Elevated EC values of the initial paste extracts after treatment indicate dissolution of the amendments and reduced EC values of extracts from the fifth equilibration/extraction after treatment indicate removal of electrolytes from the soils by leaching (Table 11). Addition of calcium chloride at a rate of 11.2 Mg/ha caused the largest increase in EC values of initial extracts after treatment (Table 11) and largest reduction in EC values accompanied addition of hydrated lime at a rate of 22.4 Mg/ha and leaching (Table 11).

Addition of amendments increased pH values of initial paste extracts after treatment above untreated soil values in 58% (62 of 107) of the treatments (Table 11). Addition of hydrated lime, fly ash, and cement kiln dust at a rate of 224 Mg/ha caused the largest increases in pH (Table 11). Addition of amendments with leaching decreased pH values of extracts from the fifth saturation/equilibration below untreated soil values in

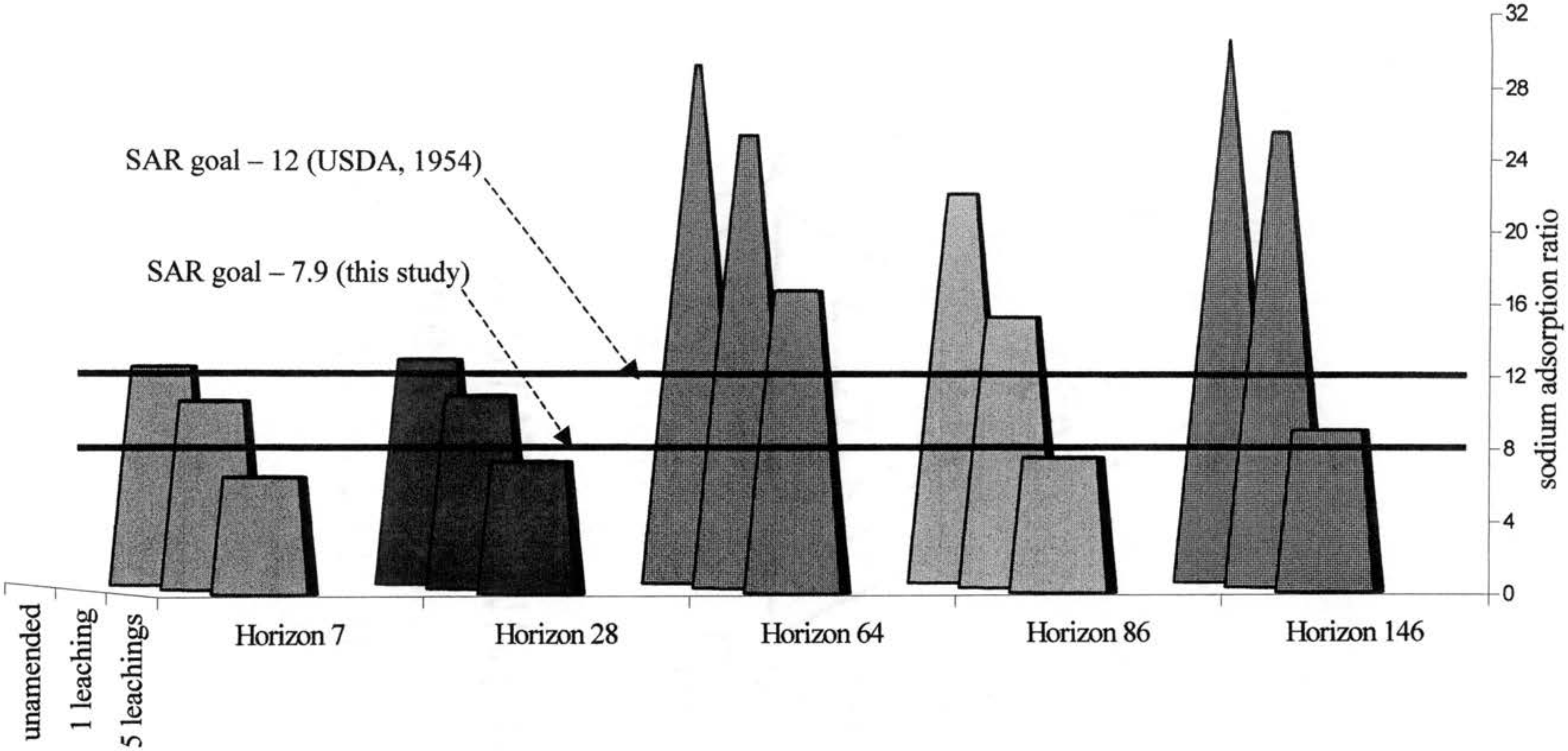

Figure 11. Effects of gypsum (11.2 Mg/ha) on sodium adsorption ratios of amended soils

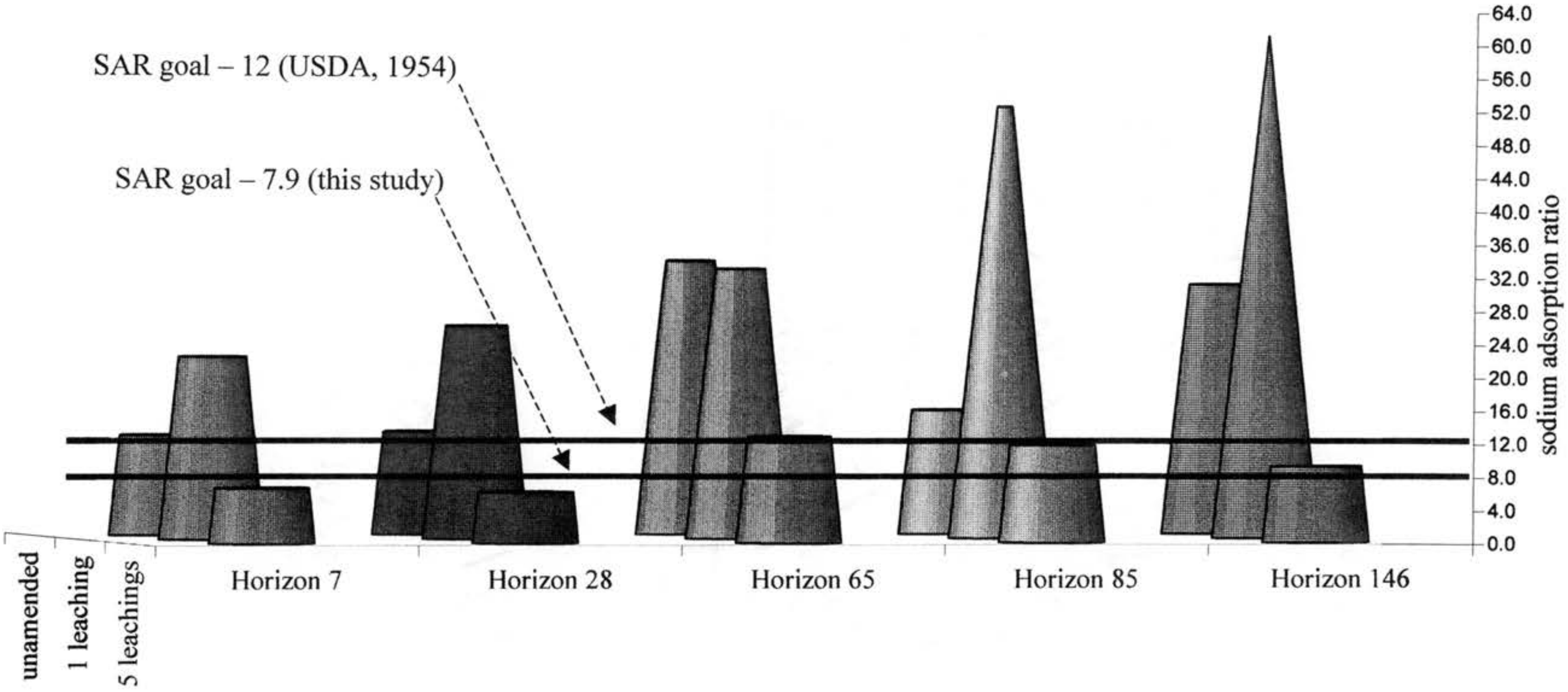

Figure 12. Effects of hydrated lime (11.2 Mg/ha) on sodium adsorption ratios of amended soils

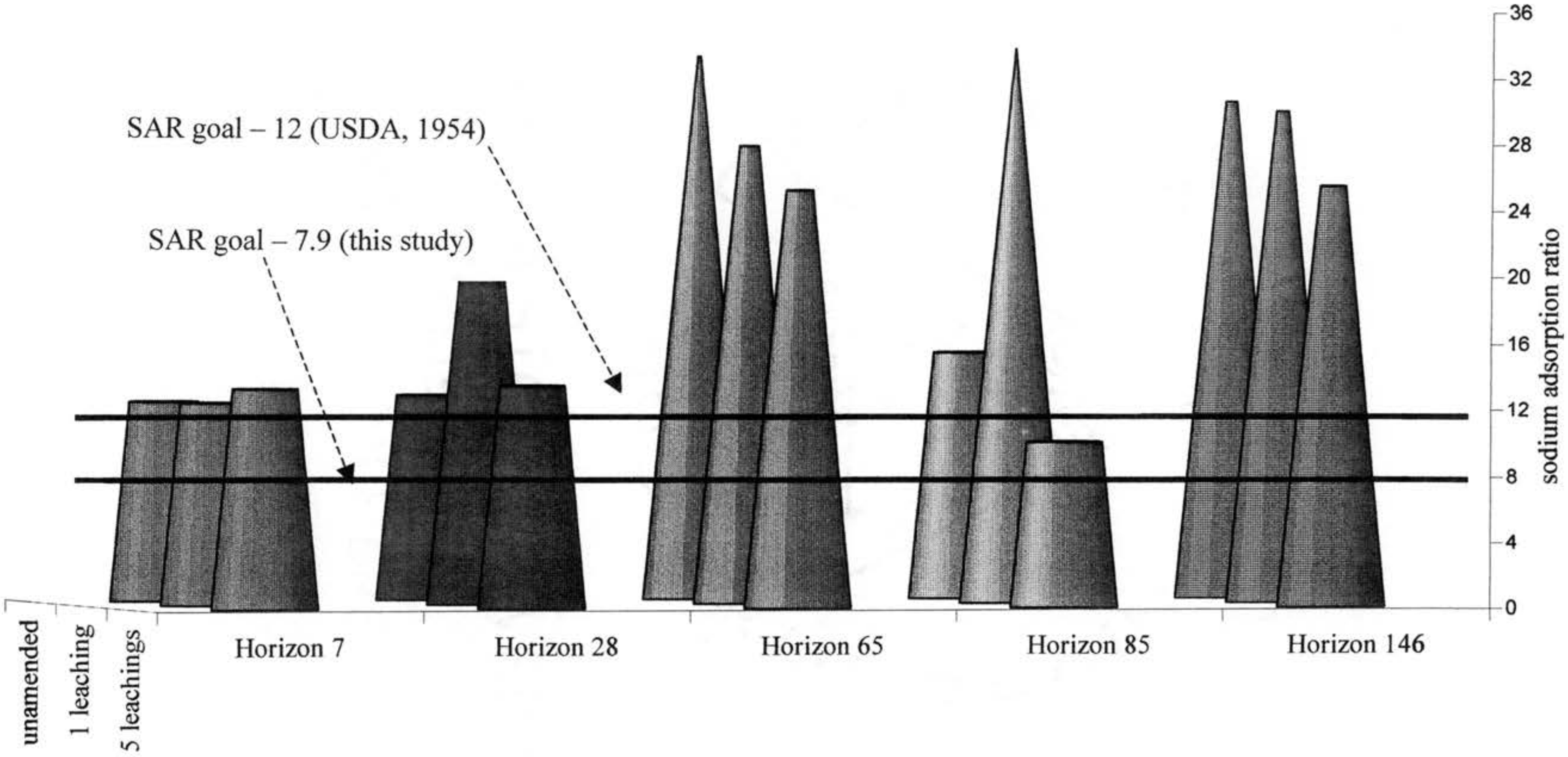

Figure 13. Effects of fly ash (11.2 Mg/ha) on sodium adsorption ratios of amended soils

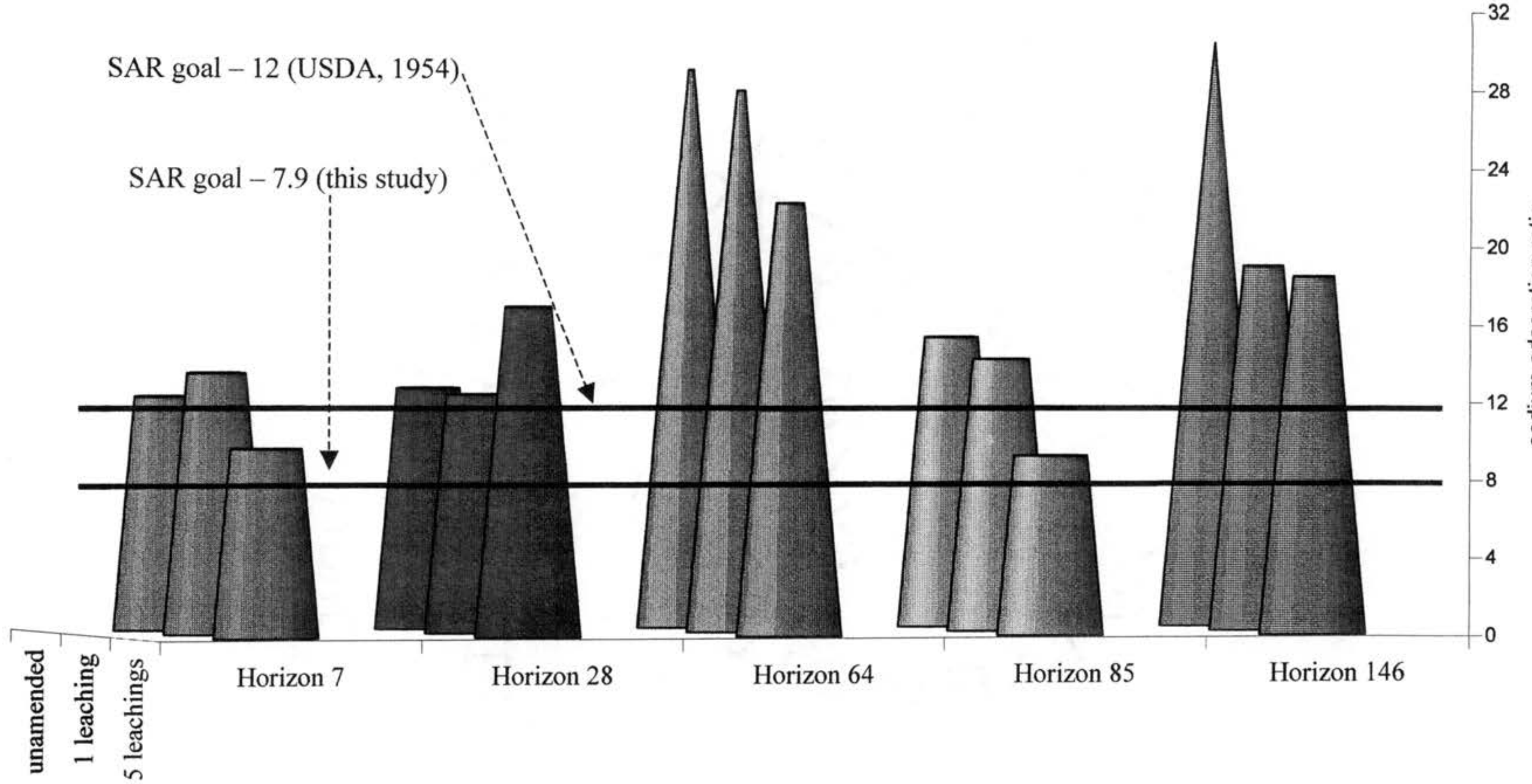

Figure 14. Effects of cement kiln dust (11.2 Mg/ha) on sodium adsorption ratios of amended soils

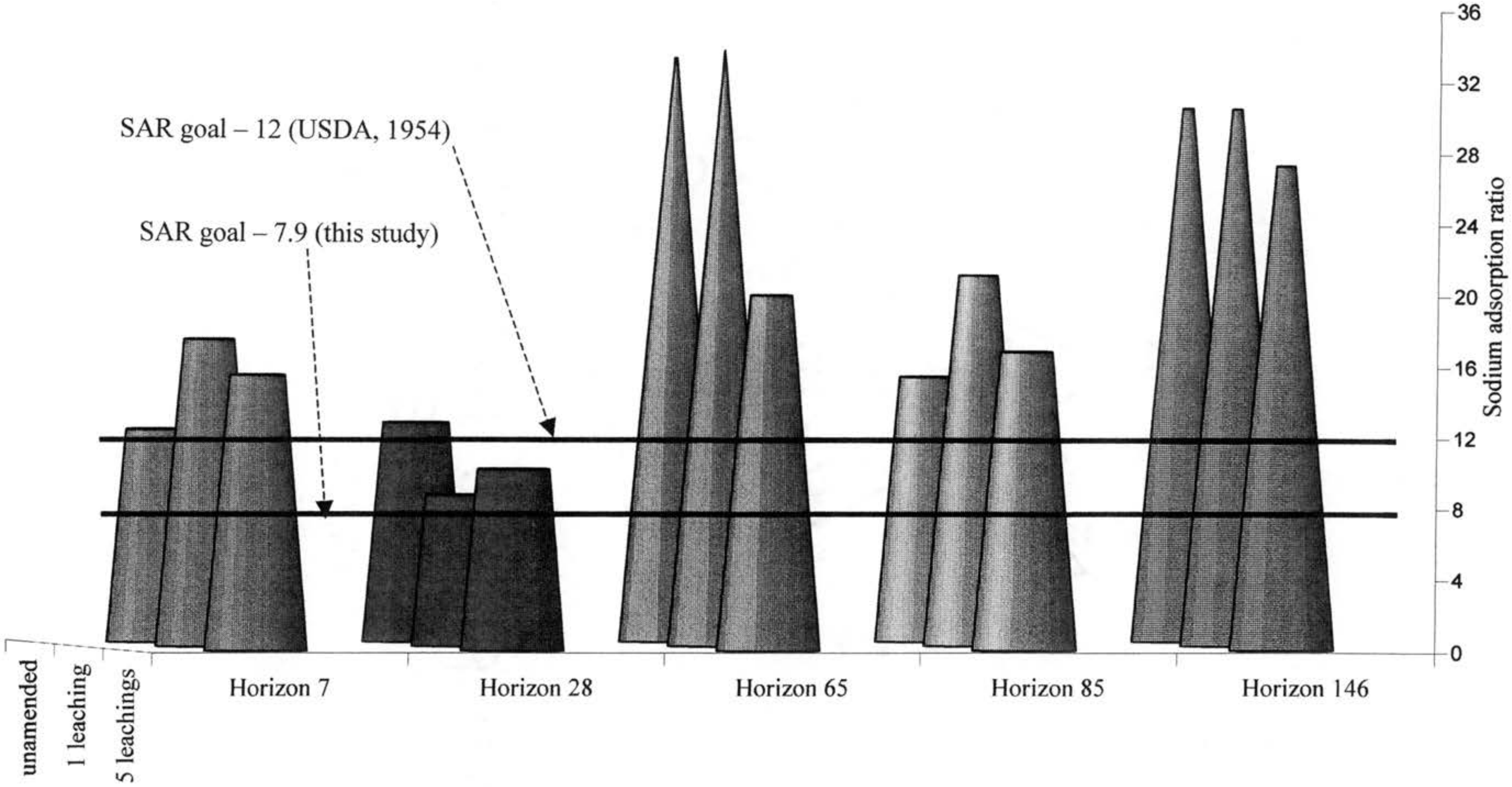

Figure 15. Effects of humate (11.2 Mg/ha) on sodium adsorption ratios of amended soils

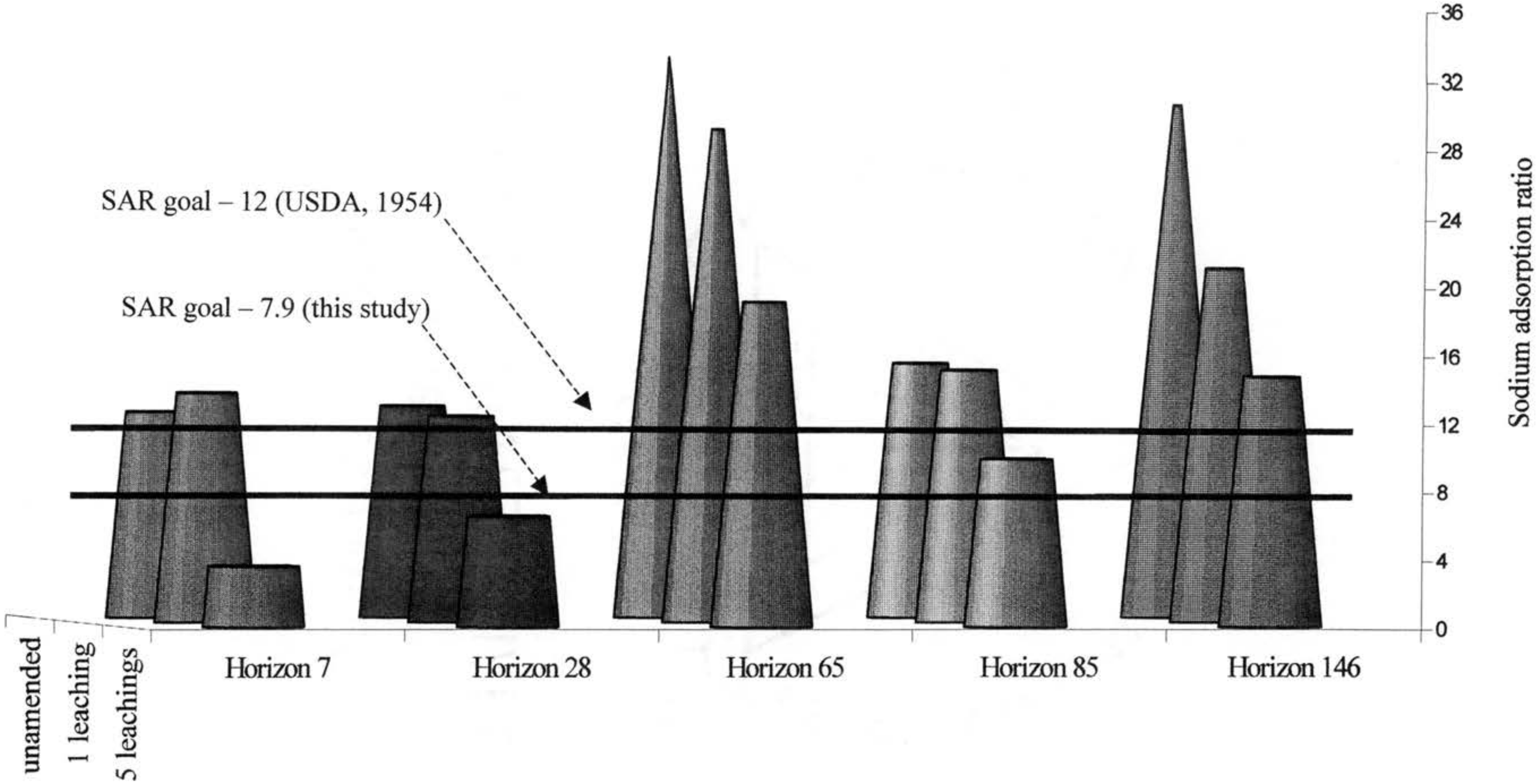

Figure 16. Effects of calcium chloride (11.2 Mg/ha) on sodium adsorption ratios of amended soils.

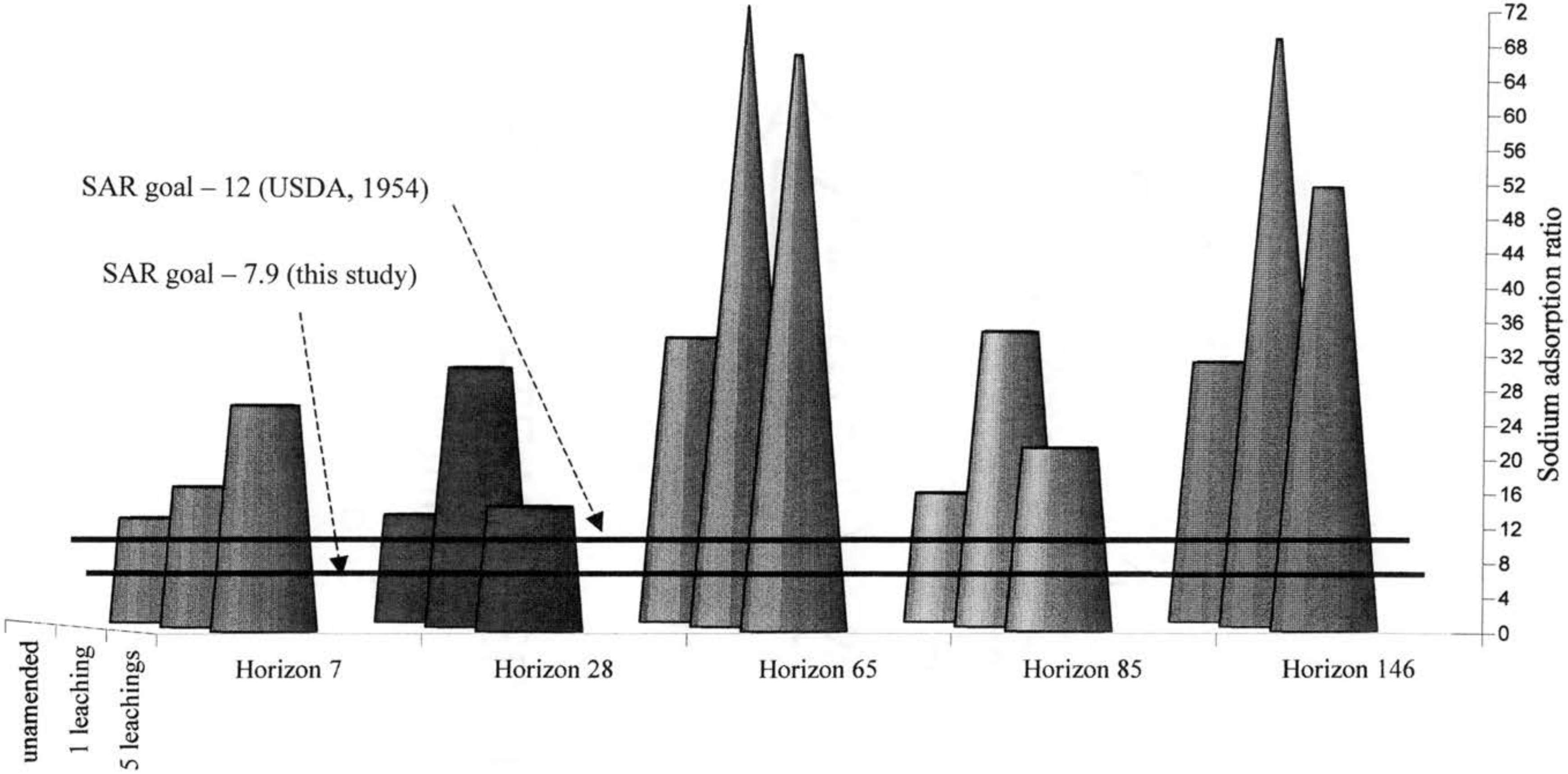

Figure 17. Effects of sulfuric acid (130,000 L/ha) on sodium adsorption ratios of amended soils

55% (41 of 75) of the leaching experiments (Table 11). Addition of gypsum, calcium chloride, and sulfuric acid caused the largest reduction in pH (Table 11).

Soil Factors Affecting Ability of Amendments to Reduce SAR Values

The ability of amendments to lower SAR values of treated horizons below standard values varied from horizon to horizon (Figs. 11 through 17 and Table 11). Treatments decreased the SAR value of Horizon No. 7 below 12 in 65% (30 of 46) of the treatments involving Horizon No. 7 (Table 11) but never lowered SAR values of Horizon Nos. 64 or 65 below 12 (Table 11). Treatments decreased SAR values below 12 in 70 treatments (Table 11) and SAR values of Horizon Nos. 7, 15, and 28 dropped below 12 in 80% (56 of 70) of those treatments (Table 11). Treatments lowered SAR values below 7.9 in 27 treatments (Table 11) and SAR values of Horizon Nos. 7, 15, and 28 dropped below 12 in all but one of those treatments (Table 11).

Differences in reduction of SAR values of soils by the same treatment for horizons indicate properties of soil affect ability of treatments to lower SAR values (Figs. 11 through 17). Horizon Nos. 7, 15, and 28 show less measured dispersion, have smaller SAR values, contain less soluble salt (reflected in EC values and total charge of ions in soil water), and hold fewer sodium ions in soil water than the other treated horizons in most cases (Table 12). Horizon Nos. 64 and 65 contain more clay-sized particles and have higher EC and SAR values than the other treated horizons (Table 12).

Effective Treatments for Reducing SAR Values of Dispersed Soil

Assuming reduction of SAR values below standard values for identifying dispersed soil indicates reduction in dispersion, than effective treatments lower SAR values of horizons below standard SAR values for identifying dispersed soil. Many more

Table 12. Other properties of treated horizons affecting ability of amendments to reduce sodium adsorption ratios

Horizon No.	B.D.	Clay, %	pH	OC	Ions	Ca:Mg	Cl:SO4	Cl^-
7	1.79	32.5	5.4	0.2	4.9	0.8	2.0	1.97
15	1.92	42.0	5.6	0.8	2.1	1.0	0.1	1.07
28	1.51	38.4	8.4	0.6	2.3	1.3	0.4	1.02
64	NA	55.5	8.1	1.0	10.2	1.0	0.4	4.60
65	NA	51.9	8.3	0.5	8.8	1.1	0.9	4.12
85	1.80	32.9	7.9	0.3	22.9	1.1	0.2	7.11
86	1.52	37.6	7.9	0.3	8.9	1.0	0.6	3.74
146	1.73	23.0	8.9	0.1	15.7	0.5	6.4	6.70

[*] B.D. - bulk density (g/cc), OC - organic carbon (%), Ions - sum of charge of major ions in soil water (cmolc/L), Ca:Mg - ratio of charge of calcium ions to charge of magnesium ions in soil water, Cl:SO4 - ratio of charge of chloride ions to charge of sulfate ions in soil water, Na/(Na+Ca) - ratio of the charge of sodium ions to the sum of the charge of the sodium and calcium ions in soil water, Cl^- - sum of charge of chloride ions in soil water (cmolc/L)

treatments lowered SAR values below 12 compared to treatments lowering SAR values below 7.9. Most of the treatments lowering SAR values below 7.9 included leaching (Figs. 11 through 17 and Table 11). All of the materials tested lowered the SAR values of a treated horizon below a standard value except for concentrated sulfuric acid by itself (Table 11). Nearly all treatments tested failed to lower SAR values of strongly dispersed soils below standard SAR values for identifying dispersed soil (Table 11). Gypsum reduced SAR values below standard values in the greatest number of treatments (Table 11). Some treatments lowering SAR values below 12 or 7.9 raised pH values of soils above tolerable levels for many kinds of soil microorganisms and higher plants (hydrated lime, fly ash, and cement kiln dust) (Table 11).

Conclusions

Treatments reduced SAR values below standard values in moderately saline soils with weak to moderate dispersion (<65% measured dispersion) having EC values near the lower limit for moderate salinity (1.0 dS/m). Treatments did not reduce SAR values below standard values in moderately saline horizons with strong dispersion (>65% measured dispersion) having EC values well above the lower limit for moderate salinity.

Strongly dispersed, moderately saline soil horizons require treatments with larger application rates or multiple treatments at the rates tested in this study. Strong dispersion, large amounts of soluble salt, and large numbers of sodium ions in soil water affects the ability of amendments to reduce SAR values of soils. Recommended treatments for remediation of dispersed soil should reduce SAR values of affected soils below standard SAR values determined in this study (4.5 +/- 0.3 for soils with EC values <1.0 dS/m and 7.9 +/- 0.8 for soils with EC values between 1.0 and 9.0 dS/m). Recommended materials for reducing SAR values of dispersed soils are gypsum and hydrated lime at rates of 11.2 and 22.4 Mg/ha because these treatments proved most successful in reducing SAR values of amended soils.

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CHAPTER 3 – FLUCTUATIONS OF TEMPERATURE AND CHEMISTRY OF WATER WITH RAINFALL IN AN UNCONFINED AQUIFER

Evaluation of the chemistry and purity of water in aquifers requires analyses of samples of the water. Samples of water from aquifers most often are taken from sample wells set into the aquifers. Water in the form of precipitation mixes with water residing in aquifers prior to rainfall events and changes the chemistry and purity of the groundwater. Samples of groundwater taken in close proximity temporally to a rainfall event may not accurately represent the chemistry of the groundwater (Noriega, 1997; Ketelle and Davies, 1999). Erroneous conclusions associated with sampling of groundwater too soon after a rainfall include, 1) an unidentified source of contaminant exists because the level of contaminant in samples of water from the aquifer is greater than ever before, or, 2) remediation of an aquifer is complete because no more contaminant exists or the concentration of contaminant is below some predetermined level in samples of water from the aquifer.

Time-based sampling schedules (random, daily, weekly, monthly, quarterly, or yearly) ignore effects of recent rainfall events on groundwater chemistry. Rainfall also changes temperatures within an aquifer (Noriega, 1997; Ketelle and Davies, 1999). Thermocouples attached to dataloggers monitor and record temperature changes within aquifers. Analyses of samples of water from aquifers indicate chemistry of water in aquifers at the times of sampling. Knowledge of temporal relationships of rainfall-induced changes in chemistry of water in aquifers and changes in temperature within aquifer materials increases the likelihood of retrieving water samples representative of the typical state of water in the aquifers. The main objectives of this study were, 1) monitoring temperatures of materials in an unconfined aquifer at several depths, 2) monitoring chemistry of water in the same unconfined aquifer during and following rainfall events and 3) identifying temporal relationships of temperatures within the aquifer materials and chemistry of water in the aquifer in relation to precipitation to assess the potential for monitoring of soil temperatures as a tool for use in groundwater remediation, particularly for improvements in timing of sampling of aquifer water for samples representative of typical chemistry of water in an aquifer.

The unconfined aquifer tested is part of an alluvial deposit along Boomer Creek in Payne Co., OK (Figs. 18 and 19). The site and aquifer tested in this study are part of a series of hydrologic and geologic research projects started and continuing since mid-1980. Studies completed concerning the aquifer examined effects of changing hydrologic and geologic conditions on the chemistry of water in the aquifer (Hoyle, 1987; Froneberger, 1987; Melby, 1986), variations in the chemistry of water in the aquifer water with depth and over time (Ross, 1987), rates of recharge of the aquifer using tracers (Zietlow, 1995; Everett, 1995), and variations in temperatures in the aquifer with depth and over an annual cycle (Poyer, 1996). Pettyjohn (1994) discusses much of the work previously completed at the site.

Reports of research concerning temporal relationships of changes in temperature and chemistry of water in aquifers with regards to rainfall events are lacking (Wayne Pettyjohn, personal communication, 2000). Similar kinds of studies from other areas include changes in temperature of aquifer materials with depth over a long time span in an aquifer (Heath and Trainer, 1981), effects of precipitation on chemistry of spring waters (Noriega, 1997; Ketelle and Davies, 1999), variability in chemistry of geothermal waters (Murray, 1996; Mayo and Loucks, 1995), and variability in chemistry of water in mines (Younger, 1995). Detailed studies of temporal relationships of changes in

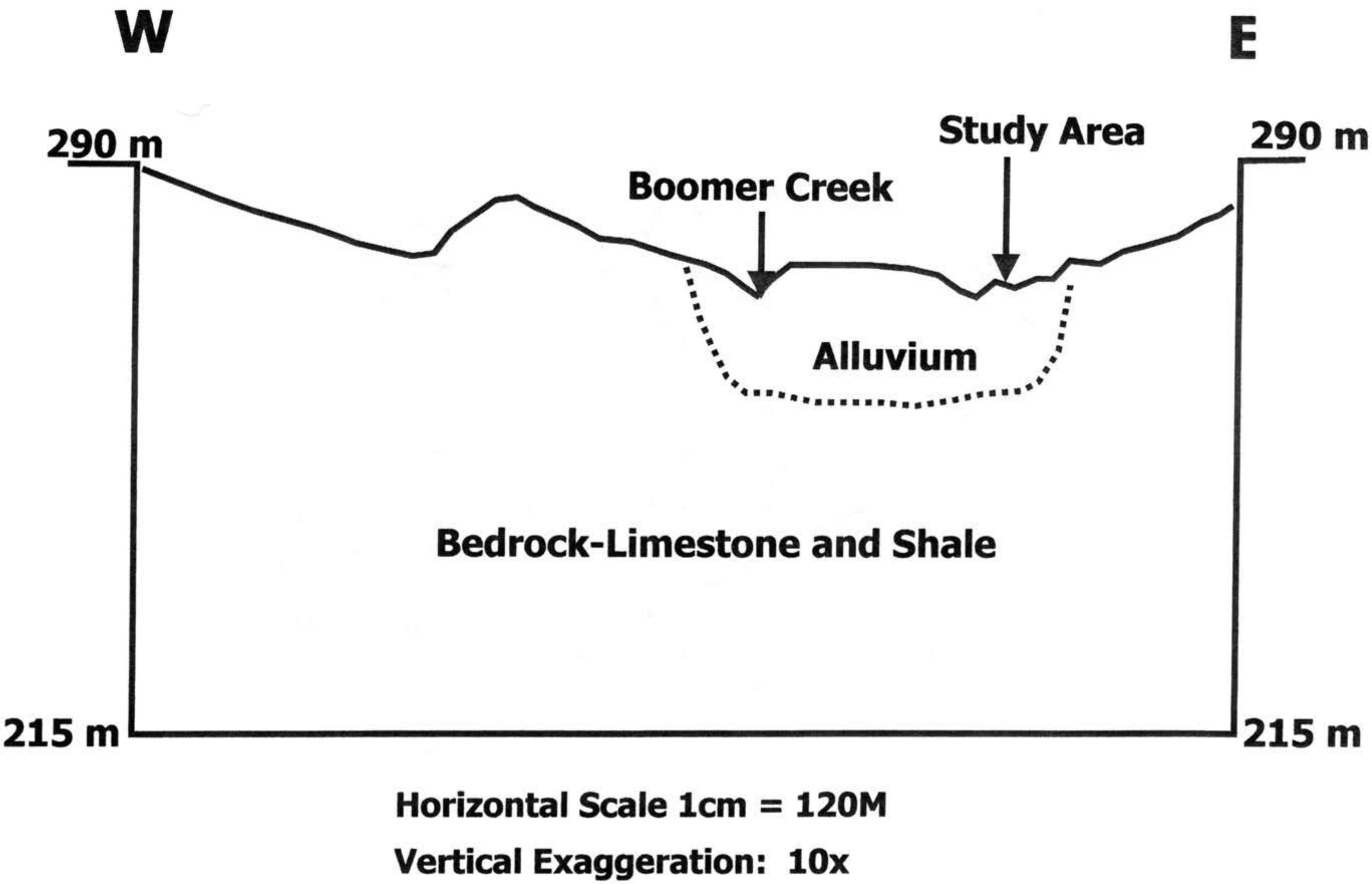

Figure 18. Topographic cross-section of Boomer Creek alluvium and site of study

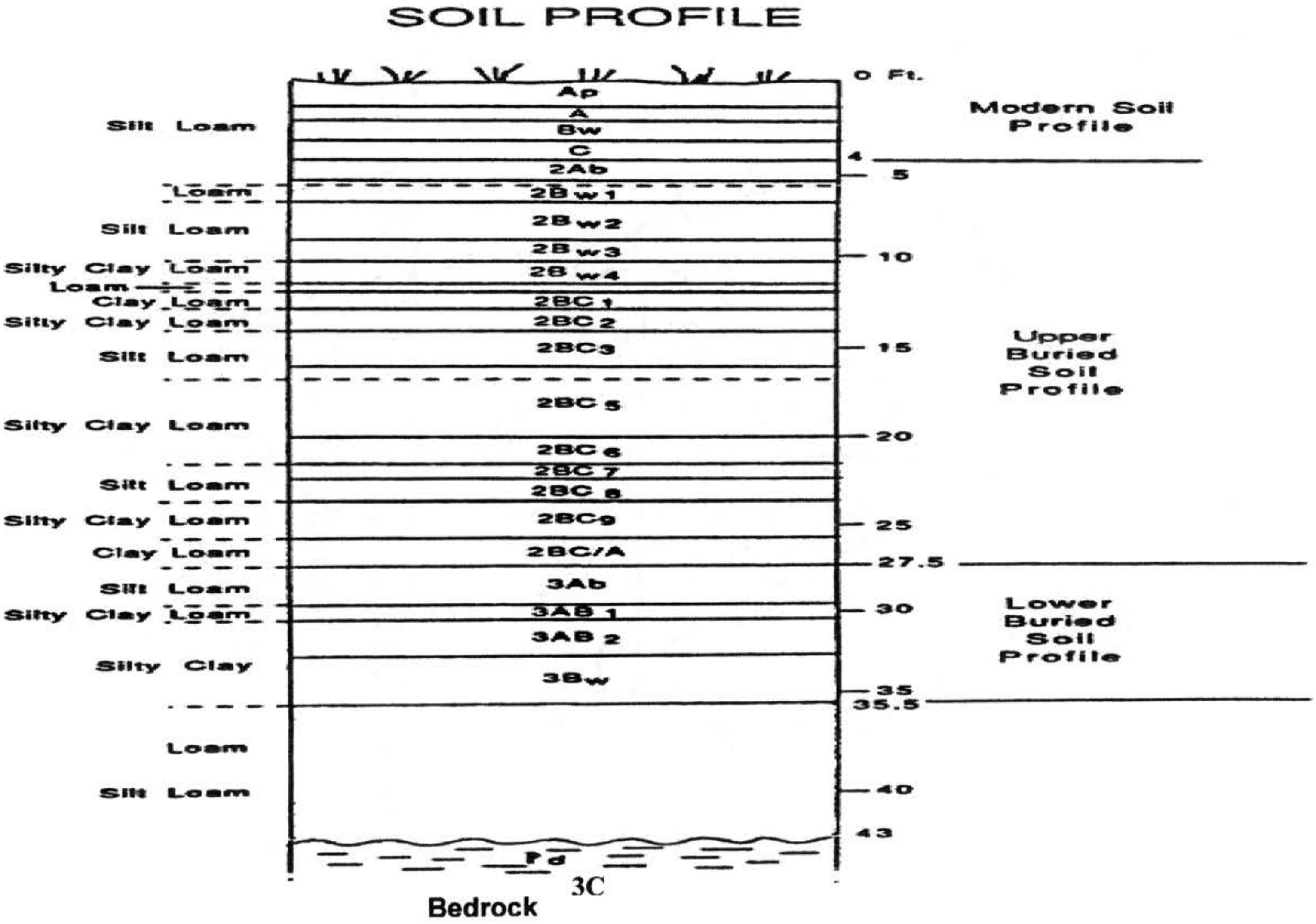

Figure 19. Soil profile of the aquifer studied

temperatures within aquifers, changes in chemistry of water in aquifers, and precipitation events are non-existent or not available.

Monitoring of Temperatures and Chemistry of Water within the Aquifer

A set of thermocouples at depths of 10, 25, 50, 75, 100, 150, 200, 300, 400, 500 cm, and in the air connected to a data logger monitored and recorded hourly temperatures within the aquifer and in the air at the study site (Fig. 20). Sampling of wells for analyses of chemistry of water in the aquifer began when rainfall event intensity exceeded 2.5 cm/day according to the on-site tipping bucket rain gauge (Fig. 20). Two separate clusters of water wells provided samples of water from the aquifer (Fig. 20). One cluster of wells is ~1 m from the set of thermocouples (Fig. 20). The other cluster of wells occurs on another area of the study site and about 25 m from the set of thermocouples (Fig. 20). Each well cluster contains five wells, slotted at approximately 258, 315, 375, and 435 cm and between 258 and 435 cm, respectively. The schedule for sampling of wells for each qualifying precipitation event was approximately 7, 17, 25, 32, 40, 48, 54, 65, 75, 85, 105, and 120 hours after rainfall reached 2.5 cm within a 24-hour period. Each sampling period produced 10 samples of water from the aquifer (1 from each well) unless depth to the water table dropped below the slotted interval of a well or wells. Analyses performed on water samples were measurements of concentrations of F^-, Cl^- Br^-, NO_3^-, and SO_4^{2-} by ion chromatography (USDA, NRCS, NSSC, 1991). Measurements of chemistry of water in the aquifer and temperatures within the aquifer also occurred between qualifying rainfall events.

Measured concentration of an ion in a water sample from a well not within the 95% confidence interval based on measurements of the ion made on water from the well

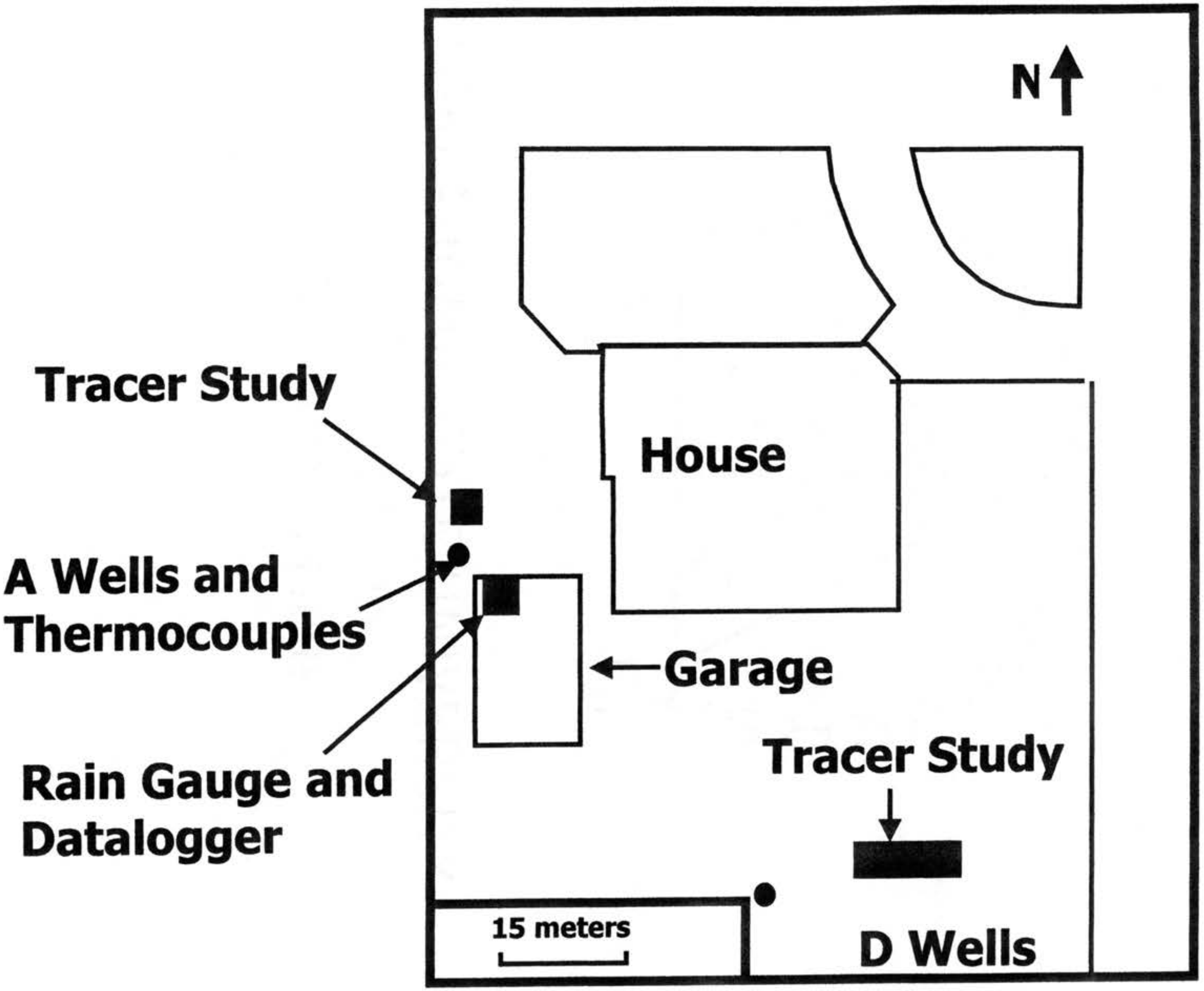

Figure 20. Implementation of the site for the study

sampled between rainfall events indicated affect of rainfall on the chemistry of the water in the aquifer. Sampling occurred for the qualifying rainfall events occurring over a several month span to assess variations associated with different amounts of precipitation and time of year. The extent and duration of significant changes in temperature of the aquifer or chemistry of water in the aquifer in response to the sampled rainfall events enabled evaluation of temporal relationships of fluctuations in temperature in the aquifer temperatures and chemistry of water in the aquifer after significant rainfalls. The total number of water samples tested was ~1000. The number of measurements of soil temperature made was much greater and significantly less labor-intensive.

Response of Aquifer Temperatures and Chemistry of Aquifer Water to Rainfall

Sampling of aquifer water occurred after three qualifying rainfalls (>2.5 cm rain in 24-hour period). Dates of Rainfall events sampled were September 21, January 30, and March 8. Each rainfall event provided data on chemistry of the water in the aquifer for several time intervals (Table 13). Sampling for analyses of chemistry of water in the aquifer between qualifying rainfalls occurred on January 28, February 10, and February 26.

Evaluations of effects of rainfall on the chemistry of the water in the aquifer are from confidence intervals (95%) (Table 14) for the ions measured on water taken from the wells between rainfall events. Measurements below or above calculated confidence intervals for any ion indicated an influence of the rainfall on the chemistry of the water in the aquifer (Table 14). Concentrations of F^-, Cl^-, NO_3^-, and SO_4^{2-} deviated from confidence intervals most often with concentrations of Br^- deviating from confidence intervals in only three samples. The sample wells had similar numbers of observations

Table 13. Sampling intervals for measured rainfall events.

Rainfall event 1 (September 21, 1998) – Depth to water table – 3.5 m

7, 35, 43, 55, 62, 68, 79, 87, 97, and 105 hours after event exceeded 2.5 cm

Rainfall event 2 (January 30, 1999) – Depth to water table – 2 m

7, 17, 30, 35, 43, 55, 66, 108, and 127 hours after event exceeded 2.5 cm

Rainfall event 3 (March 8, 1999) – Depth to water table – 2 m

7, 17, 30, 37, 43, 48, and 54 hours after event exceeded 2.5 cm

Table 14. Concentrations of ions in water from sample wells (mmol) within 95% confidence interval determined from analyses of ions in water in wells between rainfall events

Well	F^-	Cl^-	Br^-	NO_3^-	SO_4^{2-}
			mmol		
A1	0.007-0.009	0.205-0.307	0.001-0.003	0.164-0.192	0.047-0.051
A2	0.011-0.045	0.466-0.521	0.003-0.005	0.062-0.082	0.048-0.054
A3	0.010-0.012	0.307-0.601	0.001-0.003	0.201-0.211	0.047-0.049
A4	0.014-0.022	0.511-0.779	0.003-0.005	0.088-0.178	0.071-0.073
A5	0.023-0.057	0.464-0.582	0.003-0.005	0.076-0.112	0.066-0.068
D1	0.020-0.022	2.001-2.181	0.003-0.005	0.072-0.080	0.123-0.125
D2	0.017-0.019	1.837-2.041	0.003-0.005	0.014-0.056	0.106-0.110
D3	0.019-0.021	1.326-1.384)	0.003-0.005	0.057-0.091	0.106-0.112
D4	0.016-0.024	1.642-1.680	0.003-0.007	0.008-0.012	0.059-0.121
D5	0.020-0.022	1.533-1.639	0.003-0.005	0.090-0.118	0.101-0-103)

deviating from confidence intervals. Concentrations of ions in samples of water taken in conjunction with Rainfall event 1 deviated from confidence intervals for F^- (wells A4, D4, and D5), Cl^- (wells A4, A5, D4, D5), NO_3^- (well A5, D4, and D5) , and SO_4^2 (wells A4, A5, and D5) for nearly all sampling intervals, including the final interval at 105 hours after rainfall exceeded 2.5 cm in 24 hours. Similar results occurred for samples taken in conjunction with Rainfall event 2 for concentrations of Cl^- (wells A1, A2, D1 and D4), NO_3^- (wells A1, A2, A3, D1, and D4), and SO_4^2 (well A3, A4, and D1). Samples taken in conjunction with Rainfall event 3 deviated from confidence intervals for concentrations of Cl^- (wells A2, A4, A5, D3, D4, and D5), NO_3^- (wells A1, A2, A3, A5, D1, and D4), and SO_4^2 (well A1, A5, D1, D2, D3, and D5). Concentrations of ions in samples of water from the aquifer taken for the final sampling interval of each of the Rainfall events deviated from confidence intervals (Figs. 21 through 24).

Temperature changes in the aquifer near the land surface in response to Rainfall event 1 were abrupt and intense (Fig. 25). Response of temperature at 10 cm to the rainfall nearly began with the rainfall (Fig. 25). The maximum declination of temperature at 10 cm in response to Rainfall event 1 was nearly 4°C about 35 hours after rainfall reached 2.5 cm (Fig. 25). Temperature at 25 cm also dropped immediately in response to Rainfall event 1 and maximum declination in temperature was ~2.5° C about 45 hours after rainfall reached 2.5 cm (Fig. 25). Temperatures in the aquifer at 10 and 25 cm showed response to diurnal fluctuations in air temperature after temperature drops at those depths reached a maximum (Fig. 25). Changes in temperature at 50 cm and deeper in the aquifer lagged behind and were less intense compared to changes observed near the land surface (Figs. 25 and 26). Temperatures at 50 cm did not respond immediately to

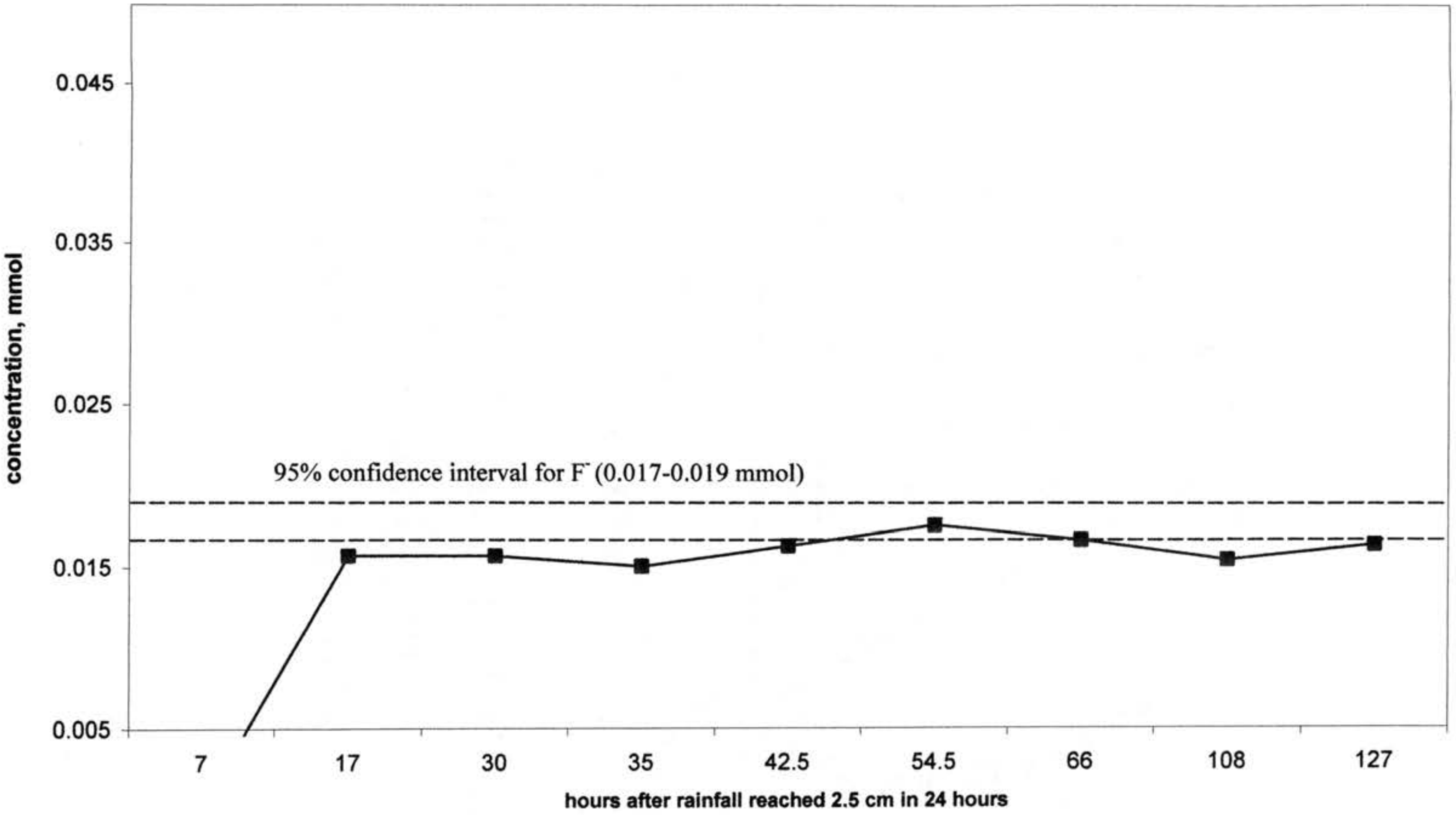

Figure 21. Concentrations of F^- in water from the aquifer associated with Well D2 after Rainfall event 2

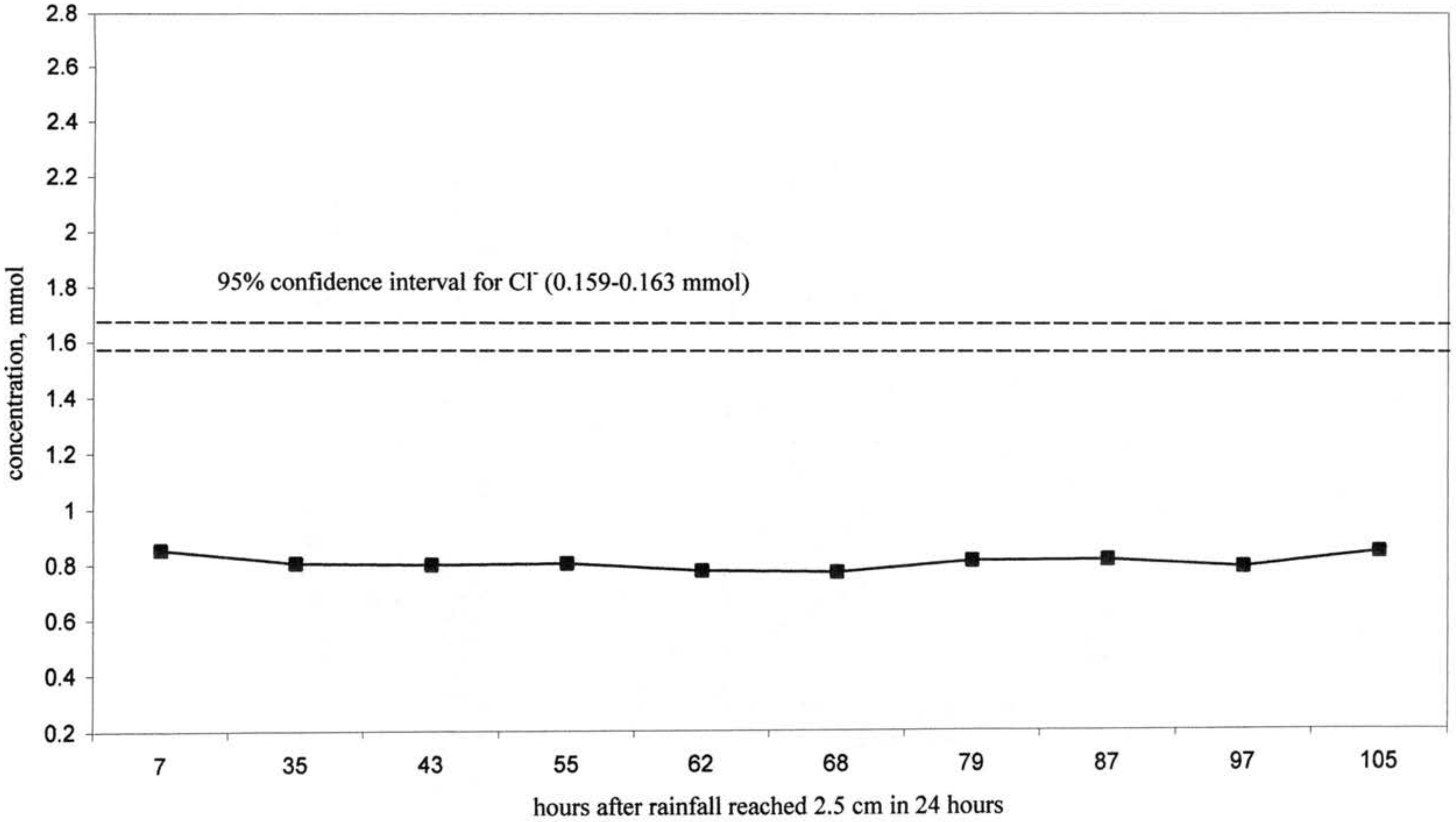

Figure 22. Concentrations of Cl^- in water from the aquifer associated with well A5 after Rainfall event 2.

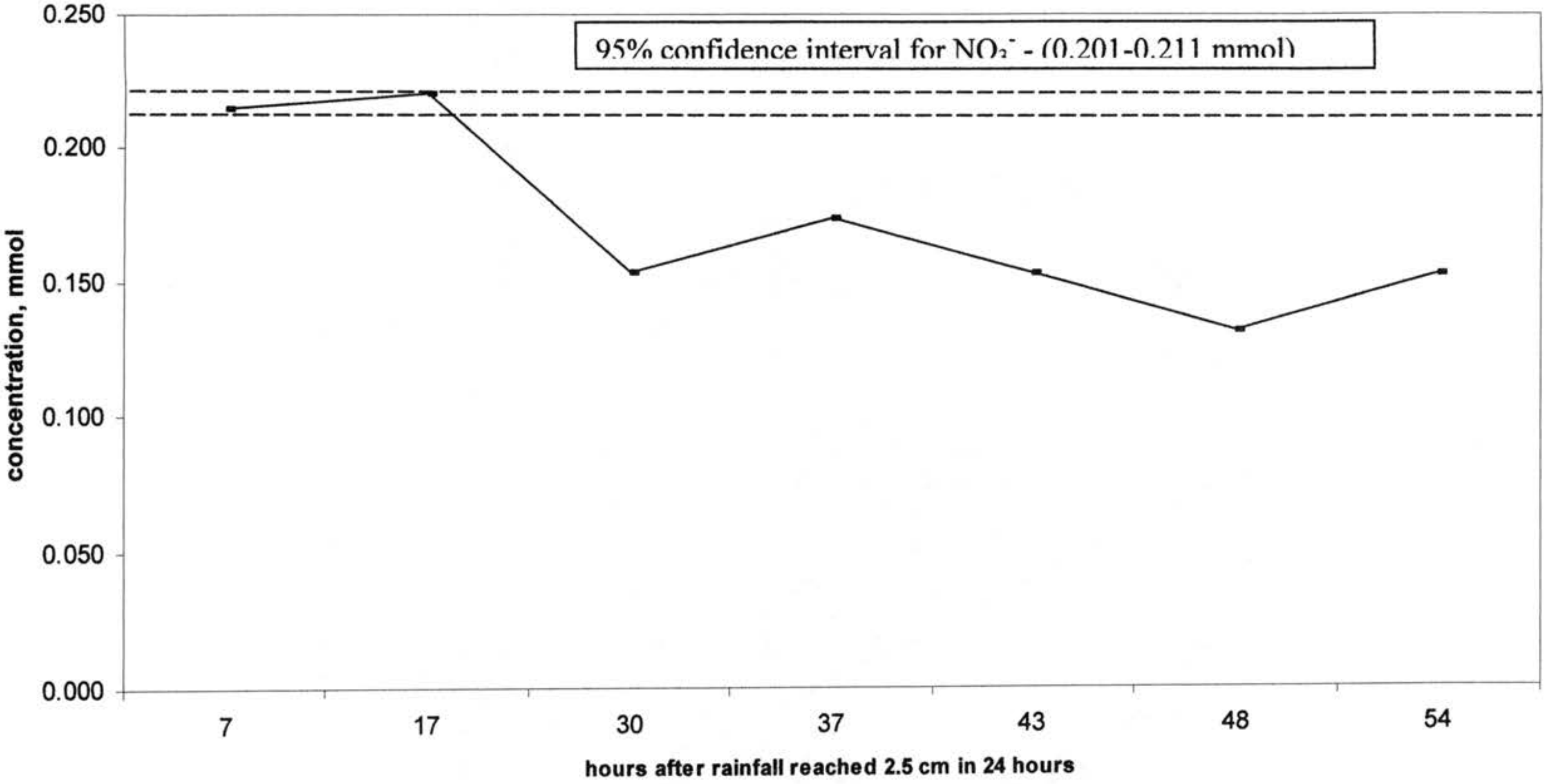

Figure 23. Concentrations of NO_3^- in water from the aquifer associated with well A3 after Rainfall event 3

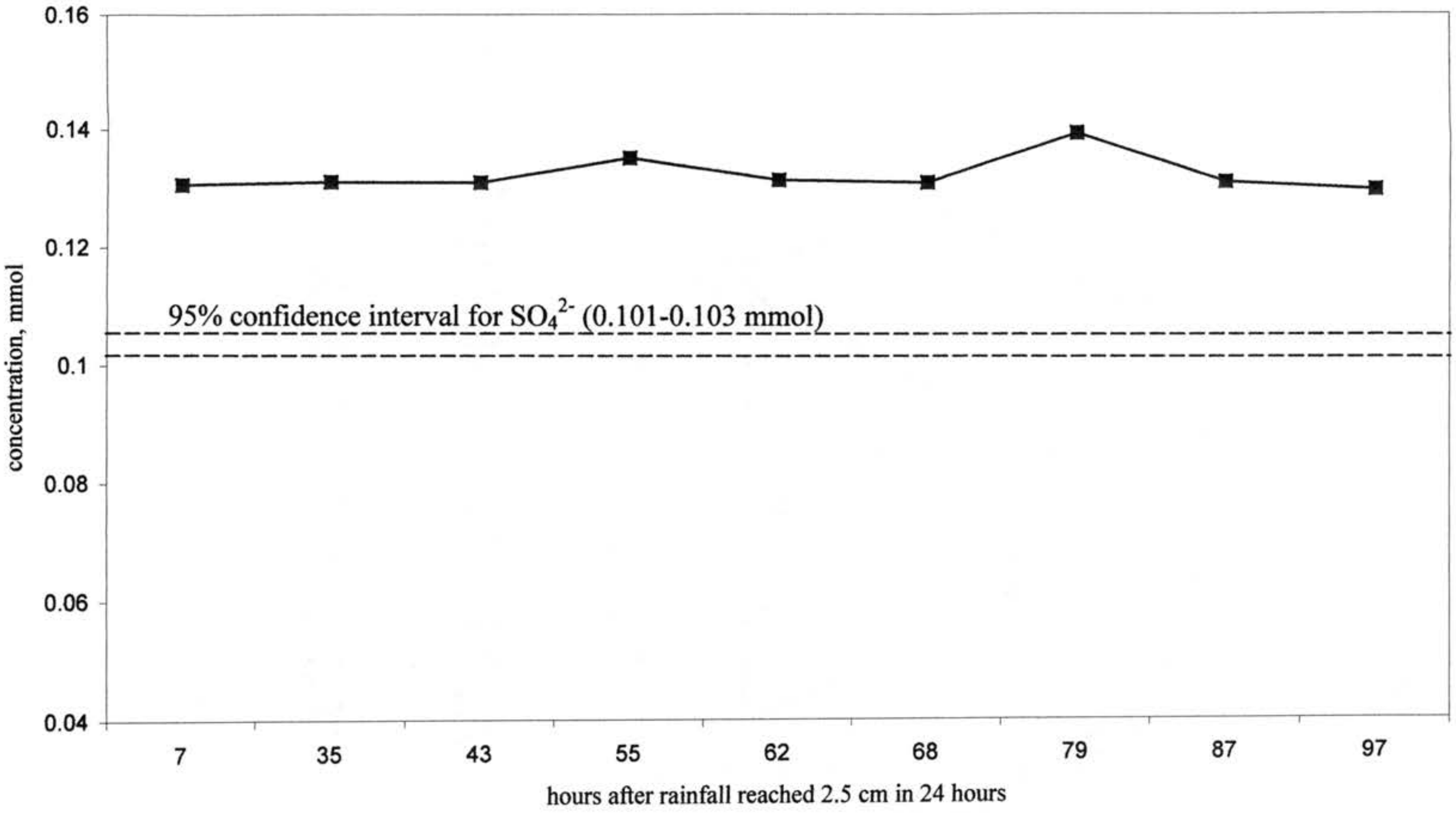

Figure 24. Concentrations of SO_4^{2-} in water from the aquifer associated with well D5 after Rainfall event 1.

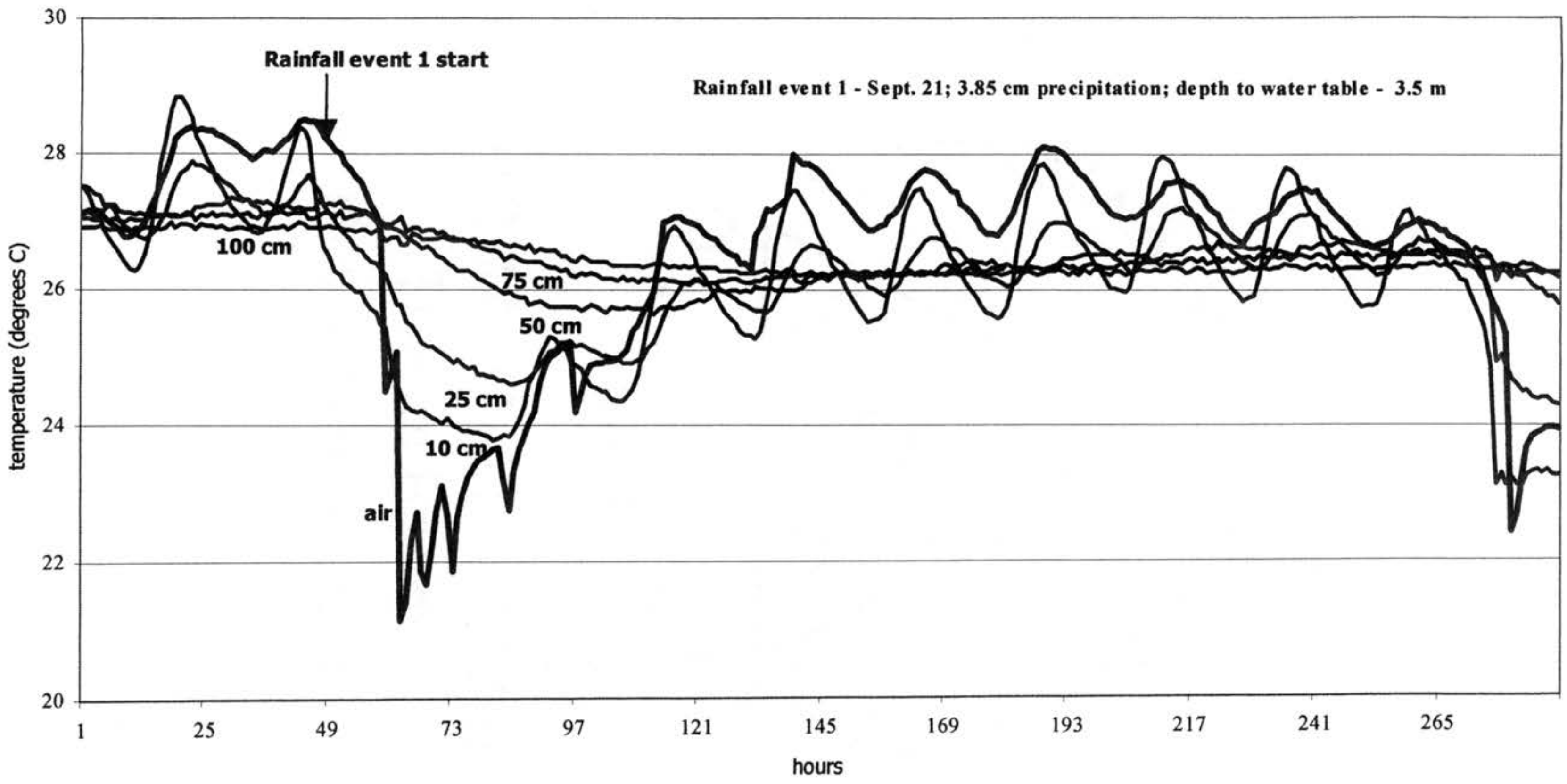

Figure 25. Temperature changes in the shallow part of the aquifer associated with Rainfall event 1

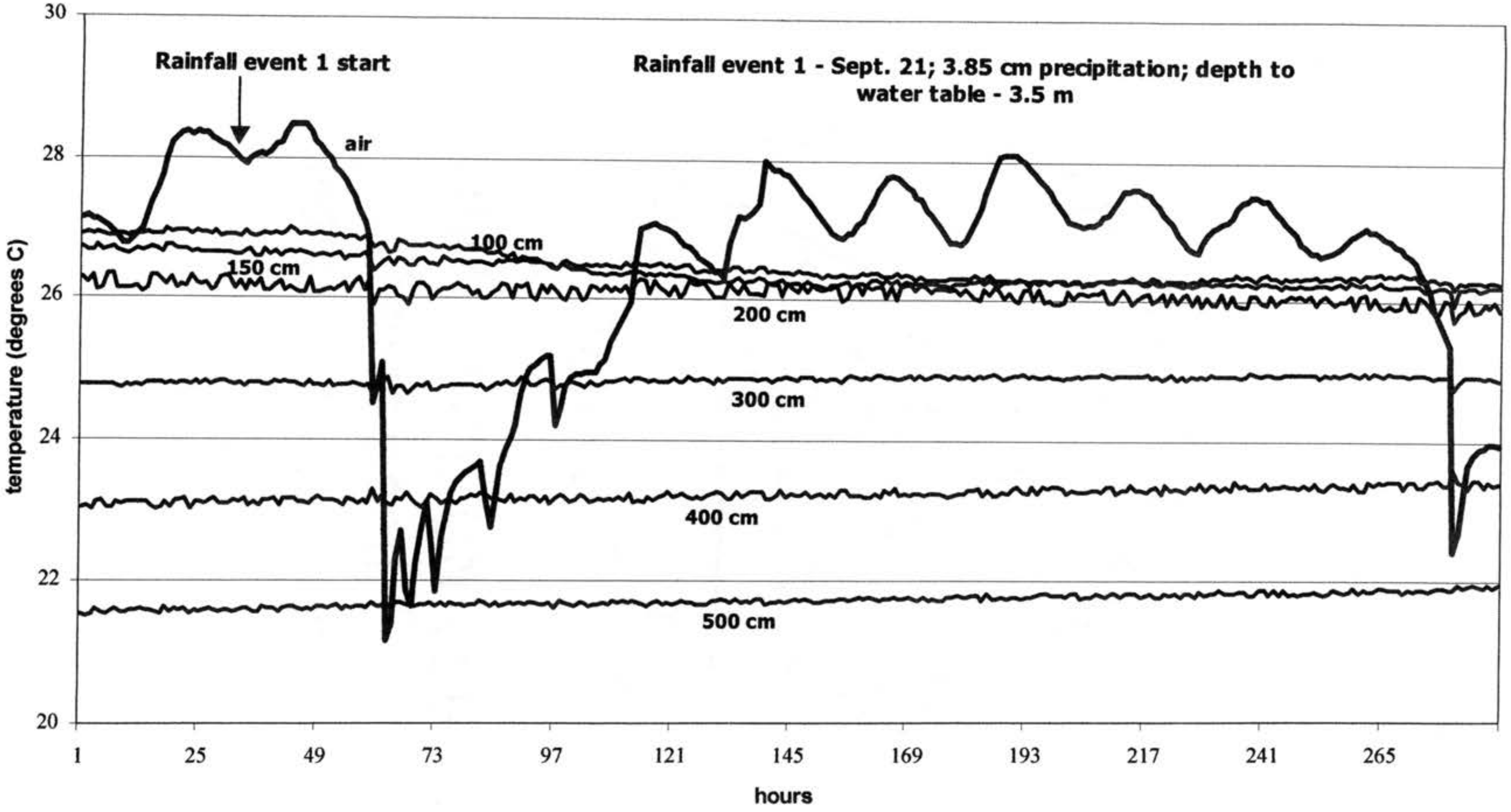

Figure 26. Temperature changes in the deeper part of the aquifer associated with Rainfall event 1

Rainfall event 1 and the maximum declination in temperature at 50 cm was slightly more than 1°C about 55 hours after rainfall reached 2.5 cm (Fig. 25). Maximum decreases in temperature at 75 and 100 cm were <1°C about 65 hours after rainfall reached 2.5 cm (Fig. 25). Responses of temperatures in the upper part of the aquifer lasted ~90 hours (Fig. 25). Changes in temperature in the aquifer below 100 cm in response to Rainfall event 1 were difficult to identify (Fig. 26).

Rainfall event 2 affected the aquifer to a depth of at least 300 cm (Fig. 27). Temperatures to 150 cm in the aquifer responded to Rainfall event 2 soon after the rainfall reached 2.5 cm (Fig. 27). Responses at 200 and 300 cm in the aquifer started ~12 hours after responses began higher in the aquifer (Fig. 27). Rainfall event 2 affected temperatures the greatest at depths of 100 and 150 cm with maximum declinations of ~2.5° C occurring ~15 hours after the start of the event (Fig. 27). Maximum declinations observed at other depths in the aquifer were between 1 and 2° C (Fig. 27) and duration of the effects of Rainfall event 2 on the temperatures in the aquifer was ~24 hours at most of the observed depths (Fig. 27). Decrease in temperature at 300 cm in the aquifer reached a maximum of <1° C about 20 hours after rainfall in event 2 reached 2.5 cm (Fig. 27).

Rainfall event 3 affected temperatures to at least 150 cm deep in the aquifer (Fig. 28). Observed effects of Rainfall event 3 on temperature in the aquifer did not last long (Fig. 28). Responses at all observed depths started ~8 hours after Rainfall event 3 reached 2.5 cm (Fig. 28). Maximum decrease in temperature in the aquifer in response to Rainfall event 3 of ~1° C occurred at 100 cm and lasted ~4 hours (Fig. 28).

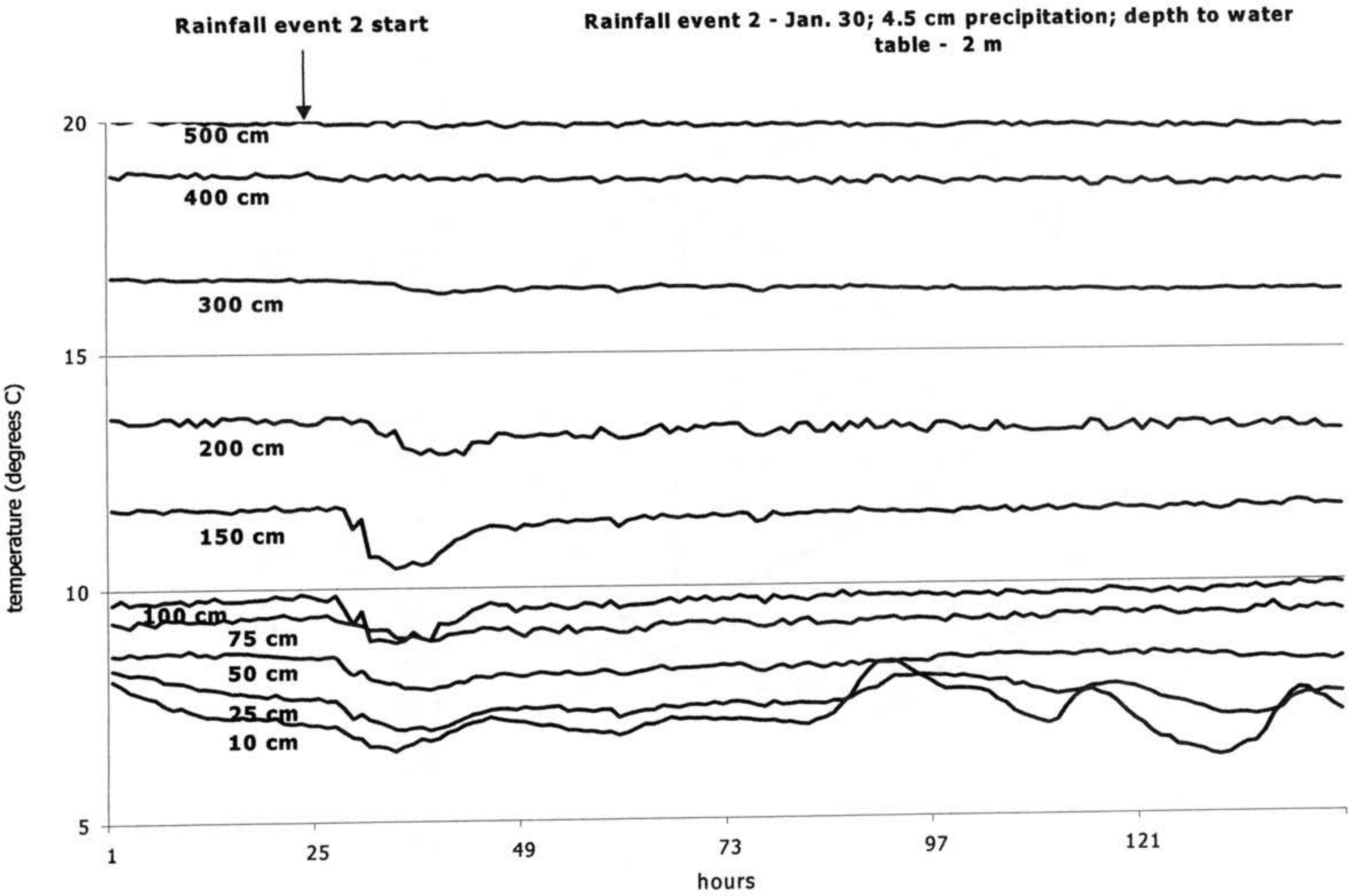

Figure 27. Temperature changes in the aquifer associated with Rainfall event 2

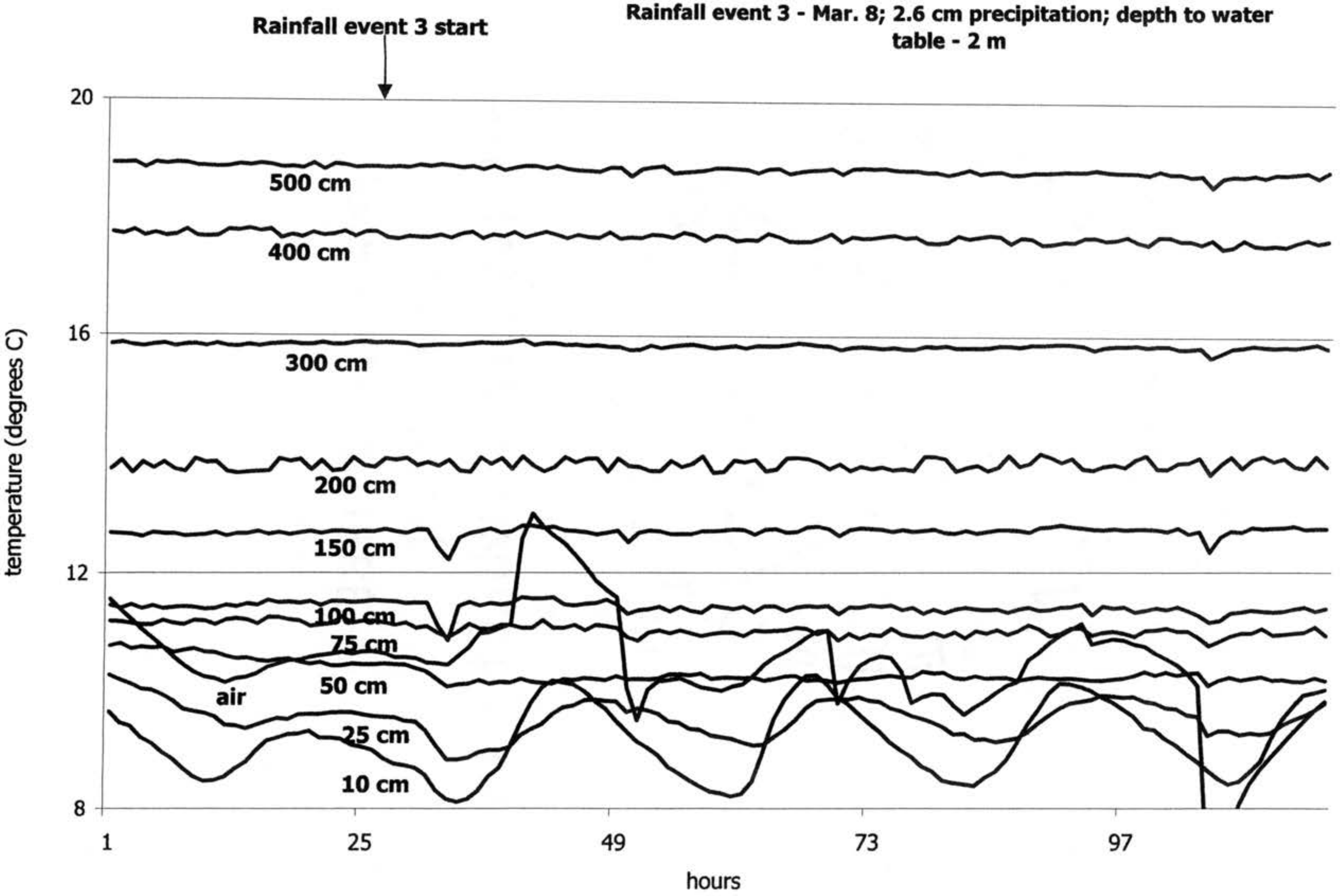

Figure 28. Temperature changes in the aquifer associated with Rainfall event 3

Conclusions

Rainfall events affected the chemistry of the water in the aquifer and temperatures within the aquifer. Temperature changes in the aquifer lasted from four to ~100 hours, depending on the rainfall event. Dry soil conditions, associated with greater depth to the water table (3.5 m deep), extended the duration of the effect of the rainfall on the temperatures of the aquifer (Rainfall event 1). Under moister soil conditions, associated with an elevated water table (2 m deep), the amount of rain in the event affected depth, duration, and degree of temperature changes in the aquifer associated with the rainfall (Rainfall events 2 vs. Rainfall event 3). The increased rainfall associated with Rainfall event 2 (~4 cm) caused maximum temperature declinations in the aquifer to be larger, affected temperatures deeper in the aquifer, and affected temperatures for a longer period of time compared to the amount from Rainfall event 3 (2.5 cm). Concentrations of ions in samples of water taken from the aquifer during the final sampling interval for each Rainfall event (105, 127, and 54 hours after precipitation exceeded 2.5 cm in a 24 hour period for Rainfall events 1, 2, and 3, respectively) deviated from 95% confidence intervals.

Results of this study indicate monitoring of temperatures within aquifers could benefit evaluation and cleanup of contaminated, unconfined aquifers. Rainfalls exceeding 2.5 cm in a 24-hour period cause changes in temperature with depth within the aquifer used in this study. Rainfalls of such intensity affect chemistry of the water in the aquifer for longer durations than effects of the rainfall on temperatures within the aquifer. Guidelines for sampling of unconfined aquifers after rainfalls based on temperatures within the aquifers result in less misinterpretation of chemistry of water in aquifers and improved identification and remediation of contaminated, unconfined aquifers.

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APPENDIXES

APPENDIX A—ABSTRACT FOR CHAPTER 1- DISPERSION IN SOILS OF SEMIARID AND SUBHUMID AREAS OF OKLAHOMA

Dispersion of 103 tested horizons ranges from 0 to 96 %. Comparisons of properties of 31 not-to-weakly-dispersed (<30% dispersion by the double hydrometer method), 30 moderately dispersed (30 to 65% dispersion), and, 42 strongly dispersed (>65% dispersion) horizons indicate multiple influences on dispersion. Many soil properties, including bulk density, sodium adsorption ratio (SAR), electrical conductivity (EC), pH, % clay, % organic matter, ratio of the charge of chloride ions to charge of sulfate ions in soil water, and ratio of charge of sodium ions to sum of the charges of sodium and calcium ions in soil water influence amounts of dispersion occurring in the soils. Dispersion increased as the amount of illite in the clay fraction increased in the soils. Critical or threshold sodium adsorption ratios for identification of dispersed soils calculated from EC, SAR, and % dispersion data are 4.5 for weakly saline (EC<1 dS/m) and 7.9 for moderately saline (EC from 1 to 9 dS/m) soils. Diagnostic SAR values identified are alternatives to existing diagnostic values for identification and management of dispersed soil in semi-arid and sub-humid regions.

APPENDIX B—ABSTRACT FOR CHAPTER 2-SELECTED AMENDMENTS FOR REDUCING SOIL DISPERSION

Dispersion of soil causes deterioration and failure of bridges, dams, and roads. Dispersion occurs in soils containing clays with cation exchange complexes affected by sodium ions. Sodium adsorption ratios (SAR values) of saturated paste extracts of soils identify soils affected by sodium. Amendments can reduce soil dispersion and SAR. Addition of gypsum, hydrated lime, cement kiln dust, fly ash, calcium chloride, sulfuric acid, and humate to dispersed soil horizons from profiles across Oklahoma enabled analyses of the effectiveness of the amendments in lowering SAR values of dispersed soils. Amended horizons have SAR values between 7.7 and 32.5, electrical conductivity (EC) between 0.6 and 6.8 dS/m, and amounts of dispersion (measured by the double hydrometer method) between 3 and 81%. Measurements of SAR and EC of saturated paste extracts from addition of amendments to ~250 g of soil, mixing, and overnight equilibration of the pastes reveal the effectiveness of the amendments. Criterion for the evaluation of amendments are: 1) diagnostic SAR values determined from SAR. EC, and % dispersion of subsoil horizons of the study and 2) a standard diagnostic SAR value (12) for soils in the U. S. Diagnostic SAR values (remediation goals) developed from properties of subsoils sampled for the study are 4.5 for weakly saline (EC<1.0 dS/m) and 7.9 for moderately saline (EC 1.0 to 9.0 dS/m) horizons. Treatments with fly ash (11.2 and 22.4 Mg/ha), gypsum (11.2, 22.4, and 224 Mg/ha), hydrated lime (11.2, 22.4, and 224 Mg/ha) , cement kiln dust (11.2, 22.4, and 224 Mg/ha), humate (11.2 and 22.4 Mg/ha), and calcium chloride (11.2 Mg/ha) successfully reduced SAR values of extracts from several treated horizons below the U.S. standard diagnostic SAR value. A large

decrease occurred in the number of treatment/horizon combinations with SAR values below standard diagnostic values developed from subsoil horizons of the study (fly ash – 3, gypsum – 9, hydrated lime – 4, cement kiln dust – 4, humate – 2, and calcium chloride – 2 of a total possible 105 combinations). Amendments lowered SAR values of soils with EC values ~1.0 dS/m affected by weak and moderate dispersion (20 to 65 % by the double hydrometer method) most successfully. Treatment success diminished much in moderately saline soils affected by strong dispersion. Results of the study indicate greater application rates and/or multiple treatments at common tested rates are necessary for successful remediation of moderately saline soils affected by strong dispersion.

APPENDIX C—ABSTRACT FOR CHAPTER 3- FLUCTUATIONS OF TEMPERATURE AND CHEMISTRY OF WATER WITH RAINFALL IN AN UNCONFINED AQUIFER

Identification and remediation of contaminated, unconfined aquifers will continue to be a world problem. Monitoring of temperatures of aquifer materials is simple and not time-consuming using thermocouples and dataloggers. Collection of large amounts of temperature data is inexpensive. This study evaluated relationships of fluctuation in temperature of aquifer materials and chemistry of water in the aquifer after significant rainfalls (>2.5 cm in 24 hours). Collection of temperature data was by thermocouples at 10 depths between 10 and 500 cm and a datalogger. Ten sample wells, slotted between 2 and 5 m supplied samples of water from the aquifer for analyses. Chemical characteristics of the water measured by ion chromatography included concentrations of F^-, Cl^- Br^-, NO_3^-, and SO_4^{2-}. Results from three separate rainfalls showed response of temperature of aquifer materials to the rainfalls. Rainfalls affected temperatures as deep as 300 cm. Duration of responses lasted between 4 and 100 hours. Lags in temperatures in response to rainfall occurred with depth in the aquifer. Concentrations of ions in samples of water from the aquifer fell outside 95% confidence intervals for the ions more than 100 hours after rainfall exceeded 2.5 cm. Guidelines for sampling of aquifers developed using temperature data from aquifer materials result in fewer analytical misinterpretations of water chemistry and improved identification and remediation of unconfined aquifers.

VITA2

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