Water Retention, Bulk Density, Particle Size, and Thermal and Hydraulic Conductivity of Arable Soils in Interior Alaska

Brenton S. Sharratt
Soil Physicist, Agricultural Research Service

Agricultural and Forestry Experiment Station
School of Agriculture and Land Resources Management
University of Alaska Fairbanks

Bulletin 83

October 1990

Water Retention, Bulk Density, Particle Size, and Thermal and Hydraulic Conductivity of Arable Soils in Interior Alaska

Introduction

The relative proportion of liquid, gas, and solid as constituents of soil depends on factors such as climate, biological activity, and management practices. Therefore, the physical state of soil is a dynamic process, changing with time and position in the profile. Temperature, thermal and hydraulic conductivity, density, and water content are some quantitative properties characterizing the physical state of soil. These properties are important in describing soil processes such as water and heat flow, movement of chemicals, biological activity, and erosion.

Water in the soil is subject to a number of forces resulting from the attraction of the soil matrix for water and presence of solutes and gravity. The energy status of water—the sum of these forces—is termed water potential. Processes such as evaporation and plant water uptake are governed by the gradient in water potential in the soil and across the root-soil interface, respectively. The term *water potential* is more descriptive of the soil water status than *water content* as movement of water is in response to differences in water potential.

Water potential can be measured directly using thermocouple psychrometers or filter paper, among other methods (Campbell and Gee, 1986). Equipment to measure water potential is generally expensive and is often imbedded in the soil prior to measurement. Thus, the measurement may be site specific. An indirect method utilizes the water characteristic curve (relationship between soil water potential, or negative suction, and water content) to estimate water potential (Hillel, 1982). The method allows for the rapid and spatially measured determination of water content, which is related to water potential by a power function (Bruce and Luxmoore, 1986). One form of the power equation (Campbell, 1985) is:

$$\psi = \psi_e \times (\theta/\theta_s)^{-b}$$

where ψ is water potential at volumetric water content θ, ψ_e is the air entry water potential, θ_s is the saturated volumetric water content, and b is the slope estimate of the log normal water characteristic curve. The ψ_e is the potential at which the largest soil pores begin to drain. The characteristic curve is dependent on pore size distribution and structure at potentials above about -1 bar (Klute, 1986) and on texture at lower potentials (Hillel, 1982).

The water holding capacity of the soil is the difference between the water content at field capacity (about -0.3 bars water potential) and wilting (about -15 bars potential). A water characteristic curve allows for the determination of the soil's water holding capacity, provided a characteristic curve is available for each soil layer differing in texture and structure. Soil survey reports published by the USDA Soil Conservation Service provide information on the water holding capacity of soils, but do not account for site specific management practices such as method of clearing, tillage, and cropping which affect the water holding capacity.

Soil particle size is a parameter that can be used to estimate soil properties such as thermal and saturated hydraulic conductivity (Campbell, 1985). Variations in particle size occur with depth due to sedimentation, erosion, weathering, eluviation, illuviation, and management practices.

Particle size, bulk density, and water characteristic curves are important in simulating heat and water movement through soils. These properties need to be quantified at various depths of agronomically important soils in interior Alaska. The purpose of this report was to assess physical properties for Volkmar and Tanana soils at the University of Alaska Agricultural and Forestry Experiment Stations in Delta Junction and Fairbanks, respectively. This information will aid researchers in water quality and soil-plant-water studies, growers having similar soils in irrigation management to optimize water use efficiency, and engineers in land use planning.

Methods

Soil samples were collected for a Tanana (loamy, mixed, nonacid Pergelic Cryaquept) and Volkmar (coarse-silty over sandy or sandy-skeletal, mixed, nonacid Aeric Cryaquept) series at the Agricultural and Forestry Experiment Stations at Fairbanks and Delta Junction, respectively. The samples were taken from a field which had been in barley production for the previous three years at Fairbanks and eight years at Delta Junction. Tillage practices for those years consisted of a fall and spring disking at Fairbanks and a spring disking at Delta Junction. Fields were cleared for agricultural usage in 1952 at Fairbanks and 1978 at Delta Junction. Organic matter content of the Tanana soil was about 4% and Volkmar soil was 8%.

Data collected from 20 0-5 cm core samples in the Fairbanks field prior to this study were used for estimating the sample size (Petersen and Calvin, 1986) to obtain θ, ψ_e and bulk density within 0.05 cm^3/cm^3, -1.5 bars, and 0.1 g/cm^3, respectively. Five samples were necessary based upon a respective sampling variance of 0.002 cm^3/cm^3, 4.5 bars, and 0.04 g/cm^3 for θ, ψ, and bulk density. Water potential of the core samples was determined using the filter paper method (Hamblin, 1981).

Soil samples for this study were taken following harvest and prior to fall tillage in 1989. Five samples were taken at depths of 2, 6, 14, 22, 52, and 74 cm in the Tanana and Volkmar soils, and at 104 and 134 cm in the Tanana soil. The soil was excavated to the appointed depth. The soil retaining ring (5 cm diameter and 2 cm height) was inserted into the soil, extracted, and transported to the laboratory for analysis.

Soil in the retaining rings was trimmed to establish a planar surface on the top and bottom of the rings. Care was taken to disturb the soil as little as possible to retain the field structure of the sample. The samples were placed on membrane plates and allowed to soak overnight. The plates were placed in a pressure plate extractor and equilibrated at 0.3, 1.0, 5.0, and 15.0 bars pressure. Equilibrium was attained within 24 hours. Following the establishment of equilibrium at each pressure, the samples were weighed. Samples were again allowed to soak overnight on the membrane plate prior to placing in the pressure chamber. Following the pressure plate analysis, the samples were oven dried at 105°C for 24 hours. Data obtained included bulk density and θ at each pressure.

Samples were then processed to determine particle size. The percent sand, silt and clay was obtained following the hydrometer procedure outlined by Gee and Bauder (1986). Briefly, the dispersed samples were placed in sedimentation cylinders and hydrometer readings taken at 0.5, 1, 90, and 1440 minutes. Comparisons of percent sand derived using the hydrometer method and measured by sieving were within five percent.

Results and Discussion

The physical properties of the two soils used in this study were different as evident from bulk density, water retention (Table 1), and particle size (Table 2).

Table 1. Soil water content at various extraction pressures (bars) and bulk density of undisturbed samples from the Tanana and Volkmar series at Fairbanks and Delta Junction, respectively.

Soil series	Depth	Bulk density	Water content at pressure:[1] 0.3	1.0	5.0	15.0	Water holding capacity
	-cm-	g/cm³	------------ cm³ /cm³			-----------	-cm/cm-
Tanana							
	2-4	1.18±.02	0.303±.004	0.192±.005	0.144±.005	0.124±.004	0.18
	6-8	1.21±.02	0.304±.003	0.201±.003	0.159±.003	0.131±.003	0.17
	14-16	1.12±.02	0.279±.003	0.175±.003	0.142±.002	0.124±.003	0.16
	22-24	1.19±.02	0.280±.004	0.194±.003	0.165±.003	0.161±.004	0.12
	52-54	1.42±.02	0.265±.004	0.173±.003	0.137±.003	0.124±.002	0.14
	74-76	1.40±.02	0.188±.004	0.117±.002	0.104±.001	0.091±.003	0.10
	104-106	1.44±.03	0.167±.002	0.112±.002	0.104±.002	0.091±.003	0.08
	134-136	1.27±.03	0.418±.021	0.222±.010	0.146±.007	0.144±.006	0.27
Volkmar							
	2-4	0.84±.01	0.288±.003	0.231±.002	0.219±.002	0.216±.003	0.07
	6-8	0.98±.06	0.301±.002	0.226±.007	0.205±.008	0.199±.008	0.10
	14-16	1.56±.02	0.229±.010	0.144±.010	0.090±.003	0.079±.004	0.15
	22-24	1.50±.01	0.216±.008	0.156±.005	0.115±.001	0.106±.010	0.11
	52-54	1.42±.03	0.302±.011	0.196±.006	0.144±.005	0.130±.008	0.17
	74-76	1.71±.05	0.113±.004	0.071±.002	0.060±.003	0.054±.002	0.06

[1]Mean and standard error of water content and bulk density reported

Table 2. Percent sand, silt, and clay at various depths of a Tanana and Volkmar soil at Fairbanks and Delta Junction, respectively.

Depth -cm-	Percent particle size[1]					
	Tanana			Volkmar		
	sand	silt	clay	sand	silt	clay
2-4	12.5±0.2	73.5±0.5	14.0±0.4	38.6±1.3	54.3±0.8	7.1±0.4
6-8	12.5±0.8	74.6±1.1	12.9±0.3	61.5±4.1	31.3±4.1	7.2±0.1
14-16	22.1±3.2	70.9±2.6	7.0±1.4	58.1±5.9	34.7±5.4	7.2±0.7
22-24	12.9±0.8	75.9±0.7	11.2±0.2	60.8±3.5	34.4±3.3	4.8±0.4
52-54	17.8±4.2	74.5±3.7	7.7±0.8	50.9±5.2	42.3±5.2	6.8±0.5
74-76	25.1±2.7	72.5±2.1	2.4±0.7	88.8±0.5	10.9±0.6	0.3±0.1
104-106	45.2±0.3	52.0±0.8	2.8±0.5			
134-136	4.4±0.9	92.2±0.8	3.4±0.2			

[1]Particle size: sand 0.05-2.0mm, silt 0.002-0.05mm, clay <0.002mm mean and standard error reported.

Bulk density in the upper 25 cm of the Tanana soil was nearly constant at 1.2 g/cm^3. The density increased to 1.4 g/cm^3 at the 50 cm depth. The bulk density of Volkmar soil was about 0.8 g/cm^3 near the surface, with an abrupt change to 1.5 g/cm^3 occurring near 10 cm (tillage depth). Bidlake's (1988) findings were similar for Volkmar soils where the density of no till and conventional till soil was 0.8 g/cm^3 at 6cm and 1.5 g/cm^3 at 18 cm.

Water holding capacity of the two soils differed. For a 50 cm soil profile (corresponding to the approximate rooting depth of barley), the capacity of the Tanana and Volkmar soil was 6.6 and 5.8 cm, respectively. The values listed in Table 1 for the Tanana soil are similar to those reported by the USDA Soil Conservation Service (Schoephorster, 1973) but lower than those calculated from data of Braley (1980). The water holding capacity of the Volkmar soil near the surface (0.1 cm/cm) was lower than those reported for Volkmar soil by the USDA Soil Conservation Service (Schoephorster, 1973) and calculated using data obtained by Braley (1980). These sources indicated a capacity of about 0.2 cm/cm near the surface, but were representative of soils with greater bulk densities (about 1.5 g/cm^3) than found in this study. However, Bidlake's (1988) data indicated a water holding capacity of 0.13 and 0.09 cm/cm at 6 and 18 cm depth, respectively, for soils with similar bulk densities as found in this study.

Textural analysis of the soils indicated a silt loam classification for the Tanana soil. The predominance of silt at 134-136 cm resulted in a silt classification. The Volkmar soil was also a silt loam, but only having that designation near the soil surface. The percentage of sand increased with depth (Table 2), resulting in a sandy loam designation below 6 cm and sandy at 74 cm. The coarse texture below 6 cm was not characteristic of Volkmar soils, those soils having silt loam underlaid by gravelly sand. Although the field was mapped as Volkmar, the soil may be more typical of the Salchaket series (coarse-loamy, mixed, nonacid Typic Cryofluvents) which have sandy loam underlaid by gravelly sand.

The relationship between ψ and θ at different depths for the two soils are given in Table 3. The ψ_e generally increased with depth for the Tanana soil. Higher ψ_e indicated larger soil pores, possibly a result of higher sand or lower clay percentages at deeper depths (Table 2). The b value was fairly constant with depth (about 4.0) except at 134 cm. The smaller b value at 134 cm indicated a narrow pore size distribution, resulting from a high portion of similar soil particles sizes or less structured (aggregated) soil. A high portion of similar particle sizes was evident at 134 cm with 95 per cent silt. A general expression for the water characteristic curve was derived for all depths (except 134cm) due to the similarity in b values, and found to be:

$$\psi = -0.19 \times (\theta/0.52)^{-2.34}$$

where ψ is in bars. Braley's data (using disturbed and repacked soil samples) indicated b values ranging from 3.40 at the surface to 1.81 at 100 cm depth, which are comparable to those listed in Table 3.

Table 3. The relationship between soil water potential (ψ) and water content (θ) expressed as $\psi = \psi_e \times (\theta/\theta_s)^{-b}$ for undisturbed samples from the Tanana and Volkmar series at Fairbanks and Delta Junction, respectively. Parameters for the equation were derived for a ψ range of -0.3 to -5 bars.

Soil series	Depth	ψ_e[1]	b[1]	θ_s[1]
	-cm-	10^{-3} bars		cm^3/cm^3
Tanana				
	2-4	-3.8±2.2	3.58±0.27	0.56±0.02
	6-8	-2.0±1.2	4.12±0.31	0.54±0.02
	14-16	-1.9±1.5	3.87±0.35	0.58±0.02
	22-24	-0.6±1.2	4.83±0.47	0.55±0.02
	52-54	-1.3±0.9	4.03±0.32	0.46±0.02
	74-76	-0.3±0.7	4.04±0.53	0.47±0.02
	104-106	-0.1±0.1	4.81±0.70	0.46±0.03
	134-136	-32.3±12.2	2.48±0.21	0.52±0.03
Volkmar				
	2-4	-0.006±0.03	8.59±1.18	0.68±0.01
	6-8	-0.2±0.6	5.96±0.83	0.63±0.06
	14-16	-4.5±2.1	2.85±0.19	0.41±0.02
	22-24	-1.3±1.8	3.66±0.47	0.44±0.01
	52-54	-4.0±2.4	3.56±0.29	0.46±0.03
	74-76	-0.1±0.1	3.79±0.46	0.36±0.05

[1]Mean and standard error reported.

The ψ_e in the till layer of the Volkmar soil was higher than in the Tanana soil (Table 3). Larger pore sizes resulting from the higher sand content at the surface of the Volkmar soil (Table 2) may contribute to the higher ψ_e. Bidlake (1988) reports ψ_e values of -0.021 bars at 6 cm and -0.028 bars at 18 cm in a Volkmar soil. Large differences are evident between ψ_e values as measured by Bidlake and those empirically derived in this study (Table 3). These differences were minimized when ψ_e was computed using water characteristic data in the -0.3 to -1 bar range, resulting in values of -0.0004 ± 0.0003, -0.003 ± 0.002, and -0.013 ± 0.010 bars for the 2-4, 6-8, and 14-16 cm depths, respectively. The tendency for ψ_e to decrease with depth in the Volkmar soil, as found in this study, indicated larger soil pores closer to the soil surface. Larger soil pores near the surface were not due to higher sand content (sand content increased with depth as indicated in Table 2) but may have resulted from the vertical distribution in organic debris in the soil or from structural differences. Structural differences between the 6-8 and 14-16 cm depths in the soil were evident from differences in bulk density (Table 1).

The b value for Volkmar soil decreased with depth and remained fairly constant below about 10 cm (Table 3). The relationship between ψ and θ at each depth was expressed as:

for the 2-4 cm depth	$\psi = -6.30 \times 10^{-6} \times (\theta/0.68)^{-8.59}$
for the 6-8 cm depth	$\psi = -0.20 \times 10^{-3} \times (\theta/0.63)^{-5.96}$
and for deeper depths	$\psi = -55.9 \times 10^{-3} \times (\theta/0.42)^{-1.52}$

where ψ is in bars. The greater b values at the surface indicated greater variations in pore sizes due to either textural variation or possibly in variation of pore size from organic matter constituents. Within the till layer, the sand fraction increased with depth (Table 3 and Bidlake, 1988) suggesting that pore size variation, and thus b value, decreased with depth. Results of this study support this argument, but neither data of Bidlake (1988) or Braley (1980) indicated a change in b value with depth. Bidlake reported a b value of 1.9 at 6 and 18 cm and the b value calculated from Braley's data was between 3.2 and 4.3. Both studies used disturbed and repacked soil samples. Therefore, the in-situ samples used in this report may have resulted in greater pore size variations due to the retention of soil structure and organic constituents. This would be of particular consequence in the till layer where large amounts of organic material reside in Volkmar soil.

Thermal and hydraulic conductivity of the two unfrozen soils were estimated using the procedure of Campbell (1985). Thermal conductivity was dependent on bulk density, θ, and percentage of clay particles. Hydraulic conductivity was estimated from the silt and clay fraction, θ, bulk density and b value. The estimated thermal

Table 4. Estimated thermal and hydraulic conductivity at various soil water potentials for unfrozen Tanana and Volkmar soils at Fairbanks and Delta Junction, respectively.

Soil series	Depth	Conductivity at water potential: Thermal		Hydraulic		
		-0.3 bar	-15 bar	sat[1]	-0.3 bar	-15 bar
	-cm-	--- W/m °K ---		-------- cm/s --------		
Tanana						
	2-4	0.9	0.5	1.5×10^{-4}	2.7×10^{-7}	2.5×10^{-11}
	6-8	1.0	0.6	1.5×10^{-4}	2.0×10^{-7}	1.7×10^{-11}
	14-16	0.9	0.6	3.8×10^{-4}	1.5×10^{-7}	1.7×10^{-11}
	22-24	0.9	0.8	1.9×10^{-4}	3.8×10^{-8}	3.2×10^{-11}
	52-54	1.1	0.9	9.0×10^{-5}	1.6×10^{-7}	3.2×10^{-11}
	74-76	1.0	0.9	1.6×10^{-4}	7.2×10^{-9}	1.8×10^{-12}
	104-106	1.0	0.9	2.5×10^{-4}	8.8×10^{-10}	2.9×10^{-13}
	134-136	1.2	0.8	1.2×10^{-4}	2.1×10^{-5}	3.4×10^{-9}
Volkmar						
	2-4	0.7	0.6	4.4×10^{-2}	1.5×10^{-9}	5.7×10^{-12}
	6-8	0.8	0.7	7.0×10^{-3}	1.1×10^{-7}	2.6×10^{-10}
	14-16	1.3	0.7	3.4×10^{-4}	2.2×10^{-6}	2.3×10^{-10}
	22-24	1.2	1.0	4.1×10^{-4}	3.2×10^{-7}	2.5×10^{-10}
	52-54	1.2	0.9	3.5×10^{-4}	4.6×10^{-6}	9.7×10^{-10}
	74-76	1.3	1.2	6.8×10^{-4}	2.4×10^{-9}	5.7×10^{-13}

[1]Saturated hydraulic conductivity

conductivity was fairly uniform with depth in the Tanana soil (Table 4). These values agreed well with field-measured thermal conductivity. Conductivity measured using the line heat source probe (Jackson and Taylor, 1986) in the Tanana soil at 5 cm over a range of soil moisture provided the following relationship:

$$k = 0.32 + 2.02 \times \theta$$

where k was thermal conductivity (W/m °K). Field-measured thermal conductivity at field capacity (-0.3 bars) was 0.9 W/m °K and at wilting (-15 bars) was 0.6 W/m °K based on the above relationship. Conductivities (6-8 cm depth) estimated from bulk density and percentage of clay at these water potentials were 1.0 and 0.6 W/m °K, respectively. Comparisons between estimated (Table 4) and measured (Bidlake, 1988) thermal conductivity for the Volkmar soil also indicated good agreement. Measured conductivity at the 6 cm depth at field capacity and wilting was 0.6 and 0.4 W/m °K whereas estimated conductivity at 6-8 cm was 0.8 and 0.7 W/m °K, respectively. Measured conductivity at 18 cm in the Volkmar soil was 1.0 and 0.4 W/m °K at field capacity and wilting whereas the estimated conductivity at 14-16 cm for these water contents was 1.3 and 0.7 W/m °K, respectively.

Estimated saturated hydraulic conductivities at various depths in Tanana and Volkmar soils are listed in Table 4. The conductivity in the Volkmar soil decreased with depth, possibly due to increasing bulk density. Schoephorster (1973) estimated saturated hydraulic conductivity for the Volkmar soil between 0.0006 and 0.002 cm/s. Bidlake (1988) found field-measured saturated hydraulic conductivity at 6 and 18 cm in Volkmar soil to be 0.002 and 0.007 cm/s, respectively. Our findings are similar with conductivities of 0.007 and 0.0003 cm/s at 6-8 and 14-16 cm depths, respectively. Estimated saturated hydraulic conductivity for Tanana soil was approximately 0.0002 cm/s (Table 4). Conductivities reported in Table 4 are comparable to those of soils with similar textural classification (Israelsen and Hansen, 1962).

Conclusions

The Volkmar series represents silt loam soils underlaid by gravelly sand. The Delta field site was mapped as Volkmar, but may possibly be an inclusion of soils in the Salchaket series. The soil profile at the site was predominantly sandy loam underlaid by gravelly sand. This soil would be very susceptible to erosion due to the lack of cohesiveness generally found in sandy loam compared to silt loam soils.

The Volkmar soil was found to have a lower water holding capacity than the Tanana soil, thus crops grown on this soil may be prone to drought in dry years. However, the greater porosity and estimated saturated hydraulic conductivity of the Volkmar soil may allow for better aeration and drainage.

Root growth in the soil profile is limited by many physical factors, including bulk density. High bulk density may limit root exploration below the till layer (10 cm) in Volkmar soil and at deeper depths in the Tanana soil. This physical limitation to rooting may reduce the effective depth of water extraction.

The physical characteristics of soils reported in this study should be used with caution. These characteristics are highly dependent on autonomous factors such as method of clearing land and type of agricultural management practice.

Literature Cited

Bidlake, W.R. 1988. Seed zone temperature and moisture conditions under conventional-till and no-till systems in Alaska. PhD Thesis. Washington State University.

Braley, W.A. 1980. Estimates of evapotranspiration from barley and rapeseed in interior Alaska. MS Thesis. University of Alaska.

Bruce, R.R and R.J. Luxmoore. 1986. Water retention: field methods. In A. Klute (Ed) Methods of soil analysis. Part I. Physical and mineralogical methods. American Society of Agronomy. Madison, Wisconsin.

Campbell, G.S. 1985. Soil physics with BASIC. Elsevier Science Publishers, Inc. New York.

Campbell, G.S. and G.W. Gee. 1986. Water potential: miscellaneous methods. In A. Klute (Ed) Methods of soil analysis. Part I. Physical and mineralogical methods. American Society of Agronomy. Madison, Wisconsin.

Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. In A. Klute (Ed) Methods of soil analysis. Part I. Physical and mineralogical methods. American Society of Agronomy. Madison, Wisconsin.

Hamblin, A.P. 1981. Filter paper method for routine measurement of field water potential. J. Hydrol. 53:355-360.

Hillel, D. 1982. Introduction to soil physics. Academic Press, Inc., Orlando, Florida.

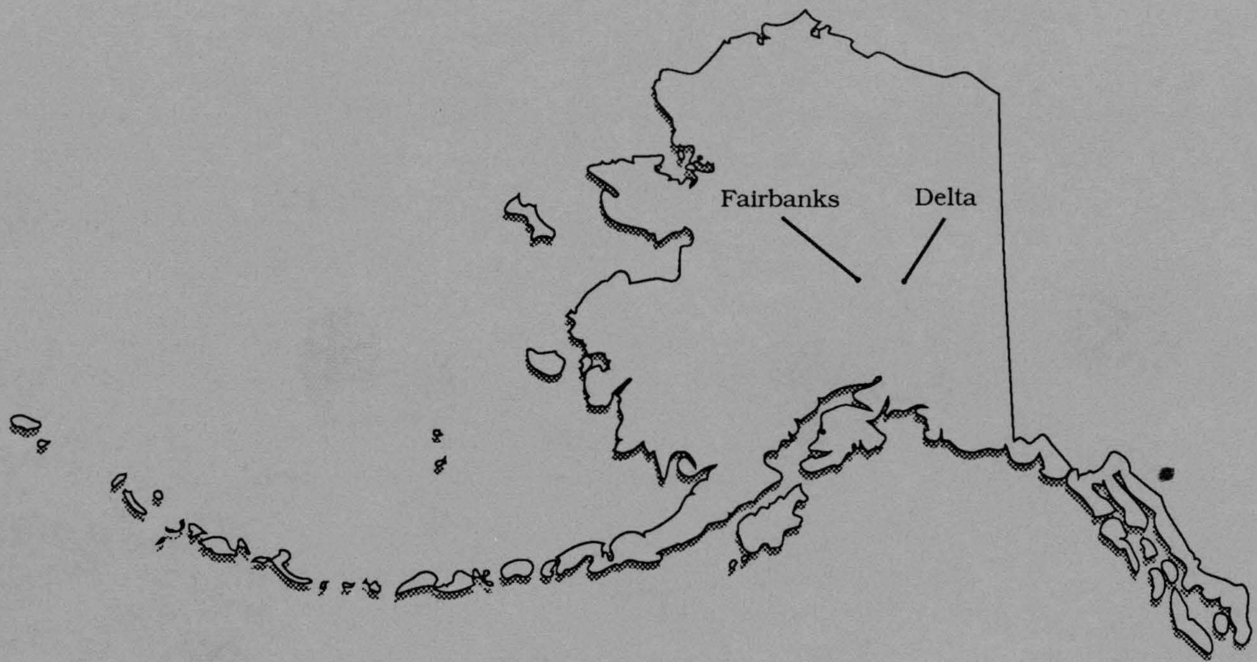
Israelsen, O.W., and V.E. Hansen. 1962. Irrigation principles and practices. John Wiley and Sons, Inc. New York.

Jackson, R.D. and S.A. Taylor. 1986. Thermal conductivity and diffusivity. In A. Klute (Ed) Methods of soil analysis. Part I. Physical and mineralogical methods. American Society of Agronomy, Madison, Wisconsin.

Klute, A. 1986. Water retention: laboratory methods. In A. Klute (Ed) Methods of soil analysis. Part I. Physical and mineralogical methods. American Society of Agronomy, Madison, Wisconsin.

Petersen, R.G. and L.D. Calvin. 1986. Sampling. In A. Klute (Ed) Methods of soil analysis. Part I. Physical and mineralogical methods. American Society of Agronomy, Madison, Wisconsin.

Schoephorster, D. 1973. Soil survey of Salcha-Big Delta area, Alaska. U.S. Department of Agriculture, Soil Conservation Service, Government Printing Office.



Agricultural and Forestry Experiment Station
School of Agriculture and Land Resources Management
University of Alaska Fairbanks
James V. Drew, Dean and Director