Erosion and Productivity of Soils Containing Rock Fragments

SSSA Special Publication Number 13

Proceedings of a symposium
sponsored by Divisions S-5 and S-6
of the Soil Science Society of America
in Anaheim, Calif., 28 Nov.–3 Dec. 1982.

Editorial Committee	**Organizing Committee**
J. D. Nichols	J. E. Box, Jr., Chm.
P. L. Brown	P. L. Brown
W. J. Grant	

Managing Editor
David M. Kral

Assistant Editor
Sherri L. Hawkins

1984
Published by the
SOIL SCIENCE SOCIETY OF AMERICA
677 South Segoe Road
Madison, WI 53711

EXHIBIT
94

Cover Design: Julia L. McDermott

Soil Science Society of America
677 South Segoe Road, Madison, WI 53711 USA

Library of Congress Catalog Card Number: 84-50174.
Standard Book Number: 0-89118-773-1.

Printed in the United States of America

Chapter 10

Physical Properties of Rock Fragments and Their Effect on Available Water in Skeletal Soils[1]

ALAN L. FLINT AND STUART CHILDS[2]

Extensive research is currently being conducted to quantify the Physical environment for reforestation in southwest Oregon. This effort was stimulated by a history of reforestation failures which are generally assumed to be due to heat or drought stresses. The Mediterranean climate of the region has high summer evapotranspiration (ET) demands and there is little water available other than that stored in the soil. Since almost 60% of the federal lands mapped in the area are classified as skeletal (de Moulin et al., 1976; Wert et al., 1977), a study was initiated to assess the available water supplies of these soils.

Several general properties of skeletal soils make measurement of soil water properties challenging. Previous studies have shown that rock fragments can hold substantial quantities of water which are available to plants (Coile, 1953; Hanson and Blevins, 1979). Soil layering also affects water supply in skeletal soils. It has been observed that genetic or depositional layers increase water retention (Clothier et al., 1977). This is particularly important for skeletal soils which have irregular layers, voids,

---

[1] Oregon Agric. Exp. Stn. Technical Paper no. 6830. Contribution of the Dep. of Forest Engineering and the Dep. of Soil Science, Oregon State Univ., Corvallis, OR. Financial support for this research was provided by the USDI Bureau of Land Management and USDA Forest Service under the auspices of the Southwest Oregon Forestry Intensified Research (FIR) Program (Grant No. PNW-80-85).

[2] Graduate research assistant and assistant professor of soil science, respectively. Dep. of Soil Science, Oregon State Univ., Corvallis, OR 97331.

Erosion and Productivity of Soils Containing Rock Fragments.

and weathering rinds around individual fragments which affect water flow and storage. A third factor is the large spatial variability in rock fragment content of skeletal forest soils (Flint and Childs, 1983). This variability should be characterized in order to evaluate water supply at a specific site. The properties of skeletal soils mentioned here were deemed sufficiently different from the properties of common agricultural soils so that a study of their interrelations and behavior was required.

The major objectives of this research were to (1) Quantity available water supply and other soil physical properties for 40 soils in southwest Oregon and (2) Identify field and laboratory techniques for measurement of water supply of skeletal soils for specific sites or estimation of water supply for planning purposes.

DEFINITION OF AVAILABLE SOIL WATER

The study presented here was designed and performed in order to provide information for forest land managers in a region of summer heat and drought stress. Available soil water was defined in a manner suitable for use in management decisions. The total soil water available per unit volume is the amount which can be stored in the root zone after drainage has reached a negligible rate minus any water which remains in the soil root zone at the driest part of the year. This amount plus any rain which falls during the growing season is the total available. This total amount is important in the skeletal soils of this region for two reasons. First, seedling survival depends on spring and early summer water use for shoot and root growth, budset, and onset of midsummer dormancy to withstand late summer heat stress events and evantual winter cold. Low water-holding capacity in skeletal soils can be deleterious if a water supply adequate for seedling budset and dormancy is not available. The second important factor is the ameliorating effect water can have on heat stress events. The higher heat capacity of water allows moist soils to receive higher radiation loads without excessively increasing soil surface temperature. This can be particularly beneficial during short or diurnal heat stress events.

In reforestation planning, total available water is compared to estimated seedling water use plus the amount of water required for protection from heat stress. If the water supply is not sufficient, site modifications such as soil mulches, artificial shade, and control of competing vegetation can be considered for water conservation.

MATERIALS AND METHODS

A major factor to consider in designing an experiment with skeletal soils is the relative fragility of their structure. Although mechanical strength may be quite high, excavation of undisturbed soil monoliths or cores is quite difficult. For the soils of southwest Oregon, Flint and Childs (1983), found that cores 76 mm in length and diameter provided accurate measurement of rock fragment content and fine soil density when rock content was less than 15% by volume. In rockier soils, excavation techniques which sample larger volumes were required. As a result, effects of soil structure on soil water retention are difficult to assess with laboratory measurements.

For this study, we felt it was important to do the following:

1. Develop a simple field method to measure available soil water.
2. Use a technique to measure rock fragment content with sample volume large enough to include fragments up to 160 mm in effective diameter.
3. Separate soil water content into two fractions: water retained in the fine earth and water retained in the rock fragments. This separation allows correction of small volume samples to reflect the average site proportions of fine earth and rock fragments.
4. Distinguish between fine and total soil density for assessment of the soil's available water capacity.
5. Assess the range in rock fragment properties (particularly porosity and density) for the dominant rock types of southwest Oregon.

Forty sampling locations were selected in southwest Oregon covering nine soil parent materials and rock fragment percentage ranging from 3 to 57. Fourteen of the sampling sites were located near the model profiles of the soil series. Parent materials were selected to cover the range found in southwest Oregon. These included granite, basalt, meta-sediment, alluvium, and volcanic ash with pumice. At each location three representative points were sampled for field bulk density (BD_t) and rock fragment content. Samples were taken from the surface to 250 mm depth to provide information about the seedling root zone. In most cases, this was not the taxonomic control section. A large volume bulk density sample (0.001 m^3) was collected using a bead cone (Flint and Childs, 1983) with the excavated soil placed in a plastic bag for laboratory analysis. Duplicate moisture can samples were also taken at each point for laboratory analysis. The sampling was done in late August and early September, which would yield the lowest seasonal water content.

A separate sampling site was selected in close proximity to the other three points to estimate field capacity water content. A plastic cylinder was placed over a 0.65 m^2 area and filled with water to a depth of 0.15 m. After the water infiltrated into the soil, the cylinder was removed and the soil surface was covered with plastic to prevent evaporation. Between 2 and 3 days later, duplicate field capacity moisture samples were taken for laboratory analysis (Salter and Williams, 1965).

In the laboratory, bulk density samples were sieved through a 2 mm screen to measure gravimetric rock fragment content (R_m). A sample of the rock fragments, between 2 and 4.75 mm, was used to determine particle density using a water pycnometer (Blake, 1965). Air bubbles were removed from the rock fragment pores by placing the rock fragment particles in water and under a vacuum. The saturated samples were removed from the pycnometer and rolled in a damp towel to remove surface water, leaving the pores saturated (A.S.T.M., 1977). Oven-dry weight loss of the sample is a measure of the volume of water in pores, which, at saturation, was the pore volume. The bulk density of the rock fragments ($BD_{>2}$) was then calculated using particle density ($PD_{>2}$) and porosity ($P_{>2}$).

$$BD_{>2} = (1 - P_{>2}) \cdot PD_{>2}. \qquad [1]$$

The volumetric rock fragment content (R_v) was then calculated for the bulk soil samples:

$$R_v = BD_t \cdot R_m / BD_{>2}. \qquad [2]$$

The bulk density ($BD_{>2}$) was used, rather than the particle density, to calculate volumetric rock fragment content in order to include the volume of the pores within the volume of rock fragments. Exclusion of the pores by using particle density would have yielded an artificially low volumetric rock fragment content and underestimated fine soil density. Fine soil density ($BD_{<2}$) was calculated as:

$$BD_{<2} = BD_t (1 - R_m)/(1 - R_v). \qquad [3]$$

The soil moisture samples were oven dried and sieved to determine rock fragment content. The water removed from the sample was partitioned into two different components; water contained in $<$ 2 mm soil and water contained in rock fragments (Berger, 1976). Water retention of rock fragments is distinctly different from the $<$ 2 mm soil and, given the high variability of rock fragment content in the small moisture samples, it was critically important to separate the two components. Ideally the rock fragments should have been sieved and measured separately; however, this was quite difficult if samples were wet or clayey. There could also be considerable water loss, especially for the field capacity sample, during the process of sieving. If the soil could not be sieved, then an estimate of water held by the rock fragments was made using an alternate procedure. Using data from several authors (Cochran[3]; Coile, 1953; Hanson and Blevins, 1979), a water release curve for rock fragments was developed to predict pore saturation percentage (S) of the rock fragments depending on their water potential (Fig. 1). The pore saturation percentage multiplied by the total porosity of the rock fragments ($P_{>2}$) gave the volumetric water content of rock fragments ($W_{>2}$). The water release curve for rock fragments was used in conjunction with a measurement or estimate of water potential to estimate the rock fragment water content at the time of sampling.

Once rock fragment water content was determined using one of the techniques above, the fine soil gravimetric water content ($W_{m>2}$) was determined from the moisture can samples using Eq. [4]:

$$W_{m<2} = (W_{mt} - W_{>2} \cdot R_{ms})/(1 - R_{ms}), \qquad [4]$$

where W_{mt} is the total sample gravimetric water content and R_{ms} is the gravimetric rock fragment content of the moisture sample can.

---

[3] Cochran, P. H. 1966. Heat and moisture transfer in a pumice soil. Doctoral Diss. Department of Soil Science, Oregon State Univ., Corvallis, OR 97331.

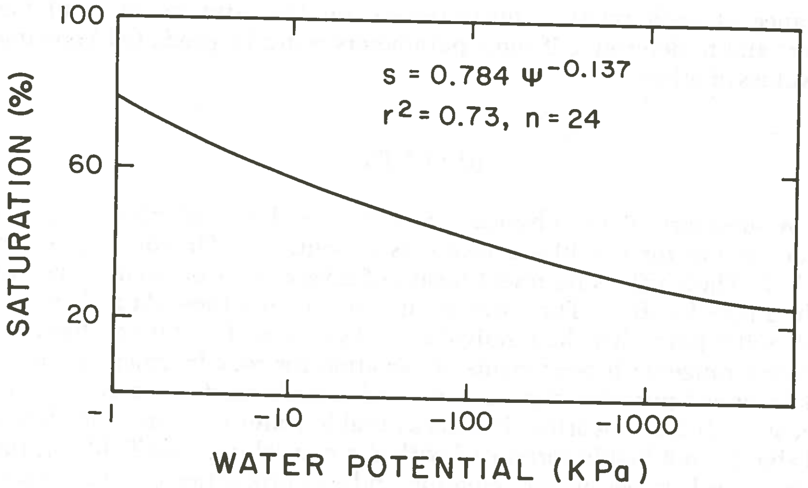

Fig. 1. Water release curve for rock fragments 2.0 to 4.75 mm in diameter.

The volumetric water content of the whole soil (W_{vt}) was calculated using the two partitioned water contents from the moisture samples and techniques above, the fine soil gravimetric water content ($W_{m<2}$) was determined from the moisture can samples using:

$$W_{v<2} = W_{m<2} \cdot BD_{<2} \cdot (1 - R_v), \qquad [5]$$

$$W_{v>2} = W_{>2} \cdot R_v, \text{ and} \qquad [6]$$

$$W_{vt} = W_{v<2} + W_{v>2}. \qquad [7]$$

The two fractions are added together in Eq. [7] to give total volumetric water content. Average rock fragment content and fine bulk density of the large bulk samples were used to calculate total water content rather than the data obtained from small moisture cans. This technique allows the higher variability of rock fragment content in small moisture cans to be corrected for (Reinhart, 1961).

At 19 of our 40 locations, a tensiometer was used to measure water potential at field capacity when early spring water samples were collected. These measurements showed the water potential at field capacity to vary from −2 to −14.5 kPa (Table 1). At the other 21 locations we assumed the water potential at field capacity to be −10 kPa in order to calculate water content of the rock fragments from the equation in Fig. 1. At all 40 locations the seasonal low water potentials were assumed to be −3000 kPa. These assumptions were made after considering the sensitivity of predictions to these arbitrary water potential values. The range of rock fragment field capacity water content was 6% over the measured range of −2 to −14.5 kPa (Fig. 1). The range in seasonal low water content was 2.5% between −1500 and −6000 kPa.

The technique outlined above was used to calculate volume average available water. The data gathered were analyzed to determine the importance of each physical measurement on the estimate of available water, and to determine if some parameters could be predicted knowing the values of others.

RESULTS

A summary of the physical properties used for calculation of soil water content for the 40 soil locations in southwest Oregon is given in Table 1. These values represent means of several measurements taken at each sample location. The correlations drawn from these data therefore relate soil types rather than individual soil samples. The data set has considerable range with coefficients of variation for rock fragment content, rock fragment porosity, clay content, and organic matter content greater than 40%. It is noteworthy that the available water measurement shown in Table 1 is not highly correlated with any one column (see Table 2); the relationship between water retention and soil properties is not straightforward in skeletal soils.

Linear correlations were performed for all measured variables (Table 2) to determine the relationships among various soil properties. These results show a number of low correlations. This was expected due to the range of parent materials and the fact that the data set consists of means for each soil rather than individual data points. It is of interest that total bulk density has a low correlation with rock fragment content (r^2 = 0.18, Table 2). At best, total density was only marginally correlated with rock fragment bulk density, rock fragment porosity, and particle density (r^2 = 0.54, 0.48, and 0.36, respectively, Table 2). Apparently, the porosity of the rock fragments is as important in determining total soil density as total volume when the population consists of soils high in rock fragments. Fine soil density also correlated marginally with total soil density (r^2 = 0.48, Fig. 2). These two results are not surprising, since the theoretical relationship between fine soil density and total bulk density is as follows:

$$BD_t = BD_{<2} + (BD_{>2} - BD_{<2}) \bullet R_v, \qquad [8]$$

which shows a complex interrelationship rather than a single important factor.

A significant factor in total bulk density and water content is the bulk density of the rock fragments. Their bulk density, which is related to particle density with a positive correlation r^2 = 0.77 (Fig. 3), accounts for the effect of natural porosity included in rock fragments. An increase in particle density yields an increase in bulk density and therefore a decrease in rock fragment porosity.

Rock fragment porosity is also important to water retention and total available water of most soils measured. Rock fragments contributed an average of 15% of the total available and ranged from 1.6 to 52.1% (Table 1). Water content was, however, difficult to predict by any one factor (Table 2). There are several factors that work in conjunction with

Table 1. Soil physical properties of southwest Oregon forest soils.†

Soil name	Parent material	Total bulk density	Fine soil bulk density	Volumetric rock fragments	Rock fragment properties: Particle density	Rock fragment properties: Porosity	Rock fragment properties: Bulk density	< 2 mm soil properties: Organic matter	< 2 mm soil properties: Clay	< 2 mm soil properties: Sand	Volumetric water content: Seasonal low	Volumetric water content: Field capacity	Volumetric water content: Available water capacity	Percentage available water contained in rock fragments	Field capacity water potentials
		—— Mg m⁻³ ——		%	Mg m⁻³		Mg m⁻³	—— gravimetric % ——			—— % ——			%	kPa
Illinois Valley	Serpentine	1.51	1.24	35.5	2.65	27.2	2.04	19.1	27.1	43.3	--	--	--	--	--
Prospect Sand	Alluvium	1.45	1.28	19.3	2.51	14.8	2.14	2.9	3.5	87.8	8.3	19.3	11.0	8.7	−5.0
M.U. 27	Breccia	1.19	0.88	25.5	2.64	25.6	2.10	12.3	11.5	62.9	10.3	19.1	8.8	18.2	--
M.U. 27	Breccia	1.14	0.70	40.8	2.52	43.7	1.75	11.0	10.8	63.4	12.3	22.4	10.1	42.8	--
M.U. 27	Breccia	1.21	0.97	22.6	2.75	34.0	2.05	16.3	15.9	50.7	12.0	23.6	11.6	15.2	--
M.U. 27	Breccia	1.14	0.79	36.7	2.56	47.5	1.74	10.9	15.3	54.7	15.1	28.5	13.4	39.2	--
M.U. 27	Breccia	1.15	0.81	33.9	2.54	39.4	1.82	11.0	12.9	58.1	12.8	28.4	15.6	23.6	--
M.U. 27	Breccia	1.24	0.92	27.2	2.63	26.6	2.08	10.1	12.4	61.1	9.2	27.3	18.2	9.7	--
Dumont Series	Andesite	1.02	0.90	16.2	2.46	31.8	1.68	12.1	16.2	46.8	15.9	26.9	11.0	14.7	--
Dumont Series	Andesite	1.25	1.05	22.5	2.50	23.1	1.92	12.0	19.1	45.9	--	42.8	--	--	−6.0
Laurelhurst Series	Andesite	1.18	1.16	3.5	2.51	32.5	1.83	9.3	30.8	34.6	20.7	37.3	16.7	2.1	--
Straight Series	Andesite	0.97	0.83	18.0	2.43	33.8	1.61	27.6	15.7	46.9	--	36.5	--	--	--
M.U. 51	Andesite	1.03	0.62	28.4	2.63	28.3	2.05	11.5	14.5	57.6	10.4	16.1	5.7	52.1	--
M.U. 51	Andesite	0.92	0.68	22.1	2.55	39.9	1.82	16.9	13.4	54.3	8.5	17.2	8.7	22.5	--
M.U. 51	Andesite	1.06	0.80	22.4	2.61	31.2	1.99	12.7	19.5	51.8	14.7	26.2	11.5	20.6	--
M.U. 51	Andesite	1.41	0.79	49.2	2.61	27.9	2.04	15.3	19.1	53.4	11.5	24.8	13.3	24.9	--
M.U. 51	Andesite	1.06	0.92	16.0	2.55	35.5	1.77	8.7	16.1	48.5	--	--	--	--	--
M.U. 51	Andesite	1.30	1.07	35.8	2.53	41.7	1.71	9.5	12.8	53.9	--	--	--	--	--
Vermisa Series	Metasediment	1.33	0.60	40.0	2.72	11.8	2.3	10.0	14.2	61.5	4.6	11.5	6.8	27.2	--
Vermisa Series	Metasediment	1.42	0.99	31.2	2.74	16.8	2.28	8.8	12.0	40.8	9.4	26.1	16.7	15.3	−2.0
Beekman Series	Metasediment	1.53	1.20	25.7	2.87	14.4	2.46	6.5	6.8	47.6	7.1	20.1	13.0	8.4	--
Beekman Series	Metasediment	1.34	0.89	37.9	2.59	20.8	2.05	9.1	19.5	45.2	9.4	24.7	15.2	11.7	−12.0
Kanid Series	Metasediment	1.13	0.80	23.5	2.61	17.1	2.16	12.1	13.7	57.3	8.0	22.6	14.6	16.8	−3.0
Tishar Series	Metasediment	1.37	1.23	17.7	2.61	18.5	2.13	8.4	12.5	55.6	12.1	25.7	13.5	6.7	−14.5
McGinnis Series	Metasediment	1.05	0.78	27.7	2.51	34.5	1.64	16.6	16.1	50.3	12.5	28.1	15.5	22.2	−5.5

(continued on next page)

Table 1. Continued. Soil physical properties of southwest Oregon forest soils.†

					Rock fragment properties			< 2 mm soil properties			Volumetric water content				
Soil name	Parent material	Total bulk density	Fine soil bulk density	Volumetric rock fragments	Particle density	Porosity	Bulk density	Organic matter	Clay	Sand	Seasonal low	Field capacity	Available water capacity	Percentage available water contained in rock fragments	Field capacity water potentials
		—— Mg m^{-3} ——		%	Mg m^{-3}		Mg m^{-3}	—— gravimetric % ——			—— % ——			%	kPa
Pollard Series	Metasediment	1.27	1.01	24.5	2.56	18.3	2.09	10.5	9.9	58.8	6.4	22.2	15.8	11.9	−5.0
Pollard Series	Metasediment	1.08	0.99	10.5	2.50	28.5	1.79	9.2	21.4	45.9	13.7	30.5	16.7	5.7	−13.0
Pollard Series	Metasediment	1.29	1.15	14.3	2.56	19.7	2.06	10.2	24.9	43.1	13.8	32.3	18.4	5.3	−6.5
M.U. 82	Metasediment	1.38	0.81	40.2	2.67	17.9	2.24	11.5	8.7	38.1	4.7	21.9	17.2	18.3	--
M.U. 82	Metasediment	1.22	0.82	31.8	2.74	23.9	2.09	12.7	11.8	42.9	6.8	26.0	19.2	12.8	--
Turkey Creek	Metasediment	1.42	1.17	23.5	2.62	13.8	2.26	7.8	10.0	46.6	3.6	22.9	19.3	6.3	−4.0
Limestone Creek	Granitic	0.98	0.88	6.9	2.78	16.5	2.35	19.1	5.2	71.8	8.6	23.0	14.4	4.1	--
Siskiyou Series	Granitic	1.32	1.23	10.0	2.62	17.3	2.17	5.1	7.1	67.9	4.2	19.5	15.2	4.1	−8.5
Holland Series	Granitic	1.32	1.27	5.5	2.62	16.5	2.19	4.4	7.1	70.0	4.0	22.5	18.5	1.6	−3.5
M.U. 42	Tuff and Breccia	0.87	0.80	11.5	2.51	58.1	1.46	17.2	13.0	49.6	17.2	30.9	13.7	12.4	−6.5
M.U. 42	Tuff and Breccia	0.95	0.91	5.1	2.64	40.4	1.72	17.5	21.4	37.1	18.2	36.8	18.5	4.8	−6.0
Mt. Mazama	Pumice and Ash	0.69	0.63	12.3	2.33	52.2	1.11	22.6	4.3	50.8	10.5	22.6	12.1	16.2	−10.5
Mt. Mazama	Pumice and Ash	0.72	0.66	32.2	2.13	60.3	0.84	6.8	3.4	57.6	13.8	34.0	20.2	24.7	−8.0
Geppert Series	Basalt	1.42	1.07	55.7	2.60	37.1	1.75	20.1	11.6	53.4	12.6	28.2	15.6	36.3	−4.5
Witzel Series	Basalt	1.65	1.31	40.8	2.66	23.3	2.14	6.6	25.1	31.3	10.2	32.9	22.7	21.1	−5.5
Means		1.20	0.94	25.1	2.58	29.1	1.94	12.1	13.9	52.5	10.7	26.0	14.5	15.1	−7.0
Standard deviation		0.21	0.20	12.3	0.12	12.2	0.32	5.1	6.0	10.8	4.1	6.4	3.8	10.2	−3.4
Range	0.96	0.96	0.71	52.2	0.74	48.5	1.62	24.7	27.4	56.5	17.0	31.4	17.0	40.3	−13.0

† Note: M.U. 51 and M.U. 27 are soil map units from the Umpqua National Forest, M.U. 42 is from the Rogue River National Forest and M.U. 82 is from the Siskiyou National Forest.

Table 2. Correlation matrix for soil physical properties and water content; r values are given to indicate positive or negative correlation.

Variable	BD_t	$BD_{<2}$	R_v	$PD_{>2}$	$P_{>2}$	$BD_{>2}$	Clay	Sand	OM	WP	FC	AWC
BD_t	40	0.688	0.428	0.596	−0.690	0.737	0.094	−0.071	−0.449	−0.440	−0.176	0.217
$BD_{<2}$	40	40	−0.209	0.274	−0.482	0.433	0.106	−0.044	−0.426	−0.142	0.196	0.456
R_v	40	40	40	0.118	0.029	0.068	−0.055	−0.081	0.014	−0.186	−0.190	−0.061
$PD_{>2}$	40	40	40	40	0.648	0.873	0.048	−0.057	−0.101	−0.339	−0.399	−0.086
$P_{>2}$	40	40	40	40	40	−0.902	0.029	−0.127	0.397	0.651	0.363	−0.049
$BD_{>2}$	40	40	40	40	40	40	0.013	0.112	−0.354	−0.574	−0.439	−0.055
Clay	40	40	40	40	40	40	40	−0.598	0.184	0.613	0.489	0.058
Sand	40	40	40	40	40	40	40	40	−0.218	−0.422	−0.537	−0.422
OM	40	40	40	40	40	40	40	40	40	−0.230	0.205	−0.230
WP	35	35	35	35	35	35	35	35	35	35	0.733	−0.001
FC	37	37	37	37	37	37	37	37	37	37	37	0.679
AWC	35	35	35	35	35	35	35	35	35	35	35	35

† r's in upper triangle, N's in diagonal, contingent N's in lower triangle.

‡ BD_t = field bulk density, $BD_{<2}$ = fine soil bulk density, R_v = volumetric rock fragment content, $PD_{>2}$ = particle density of rock fragments, $P_{>2}$ = porosity of rock fragments, $BD_{>2}$ = bulk density of the rock fragments, Clay = gravimetric percentage clay in < 2 mm mineral soil, Sand = gravimetric percentage sand in < 2 mm mineral soil, OM = organic matter percentage in < 2 mm soil, WP = volumetric water content percentage at the seasonal low, FC = volumetric water content percentage at field capacity, AWC = volumetric available water capacity percentage (FC–WP).

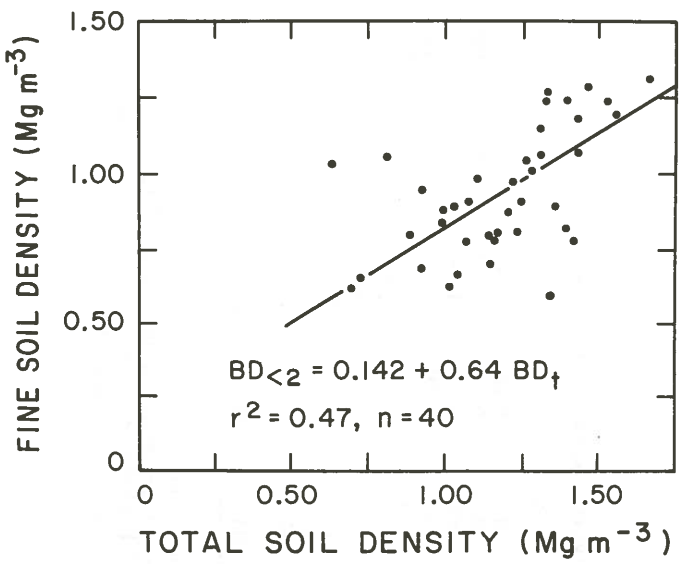

Fig. 2. Calculated fine soil density vs. field total bulk density.

each other to determine the water content at any particular time. Multiple regressions were used to determine which factors were most useful for estimating total available water and water retention at the seasonal low and field capacity (Table 3).

The rock fragment porosity and clay content gave an r^2 of 0.76 for predicting seasonal low while the rock fragment porosity and sand content gave an r^4 of 0.38 for predicting field capacity. These parameters made the most significant contribution of any two parameters to their respective water contents and indicate the importance of clay in holding water at low potentials (seasonal low) and its lesser importance at high potentials (field capacity). The addition of total bulk density, fine bulk density, bulk specific gravity, volumetric rock fragment content, organic matter content, and sand or clay increased the r^2 for the seasonal low to 0.82 and the field capacity to 0.70. Prediction of available water capacity using this model had a poorer correlation ($r^2 = 0.54$) than either field capacity or seasonal low water content. This was expected because available water capacity estimates would include the error associated with both water content estimates. Clearly, much of the variation in a soil's ability to supply water depends on factors other than those measured in this study.

DISCUSSION

To properly quantify available soil water for a skeletal soil several measurements or estimates must be made: total bulk density, rock fragment content, water content at the driest part of the season, water content at field capacity, rock fragment particle density, and rock fragment porosity. From this data set available water can be calculated using the equations in this chapter. This is a preferred method since it accounts for soil variability and profile layering, which can be of considerable importance in skeletal soils. There are several simplifications that can be used if only general information is needed for a soil.

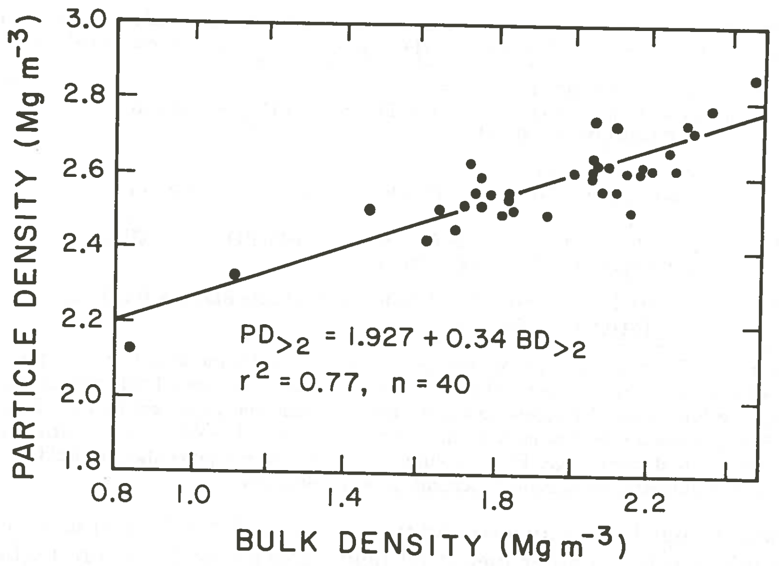

Fig. 3. Particle vs. bulk density for 2.0 to 4.75 mm diam rock fragments.

Bulk density measurements for skeletal soils require sampling a large volume and making several determinations in order to estimate variability. The total bulk density samples are also used to calculate rock fragment content and fine soil density. If measurement of all quantities is not possible, estimates may be made with limited accuracy. Two approaches are possible. The first is to estimate those soil properties that cannot be easily measured. These estimates should be based on some knowledge of the soil in question; personal experience or soil survey information would be the most valuable. The measured and estimated values can then be used in the various deterministic equations presented to calculate water retention. The second approach is to use some type of regression equation, such as those reported here (Table 3). These regression equations also require several estimated or measured soil properties. The regression equations are based on probabilistic relationships rather than the deterministic relationships shown throughout the text. This difference makes regression equations well suited for accurate estimates of average values. Probabilistic estimates may therefore be quite appropriate for planning efforts but measurements are preferred for management of specific sites.

The measurement of water content should be expressed on a whole soil basis by correcting small moisture can samples to field basis using the techniques described. Field capacity water content can be measured by using a wetting procedure in the summer, at the same time that the dry season measurement is made. The site should be wet up and allowed to

Table 3. Multiple regression of soil physical properties† to predict available water capacity (AWC), water content at field capacity (FC), and water content at the seasonal low (WP).

$\mathrm{WP} = 0.405 \cdot \mathrm{CL} + 0.202 \cdot \mathrm{P}_{>2} - 0.480$	$r^2 = 0.76$
$\mathrm{WP} = 0.452 \cdot \mathrm{CL} + 0.192 \cdot \mathrm{P}_{>2} - 6.158 \cdot \mathrm{BD}_t + 8.52 \cdot \mathrm{BD}_{<2} + 0.037 \cdot \mathrm{R}_v + 0.040 \cdot \mathrm{OM} + 0.038 \cdot \mathrm{SA} - 4.824$	$r^2 = 0.82$
$\mathrm{FC} = 0.288 \cdot \mathrm{SA} + 0.153 \cdot \mathrm{P}_{>2}$	$r^2 = 0.38$
$\mathrm{FC} = 0.264 \cdot \mathrm{CL} + 0.302 \cdot \mathrm{P}_{>2} + 11.077 \cdot \mathrm{BD}_t - 0.179 \cdot \mathrm{R}_v - 0.188 \cdot \mathrm{SA} + 14.941$	$r^2 = 0.51$
$\mathrm{FC} = 0.414 \cdot \mathrm{CL} + 0.007 \cdot \mathrm{P}_{>2} - 38.611 \cdot \mathrm{BD}_t + 39.645 \cdot \mathrm{BD}_{<2} + 0.351 \cdot \mathrm{R}_v + 0.064 \cdot \mathrm{OM} - 0.173 \cdot \mathrm{SA} + 29.411$	$r^2 = 0.70$
$\mathrm{AWC} = -0.199 \cdot \mathrm{CL} - 0.098 \cdot \mathrm{P}_{>2} - 21.773 \cdot \mathrm{BD}_t + 22.266 \cdot \mathrm{BD}_{<2} + 0.211 \cdot \mathrm{R}_v - 0.164 \cdot \mathrm{OM} - 0.207 \cdot \mathrm{SA} + 31.894$	$r^2 = 0.54$

† Symbols: CL = gravimetric percentage clay in < 2 mm mineral soil, $\mathrm{P}_{>2}$ = porosity of rock fragments, BD_t = field bulk density (Mg m^{-3}), $\mathrm{BD}_{<2}$ = fine soil bulk density (Mg m^{-3}), R_v = volumetric rock fragment content, OM = organic matter percentage in < 2 mm soil, SA = gravimetric percentage sand in < 2 mm mineral soil, AWC = volumetric available water content percentage, FC = volumetric water content percentage at field capacity, WP = volumetric water content percentage at seasonal low.

drain. It may be wet up a second time to reduce lateral water loss and hysteresis effects. Summer-measured field capacity estimates are useful for planning, but measurements taken in early spring give a better estimate because they would include water held in the profile due to layering that may not be easily seen from the summer wet up (Salter and Williams, 1965; Clothier et al., 1977).

Bulk density can be estimated from Fig. 3 if particle density is known or estimated based on parent material. If particle density is measured by using a water pycnometer, it is convenient to measure porosity with the same sample. These two values allow calculation of rock fragment bulk density. In our study, prediction of field capacity water content depended significantly on rock fragment porosity and sand content. Since the sand fraction is usually derived from the same material as the rock fragments, natural porosity of these fractions may be closely related. Therefore this porosity may contribute to the water-holding capacity of the sand as well as the rock fragments.

Measurement of soil water supply in skeletal soils is complicated by the fact that rock fragments hold water. In soils where the rock fragment porosity is low, the effect of rock fragment content should be quite important since a primary factor affecting water supply would be the decrease in water storage volume. In soils with high rock fragment content, the total rock fragment content becomes less important than knowing rock fragment porosity. Since it is known that smaller fragments are more porous than larger, less weathered fragments (Coile, 1953; Hanson and Blevins, 1979), it may be that incrasing the upper size limit of the "fine soil fraction" may be a reasonable way to simplify soil water measurement procedures. The significance of the water-holding capacity of the remainder of the larger, less porous rock fragments may be reduced by including all soil particles up to 5 mm in diameter in soil water measurements, i.e., fine soil density and gravimetric water content. This shift in the arbitrary break between fine and coarse soil material would, however, increase the variability of properties of the fine soil fraction.

LITERATURE CITED

1. A.S.T.M. 1977. Adsorption and bulk specific gravity of natural building stone. American Society for Testing and Materials. ANSI/ASTM R 97-47 Annual Book of ASTM Standards, Part 19.
2. Berger, E. C. 1976. Partitioning the parameters of stony soils, important in moisture determinations, into their constituents. Plant Soil 14:201–207.
3. Blake, G. R. 1965. Particle density. *In* C. A. Black, D. D. Evans, J. L. White, L. E. Ensminger, and F. E. Clark (ed.) Methods of soil analysis: Part I. A.S.A. Monograph 9: 371–373. Am. Soc. of Agron., Madison, Wis.
4. Clothier, B. E., D. R. Scotter, and J. P. Kerr. 1977. Water retention in soil underlain by a coarse-textured layer: Theory and field application. Soil Sci. 123:392–399.
5. Coile, T. S. 1953. Moisture content of small stone. Soil Sci. 75:203–207.
6. de Moulin, L. A., J. A. Pomerening, and B. R. Thomas. 1975. Soil inventory of the Medford District. United States Dep. of Interior Bureau of Land Management. Medford, Oreg.
7. Flint, A. L., and S. W. Childs. 1984. Development and calibration of an irregular hole bulk density sampler. Soil Sci. Soc. of Am. 48:374–378.
8. Hanson, C. T., and R. L. Blevins. 1979. Soil water in coarse fragments. Soil Sci. Soc. Am. J. 43:819–820.
9. Reinhart, K. G. 1961. The problem of stones in soil-moisture measurement. Soil Sci. Soc. Am. Proc. 25:268–270.
10. Salter, P. J., and J. B. Williams. 1965. The influence of texture on the moisture characteristics of soils. I. A critical comparison of techniques for determining the available-water capacity and moisture characteristic curve of a soil. Soil Sci. 16:1–15.
11. Wert, S. R., J. A. Pomerening, and T. S. Gibson. 1977. Soil inventory of the Roseburg District. United States Dep. of Interior Bureau of Land Management. Roseburg, Oreg.