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Assessment of Available Water Storage Capacity of Soils With Restricted Subsoil Permeability

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The pasture production of most of the tropics is largely a function of the water regime. One of the few options for control of the water regime in these environments is choice of site. A site parameter of great importance is the available water storage capacity (AWSC) in the root zone. Although estimation of the AWSC is straightforward on freely drained soils, it is complicated on poorly drained soils by the inapplicability of the concept of field capacity. The latter soils, however, commonly have a buildup of salts at depth in the profile, presumably due to prevailing leaching conditions. The study reported herein was conducted to test the hypothesis that this salt profile can be used to indicate the depth of wetting under conditions similar to those producing maximum subsoil water recharge in this climate. Twenty sites on mainly texture contrast soils, most with poorly drained subsoils, were examined in detail. A close relationship between the observed depth of wetting and the depth to the salt bulge was found. This relationship, together with the total porosity of the top (wettest) stratum of the B horizon, provides a means of estimating the AWSC of the subsoil.

Introduction

In climates with a highly seasonal rainfall distribution, plants growing on soils with restricted internal drainage must endure periods of waterlogging as well as an early onset of water deficits due to the restricted depth of wetting. Although the effects of excessive water are serious for many crops, both *Loveday and McIntyre* [1966] and *McCown* [1971] found that for pasture legumes on such soils, by far the more serious limitation to production was the limited water storage. This paper is concerned with the problems of quantitatively assessing the amount of water that such a soil can take in and store for subsequent supply to plants.

In the case of a freely draining soil the available water storage capacity (AWSC) is the integration of the available water range over the rooting zone of the vegetation of interest. The permanent wilting percentage and the field capacity can be estimated quite simply in the laboratory or in the field. In the case of a soil which contains a stratum of sufficiently low permeability to prevent water from draining beyond the root zone within a few days the classical concept of field capacity is not applicable. In addition, rooting depths are restricted by the limited depth of wetting [*McCown*, 1971]. In such soils the AWSC is the amount of water that enters rather than the amount that is retained against gravity.

This paper deals with the water accession in the B horizon at 20 sites relative to clay content, exchangeable sodium, porosity, and soluble salts and discusses the implications for improved methods of assessing AWSC from soil variables. Consideration of the A horizon is excluded only because estimation of its AWSC is relatively straightforward. Since this horizon experiences unrestricted drainage until it is limited by the permeability of the B horizon (after which the upper limit of storage is the saturation water content), conventional determinations of field capacity and total porosity as well as of 15-bar water contents are sufficient.

In this paper the term 'water accession' refers to the wetting of a soil profile under standard ponding conditions. The amount of additional water in the profile after this wetting is termed the 'water increment.' Since it was found in an early study under similar conditions that the water content before ponding approximated the wilting percentage (approximately 15 bar) [*McCown*, 1971], the water increment is taken to be the AWSC. Permeability is used in a qualitative sense as the intrinsic attribute of a soil that determines the depth of wetting.

Sites and Methods

Detailed soil mapping by *Hubble and Thompson* [1953], *Murtha and Crack* [1966], and *Murtha* [1975] has delineated and defined a range of texture contrast soils in the lower Burdekin Valley and on the coastal plain around Townsville, Queensland, Australia. The soils included in this study were chosen to cover a wide range of subsoil permeabilities.

With the exception of site 16, a black earth, and site 18, a neutral red duplex soil, all soils are in the solodic and solodized-solonetz great soils group as described by *Stace et al.* [1968]. The most striking morphological features of this group of soils are the contrast in texture and the abruptness in change between the A and the B horizons. The texture of the A horizon ranges from sandy loam to fine sandy or silty clay loam. Most soils have a strongly bleached A2 horizon, the bleach extending to the surface in some cases. In general, the A horizon depths range from 3 to >60 cm, but most fall between 10 and 30 cm. The B horizons may be single colored or mottled, colors ranging from yellowish brown to light brownish grey and dark grey. Heavy clay textures are most common, but many have a prominent coarse sand fraction. Structures range from medium to coarse angular blocky to strong columnar.

Selection of the 20 study sites was based primarily on the nature of the salt profiles and/or known internal drainage characteristics, the aim being to include soils which provided the maximum range of variation in both.

The study was conducted in the dry season, when all available soil moisture was depleted, as was evidenced by the complete absence of green tissue on the perennial grass on the sites. At each of the 20 sites, three cores were taken with a thin-walled tube 50 mm in diameter. These cores were positioned at the apices of an equilateral triangle having sides of approximately 3 m. Depth varied from 1.5 to 2 m. Each hole was cased with a tight-fitting aluminum tube to provide access for a neutron probe. Soil cores were cut into 10-cm segments, dried, and milled to pass a 2-mm sieve. At each access tube a steel water-retaining ring 1 m in diameter and 20 cm high was installed with the access tube at the center. Water was ponded at a depth of 10 cm for 7 days. The water level was maintained by reticulation from a storage tank and was regulated by a float valve. Soil water profiles were measured at 10-cm intervals with a Wallingford neutron moisture meter (NMM) prior to ponding, after 4 hours of ponding, and after 1, 3, 5, and 7 days of ponding.

It should be emphasized that the access tubes were very tight fitting. The walls of the holes made by the coring apparatus were very regular, and the tubes had to be polished and oiled to be driven into position. The tubes were not sealed at the bottom end, but at no time was free water detected. The NMM calibration used for all soils was determined on sites 12 and 13 for a previous study. Calibrations for these two sites were essentially identical and were used for all other sites.

Three samples for bulk density were taken after partial drying of the surface soil but before appreciable drying of the B horizon. After excavation of the A horizon a soil block in the B horizon approximately 15 cm in diameter was exposed, and a core was removed from this with a sampler similar to that of *Richards* [1974] but with a sample retainer 73 mm in diameter and 76 mm in length. The sample weight after drying at 105°C for 24 hours was used to calculate bulk density. The saturation water content was estimated from bulk density, a specific density of 2.68 being assumed [*Lang*, 1968].

Clay percentages were determined by sedimentation analysis with pipette sampling [*Day*, 1965]. Twenty-five-gram samples of oven-dried soil were shaken overnight in 200 ml water + 5 ml 1 N NaOH + 10 ml 10% calgon. This was made up to a final volume of 1250 ml prior to analysis.

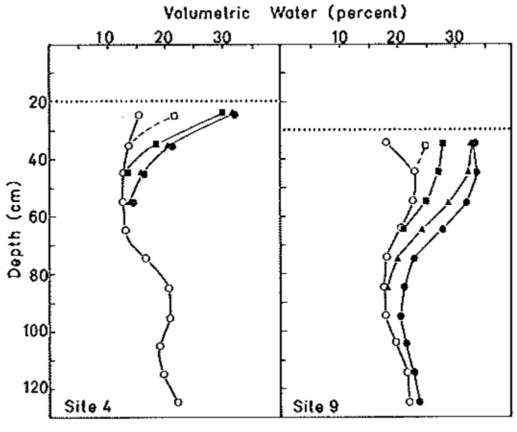

Fig. 1. Water content profiles at two sites before ponding (open circles) and after 1 day (solid squares), 3 days (solid triangles), and 7 days (solid circles) of ponding and the 15-bar water content (open squares). The dotted line indicates the interface between the A and the B horizons.

Electrical conductivity was measured by using 1:5 soil-water suspensions, and a factor of 336 was used to convert millimhos per centimeter to percentage of total soluble salts (TSS). Exchangeable cations were determined by method B of *Loveday et al.* [1972].

Fifteen-bar water percentages were determined on samples from the upper 10 cm of the B horizon by using a pressure membrane apparatus.

RESULTS

Water Accession

The effect of the duration of water application on subsoil water accession varied greatly among sites. Figure 1 shows changes in water content profiles after various periods for two soils representative of the least and most permeable soils. On site 4 there was no further wetting after 3 days; on site 9, water continued to enter up to the last measurement. Clearly, periods longer than 7 days would be necessary to show maximum differentiation among soils. It was decided, however, to accept the underestimate of the maximum water accession on the soils with the higher permeabilities in view of the impracticability of ponding and measuring for longer periods on a widely dispersed network of sites. Thus the available water storage capacity values reported here represent the water increment between the dry profile and the profile after ponding for 7 days. (Although the choice of any standard wetting period is necessarily quite arbitrary, local experience and simulated excess rainfall for a 60-year period [*McCown et al.*, 1974] indicate that natural recharge conditions similar to ponding for 7 days are not uncommon in this environment.) The water increments for the 20 sites are shown in Figure 2. Most soils demonstrated very restricted permeabilities, water moving as little as 30 cm into the B horizon. Others, e.g., 3, 18, and 9, were relatively permeable.

Previous experience has shown that in the absence of the rare event of substantial rainfall the water contents of these soils change very little during the latter half of the dry season. In an earlier study these terminal water contents have been found to be slightly lower than 15-bar values in all but the upper 10 cm in the B horizon, which was found to dry well below 15-bar values [*McCown*, 1971]. Consequently, in this study, in calculating the water increments of the subsoil, 15-bar contents have been used for the top 10 cm, and dry season field water contents for the remaining strata.

Soil Variables Related to Water Accession

Clay content might be expected to be a major factor influencing water accession. However, examination of Figure 2 does not substantiate this for these sites, all of which had at least one stratum of 30% clay or greater. The two sites with the lowest clay contents were 3 and 4, one of which was among the most permeable and the other of which was among the least permeable. Two sites with very high clay contents were 8 and 9, and these also represent opposite ends of the permeability range. Over all sites the correlation coefficient between the clay content of the upper 10 cm of the B horizon and the water increment is −0.25, a not very useful value.

The relative dispersion or flocculation of clay, and thereby its water conductivity, is largely a function of the proportion of the exchange complex occupied by Na ions [*Quirk and Schofield*, 1955]. When the same two pairs of soils (3 and 4; 8 and 9) are compared, their exchangeable sodium percentages

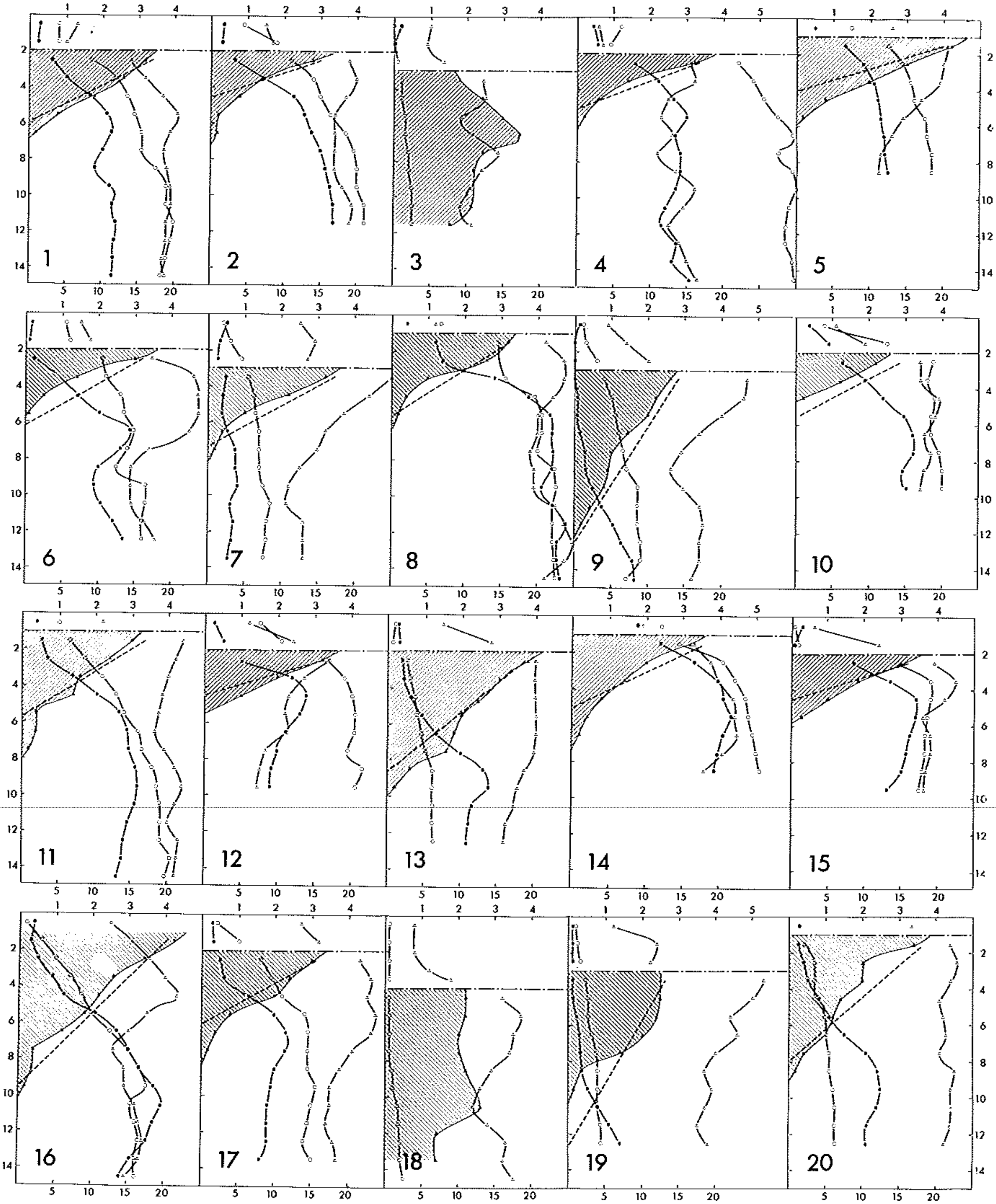

Fig. 2. Vertical distribution of measured water increment (solid triangles), predicted available water range (dashed line), TSS (solid circles), exchangeable Na (open circles), and clay (open triangles). The scale of the upper horizontal axes represents percent of TSS times 10, percent of exchangeable Na times 10^{-1}, and percent of clay times 10^{-1}; the scale of the lower horizontal axes represents percent of volumetric water; the scale of the vertical axis represents centimeters times 10. Water increments for entire subsoils are represented by shaded areas. (The dotted-dashed line indicates the interface between the A and the B horizons.) Site numbers referred to in the text are the bold numerals.

(ESP) being considered, it is clear that the soils with low ESP have high permeability relative to those with high ESP. Over all sites the correlation coefficient between the water increment and the ESP of the top 10 cm of the B horizon is −0.69.

Our main hypothesis at the outset was that water entry was related to the vertical distribution of soluble salts. If a further comparison of sites 3, 4, 8, and 9 is made, it can be seen that the most permeable of the four (site 3) has no accumulation of salt (<0.01%) in the B horizon. The second most permeable soil (9) has a salt profile with a maximum concentration at a considerable depth (140 cm) and a modest maximum concentration value (0.16%). Both 4 and 8 have low permeabilities and salt profiles with a buildup of salts of ≥0.3% at shallow depths. It is clear from examination of the remaining 16 sites in Figure 2 that there is a general inverse relation between water increment and these attributes of the salt profile.

Prediction of the Subsoil Water Increment

If the subsoil water increment could be estimated from relatively easily measured soil variables rather than measured directly, a sizeable saving in time and expense could be made in assessment of these sites. In general, on the sites with seriously restricted permeability the stored available water volume declined progressively from high values near the surface of the B horizon to zero at some depth in the profile. The amount stored in the upper 10 cm and the depth in the profile beyond which no water was stored vary among the 20 soils. This suggests a linear model with two parameters: (1) an estimate of the maximum water content of the top of the B horizon and (2) an estimate of the minimum depth of zero storage.

Van Bavel et al. [1968] found that flood irrigation resulted in quantities of entrapped air of >0.10 of the total pore volume. Maximum water contents in the top of the B horizons averaged 85% of total porosity. By using this for parameter 1 and the depth to the top of the salt 'bulge' as the estimate for parameter 2 the water increment in each of these soils has been estimated (Figure 2). The relation between actual and estimated water increments is shown in Figure 3. (Estimates for sites 3 and 18 could not be made because of the lack of salt accumulation, but of course the available water range can be calculated by using field capacity as the upper limit on these rather freely draining soils.) Although there is a departure from a 1:1 relationship, due to the overestimation of values at the higher end of the range, the correlation coefficient is 0.93. A possible explanation for the overestimation on the more permeable soils is that the 7-day period was too short (see the section on water accession). If this was the case, the estimate is closer to the 'true' AWSC value than is the value obtained by ponding.

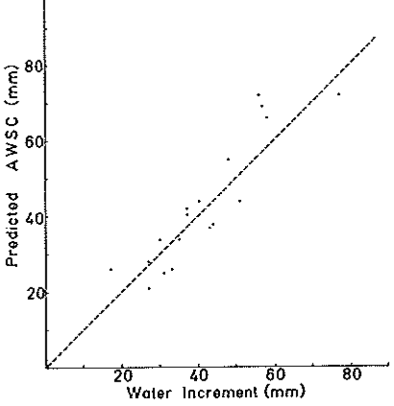

Fig. 3. Scatter diagram of predicted AWSC versus measured water increment.

Discussion

The most obvious and direct method of assessing water storage capacity is that of measurement of amount or rate of water accession following application, for example, in ponded bays [*Loveday and Scotter,* 1966], ring infiltrometers [*Stirk,* 1957], or auger holes [*Williams,* 1968*a*]. However, for dryland survey purposes there is considerable incentive to find relationships between water permeability and more simply measured soil variables that would facilitate prediction of the former from the latter.

In subsoil the main determinants of stability of structure, and thereby permeability, are the factors influencing the colloidal properties of clay in suspension, e.g., clay amount and mineralogy, the proportion of the exchange complex occupied by sodium ions, and the concentration of the soil solution [*Childs,* 1957]. It would therefore be expected that measurement of the latter soil variables might enable quantitative prediction of permeability, and, indeed, good quantitative relationships have been reported for ideal soil systems [*Quirk and Schofield,* 1955; *McNeal and Coleman,* 1966]. *Williams* [1968*a*] concluded, however, that permeability in the field cannot be assessed by using these variables, owing to the overriding importance of such factors as depth, porosity, bulk density, microstructure and macrostructure, land use, and root penetration. Further, in real soils the variable proportions of clay minerals down the profile prevent application of existing laboratory relationships.

An alternative to this mechanistic approach to prediction of the AWSC is the use of leaching patterns as indicators of wetting history. In subpercolative conditions, due simply to insufficient rainfall and compounded by low permeability of the soil, salts generally accumulate. The existence of a relation between the depth at which this accumulation occurs and the depth to which soil wets has been pointed out by numerous authors, most notably by *Greene* [1928], *Groenewegen* [1959], *Arkley* [1963], *Yaalon* [1965], and *Williams* [1968*b*]. It is clear from Figure 2 that our results confirm these reports. However, the important issue is the resultant utility of this relationship. *Greene* [1928] usefully classified soils as to their relative permeabilities and consequent productivity, using salt profiles. We have put forward a simple model for estimating the AWSC which uses the salt profile to define the depth limits to wetting, with encouraging results. However, a number of questions pertaining to this approach need to be dealt with.

Our results show that both ESP and salt profiles are closely related to depth of wetting. The chief advantage of TSS over ESP is the ease of determination using conductivity of 1:5 soil-water suspensions. Since the concern here is not agronomic salinity but merely the vertical distribution pattern, there seems to be no reason to use preparations more difficult to obtain or to handle, i.e., saturation extracts or 1:1 suspensions.

A further question is whether the reliability of salt distribution as a tracer may be suspect owing to the degree of mobility of the ions. The evidence is that a profile reaches equilibrium with the climate, resulting in a stable distribution pattern. *Raupach and de Vries* [1958] were unable to detect annual variation in salt distribution. With change in climate the salt distribution pattern reaches steady state conditions with mean effective rainfall rather rapidly, even though other soil profile properties may still show signs of previous climatic regimes [*Yaalon*, 1965]. *Greene* [1934] inverted a normal soil profile, replacing low-salt strata near the surface with high-salt soil from below, and 3 years and 30 wettings later the profile had reverted to the original pattern.

The fact that the salt distribution pattern is a product of climate as well as of soil presents no problem in evaluation of soils for dryland use. However, for irrigation purposes, a ranking according to relative permeabilities is perhaps the most that can be expected from salt profile information, since the new use will impose a new water regime.

There are practical problems associated with using the two parameters (1) depth to the salt bulge and (2) porosity in the upper B horizon. Determination of a depth value from a salt profile is somewhat arbitrary and/or subjective. In this paper we have chosen the top of the salt bulge as the inflection point determined by eye. However, the importance of the choice of criterion is lessened by the fact that the area of the triangle whose hypotenuse is the predicted available water range (Figure 2) is relatively insensitive to changes in depth. Since the bulk density measurement is used to determine the maximum volumetric water content, it is appropriate that this be the wet bulk density. Although this may appear to be an inconvenient survey measurement, we have found the following procedure to be suitable and practical for detailed survey: a 25-cm-diameter hole is dug to expose the top of the B horizon, the hole is filled with water, and a core 10 cm long is taken for bulk density 24 hours later.

Perhaps the greatest barrier to practical application of this concept at present is ignorance with regard to areal variation and appropriate sampling scales. *Raupach and de Vries* [1958] concluded that areal variation in salt profiles was too great to use them for characterization of soils. However, if in their study, salt distribution profiles accurately reflected permeability, then high variability would be expected, since small-scale areal variability of this parameter is notoriously high [*van Bavel et al.*, 1968]. Further research on this aspect is planned.

In conclusion, it appears that description of the water regime of subhumid areas where soils are relatively impermeable can be aided by knowledge of the vertical distribution of salts and that more widespread verification is warranted.

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