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Soil moisture deficit and water-table depth in London clay beneath neutral grassland

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SUMMARY

During the period 1954 to 1964 the amount of water was estimated and the depth of the water-table was measured in a soil profile beneath meadow grass at a site on London clay at Uxbridge, Middlesex.

Each winter the soil profile was saturated and draining freely and the water-table was within six inches of the surface. During the spring and summer the soil profile dried out from the surface downwards with a corresponding lowering of the water-table. By late autumn the water-table reached a depth of six feet, and the moisture deficit in the soil profile reached a value of from five to six inches. Re-charge of the soil profile to the winter conditions occurred in late autumn or early winter.

Measurements of humidity, sunshine, wind, temperature and other data were used to calculate the monthly potential evaporation, and this information, combined with rainfall data, permitted the calculation of the total deficit of soil moisture at any time from that held at field capacity.

For the particular site investigated, the observed depth of the water-table at any season varied linearly with the calculated moisture deficit in the soil profile beneath the grass, thus providing a simple method for continuously logging the moisture deficit in the soil. The result also provides a basis for correlating weather data with moisture conditions in the soil beneath roads; the moisture conditions are largely controlled by the depth of the water-table.

1. INTRODUCTION

This paper describes experiments carried out from during 1954 to 1964 at a site on London clay at Uxbridge, Middlesex, to determine the relation between the soil moisture deficit and the depth of the water-table beneath the vegetation (neutral grassland) at the site. It was found that a simple linear relation existed.

The result is of potential value to the engineer concerned with the design of roads (Black, Croney and Jacobs 1958) and the trafficability of grassland. It is also of value in the study of herbage grasses for cattle (Williams 1964) and in ecological studies of the growth of soil micro-fungi concerned with soil formation (Griffin 1963). An important further application is to the simple and continuous logging of soil moisture deficit in hydrometric schemes for estimating water resources.

Studies similar to those reported in this paper have been made by Hamilton (1963) in Manitoba, where the depth of water-table in glacial lacustrine clays was measured and the moisture deficit calculated from the Thornthwaite formula.

2. GEOLOGY OF THE EXPERIMENTAL SITE

The experimental site used for the present experiments is situated near Uxbridge, Middlesex (National Grid reference 064 845) at an altitude of 150 ft with respect to ordnance datum. It is sited on the slope of a hill, of maximum altitude 210 ft, the gradient of the hill being 1 in 15 at the site. The aspect faces north-east. The site lies on London clay, near the north-western edge of the London clay basin of the Thames Valley; the hill is composed entirely of London clay overlain, at the top of the hill, with a cap of Pleistocene terrace gravel (glacial gravel with Bunter pebbles). The site, which is triangular (sides approximately 155 ft, 370 ft and 380 ft) lies about half-way down the slope of the hill and the line dividing the cap of gravel from the underlying London clay passes through the top of the site.

Natural drainage for the site is provided by a small river (River Pinn) which flows by the foot of the hill below the site at an altitude of 110 ft. The tract of level ground adjacent to it is covered with alluvium which overlays the London clay in the area and, although it is still used for grazing, it is subject to seasonal flooding.

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3. The soil profile and the vegetation at the site

Pits on the site, excavated to a depth of five feet, showed a black surface *A* horizon about 1 ft in depth and containing most of the roots of the grass. Beneath, the *B* horizon, about 1 ft 6 in. thick, consisted of brown fissured clay and then, abruptly, the *C* horizon started. This, too, was brown and fissured but contained small patches of blue clay, produced, almost certainly, by periods of water-logging long enough to reduce ferric iron (limonite or goethite) to the ferrous (blue) form. These observations suggested that the *A* and *B* horizons were freely drained, but that the *C* horizon was imperfectly drained.

Small brown nodules found at a depth of 5½ ft were X-rayed and found to consist largely of goethite (hydrated alpha ferric oxide). X-ray studies of the soil by P. A. Sabine (private communication) combined with optical petrographic studies showed calcite, dolomite, quartz, illite, a member of the kaolin group, and a montmorillonoid with iron staining. The last mineral is characterized by large volume changes as it is wetted and dried.

A vegetation survey at the site showed a mixture of about nine species of grass dominated by meadow foxtail and smooth-stalked meadow grass. Rye grass was present only in small quantities indicating that the pasture did not consist predominantly of grasses that would be sown for a ley (Williams 1964) or on a road verge (Ministry of Transport 1963). The survey indicated a poorly drained, but not marshy pasture, typical of neglected permanent grassland on heavy soils of neutral reaction and high base status.

4. Depth of the water-table, 1954-1964

The depth of the water-table was measured weekly from June 1954 to August 1956, at a borehole at the lower (north-east) end of the site. This consisted of a 13 ft length of 2 in. diameter gas pipe inserted into a bored hole and back-filled with soil. In August, 1956, this was replaced by a

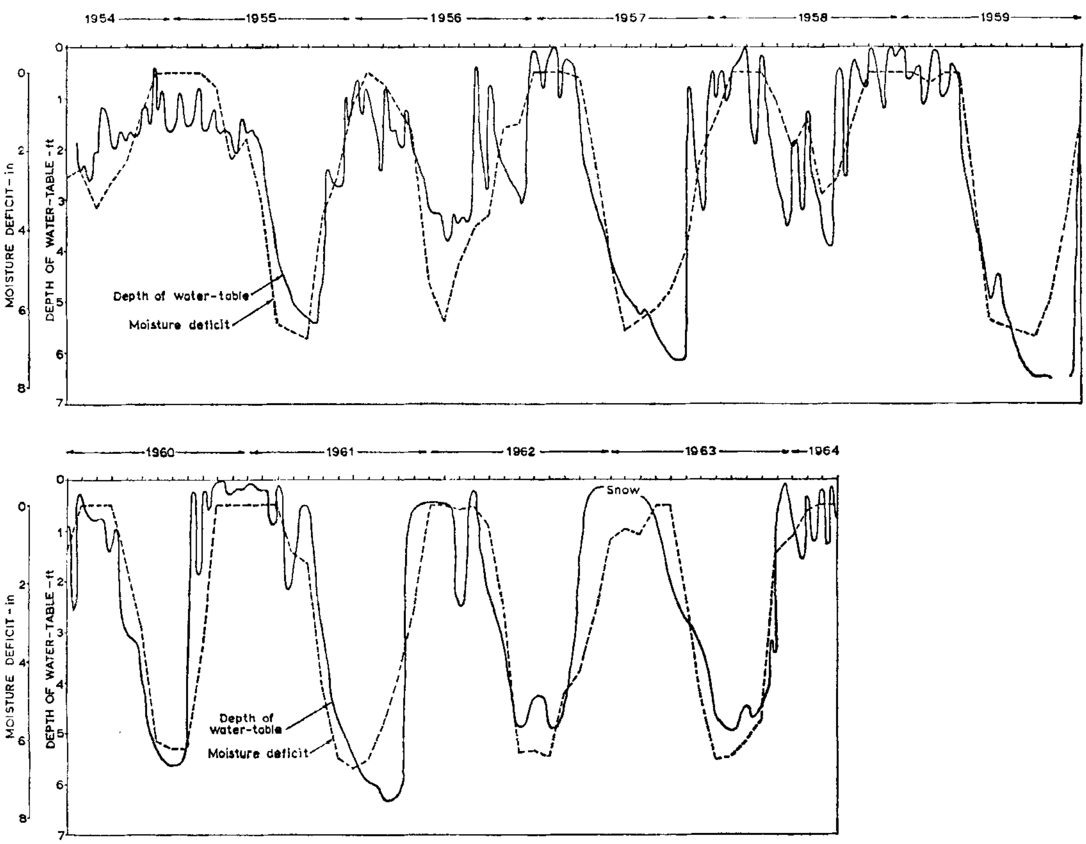

Figure 1. Observed depth of the water-table, and calculated **moisture deficit.**

borehole at the upper (south-west) end of the site. It was made by boring a 4 in. diameter hole to a depth of 7 ft, inserting a 1 in. internal diameter brass tube to a depth of 6 ft 6 in. and back-filling the space round the pipe with a gravel-sand mixture.

Fig. 1 shows a continuous record from 1954 to 1964, apart from a period of drought in 1959, when the water-table fell below the bottom of the borehole and the winter of 1962 to 1963, when the site was inaccessible.

There was a marked seasonal fluctuation in the depth of the water-table. Every winter the water-table rose to within a few inches of the surface and the field drains were observed to run after rain. In summer, the water-table fell away to a depth that always exceeded 3 ft and exceeded 6 ft in several years and no drainage from the soil was observed. At some time in each year during the late autumn, the water-table returned abruptly towards its winter level. In addition, the ground level was regularly measured by comparing bench marks anchored at the surface and at a depth of 18 ft. During each winter the ground level rose above the mean level and each summer fell below the mean level, the total seasonal movement rarely exceeding one inch.

5. Climatic data and the calculation of soil moisture deficit

The moisture conditions at the surface of the exposed soil were determined by the difference between the water added as rainfall and other forms of precipitation and that removed by evaporation, surface run-off, and sub-surface drainage. The latter quantities are not easily measured directly, but several authors have proposed methods for calculating the evaporation term from meteorological data (e.g., McIlroy 1957). The method proposed by Penman (1949) was derived from a study of grassed sites in Britain and was considered to be the most suitable for this site's conditions.

Using this method, the rate of evaporation from an open-water surface (E_0) was first calculated using measurements of air temperature, vapour pressure, sunshine, and mean daily wind speed. All the meteorological data were taken whenever possible from London Airport, about 6 miles south of the site. Records of sunshine prior to 1957 and of wind speed prior to 1960, were not available at this station and were therefore taken from Kew, about 10 miles to the south-east. The calculation of the evaporation from an open-water surface (E_0) was performed on a Ferranti Pegasus II computer, using a programme developed at the Road Research Laboratory by Young (1963). To give the rate of evaporation appropriate to a site under short grass for which water is freely available, the open-water evaporation E_0 was multiplied by a seasonally varying factor f, where f has the approximate values 0·6 for November-February, 0·7 for March, April, September and October, and 0·8 for May-August (Penman 1949).

Allowance was then made for the fact that in most summers water is not freely available for evaporation. During summer, more water is always removed by evaporation than the amount added by rainfall, i.e., there is a moisture deficit in the soil. Penman suggested that the water which can be freely removed at the rate fE_0 is limited to an amount dependent on the nature of the soil and vegetation, and termed the root constant, C. C was found to be 4 in. for a site on silty clay at Harmondsworth, Middlesex (Black *et al.* 1958) and was taken to be 5 in. for the present site on London clay. Once the moisture deficit exceeds C in. the actual moisture deficit is less than the potential moisture deficit calculated on the assumption that water is freely available for evaporation. Allowance for this limitation to the evaporation process can be made only semi-empirically. In Fig. 2 (after Penman 1949) the actual moisture deficit is plotted as ordinate against potential moisture deficit as abscissa. Factors read from this relation were used to correct the evaporation rate fE_0 once a deficit of C in. was exceeded and to calculate the actual evaporation.

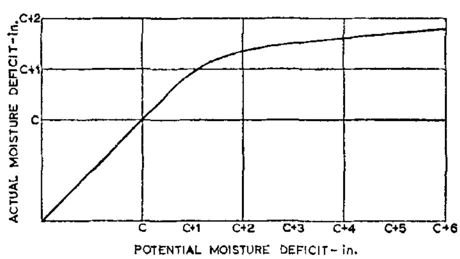

Figure 2. Relation between actual and potential moisture deficit (after Penman 1949).

Finally, the monthly moisture balance at the site was obtained from the difference between the observed precipitation and the calculated evaporation. The excess of evaporation over rainfall was determined for each month and added to the moisture deficit for the previous month to give the potential moisture deficit. When this exceeded 5 in., Fig. 2 was used to determine the actual moisture deficit; when rainfall was sufficiently heavy to eliminate the moisture deficit, excess water would be removed as drainage and further precipitation was not included in the determination of the moisture deficit.

The calculated monthly moisture balance is plotted in Fig. 1. The moisture deficit was taken to be zero at the end of December 1953.

6. Relation between the observed depth of the water-table and the calculated soil moisture deficit

The calculated soil moisture deficit is shown in Fig. 1, together with the depth of the water-table. Both show broadly similar variations with season, the zero and scale of the deficit axis having deliberately been chosen to make the variation of the depth of the water-table (h ft) and the moisture deficit (d in.) coincide as nearly as possible. This fitting process corresponds to the selection of the equation:

$$d = 1{\cdot}3\,h - 0{\cdot}65 \qquad (1)$$

as the best relation between these quantities.

The most noticeable discrepancy is during late autumn when the water-table usually returns abruptly towards the surface and then fluctuates, whereas the moisture deficit decreases more slowly and steadily over a period of a few months. This effect was repeatedly confirmed by noticing the flow of field drains after rainfall equal to or less than the current deficit in autumn. The most likely interpretation is that the rain is temporarily stored in fissures (which were noticed in the dry soil), without completely wetting the soil. In most winters the soil is substantially re-wetted by the New Year.

In Fig. 3 the observed depth of the water-table during each month, taken as the mean of the depths at the beginning and end of the month, is plotted against the corresponding calculated soil moisture deficit. The line corresponding to Eq. (1) is drawn in Fig. 3 to illustrate the reasonable fit of the data.

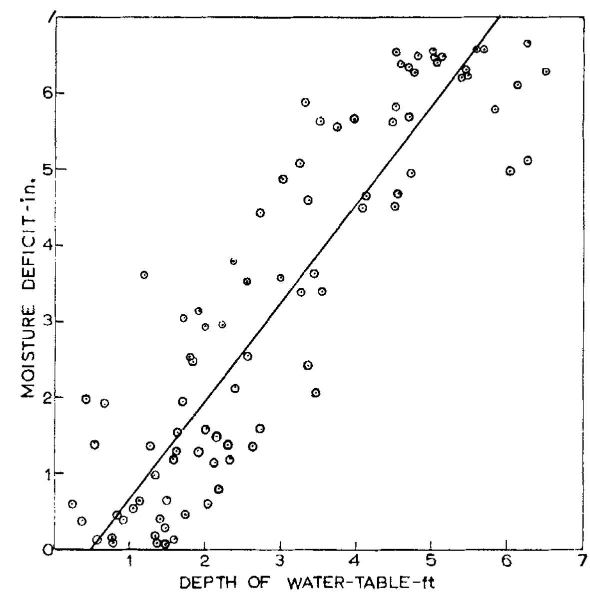

Figure 3. Relation between calculated soil moisture deficit and observed depth of water-table in soil beneath meadow grass.

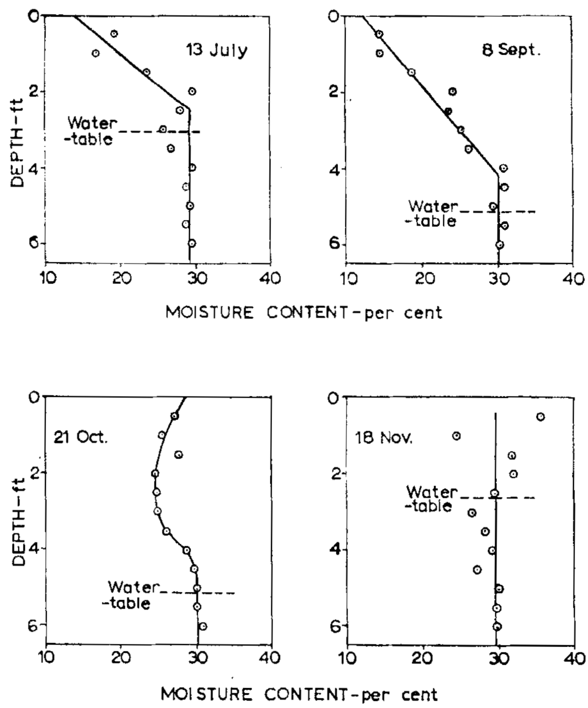

Figure 4. Seasonal changes in moisture profile and depth of water-table beneath grass during 1955.

7. Moisture profiles

A possible explanation of the empirical linear relation observed between the depth of the water-table at this site and the soil moisture deficit calculated from meteorological data can be obtained from an examination of the moisture profile at the site.

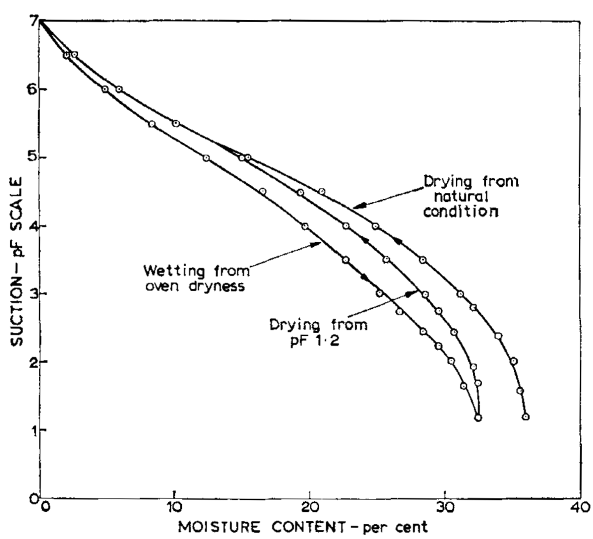

Figure 5. Relation between suction and moisture content for an undisturbed sample of soil from a depth of 4 ft.

The results for four moisture profiles, obtained at different times in 1955, are shown in Fig. 4. In Fig. 5, where the *pF* scale is used to relate water content and suction, the *pF* value is the common logarithm of suction or (negative) soil water potential expressed in centimetres. In a very wet soil when water is held at a small suction of $-$ 16 cm, say, the *pF* is log 16 or 1·2 and the suction at which many plants are found to wilt is about $-$ $1{\cdot}5 \times 10^4$ cm, or *pF* 4·2. From Fig. 5, this wilting point is reached in London clay when the soil water decreases to about 14 per cent by weight. A drying front was established which moved into the soil profile, with a corresponding lowering of the water-table to about 5 ft by September. The moisture content of the soil increased linearly with depth to a maximum of 30 per cent by weight at about 0·8 ft above the water-table. In autumn, the soil surface again became wet, and a wetting front began to move into the drier soil which remained below. By November, the soil was virtually saturated, and the water-table had returned to the surface. The summer moisture profiles may be used to obtain a theoretical relation between moisture deficit d and depth of water-table h. If h_0 is the height of the saturated fringe above the water-table, w_2 the water content by weight (v_2 by volume) at the water-table, and w_1 (and v_1) the corresponding values at the surface, then the total deficit at any time is $(v_2 - v_1)(h - h_0)/2$. If ρ_b is the dry bulk relative density of the soil then, neglecting shrinkage, $(v_2 - v_1) = \rho_b (w_2 - w_1)$. The specific gravity of the soil particles was observed to be 2·78, so with the pore-space full at $w = 0{\cdot}30$, $\rho_b = 1{\cdot}52$. Hence

$$d = 0{\cdot}76\,(w_2 - w_1)\,(h - h_0)$$

with d and h in the same units. If d is in inches, and h is in feet then

$$d = 9{\cdot}12\,(w_2 - w_1)\,(h - h_0)$$

For $(w_2 - w_1) = 0{\cdot}16$, then

$$d = 1{\cdot}46\,h - 1{\cdot}46\,h_0$$

The value of h_0 is not known with any certainty. From Fig. 5 a minimum value of about 0·5 ft can be inferred; from Fig. 4 the value on 8 September was about 1·0 ft. Taking a mean of 0·8 ft, the expected relation is

$$d = 1{\cdot}46\,h - 1{\cdot}17 \text{ in.}$$

This is in reasonable agreement with the relation obtained empirically and given by Eq. (1).

The autumn moisture profile provides an explanation of the poorer fit of Eq. (1) at this season. At this time, the soil surface is becoming wetter, but a dry zone remains below. The moisture deficit is therefore reduced, but the water-table remains lowered until either the dry zone is completely eliminated, or a temporary higher water-table is formed above it.

8. Conclusions

It has been shown that, for the site investigated, the observed depth of the water-table varied linearly with the calculated moisture deficit.

This observation is of interest in road engineering because it suggests the possibility of determining the seasonal variation of the water-table from meteorological data. This would be of practical value in designing the subsoil drainage system to prevent the ingress of water into the road foundations and also to enable the ultimate moisture content beneath the road to be estimated (Black *et al.* 1958).

The observation is also of considerable potential value to the hydrologist concerned with the water balance in a catchment area. The moisture deficit is normally calculated from observed meteorological data or open-water evaporation and direct observation of moisture deficit is not easy. The present investigation suggests that it may be possible for suitable sites on heavy clay under grass to estimate the approximate moisture deficit continuously from a simple measurement of the depth of the water-table, and by use of a depth recorder the moisture deficit could be incorporated into an automatic data-logging system.

Acknowledgment

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