WELL-POINT TECHNIQUES AND THE SHALLOW WATER TABLE IN BOULDER CLAY

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Summary

The reliability of water-table measurements in clay soil is currently under review (Twocock, 1971; Bonell, 1971; Visvalingam, 1972). This paper summarizes some of the experimental results from a boulder clay catchment in East Yorkshire. The experiments investigated the functioning characteristics of cased auger holes and piezometers in clay soil and compared the results with observations made with a neutron moisture probe. It appears that well-point technique, especially piezometers, are extremely unreliable in clay soil. The measured water level is demonstrated to be influenced by not only the position of the 'water table' but also the permeability of the soil; in which context the type, diameter, and length of tubing, as well as the time of installation, become important considerations.

Introduction

The water table

In granular material the water table is easily conceived as the water level in supercapillary openings. In fine-grained material, however, there is a gradual decrease in moisture content with height, ranging from capillary saturation just above the water table to the inclusion of more and more air in all except the finest interconnected voids with increasing height above the free water surface. Although there has been some discussion on whether the upper or the lower surface of the capillary fringe is the more meaningful parameter in the study of the water table (Vaidhianathan and Singh, 1942; Luthin and Day, 1955), Richards's (1952) concept of the water table as the locus of points in the soil water at which pressure equals atmospheric pressure, has been widely accepted and is used in the present study.

Problems of measurement

The measurement of the water table in anisotropic soil is difficult, owing to the formation of perched-water bodies and lateral drainage in near surface layers (Fukunda, 1964; Whipkey, 1965). In such conditions the disadvantages of the electric resistance, tensiometer, and auger hole methods are associated with the alteration of the natural soil conditions. In layered soil, the horizontal hydraulic conductivity may be much greater than the vertical, and the installation procedure may greatly alter this condition locally at the point of measurement. Theoretically, a nest of piezometers of different lengths seemed to offer the best means of detecting separate zones of saturation.

It has been appreciated that the well-water level may not correspond to the water table in the surrounding soil. Some of the instrumental factors observed to contribute to the discordance are smear (Twocock, 1971), and the diameter of the tube (Vaidhianathan and Singh, 1942;

Kirkham and De Zeeuw, 1952; Benz *et al.*, 1963). Moreover, the creation of a bore in itself may lower the water table just at the point where the observation is being made (Childs, 1943). Kirkham (1947) also pointed out the influences of pressure gradients and permeability on the level of the water surface in perforated pipes and piezometers.

Doubts about the validity of piezometric methods have been raised by a number of authors (e.g. Twocock, 1971) and confirmed by early observations in the Catchwater Catchment. Also most investigators have selected the time of installation of tubes, as well as the length of piping, in a rather arbitrary manner, and have sometimes arrived at conclusions using just one tube per site.

Hence, an experiment was conducted to evaluate the reliability of the piezometer method. As piezometric observations could not be assessed independently, cased auger holes and the neutron method were also included for comparison.

Method

The experiment was conducted in the University of Hull Catchwater Catchment in East Yorkshire (Fig. 1). Ward (1967) and Bonell (1971) discussed various aspects of the geographic and hydrologic details of the area. A plot, 15·24 m square, with a relative relief of less than 0·3 m was selected in a boulder clay site under pasture, close to the Hydrological Station at Westlands (Fig. 1). The field was known to be tile drained.

Bonell (1971) observed that the clay-loam soils associated with the surface Hessle Till have a distinctive zonation of soil in the Catchwater Catchment. The A horizon has a relatively low clay content of 25–30 per cent with the greatest concentration of medium and fine sand. This layer was also less compact owing to ploughing and a greater concentration of biological activity nearer the surface of the soil mass. The centre of the clay pan that immediately followed the A horizon was chiefly located 30–90 cm below the surface, where the amount of clay attained the greatest concentration of 34 to 55 per cent. The parent boulder clay beneath the clay pan was fairly uniform with depth: 40 per cent silt and 25–30 per cent clay. Saturated hydraulic conductivity ranged from 0·12 to 3·79 cm/day but increased considerably in sand, silt, and gravel lenses which could occur at any depth within the till.

Even within the small experimental plot, the boulder clay was found to be quite variable. The most notable feature was the occurrence of a lens of fine sand to the north of the tile drain commencing at about 20 cm from the soil surface. Minor variations were found within this area as well as in the more typical stratified clay soil to the south of the tile drain; a more uniform parent boulder clay extended to within 1·52 m of the surface.

Well-point techniques

Instrumentation in the experimental plot is shown in Fig. 1. Varying lengths of piezometers were used. These were fitted with wooden bungs and driven into the soil with a sledgehammer, leaving 15·24 cm

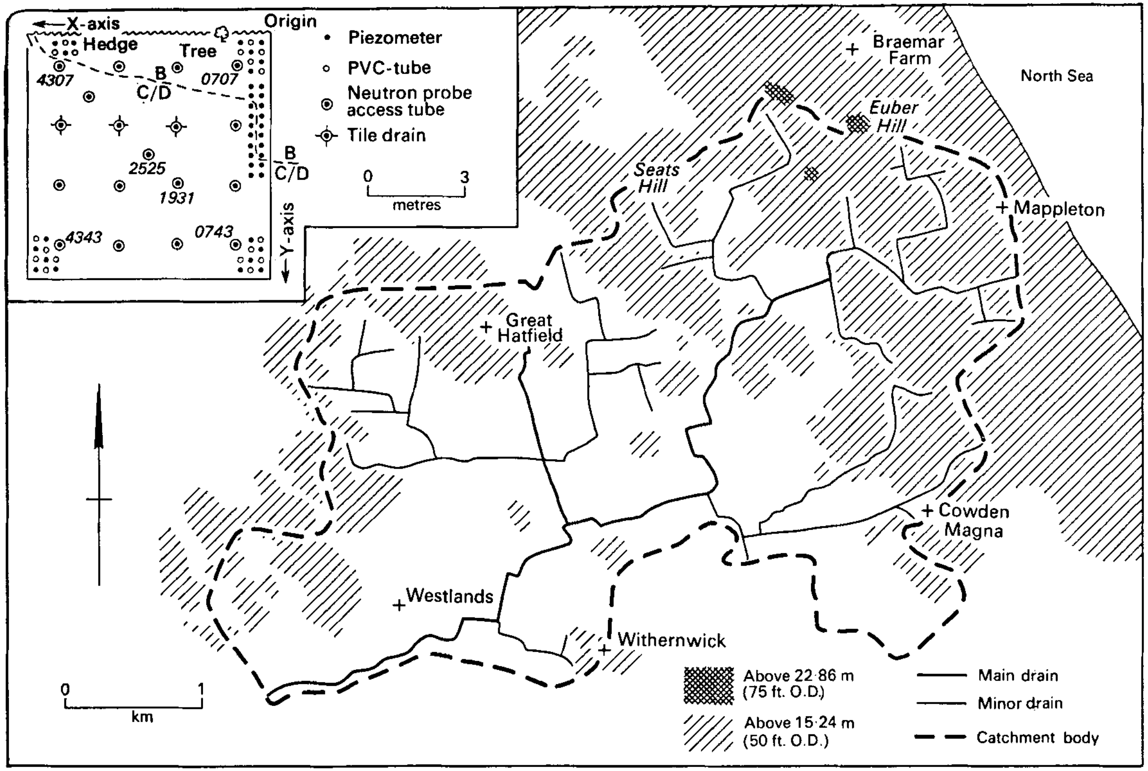

FIG. 1. Location of the experimental site, with inset showing the instrumental lay-out.

protruding above the soil surface. A narrow iron rod was then inserted into the pipe to punch out the bung, thereby exposing a basal cavity.

Different lengths of 5·08 cm diameter polyvinyl chloride (PVC) tubes were perforated with 0·476 cm diameter holes, at 2·54 cm intervals along equally spaced axial lines, leaving only the protruding 15·24 cm free of perforations. The tubes were then installed into bores made with a 7·62 cm bucket auger and the space between was then backfilled. The depth of the water surface in the tube was measured with an electric probe similar to that used by Russell (1945) and Ward (1962). Minor alterations to the original design consisted of the replacement of the flat contacts by brass prongs to minimize the adhesion of water between them.

All installations within the plot were located in terms of coordinates with the origin at the north-east corner of the plot (Fig. 1). The piezometer nest along the eastern side of the plot consisted of 20 tubes, varying in length from 7·62 to 152 cm in increments of 7·62 cm. These were installed in early December to detect any significant layering of soil which might produce a perched water body. Owing to marked soil variations over short distances, it was important not to spread the nest over too wide an area. Hence a 0·6 m grid was selected and the shorter and longer lengths of tubes were alternated along the two lines to minimize any mutual interference.

The corner clusters of well-point techniques consisted of 45·7, 91·4, and 152 cm lengths of piezometers and PVC tubes. The aim was to determine whether there was a significant deviation between the level of free water in the piezometers and PVC tubes of the three selected lengths. It was hoped that these, together with the piezometer nest would also check the effects of tube length on the measured water level. All discussion refers to data collected between the period August 1970 to August 1971.

The neutron moisture meter

The neutron moisture meter used was manufactured by Nuclear Enterprises (G.B.) Limited. The 53·6 cm long moisture probe, 3·8 cm in diameter, consists of a 30 mC Am^{241} Be source, side placed on a BF_3 proportional counter. The aluminium alloy access tubes used were a standard 10·2 cm in length. These were driven into slightly undersized auger holes, leaving 15 cm protruding above the surface. The access tubes were covered with rubber bungs, with silica-gel bags suspended from them to keep the tubes as dry as possible. Observations were made in 15 access tubes, all of which were to have been located at the intersection of grid lines spaced 3·66 m apart. However, tile drains were encountered at 1919, 3119, and 4319. Thus the sampling points were modified as indicated. Readings commenced at the 7·62 cm depth and extended to 91·4 cm below the surface in increments of 7·62 cm. A more thorough analysis of neutron probe data will be made in a separate paper.

Discussion

Piezometer nest

The results indicated a general pattern of lower equilibrium water levels in deeper tubes in the piezometer nest. However, there were discernible differences in the patterns of reaction, which enabled a classification of these tubes. The tubes which were dry at least half the number of times they were read were classed as Group A and are omitted from the discussion, as the scarcity of data denied any useful interpretations. The differences between groups B, C, and D were visually gauged (Fig. 2). Members of group B reacted more readily to recharge and discharge compared with group C, in which the movements of the water level are less extreme. The members of group D show some response to rainfall but the most marked feature is that of a rising water level until June even though others begin to decline from about May. The areal distribution of groups B and C (Fig. 1) suggest a difference in the permeability of the soil rather than the compaction of soil around the basal cavity of the tubes in group C. The difference could result from the length of the piezometers. For the greater the distance between the water table and the basal cavity, the less would be the immediate effect of an addition of moisture during rainfall. However, this alone does not explain all the features present. The members of group D seem to show rising water levels until 24 June, while those in group C recorded a fall much earlier. This seemed to suggest that subsurface drainage from the basal cavity of group D was less rapid than from group C. The most likely explanation is that group D was penetrating a more impermeable stratum and that some lateral flow may have occurred above this substratum. This would explain the more gradual rise of the water level in group D. After this rise, downward percolation through the substratum would occur only very slowly. During the recession of the water table, tubes in group C would dry out more rapidly by percolation through a relatively more permeable stratum and lateral movement above the impermeable substratum.

The corner clusters

The time-series of the 152 cm piezometers from the four corner clusters show a broad similarity in trend (Fig. 3). All indicate declining water levels until mid November 1970, rising levels until the end of April or early May 1971, followed by a fall in water levels after that. For most of the period under observation the hydraulic gradient is to the north-east. This is not unusual as the ground slopes in the same direction. The time-series also suggest that the magnitude of this gradient, and possibly also the direction, is not constant with time. The difference in water levels seems to decline during the recession of the water level and increase again during recharge. This is a result of the relatively more rapid rise and fall of the water levels in the tubes to the south-east and south-west (tubes 0248 and 4848 respectively) compared to tubes 0202 and 4402. The former also responded earlier to recharge. The hedge, the tile drain, and the sandy substratum, commencing at about 91·4 cm below the surface in the north-east, would partly explain the relatively slower rise and fall of the water table. This would be so, not only because of the larger drainable porosity, but also because sand would act as a localized discharge area into which water from the surrounding soil would drain. From Fig. 3 it is also apparent that the much lower

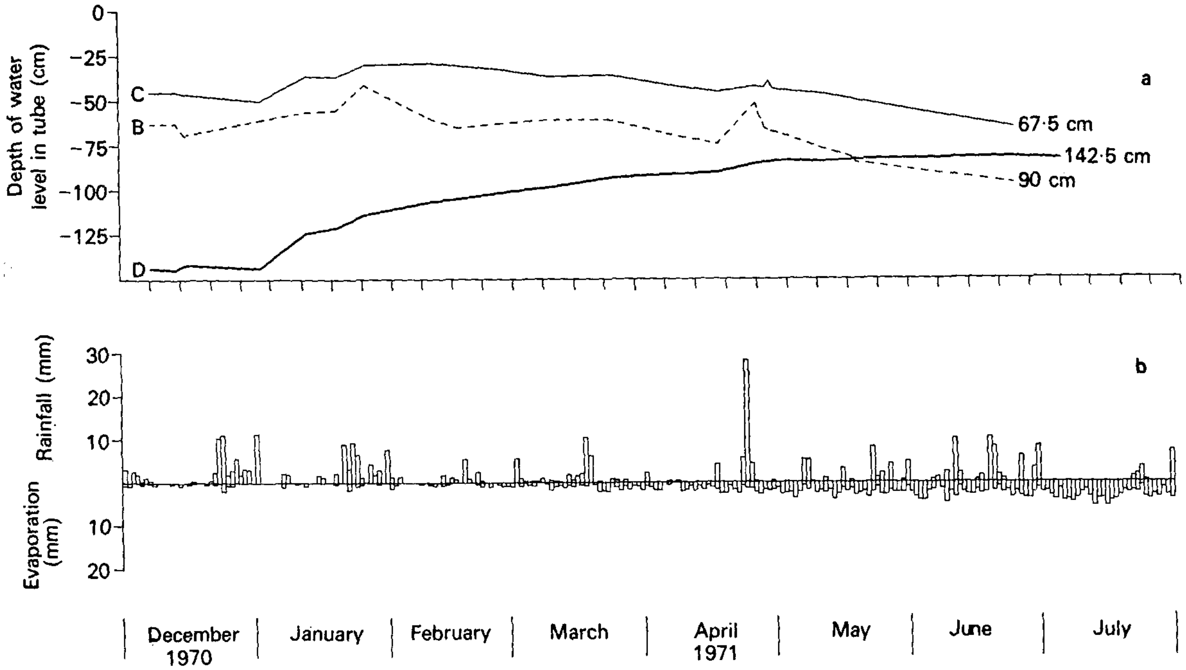

FIG. 2. Time series of three tubes in the piezometer nest, illustrating the differences between groups B, C, and D (a), with precipitation and evaporation during the same period (b).

level in the 152 cm piezometer (0329), does not conform to the suggested hydraulic gradient.

Although the 152 cm piezometer showed a gradual rise of the water table, all other observations showed that the soil was saturated to within 91·4 cm of the surface by the end of November (Fig. 4). All indicated a hydraulic gradient to the north-east.

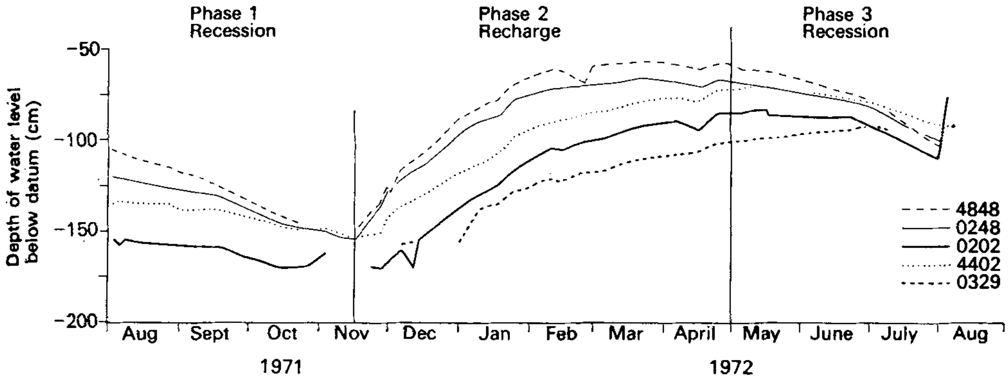

FIG. 3. Time series of the 152 cm piezometers.

Although there was some degree of discordance within each corner cluster, the difference in the behaviour of the northern and southern tubes seemed to reflect the differences in subsoil conditions and hence water movement within the plot. Like group C/D in the piezometer nest, the piezometric observations in the south-east indicated a downward pressure gradient (Kirkham, 1947). The close similarity in the pattern of water level fluctuation in the three lengths of tubing suggested a fairly homogeneous subsoil. The PVC water levels in the south were by no means identical but there was as much difference between the pairs of 45·7 cm and 91·4 cm tubes as among them. The water level in the 152 cm tube (Fig. 4), on the other hand, was consistently about 2·5 cm to 5·0 cm lower than water levels in the shorter lengths, except during water-level peaks. From Fig. 4 it is also apparent that the 152 cm piezometer in the south was lagging in response. The observations from the south-west and south-east corners of the plot suggested the sort of situation, described by several authors including Fukunda (1964) and Whipkey (1965), which encourages the formation of perched water tables and interflow in near-surface layers. Investigations in the Catchwater Catchment by Bonell (1971) suggested that the soil conditions in the boulder clay areas foster the occurrence of perched zones of saturation and interflow in the cooler parts of the year. In the south-west corner of the Westlands experimental plot, augering for PVC tubes did indicate a stony, clay indurated layer from about 45·7 cm below the surface. As even 45·7 cm piezometers showed a lag both in the rise and fall of the water table, it is likely that the basal cavities of the latter were in a relatively impermeable stratum. The observations seem to suggest

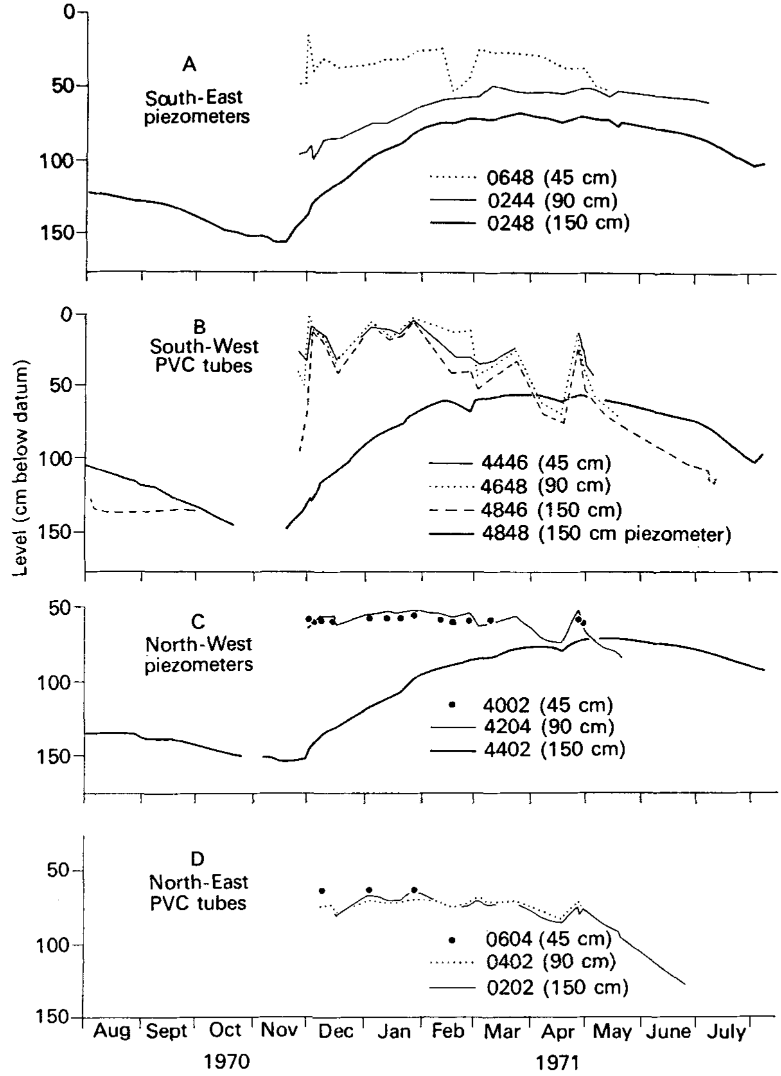

FIG. 4. Piezometer and PVC tube behaviour in the north and south parts of the experimental plot.

a superficial layer of saturation with a large component of lateral flow. The hydrographs of the PVC tubes, with sudden peaks and rapid recession (as for example in April 1971) suggest fairly high horizontal flow velocity. This was probable as Fig. 3 indicates a small but significant gradient, especially when it is noted that the sampling points are astride the only observed tile drain. Hence, the maximum hydraulic gradient is likely to be steeper if a section normal to the tile drain was observed.

Neutron probe readings from access tube 4343 (Fig. 5) suggested a zonation of either moisture content, soil, or both. The indicated moisture content of the A horizon is greater, probably due to the more open structure of the soil. Although the high standard error masked the actual movements, the distribution near the surface is not so peaked as at lower depths, suggesting a more variable moisture content. The B and C horizons show a progressive decline in median count rate, reflecting a lower drainable porosity in the subsoil. If the tight layer in the B horizon is the result of clay illuviation, the higher density may have resulted in the slightly higher median count rate in the B compared to the C horizon. Note also that significantly lower count rates were observed on 17 November 1970 at all depths (except the 23 cm depth). However, the B horizon attained capillary saturation (at least) by 24 November 1970. Although the actual depth to the water table of 30·5 cm in PVC tube 4842 may not correspond to the depth of the water table at location 4343, it indicated that a perched zone of saturation had formed by 24 November 1970 and this is significant because the moisture profiles support the belief that a vertical diffusion of water through the restricting horizon is possible even if the major direction of moisture flow is lateral, above the restricting horizon.

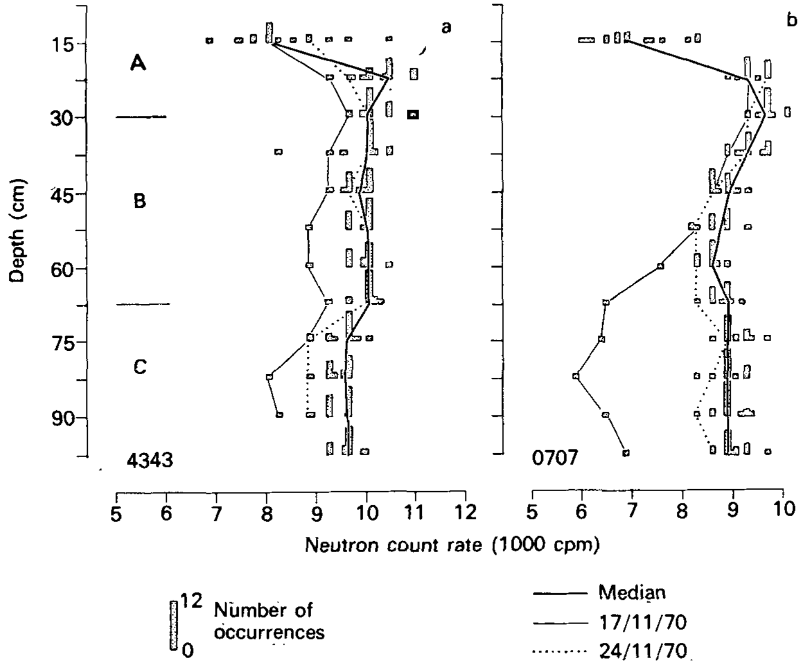

FIG. 5. Differences in neutron count rate distribution with time and depth in a distinctly zoned clay profile (a) and a clay-loam with a sand lens (b).

Observation from the north of the plot showed different controlling factors and effects. Both PVC tubes and piezometers showed good drainage conditions within 66·0 and 55·9 cm of the datum level in the north-east and north-west respectively. The downward diffusion of moisture to a greater depth is encouraged by the occurrence of sand, but even this seemed to give way to lateral flow above the tight layer, which the 152 cm piezometers seem to penetrate (Fig. 4c). On the whole, the 45·7 cm and 91·4 cm tubes show less fluctuating, concordant levels stabilized at relatively lower levels compared with the north.

Access tube 0707 (Fig. 5) when compared with tube 4343 illustrates some of the striking differences within the 15·2 m square. However, despite the larger drainable porosity of the soil, capillary saturation is attained fairly rapidly.

Conclusions

From the above observations one may comment further on the functioning characteristics of well-point technique. The results as a whole emphasized that observations from different lengths of piezometers and cased auger holes are comparable only when they terminate in a porous, permeable, and homogeneous medium like sand. Under such conditions the water level in an auger hole would correspond quite closely to the water table in the surrounding soil. The tube being 'open' along its entire length, the expected lag is small and would depend on the hydraulic conductivity of the soil and the aperture of the tube. However, the relationship between the well-water level and the water table(s) in glacial drift is difficult to ascertain. The well-water level is likely to correspond to the perched water table if the perforated tube penetrates the perched zone of saturation and terminates in a restricting horizon of low conductivity. This is probably the case with the 45·7 and 91·4 cm PVC tubes in the south-west. However, the water level in a tube is likely to be displaced some distance below the water table where the tube penetrates further, past the restricting horizon, into layers where the subsoil drainage is more rapid. During periods of rainfall, the rapid inflow of infiltrating moisture compensates for the downward percolation of water, but when this source is cut off during periods of recession, effects of good subsoil drainage become detectable (see: 152 cm PVC tube 4846, Fig. 4).

In the hydrologic conditions present in the Westlands Soil Moisture Plot, the length of the PVC tube is likely to be of importance only in an indirect manner. For the longer the tube, the more likely it is to traverse layers of different hydraulic conductivity.

The cased auger hole is capable of locating the uppermost phreatic surface only in some circumstances. Consequently, it can measure the main water table only in the absence of a perched one, or when both coincide. Furthermore, the measured water level in itself gives no indication of whether it refers to the perched zone of saturation, a permanent one, both, or whether it refers only to the balance between inflow and outflow in the open column.

Although in some circumstances the PVC tube water level may be a reasonable index of drainage in the surface layers of the soil, it has to be used cautiously in other applications, for example in the estimation of soil moisture storage.

Piezometric surfaces may or may not be in equilibrium with the water table in the surrounding soil. The influencing factors are again the hydraulic conductivity of the soil, the aperture of the tube, variations in flow patterns, and probably the direction of the pressure gradient. The results from the piezometer nest and the corner clusters indicate that the variation in soil type is the most important single factor. It affects piezometric levels in two ways:

1. Heterogeneous soil produces locally different flow patterns so that varying patterns of piezometric fluctuations tend to reflect, in part, actual differences in the movement of the water table. For example, the differences in the behaviour of the northern and southern tubes or members of groups B and C in the piezometer nest are partly a reflection of different conditions.
2. Variations in the hydraulic conductivity of the soil can also affect the response of the piezometer to pressure fluctuations in the surrounding soil. The movement of the water level in a piezometer can be expected to correspond to the movements of the water table only when the tube terminates in soil of high hydraulic conductivity. The depth and pattern of fluctuation of the water levels in 91·4 cm PVC tubes and piezometers were comparable in sand.

However, where the hydraulic conductivity of the basal cavity is poor, the piezometer lags in response. The 152 cm piezometer was observed to show a gradual rise and fall of the water level, while all PVC tubes showed rapid fluctuations in water level at a shallow depth during most of the cooler parts of the year. This tends to suggest that the movement of the water level in a piezometer terminating in tight clay is influenced not only by the position and movement of the water table but also by the maximum rate at which water can enter the tube. In this respect the length, aperture, and time of installation of the tube become important factors. The much lower water level in tube 0329 (Fig. 3) compared with the other 152 cm piezometers demonstrates the effects of hydraulic conductivity. As the tube was installed later, it began filling in from the base later and thus constantly lagged behind the others until the recession phase.

The downward displacement of water levels in deeper tubes within groups C and especially D in the piezometer nest may be, in part, indicative of the downward pressure gradient. I believe that this is yet another example of the combined effects of poor conductivity, relatively large aperture of the tube compared with the drainable porosity of the soil, and the length of the tube.

In the kind of situation found in the experimental site, unless piezometers terminate above the restricting horizon of poor conductivity, they are incapable of following the fluctuations of the uppermost level of saturation. In drainage and moisture-balance studies one might be tempted to choose long piezometers as representative tubes primarily because they are least likely to dry out and hence give the longest numerical records. However, from the above observations and those of Kirkham (1947) longer piezometers are the least reliable owing to the effects of permeability and pressure gradients. Finally, the above investigation points out the danger of forming conclusions from the indications of one method or one length of tubing. The investigation also questions the use of the water level in an observation well in layered clay soil for the estimation of soil-moisture storage throughout the hydrologic year.

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