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FIELD INVESTIGATIONS OF THE NATURE OF WATER-TABLE RESPONSE TO PRECIPITATION IN SHALLOW WATER-TABLE ENVIRONMENTS

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FIELD INVESTIGATIONS OF THE NATURE OF WATER-TABLE PESPONSE TO PRECIPITATION IN SHALLOW-WATER-TABLE ENVIRONMENTS

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MANAGEMENT PERSPECTIVE

This paper briefly describes the results of a number of field experiments conducted to prove the influence of the capillary fringe in shallow-water-table environments. The results indicate that the influence is substantial and locally widespread although probably of little importance outside certain low-lying and geologically-complex ground water discharge zones. Possible of some significance in terms of ground water contamination in these discharge zones.

PERSPECTIVE ADMINISTRATIVE

Ce rapport donne un bref aperçu des résultats d'un certain nombre d'expériences effectuées sur le terrain pour établir l'influence de la frange capillaire dans les milieux où la nappe phréatique est peu profonde. D'après les résultats, cette influence est importante et largement étendue localement, bien que probablement de peu d'importance à l'extérieur de certaines zones de décharge des zones d'eaux souterraines basses et géologiquement complexes. Il est possible que cela ait une certaine importance pour la contamination des eaux souterraines dans ces zones de décharge.

ABSTRACT

Several water-table response tests performed in undulating topography at a field site near Chalk River, Ontario are analysed. The objective of the experiments was to gather detailed field information on the nature of the water-table rise in response to precipitation in a shallow water-table environment. The tests were performed by applying simulated rainfall to a study site instrumented in detail with porous membrane tensiometers. Changes in hydraulic head were measured using a pressure transducer and a hydraulic switch.

A disproportionate rise in the water table was observed in areas where the zone of tension saturation (capillary fringe) extended to ground surface. For example, for rainfall of 5 mm over a duration of 5.3 min, the water table in the lowest-lying areas rose about 13 cm while the rise in the area of higher ground was only 5 cm. Furthermore, as a result of the difference in response between the low-lying and higher ground, complex and transient hydraulic gradients were established directed away from the low-lying area. The magnitude of the response in the low-lying area can only be explained by the presence of the capillary fringe.

RÉSUMÉ

Plusieurs essais de réactivité de la nappe phréatique effectués sur un terrain à topographie ondulante situé près de Chalk River en Ontario ont été analysés. L'expérience avait pour but de recueillir des données détaillées sur la nature de la hausse de la nappe en réponse aux précipitations dans un environnement où la nappe est peu profonde. Les essais ont été effectués à l'aide de précipitations simulées sur un terrain d'étude parsemé de tensiomètres à membrane poreuse. Les changements dans la charge hydraulique ont été mesurés à l'aide d'un capteur de pression et d'un interrupteur hydraulique.

Une hausse disproportionnée de la nappe a été observée dans les sections où la zone de saturation de tension (frange capillaire) s'étend jusqu'à la surface du sol. Par exemple, pour une précipitation de 5 mm d'une durée de 5.3 minutes, la nappe phréatique dans les zones les plus basses s'est élevée d'environ 13 cm, tandis qu'elle ne s'est élevé que de 5 cm dans les secteurs où le sol est plus élevé. En outre, par suite de la différence de réponse entre les sols bas et les sols hauts, les gradients hydrauliques complexes et transitoires ont été établis en s'éloignant du secteur bas. L'ampleur de la réponse dans ce secteur bas ne peut s'expliquer que par la présence de la frange capillaire.

INTRODUCTION

Several field observations (Meyboom, 1967; Gillham, 1984) and some recent simulations (Abdul and Gillham, 1984) have shown that shallow water tables can often rise disproportionately in response to rainfall. The magnitude of the response is often greater than the specific yield of the geological material in which the process occurs and is thought to be a very dynamic and transient phenomenon. In the past such responses have been attributed to either an increase in the gas phase pressure caused by the infiltrating wetting front (the Lisse Effect) or to the presence of the capillary fringe (Meyboom, 1967). Gillham (1984) presents theoretical and limited field evidence indicating that the capillary fringe may strongly influence the magnitude and transient nature of a shallow-water table response to rainfall. Abdul and Gillham (1984) provide laboratory and simulation data which supports this hypothesis with particular reference to streamflow generation.

Mechanism of Water-Table Response

Unsaturated soils are characterized by a moisture content - pressure head relation commonly referred to as the moisture retention curve. This non-linear relation describes how the moisture content of a soil changes with changing negative pressure head. Figure 1 shows the moisture retention curve for a medium grained sand. A brief description of one drying cycle will introduce the necessary terms. At a pressure head of zero the sand is fully-saturated (θ_s). With decreasing pressure the soil remains saturated until the capillary forces maintaining saturation are overcome and the largest pore drains. The negative pressure at which this occurs is termed the air entry value and the zone between zero pressure head and the air entry value is called the zone of tension saturation. An air entry value in the order of -30 cm of pressure head is common for a sand of this type. Further decrease in pressure below the air entry value results in successive drainage of the sand. This continues until the residual moisture content is reached (θ_r) where the sand stops draining and the remaining water is held mostly by electrochemical forces which further decreases in pressure head will not remove. Childs (1969) provides a more thorough description of the stages of water drainage in a porous soil.

In a natural hydrogeologic environment the zone of tension saturation is referred to as the capillary fringe and occurs as a three-dimensional region above the water table. Soil texture is the major factor controlling the thickness of the capillary fringe, and as indicated in Figure 1 would be approximately 30 cm thick for a medium grained sand. It is clear that when the top of the capillary fringe meets the surface of the ground (the soil is saturated to ground surface) any influx of water will relieve the capillary tension allowing the water table to rise rapidly to the ground surface. In fact, hypothetically most of the incident rainfall should pond or escape as overland flow.

Gillham (1984) provides a more thorough discussion of the mechanism of the water table response and presents the results of a field experiment which demonstrate its rapid and transient nature. He also introduces several hydrogeologic situations where the capillary fringe may play an important role in governing hydrogeologic processes. In particular Gillham describes a hypothetical field situation in a ground water discharge zone with undulating topography where the capillary fringe extends to ground surface in the lowest-lying areas. He then proceeds to describe the anticipated response to a rainfall event. The purpose of this note is to present the results of simulated rainfall experiments in a real hydrogeologic setting similar to that Gillham describes. Specifically, our objectives were to demonstrate that under shallow-water table conditions, the presence of the capillary fringe can induce a rapid and disproportionate response to precipitation and that in areas of rolling or undulating topography a disproportionate water-table response can result in highly transient and complex hydraulic head distributions.

EXPERIMENTAL METHOD

The field investigations were conducted in a swampy area of the Perch Lake Basin on the property of the Chalk River Nuclear Laboratories, Atomic Energy of Canada Ltd. in Northeastern Ontario. The topography over much of the swamp consists of elongated roughly parallel ridges separated by distances in the order of 10 m. The difference in elevation between the top of the ridges and the base of the troughs between varies from about 0.3 m to 1.5 m. The topography is thought to be primarily aeolean in origin (Jackson and Inch, 1980).

The site selected for detailed study encompasses an area of approximately 3 by 5 m and is siutated near the centre of the swamp. Figure 2 shows a cross section of the site to approximately one m depth. This cross section lies perpendicular to the axis of a long ridge that forms the high point. A trough, with its lowest point 34 cm below the peak of the ridge, lies parallel to the ridge. The site is covered by eastern lowland grasses with some alders and ferns. An effort was made to minimize the disturbance to the natural vegetation during the instrumentation of the site.

The stratigraphy underlying the trough and ridge is also shown in Figure 2. The surface cover consists of a dark greyish-brown mat which varies in thickness from 7.5 cm in the trough area to 22 cm on the ridge. This layer is comprised of a mixture of sand, plant roots and organic debris. A pinkish-grey medium- to fine-grained sand underlies the organic layer and thickens from 20 cm in the trough area to 30 cm on the ridge. This layer grades into a grey bedded sand of similar texture below.

The study site was instrumented with 13 tensionmeters to provide measurements of hydraulic head during each of the infiltration experiments. The tensiometers were constructed of acrylic tubes approximately 100 mm in length and 19 mm in outer diameter. The lower half of each tensiometer was slotted and covered with a porous membrane which has a bubbling pressure of approximately five m of hydraulic head. The porous membrane maintains a hydraulic connection between the soil and the interior of the tensiometer under negative values of pressure head. When the pressure becomes positive the tensiometer functions in a manner identical to a piezometer. Each tensiometer was connected to a pressure measuring device by means of 1.6 mm inernal diameter polyvinylchloride tubing attached to a single hydraulic switch. The hydraulic switch was activated by a variable time relay to sweep through 24 input ports providing a direct hydraulic connection to a single output port. A pressure transducer (strain gauge type) with a pressure range of ±5 m of head was used as a pressure measuring device and attached to the output port on the hydraulic switch. Two standards of known elevation head were also attached to input ports to correct for temperature drift in the transducer signal. The tensiometers were installed at depths ranging from a few cm to 1.5 m (Figure 2).

A sprinkler system was designed in order to provide simulated precipitation of varying intensity and duration. The sprinklers were arranged in a configuration such that an even distribution of water was maintained over the entire study site. Two rain gauges were used to measure the amount of simulated rainfall for each test. Water for the sprinkler system was drawn from a developed well approximately 125 m away. A shallow water table well was installed in the trough area and monitored periodically throughout the test period. The water table was approximately 30 cm below ground surface just prior to the first infiltration experiment.

Three infiltration experiments were conducted with rainfall varying in intensity between 43 mm/hr and 63 mm/hr. The test duration ranged from 1.4 minutes to 23.4 minutes. Table 1 summarizes the experimental conditions for each test. Prior to each infiltration experiment, numerous background measurements of the hydraulic head distribution over the site were collected. These data show that the initial water table elevation was at approximately 30 cm depth in the trough area and 60 to 65 cm in the ridge area. Very small vertical gradients were evident during this period, probably as a result of soil compaction created by human activity on ground surface. The initial water content distribution was inferred from the pressure head distribution and the main drainage curve of the water content-pressure head relation for Chalk River sand (See Abdul and Gillham, 1984). Figure 4 shows the water content distribution for the trough and ridge areas.

The infiltration experiments were conducted over a span of one week. The results of the second experiment only will be presented in detail although the results of the first and third experiments will be introduced briefly in a broader context in the discussion. We wish to draw attention to the results of the second experiment because the application rate, intensity and duration of rainfall best approximate a brief, intense summer rain storm very common in eastern North America.

RESULTS AND DISCUSSION

Prior to the start of the second infiltration experiment, the depth to the water table was approximately 29.5 cm and hydraulic head measurements indicated equilibrium conditions. Simulated rainfall was applied for 5.3 minutes at an intensity of 60 mm/hr for a total application of 5 mm. Figures 4 and 5 show the hydraulic head in the trough area and ridge area, respectively, in response to the simulated rainfall applied during experiment two.

Response was evident at all measuring points in the trough area immediately following the initial application of rain. The largest (24 cm) and most rapid response was observed in the shallowest tensiometer (No. 5) in the trough area. The other tensiometers showed similar but somewhat slower responses. The deepest tensiometer (No. 6) in the trough area, well below the initial water table surface, showed an increase in hydraulic head of 12 cm resulting in a strong vertical gradient of approximately 0.26. This suggests that the influence of the water-table response may extend to considerable depth, probably in the order of several metres. Following the initial rise, hydraulic head declined at a rate approximately one-twelfth the rate of rise starting at the end of the period of rainfall application.

Response to rainfall in the ridge area was considerably less pronounced then that observed in the trough. A maximum of 5 cm rise in head was observed 25 minutes after the rainfall application. A brief decline in hydraulic head of 3 to 4 cm was observed immediately following the initiation of rainfall possibly as a result of increased gas phase pressure due to the infiltrating wetting front.

The position of the water table during the infiltration experiment was determined by plotting the pressure head against elevation. The point at which the line joining the data crosses zero pressure head was taken as the water table elevation. Figure 6 shows the elevation of the water table in the trough area for six specified times during experiment two. Note that during early time the presence of two water tables is observed. This is believed to be the result of heterogeneity in hydraulic conductivity near the ground surface, and in particular heterogeneity in the organic-sand layer. In the absence of the organic layer the rise of the water table would be expected to be even larger. As a conservative measure only the lower water table elevation is shown. Figure 7 shows the elevation of the water table below ground surface in the trough area for both the trough and ridge areas against elapsed time. It is evident that during early time significant lateral gradients are generated away from the trough towards the ridge.

Of particular interest in this study is the marked difference in hydraulic-head and water-table response between the trough and ridge areas. The delayed response to rainfall observed in the ridge area was duplicated in both experiment one and three. This delay is a result of the less than saturated porous media between the capillary fringe and the ground surface where the simulated rainfall simply established a wetting front resulting in a relatively diminished and much slower response.

The rise in hydraulic head in the trough area was similar during experiment three and in particular experiment one. The rate of rise, however, was dependent on the application rate of rainfall. The most rapid rise was observed during experiment two as a consequence of the very rapid rate of rainfall application.

The rate of hydraulic-head response in both the ridge and trough areas appears to be largely dependent on the nature and degree of heterogeneity of the porous material in which the capillary fringe is situated. The organic mat which covers our study site had the effect of storing and later releasing water in the ridge area while in the trough area the organic layer lead to the development of a second, perched water table during the beginning of experiment two. Hydraulic head was irregular at shallow depth in both experiment one and three also as a result of heterogeneity.

CONCLUSIONS

The results of these field experiments have demonstrated that the response of shallow water tables to rainfall can be very dynamic although of relatively short duration. In low-lying areas of undulating topography, precipitation and evapotranspiration can lead to the development of complex and highly irregular flow patterns for much of the year. The influence of these processes can be expected to influence the flow system to considerable depth and to rapidly move considerable quantities of ground water over short durations. In the case where point-source contamination is introduced into such an environment, the effect would be to widely disperse and homogenize contaminant concentrations particulary where the geolog materials are heterogeneous.

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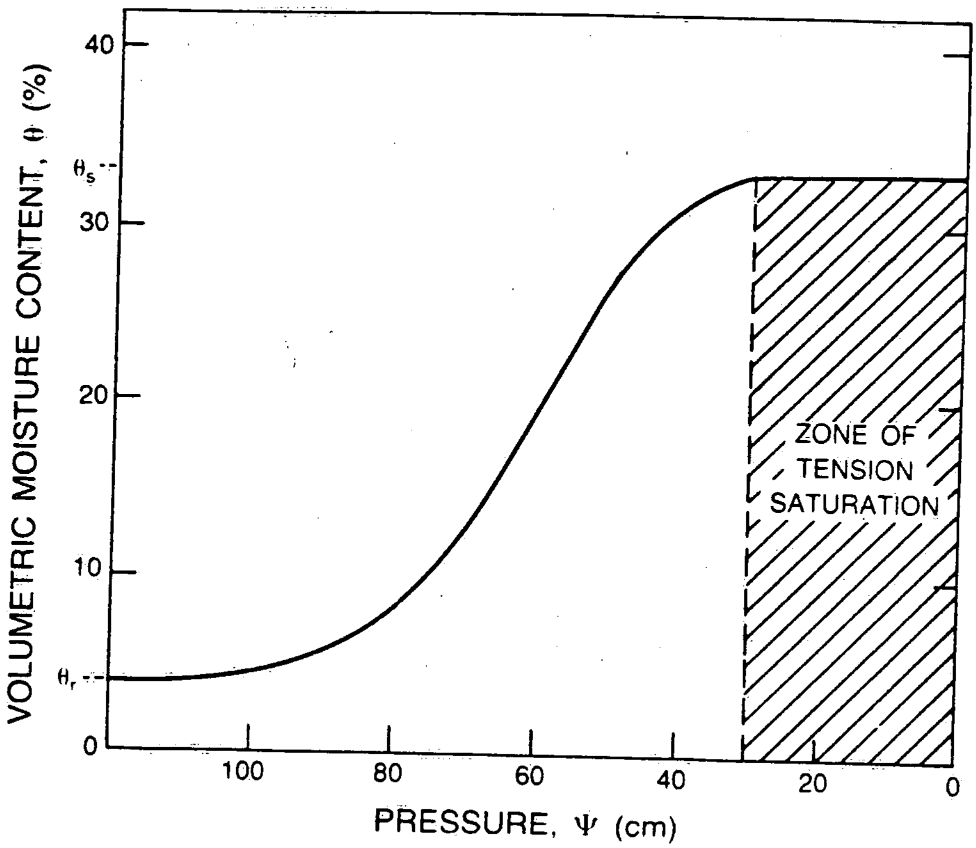
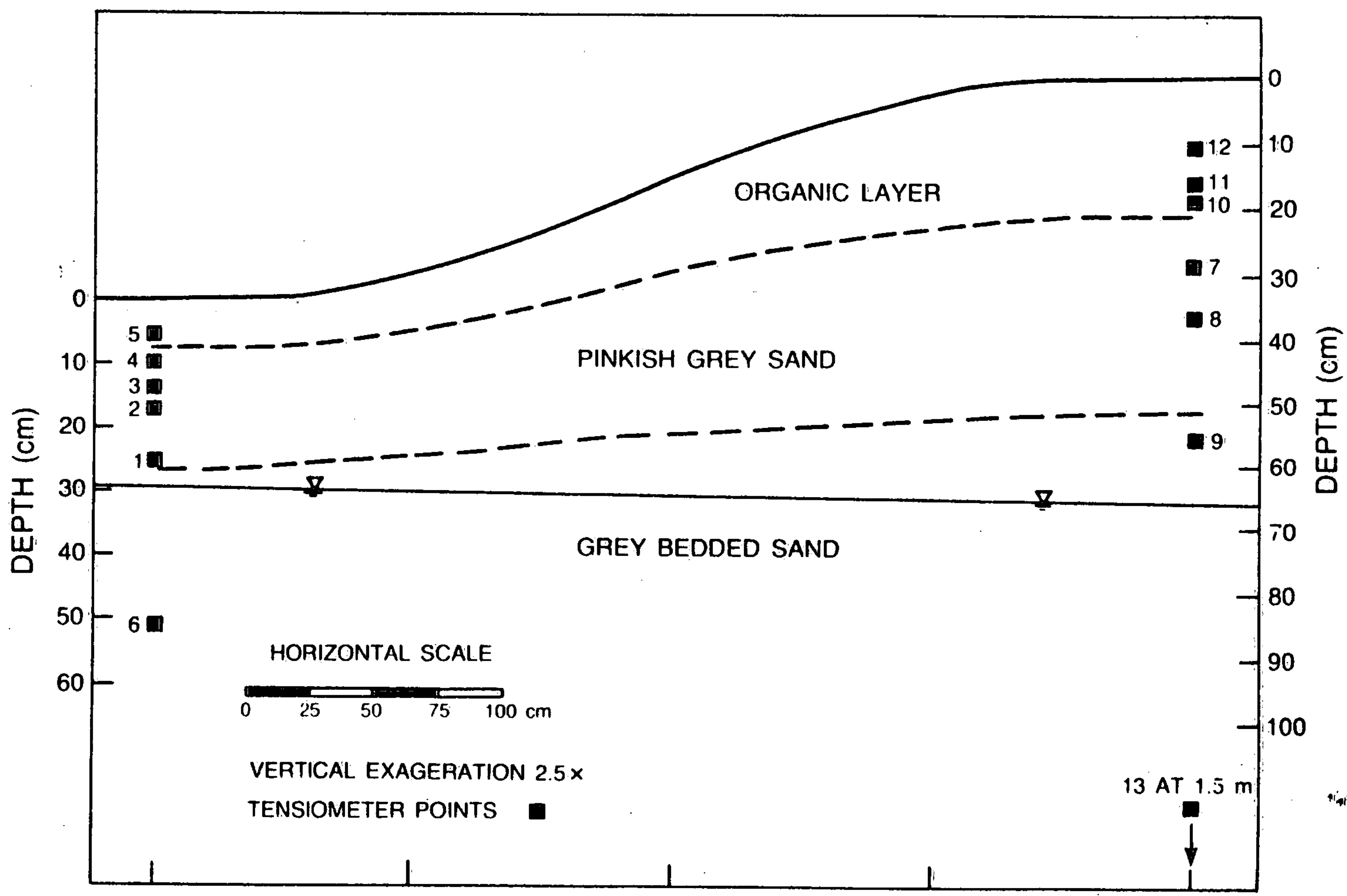
LIST OF FIGURES

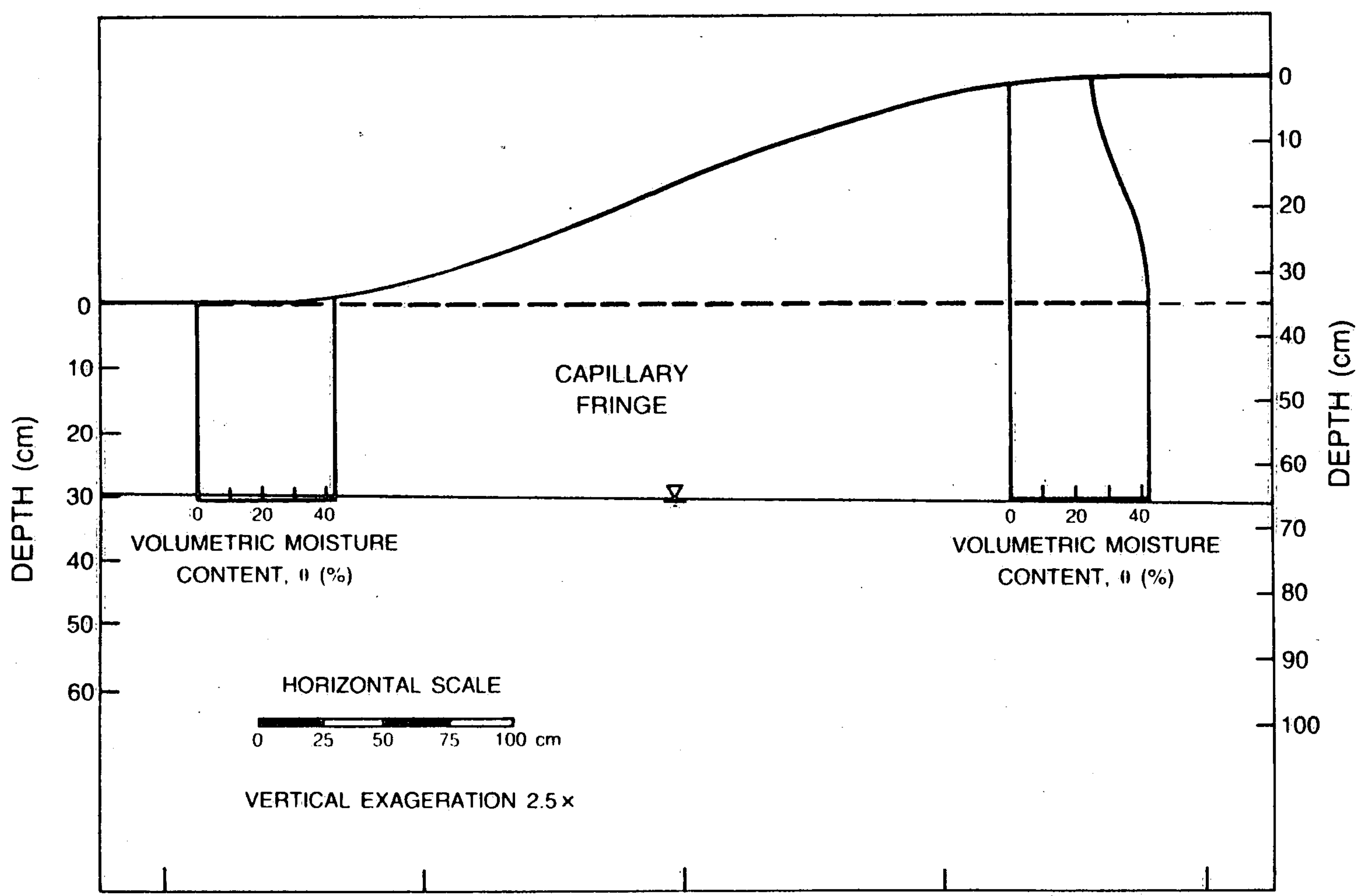
TABLE 1. Rates and volumes of rainfall applied in each of the infiltration experiments

Test	Duration of Rainfall (min)	Rate (mm/hrs)	Total Rainfall (mm)
1	23.35	43	16.7
2	5.31	60	5.3
3	1.42	63	1.5

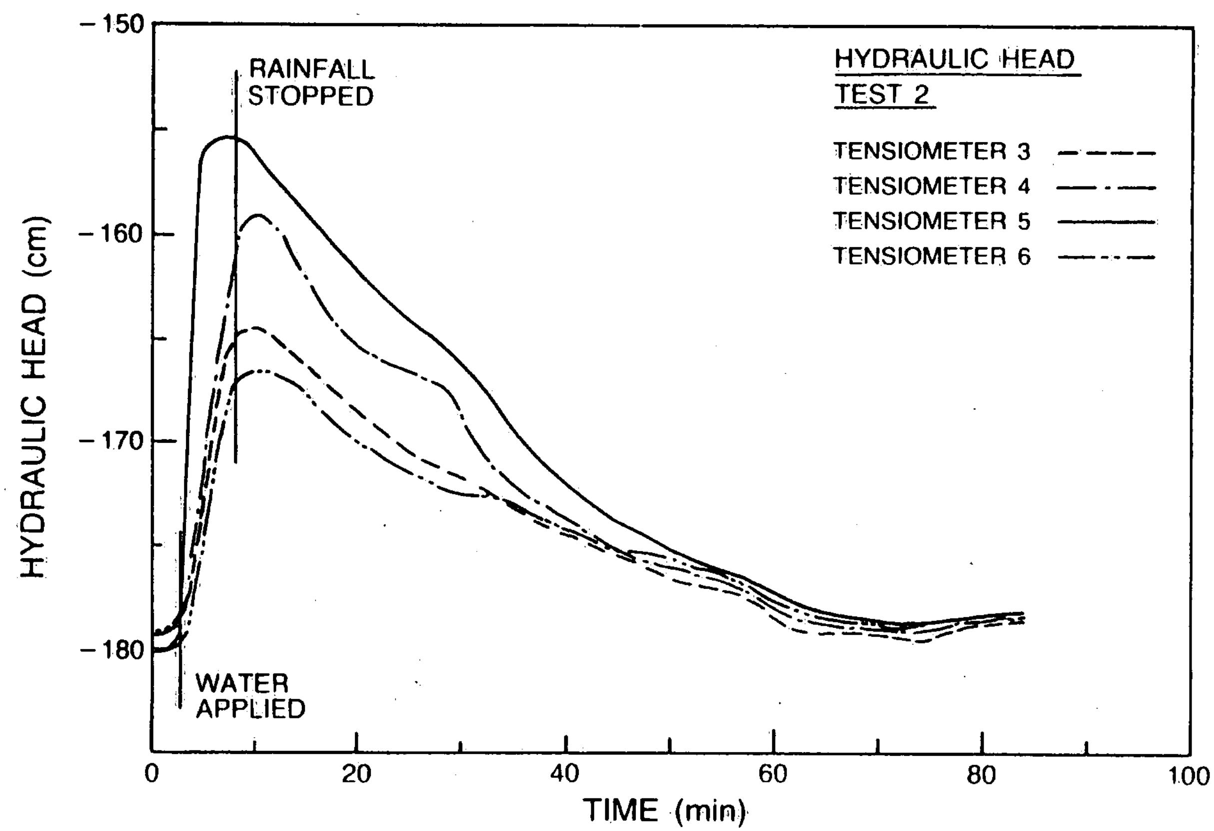

VOLUMETRIC MOISTURE CONTENT, θ (%)
40
θs
30
20
10
θr
0
100
80
60
40
20
0
PRESSURE, Ψ (cm)
ZONE OF
TENSION
SATURATION

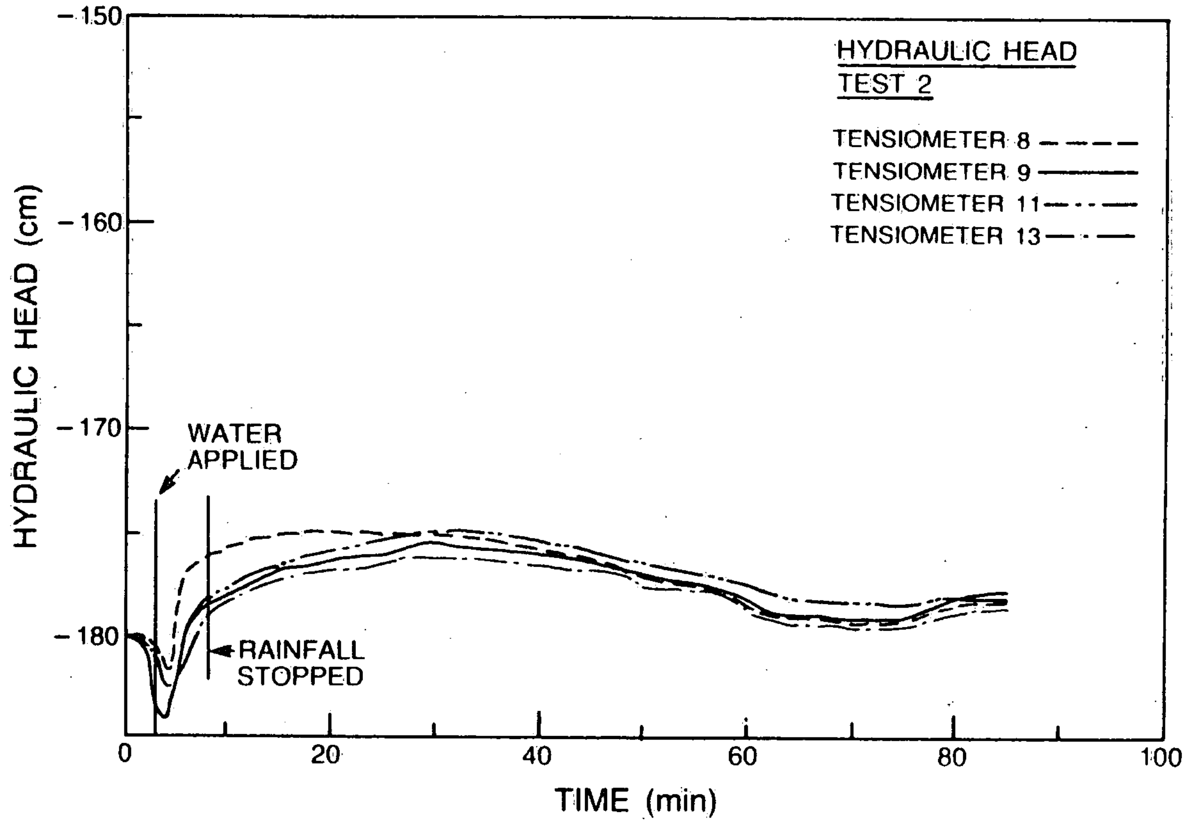


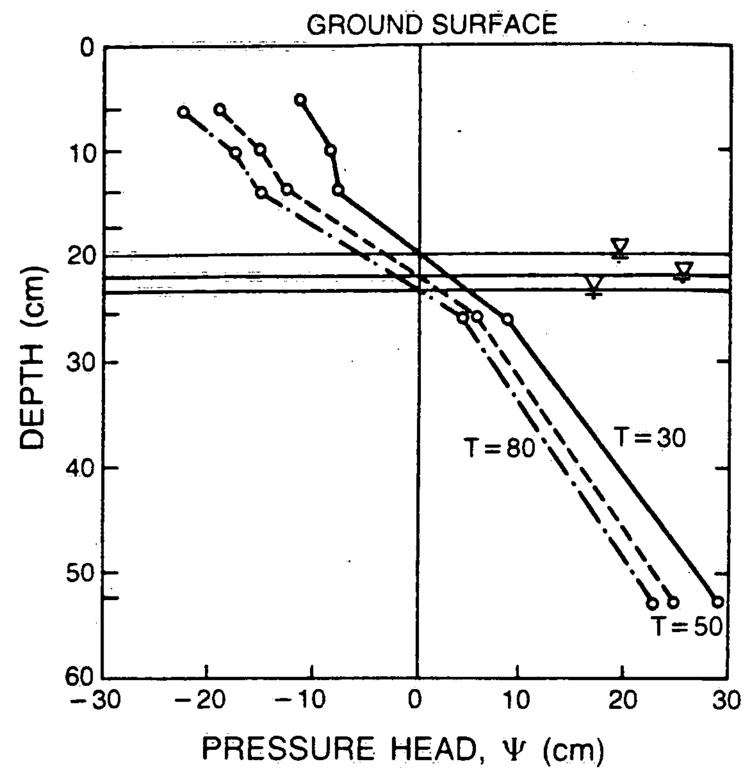
ORGANIC LAYER
PINKISH GREY SAND
GREY BEDDED SAND
DEPTH (cm)
0
10
20
30
40
50
60
DEPTH (cm)
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
13 AT 1.5 m
HORIZONTAL SCALE
0
25
50
75
100 cm
VERTICAL EXAGERATION 2.5×
TENSIOMETER POINTS



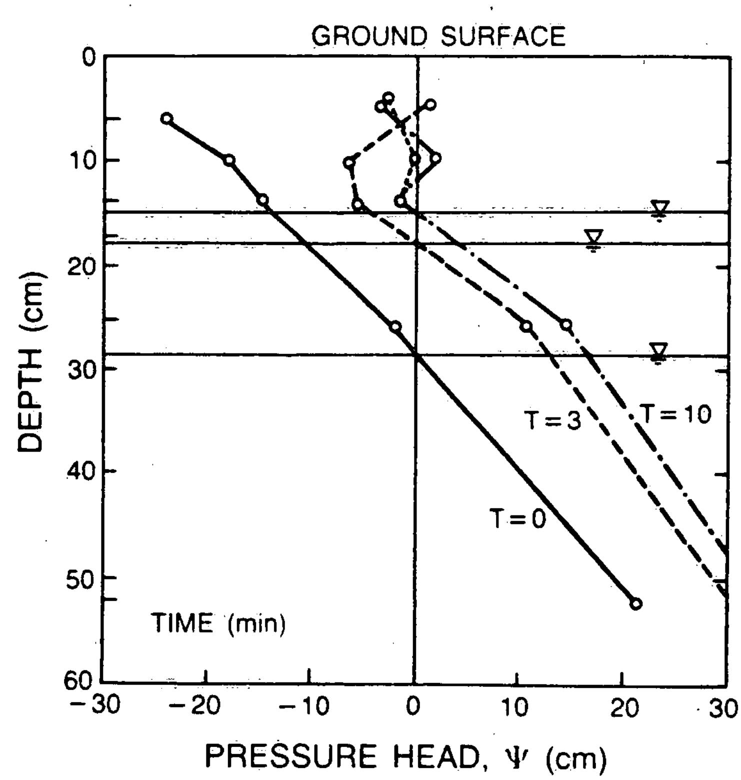
DEPTH (cm)
0
10
20
30
40
50
60
CAPILLARY
FRINGE
0 20 40
VOLUMETRIC MOISTURE
CONTENT, θ (%)
HORIZONTAL SCALE
0 25 50 75 100 cm
VERTICAL EXAGERATION 2.5×
DEPTH (cm)
0
10
20
30
40
50
60
70
80
90
100


HYDRAULIC HEAD
TEST 2
TENSIOMETER 3
TENSIOMETER 4
TENSIOMETER 5
TENSIOMETER 6
RAINFALL STOPPED
WATER APPLIED
HYDRAULIC HEAD (cm)
-150
-160
-170
-180
TIME (min)
0
20
40
60
80
100

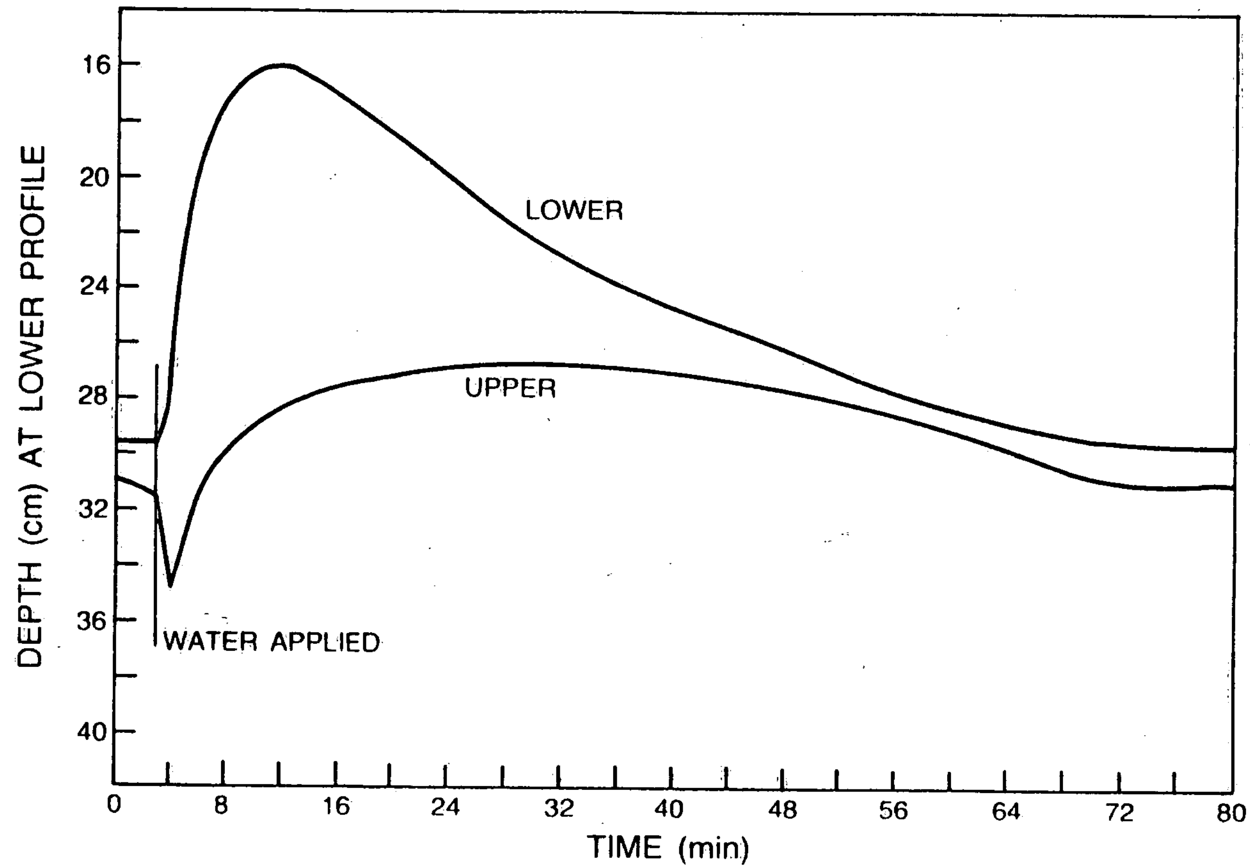

HYDRAULIC HEAD
TEST 2
TENSIOMETER 8
TENSIOMETER 9
TENSIOMETER 11
TENSIOMETER 13
WATER APPLIED
RAINFALL STOPPED
HYDRAULIC HEAD (cm)
-150
-160
-170
-180
0
20
40
60
80
100
TIME (min)



GROUND SURFACE
DEPTH (cm)
PRESSURE HEAD, Ψ (cm)
T = 30
T = 80
T = 50



GROUND SURFACE
DEPTH (cm)
PRESSURE HEAD, Ψ (cm)
T = 3
T = 10
T = 0
TIME (min)


LOWER
UPPER
WATER APPLIED
DEPTH (cm) AT LOWER PROFILE
16
20
24
28
32
36
40
0
8
16
24
32
40
48
56
64
72
80
TIME (min)