HYDROLOGIC RESPONSIVENESS OF A LOWER FRASER VALLEY LOWLAND SOIL

by

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56

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ABSTRACT

Soil degradation in the lowland soils of the Lower Fraser Valley area is an off-season (September-April) problem. The legacy of the degradation process is encountered every year in the form of ponding which delays farming operations such as cultivation and seeding.

It is common for the lowland soils in west Delta to be left in a bare, loose, and therefore unstable state in the fall after harvest. As the result of raindrop impact on such a soil, a disaggregation process takes place which decreases the saturated hydraulic conductivity, the saturated water content, the air entry pressure head, and the water releasing ability of a soil. As a result of these changes the hydrologic responsiveness of a soil will decrease, decreasing its ability to allow rapid infiltration and drainage.

The objective of this thesis was firstly, to investigate the causes of the soil structural degradation and secondly, to use some of the soil structural parameters to optimize the responsiveness of a soil and thirdly, to suggest a management model with the objective of improving the hydrologic responsiveness of a lowland soil.

To fulfill the above objectives, in the first chapter, the process of soil degradation was studied on large undisturbed soil columns removed from two adjacent locations within an area of Ladner in west Delta, British Columbia. It was found that a disaggregation process caused by the impact

of raindrops on a weakly aggregated soil was the main cause of a low hydrologic responsiveness at the beginning of the cultivation season.

As a result of degradation of the soil surface layer, a surface seal can form with a saturated hydraulic conductivity in the order of 9.7×10^{-10} m s^{-1}. A surface seal can effectively decrease the infiltration rate, leading to the formation of a persistent pond which will make a soil untrafficable and unworkable.

In the second chapter, a concept of "designer soil" was developed, where a set of "design hydrologic parameters" were identified for a partially hypothetical soil. A soil possessing hydrologic parameters better than the design parameters would therefore display a certain desired hydrologic responsiveness.

In the third chapter, a descriptive management model was suggested with the objective of achieving the design parameters as identified in the second chapter.

TABLE OF CONTENT

TITLE PAGE

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Symbol		Unit
A	drainage intensity	s^{-1}
c	specific water capacity	m^{-1}
h	soil water pressure head	m
h_a	air entry pressure head	m
h_D	height of water table at mid-point between drains	m
h_o	initial height of water table above drain depth at mid-spacing	m
h_t	final height of water table above drain depth midway between drains	m
I	rainfall intensity	$m\ s^{-1}$
K	hydraulic conductivity	$m\ s^{-1}$
K_s	saturated hydraulic conductivity	$m\ s^{-1}$
K.E	kinetic energy	j
m	mass of one rain drop	kg
$q>0$	drainage discharge	$m\ s^{-1}$
$q<0$	recharge	$m\ s^{-1}$
$r>0$	rainfall rate	$m\ s^{-1}$
$r<0$	evaporation rate	$m\ s^{-1}$
t	time	s
v	velocity	$m\ s^{-1}$
z	depth (positive upward)	m
β	hydrologic parameter describing the shape of the water retention curve	dimensionless
Θ	soil water content	$m^3\ m^{-3}$
Θ_s	saturated water content	$m^3\ m^{-3}$

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INTRODUCTION

This thesis is the product of an investigation carried out to determine the causes of a low hydrologic responsiveness, manifested by widespread ponding during the off-season period (September-March), in a lowland soil in the Lower Fraser Valley (LFV) of British Columbia.

The thesis is a composite of three chapters. Chapter 1 is a report of experiments designed to investigate the processes which lead to the degradation of the surface layer of an unprotected, freshly cultivated soil. These experiments were carried out in the laboratory on undisturbed soil columns 50 cm deep and 25 cm in diameter. It was found that a disaggregation process caused by the impact of raindrops on a weakly aggregated soil triggers a degradation process which leads to the formation of a surface seal. Formation of a surface seal was identified as the main cause of a low hydrologic responsiveness.

Existence of a high resistance layer, referred to as "internal seal", was detected on top of a compacted pan approximately 10 cm below the soil surface. Since to the best of our knowledge an internal seal has never been reported in the literature, further investigation is necessary to determine the mechanisms of its formation in the field. In the laboratory however, an internal seal was produced several times. Transport of very fine sediment by conductive flow through a freshly cultivated, loosely structured soil was identified as the main mechanism for its formation.

Chapter 2 is devoted to the development of a concept which optimizes the hydrologic responsiveness of a soil by using some design structural parameters. As soil structure degrades as a result of raindrop impact or compaction, soil response time increases due to changes which occur in the soil hydrologic characteristic functions. Soil hydrologic characteristic functions which are intimately related to the soil structure can be defined by four parameters: saturated hydraulic conductivity, saturated water content, air entry pressure head and a parameter referred to as β which describes the shape of the partial water retention curve. As the degradation process is set in motion by the disintegration of the surface aggregates, soil hydrologic parameters require new values in response to the changes in soil structure. In order to determine the sensitivity of a soil system to the changes in the hydrologic parameters, soil response time was evaluated at different stages of soil degradation by using a mathematical model.

In chapter 3, a mechanism is offered for the formation of a surface and an internal seal. This mechanism is based on the findings in chapter 1, and what has been reported in the literature on the topic of surface sealing.

Also presented in chapter 3 is a descriptive management model designed to improve the hydrologic responsiveness of the LFV lowland soils. In this model a set of criteria proven to be essential in soil and water management of a lowland soil are systematically stated. It is suggested that any deviation from the optimum management practices should be remedied by certain appropriate actions. This model can be used as an algorithm for development of an expert system which could be used by farmers and soil scientists as a management tool.

CHAPTER 1

CAUSES OF A LOW HYDROLOGIC RESPONSIVENESS

CAUSES OF A LOW HYDROLOGIC RESPONSIVENESS

1.1 ABSTRACT

Research was conducted on 50 cm deep undisturbed soil columns removed in April of 1987 from ponded depressions in an intensively cultivated undrained field (site 1) in west Delta. The degree of degradation of the soil was judged to be maximum as indicated by ponding. The objective was to investigate the causes of a low hydrologic responsiveness to rainfall events. Initial investigation showed the existence of a surface seal with a saturated hydraulic conductivity (K_s) of $9.7 x 10^{-10}$ m s^{-1} for the 5 mm-layer thick surface. Also an internal seal with a K_s of $1.0 x 10^{-9}$ m s^{-1} was detected on top of a compacted pan approximately 10 cm below the surface. The above soil was compared with an uncultivated soil column removed from an adjacent drained field (site 2). The degree of degradation for the soil was judged to be minimal. There were no seals present in this soil, which had an effective K_s of $2.8 x 10^{-4}$ m s^{-1}.

Both soils were subjected to simulated cultivation in the laboratory. The process of surface seal formation was investigated under controlled conditions of simulated rainfall. Surface and internal seals were regenerated in the soil columns from site 1, however no seal formed on the column of site 2. K_s of the surface 5 mm for the site 1 soil decreased from an initial value of $2.1 x 10^{-5}$ after cultivation

to 1.4×10^{-9} m s^{-1} after an effective seal had formed, while that of the site 2 decreased only from 7.0×10^{-5} to 1.5×10^{-5} m s^{-1}.

It was found that a disaggregation process, which results in the formation of a surface seal, was the main cause of the reduction in the hydrologic responsiveness of the cultivated soil. The most important factor governing the process of surface seal formation was identified as the surface aggregate stability. It was also found that development of a suction force at the surface was an essential factor in the formation of a hydrologically effective seal. A cover crop was found to be an extremely effective tool in preventing the formation of a surface and an internal seal.

1.2 INTRODUCTION

The importance of stable soil aggregates to crop growth is well documented (Baver et al. 1972). This importance is largely due to a desirable hydrologic responsiveness defined as: the ability of a soil to allow rapid infiltration and drainage. A soil with good hydrologic behaviour has a short response time, defined in this thesis as: the time to reach a workable state from a flooded condition with the water table at the soil surface. Workable state is a condition where the soil water content is less than the lower plastic limit (Hillel 1980).

It is widely known that soil aggregates become unstable and slake upon rapid wetting (Emerson 1977). Also reported is the disintegration of surface aggregates due to raindrop impact (McIntyre 1958; Ellison 1944). The combined effect of these disaggregation processes is the clogging of pore-necks (Uebler and Swartzendruber 1982) and reduction of porosity in the soil surface layer. Pore-clogging at the surface is a precursor of surface seal formation (Bonsu 1987).

Surface seals may range in thickness from less than 1 mm to greater than 5 cm (Tackett and Pearson 1965). They are normally more compact, harder and more brittle when dry than the soil just beneath them. Surface seal formation is an important process in terms of its effects on infiltration, erosion, seedling emergence, and ponding. This phenomenon has been extensively studied in the last four decades.

Duley (1939), Lemos and Lutz (1957), and McIntyre (1958) have proposed mechanisms of seal formation. Tarchitzky et al. (1984), and Evans and Buol (1968) studied the micromorphology and structure of seals. Meyer and Monke (1965), Free (1952), and many others reported on runoff and soil erosion. Hillel and Gardner (1969) examined the effect of sealing on infiltration. Falayi and Bouma (1975) studied relationships between the hydraulic conductance of surface seals and soil management.

In the Lower Fraser Valley (LFV), soil degradation is an off-season process which begins early in the fall. Its legacy is encountered every year at the beginning of the cultivation season in the form of ponding. Windshield surveys, conducted in the Western region of the LFV since 1982 (de Vries, personal communication 1987), show ponding to be an increasing problem in more than 90% of the cultivated fields. This observation indicates that soils in this region are in an on going state of hydrologic deterioration, resulting in a continuous reduction in saturated hydraulic conductivity. In the extremely wet spring of 1984, cultivation and seeding were delayed by two months as the result of ponding which rendered the soil untrafficable (windshield surveys and communication with farmers). Because of its effect on the timeliness of farming operations, ponding is a major source of economic loss. Due to the importance of the LFV lowland soils to British Columbia's economy, the present work was undertaken with the following objectives: 1) to investigate the mechanisms which contribute to the reduction of the soil hydrologic responsiveness, 2) to develop a concept of optimizing the hydrologic responsiveness of a soil by using some design structural parameters 3) to propose a soil and water management model for the western lowlands of the LFV area.

1.3 MATERIALS AND METHODS

1.3.1 Soil and Site Description

Large undisturbed columns were removed from two adjacent sites within an area of Ladner soil in west Delta. Site 1 was located in a ponded depression in an undrained field. The soil at this site has been under continuous cultivation and the degree of structure degradation is at a maximum. In contrast, site 2 was located in an unused portion of a drained field (Boundary Bay research station). This site was under permanent grass and the degree of soil structure degradation was at a minimum.

Ladner soils are classified as Humic Luvic Gleysol (Luttmerding 1981). They have developed from moderately fine and some fine-textured stone-free, mixed marine and freshwater deltaic deposits which are underlain by sandy materials at depths below 100 cm or more. Surface textures are mostly silty clay loam with variations to silt loam, sub-surfaces are usually silty clay and sub-soil textures range from silty clay loam to silt loam. Ladner soils are moderately poorly to poorly drained. They are moderately to slowly pervious and have high water holding capacity and slow surface runoff. High water tables are usual during the winter and surface ponding is common during and after heavy rains. Ladner soils generally have a very dark gray, firm, silty to clayey, cultivated surface layer between 15 and 20 cm thick. It is underlain by 5 to 10 cm of grayish, partially leached, very firm, silty to clayey material containing common, reddish-brown mottles. This, in turn, is underlain by a clayey layer about 30 cm thick which is grayish brown, very firm and plastic, has strong, prismatic structure and contains many reddish or brownish mottles. Surface and sub-surface soil reaction is variable depending on management practices but is usually very strongly or strongly acid (Luttmerding 1981).

The soil profile for site 1 in April of 1987 prior to cultivation consisted of a surface seal, a cultivation layer, a compacted pan, and sub-soil. Site 2 soil consisted of about 30 cm of top soil containing many stable worm holes underlain by sub-soil of massive silty material consisting of many stable old root holes. The characteristics of sub-soil in both sites were the same (Table 1).

1.3.2 Sampling Procedure

The sampling method used was a modification of the method introduced by Bouma and Denning (1972). Three undisturbed columns 50 cm in depth and 25 cm in diameter encased in 2 cm thick concrete were removed in April of 1987 from two ponded depressions 40 m apart and approximately 50 m^2 in area (columns A and B from the same depression, and C from the other one) with well-formed surface seals. One undisturbed column was taken from site 2 (column D). A detailed explanation of the sampling procedure is offered below:

In the field, a concentric pit was dug and a cylindrical soil column 55 cm long and 25 cm in diameter was carefully carved out (Fig. 1). A cylindrical casing 50 cm long and 29 cm in diameter was constructed using 0.75 mm thick sheet metal. Different layers in the soil profile (i.e. cultivation layer and compacted pan) were carefully identified

Table 1. Soil profile description and some pertinent information for the Ladner soil under consideration

	thickness (cm)	aggregate stability (n=12) (%)	bulk density (n=6) ($kg\ m^{-3}$)	K_s ($m\ s^{-1}$)	particle size distribution %clay	%silt	%sand	organic matter content (n=6) (%)
					(soil type)			
Site 1								
surface seal { skin layer	.05-.1	30±3	-	-	20.0	57.2 (silt loam)	22.8	
surface seal { compacted layer	1 - 2	41±5	1420±28	-	-	-	-	7.4±2.3
cultivation layer	7 - 10	47±4	1105±33	-	20.8	67.2 (silt loam)	12.0	9.3±2.5
compacted pan	10 - 17	-	1250±50	-	-	-	-	-
sub-soil	-	-	-	10^{-6}*	-	-	-	-
Site 2								
top layer	25 - 31	92±2.5	-	10^{-4}**	23.0	62.0 (silt loam)	15.0	19.6±3.1
sub-soil		same as above						

*Single auger hole method, personal communication, S.T. Chieng, Bio-Resource Eng. Dept., U.B.C. 1988.
**Personal communication, J. de Vries, Soil Science Dept., U.B.C. 1988.

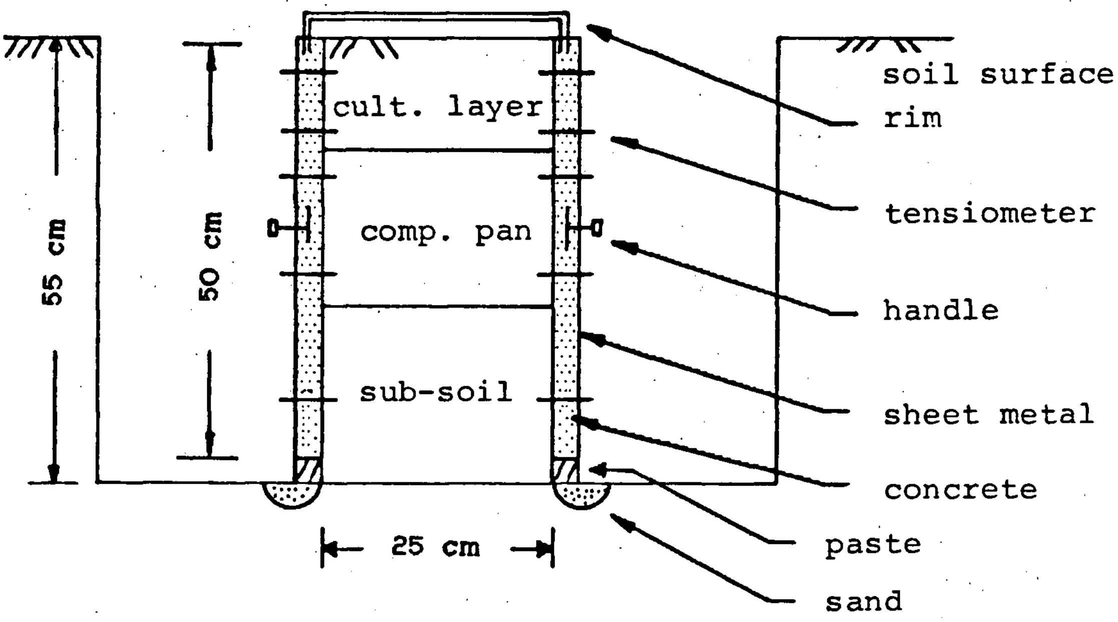

FIG. 1 SCHEMATIC DRAWING OF FIELD SAMPLING

and their thicknesses were measured, since two tensiometers were to be fitted in each layer at different depths along with one tensiometer in the sub-soil. At each depth three tensiometers were to be fitted at 120 degrees apart to triplicate the pressure head readings. Appropriate locations were marked along the length of the cylindrical casing and 7 mm diameter holes were drilled to allow the installation of the tensiometers.

The tensiometers used were porous ceramic cups 5 cm long, and of 6 mm outside diameter with an air entry value of about 4 meters of water. The tensiometers were cemented to 6 cm long and 6 mm inside diameter plastic tubes.

To facilitate transportation of the columns, four cast iron rods 6 cm long and 6 mm in diameter were installed in the sheet metal cylinder at symmetrical positions. These were used as handles for lifting the soil columns. In order to reinforce the handles within the concrete casing, pieces of 5 cm by 5 cm wire mesh were positioned at the tip of the rods inside the cylindrical casing.

Beach sand was placed around the bottom of the core to give a smooth base. The sheet metal sleeve was lowered to fit evenly around the soil core. A drill bit was used to make holes in the soil column to receive the tensiometers. Tensiometers were then fitted in the sample.

A gypsum paste was poured on top of the sand in order to prevent the concrete from seeping out. Concrete was then poured and continuously vibrated with a rod until the space between the soil core and the sheet metal casing was filled. A rim of 6 cm deep and 27 cm in diameter supported by sheet metal screws was pushed about 2 cm deep into the wet concrete at the surface to create space for ponding of water.

The concrete was left to set in the field, with the soil core attached to the ground. After two days, the core was detached from the base, and the column was removed using a tripod and tackle and transported to the laboratory. To conserve the columns between the experiments, they were kept outside in pre-dug holes with their surface even with the ground surface and their bottom kept moist at all times.

1.3.3 Laboratory Procedure

In the first experiment, to determine the initial soil condition, the hydraulic conductivities of various soil layers were measured for the three columns of site 1 (A,B, and C), as they were brought in from the field. The hydraulic conductivity of seals was assumed to be saturated due to the large negative air entry pressure heads, while those of other layers were unsaturated. The upper boundary for the columns A and B had not changed from the field condition, while the surface of column C had developed tension cracks. To control the lower boundary condition, the columns were placed on a cylindrical pail filled with tension-saturated medium sand, ensuring a perfect hydraulic contact (Fig. 2). The sand surface was kept within the tension saturated zone at all

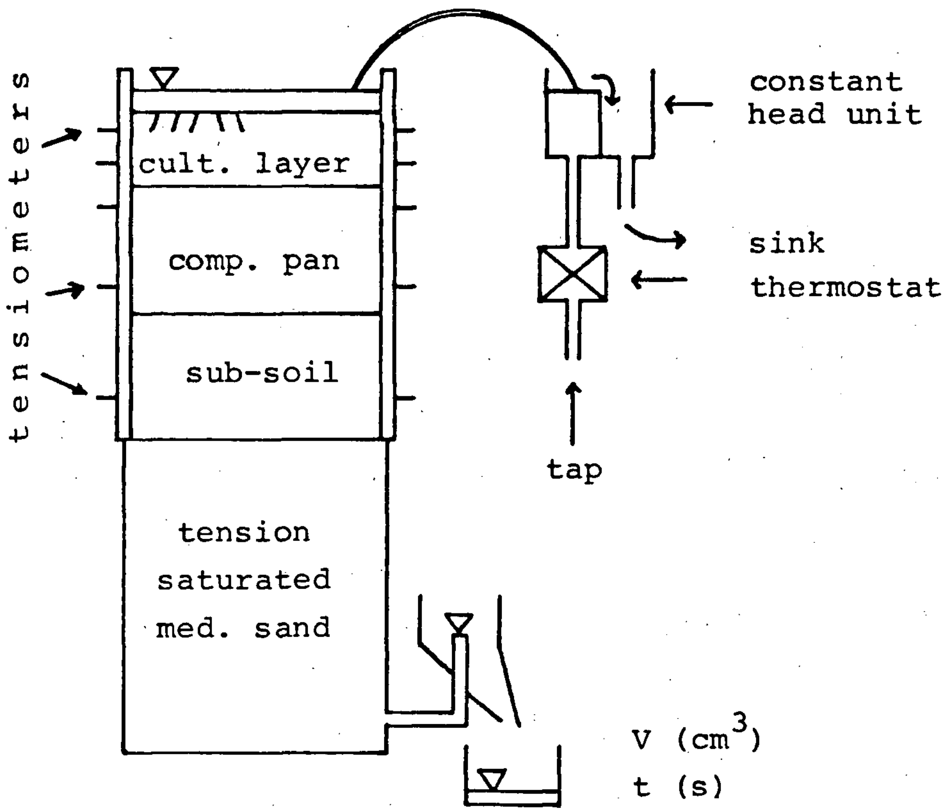

FIG. 2 SCHEMATIC DRAWING OF FLOW MEASUREMENT SYSTEM

times by means of an outflow unit. A thermostat was used to keep the temperature constant at 18^{o}C. To carry out flow measurements, a constant head was maintained at the soil surface and the volume flow rate was directly measured from the outflow unit at steady state. The gradient was calculated from the tensiometer readings, enabling calculation of the hydraulic conductivity profile by using Darcy's law. For the latter calculation it was assumed that all seals were 5 mm thick, and that the pressure head distribution within each layer was linear. At this stage an effective hydraulic conductivity for column D was also determined using the same procedure. Due to technical problems with the tensiometers a hydraulic conductivity profile could not be determined for this column.

In the second experiment a surface seal was generated in the laboratory by applying simulated rainfall with close observation of the sealing process and constant monitoring of the changes in the hydraulic conductivity of different soil layers. The procedure was as follows:

The cultivation layer of columns A and D were left to dry to below the plastic limit, a condition necessary for cultivation. The effects of discing and plowing were simulated in the laboratory to a depth of 10 cm by use of a knife and a spade. The soil was cut with a knife perpendicular to the surface, and then turned over by the spade. Nine sets of high intensity (120 mm hr^{-1}) and short duration (2 to 5 minutes) simulated rainfalls, each set containing five events were applied to the surface. Each time rainfall was applied until a pond was formed. The pond was kept at a constant depth until steady state was reached and the tensiometer readings were recorded.

To produce rainfall, a laboratory rain maker unit was used with hypodermic needles of gauge 21 placed at 2 cm by 2 cm grid spacing. Rainfall intensity was controlled by a movable constant head unit. Simulated rainfall was applied from a distance of 30 cm above the soil surface.

In the third experiment the effect of formation of a suction force at the bottom of the surface layer upon surface sealing was examined. The water table was gradually raised from below to the top of a freshly cultivated column B and maintained there. Rainfall was applied as before. A flooded condition quickly developed. Using an inflow unit a constant 3.5 cm depth of pond was maintained and the outflow unit was slowly lowered to the bottom of the column to create a gradient. The purpose of this procedure was to avoid the formation of a large suction force at the surface. Hydraulic conductivity of different layers was calculated as before. Five rainfall events were applied, each time allowing the free water to just withdraw below the surface between the rainfall events. Therefore, the cultivation layer was kept saturated at all times. After the fifth rainfall event the free water was allowed to withdraw below the surface until the tensiometers in the cultivation layer indicated negative readings, another rainfall event was applied and hydraulic conductivities calculated again.

The effect of a cover crop on the formation of the surface seal was studied in the fourth experiment. Column C was cultivated and planted to wheat. When the wheat was 5 cm long, simulated rainfall was applied and hydraulic conductivity of different layers calculated as before.

In the first experiment a high resistance was discovered to exist on top of the compacted pan. During the course of the second experiment a high resistance developed at the cultivation layer-compacted pan boundary, simultaneous to the formation of a surface seal. To investigate this effect in more detail, a soil column was made up in the laboratory in a 20x15 cm acrylic plastic box. This column consisted of a porous plate made of carborundum at the bottom, for the purpose of controlling the lower boundary condition. On top of the porous plate a compacted pan with a bulk density of 1260 kg m^{-3} and a depth of 10 cm was artificially formed using air dry pan material which had been passed through a 0.5 mm sieve. Soil removed from the cultivation layer of site 1 was directly placed on top of the pan and the column gently vibrated at the sides until a depth of 10 cm was reached. The bulk density of the cultivation layer was calculated to be 1100 kg m^{-3}. Four tensiometers were installed, two within the pan (at 1 and 5 cm below the pan surface), and two within the cultivation layer (at 1 and 5 cm above the surface of the pan). Simulated rainfall events of different intensities (55, 60, 139, 173, 175 mm hr^{-1}) were applied at the surface, each time until a pond was formed. The pond was kept at a constant depth of 2 cm and after steady state had been reached the flow rate was measured and the pressure heads were recorded. Using Darcy's equation, resistance was calculated between the two tensiometers 1 cm above and 1 cm below the pan surface as a function of rainfall events.

1.3.4 Physical Properties of the Soil

i. Determination of aggregate stability

A wet-sieving method was used to determine the aggregate stability of the soil in each column after the first experiment. This method is described by Kemper (1965). The wet-sieving equipment consisted of a motor-driven mechanical device that would raise and lower the sieve holder through a distance of 2.5 cm, and at a frequency of 30 strokes per minute. The motion of the system has both an upward stroke and an oscillating action through an angle of 30^{o}.

A special sieve holder capable of receiving 12 separate sieves in each determination was used. The sieves had an inside diameter of 7.5 cm and 0.25 mm mesh openings. 4 g of air dry aggregates (1-2 mm) placed on the sieves were pre-wetted with an atomizer spray (Baver et al. 1972).

The samples were wet-sieved with the whole set of sieves completely immersed in a basin of water for 10 minutes. The aggregates retained on the sieve after wet-sieving were ovendried at 105°C for 24 hours and weighed. The aggregate stability was expressed as the ratio of the oven-dry mass of the stable aggregates after wet-sieving to the oven-dry mass of a 4 g sub-sample.

ii. Determination of Organic Matter Content

The organic matter content was determined by igniting 2 g of oven-dry aggregates (0.5-2 mm) in a muffle furnace at a temperature of 400°C for 8 hours. The loss-on-ignition was taken as a measure of the organic matter content.

The major drawback of using loss-on-ignition as an estimate of organic matter of a noncalcareous soil is the error associated with loss of clay mineral water (Ball 1964). This loss of adhered water is important in the temperature range of 450-600°C (Ball 1964). Thus, provided the temperature is kept below 450°C, the loss-on-ignition method is sufficiently accurate for estimating organic matter of a noncalcareous soil (Ball 1964). The organic matter content was expressed as the ratio of the mass lost upon ignition to the mass of the solids.

1.4 RESULTS AND DISCUSSION

Effective hydraulic conductivity measured in the laboratory for column D was 2.8×10^{-4} m s^{-1}. This datum agrees with the value measured by de Vries in 1983 (personal communication 1988) (Table 1). This agreement shows the stability of the soil in site 2.

Fig. 3 shows the field water content distribution at the time of sampling at the location where column A was removed. With the exception of the surface seal the rest of the profile is unsaturated. It is assumed that under a pond the seal remains saturated due to a large negative air entry value. Fig. 3 is a graphical demonstration of a hydrologic event referred to as "ponding", where free water is present at the surface while the soil below the surface is unsaturated down to the water table. This phenomenon is very interesting in that, the soil can remain unsaturated while sitting under 10 to 15 centimeters of pond for a number of months.

Fig. 4 shows the pressure head distribution for column A in the first experiment. This is a typical pressure head distribution recorded from the three sets of tensiometers installed in all columns. The wide range of values shows the complexity of flow paths in a structured soil. This indicates that caution should be exercised when using tensiometry under a natural setting. If a soil contains preferred flow paths such as worm holes and root channels, then depending on whether or not a tensiometer intercepts one of these channels, a large or small pressure head reading would be recorded.

There have been instances recorded where the average total pressure profile indicated "counter-flow" gradient. This point raises a question as to the degree of accuracy provided with the three sets of tensiometers. It should however be

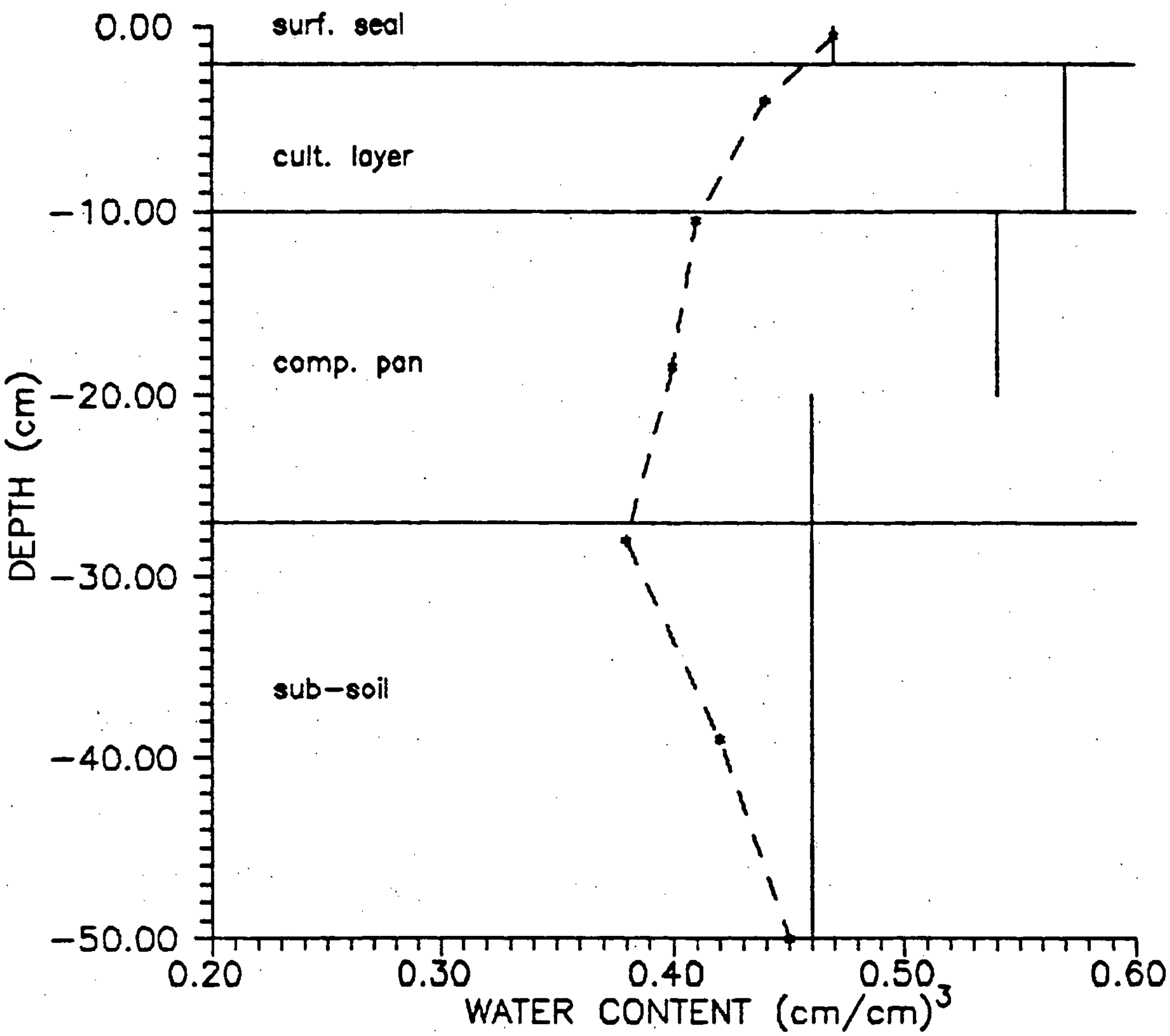

FIG. 3 FIELD MEASUREMENT OF WATER CONTENT VS. DEPTH FOR A SOIL PROFILE UNDER A PONDED DEPRESSION. SATURATION IS INDICATED BY SOLID VERTICAL LINES.

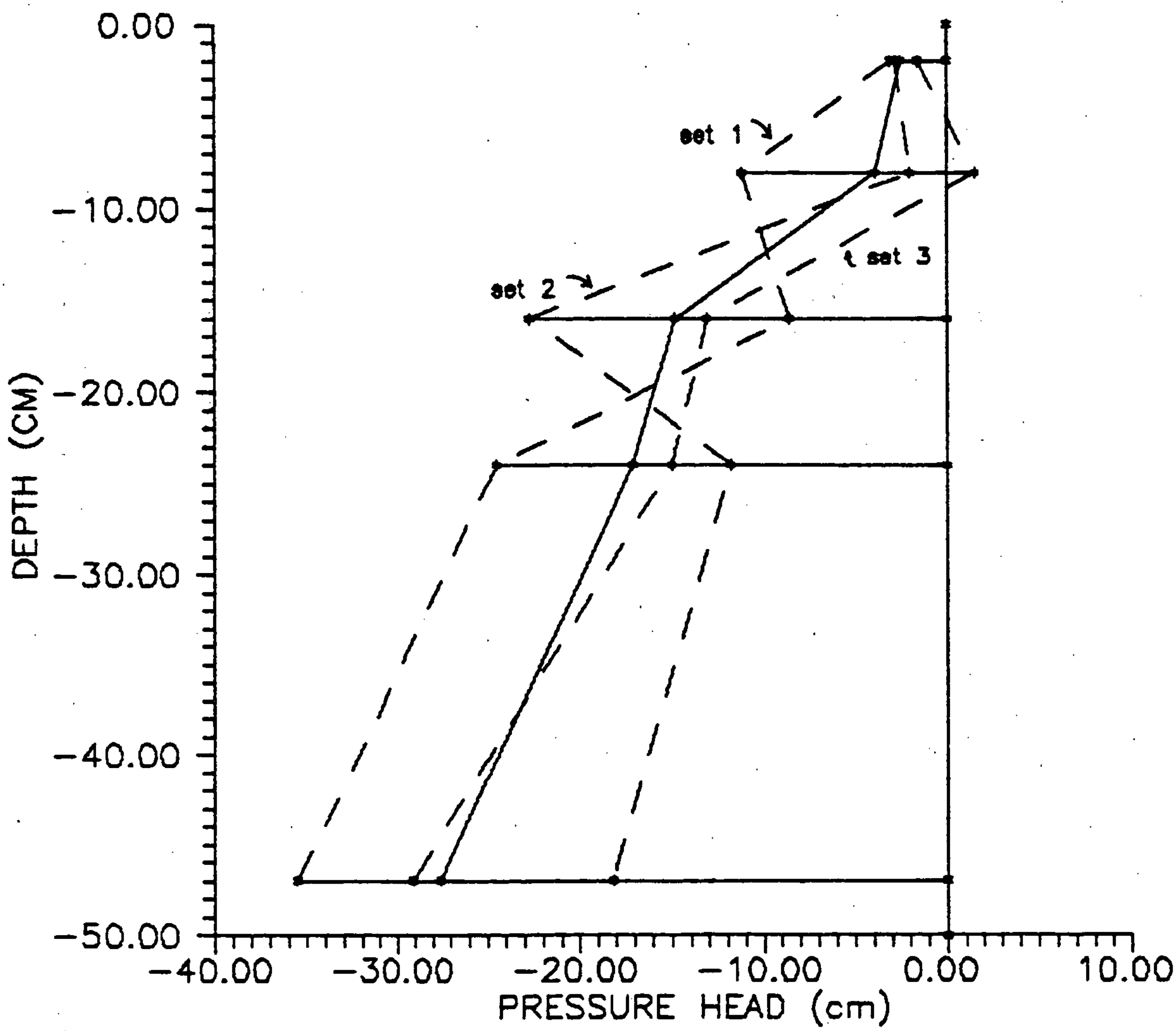

FIG. 4 PRESSURE HEAD VS. DEPTH FOR THE THREE SETS OF TENSIOMETERS IN COLUMN 'A'. SOLID HORIZONTAL LINES SHOW THE LOCATION OF TENSIOMETERS. SOLID CURVE SHOWS THE AVERAGE VALUE OF PRESSURE HEAD.

kept in mind that although the overall direction of an unsaturated flow may be downward, this does not exclude the possibility of an upward flow at some locations within the soil profile.

Fig. 5 shows the curve of total head versus depth for column A as it was brought in from the field. Also shown are hydraulic conductivities for the different layers. The total head values are an average of the three tensiometers at each depth (Fig. 4). Values for column B in the first experiment (not shown) are similar to those of column A. Fig. 5 shows Ladner soil at its worst condition. Since the gradient through the surface seal is equal to 15 a simple calculation shows that it would take almost 40 days for a 5 cm pond to recede if there were no evaporation taking place. Surface sealing, therefore, can be regarded as the main cause of ponding.

Fig. 6 shows the total head as a function of depth in experiment 1 for column C which had developed tension cracks at the surface on arrival at the lab. This process also takes place in the field upon drying. A significant increase in the hydraulic conductivity of the surface 5 mm can be attributed to the disruption of the surface seal. All three columns from the cultivated field showed evidence of a high resistance at the bottom of the cultivation layer.

Fig. 7 shows the result of regenerating the surface seal after cultivation in experiment 2. The hydraulic conductivity of different soil layers in column A and the effective

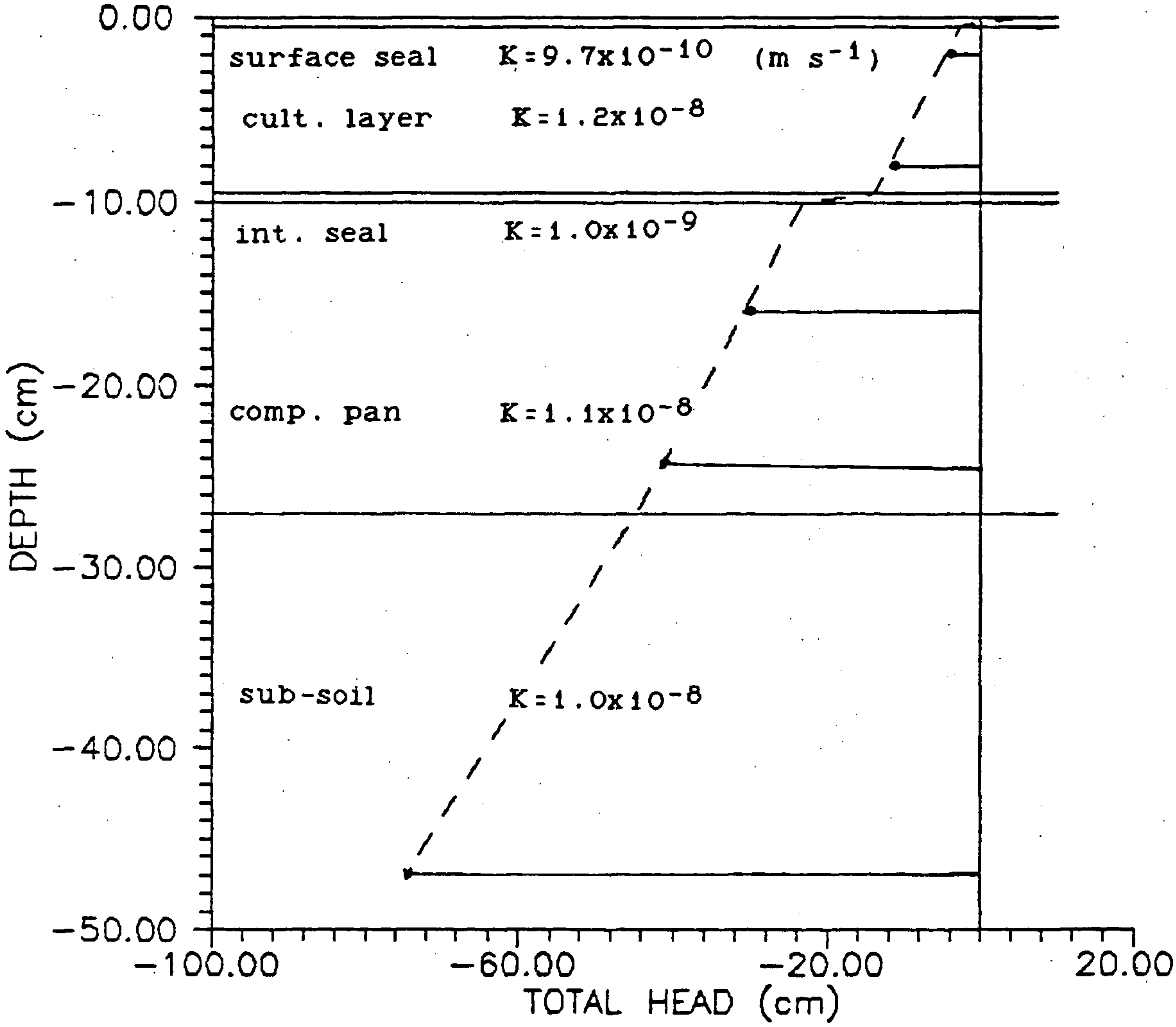

FIG. 5 TOTAL HEAD VS. DEPTH FOR COLUMN 'A'. SHORT HORIZONTAL LINES SHOW THE LOCATION OF TENSIOMETERS.

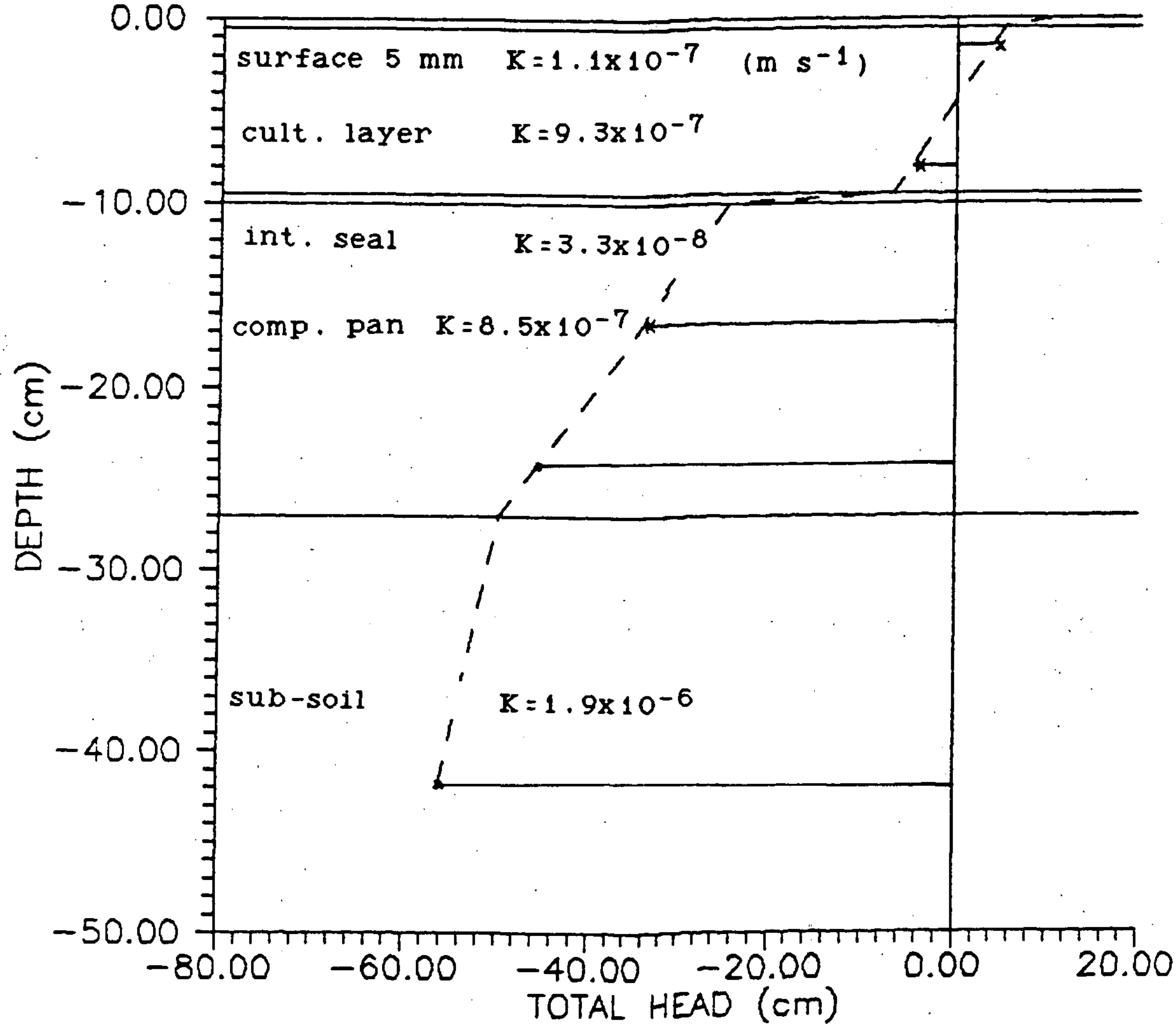

FIG. 6 TOTAL HEAD VS. DEPTH FOR COLUMN 'C'
SHORT HORIZONTAL LINES SHOW THE LOCATION
OF TENSIOMETERS.

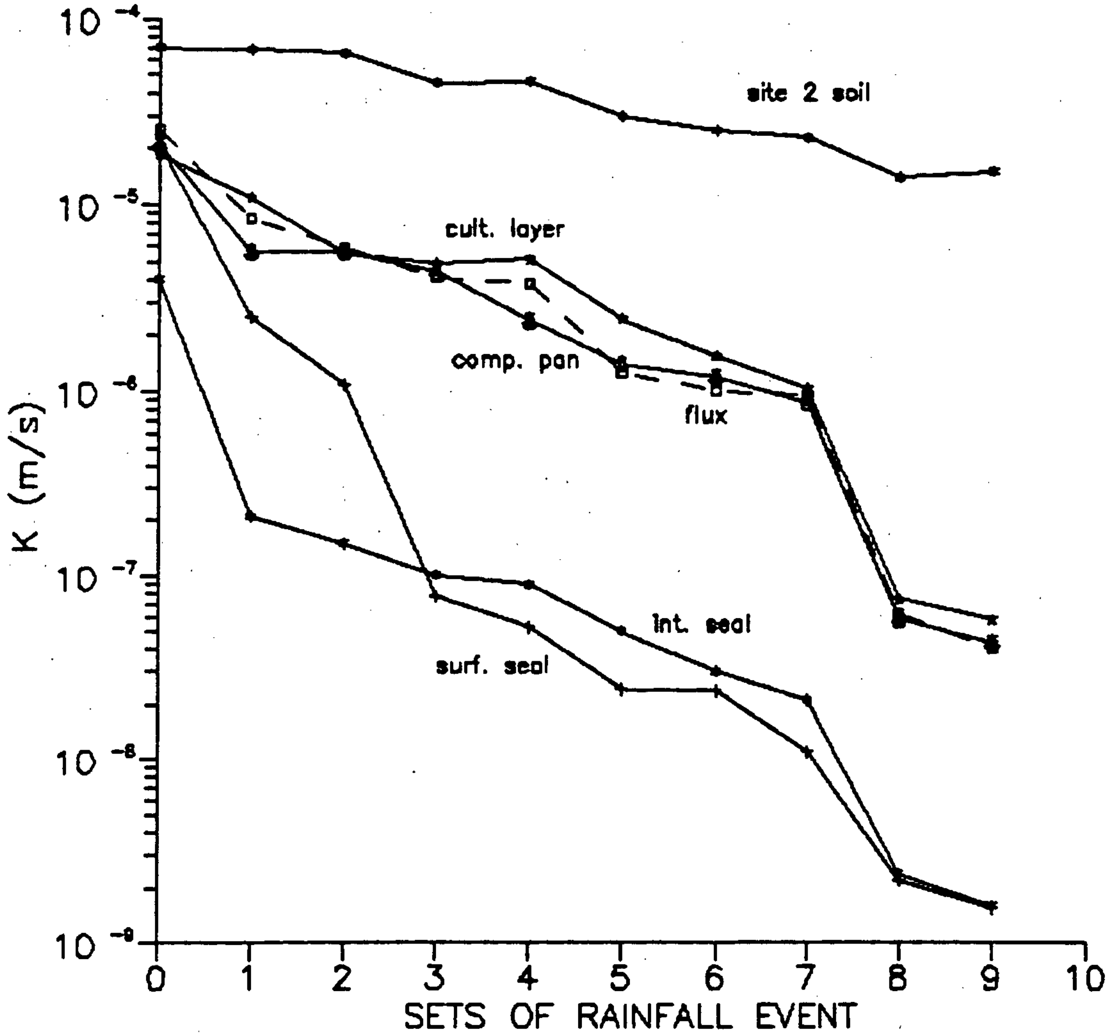

FIG.7 HYDRAULIC CONDUCTIVITY REDUCTION AS A FUNCTION OF RAINFALL EVENTS FOR DIFFERENT LAYERS OF COLUMN 'A'. ZERO EVENT CORRESPONDS TO A FRESHLY CULTIVATED SOIL SATURATED FROM BELOW.

hydraulic conductivity of column D are plotted as a function of rainfall events.

An interesting observation in Fig. 7 is the proximity of the flux to the unsaturated hydraulic conductivities of the cultivation layer and the compacted pan. This shows that the unsaturated hydraulic conductivity of the soil below the seal adjusts itself to the flow rate through the seal (Hillel and Gardner 1969).

Comparison of Figs. 5 and 7 show that the final hydraulic conductivity of different layers in column A are approximately equal to the values measured in experiment 1 while the column was in its original state, despite the high intensity rainfall applied in the laboratory. Many investigators (e.g., McIntyre 1958, Falayi and Bouma 1975) who compared hydrologic properties of surface seals formed under high intensity simulated rainfall, with those formed naturally in the field, concluded close similarities between the two. Bertrand and Sor (1962), however, studied the effects of different rainfall energies on soil permeability. They concluded that the effects of the 70 and 100 mm hr^{-1} rainfall intensities were of the same magnitude, while the effect of a 40 mm hr^{-1} rainfall was less. In general, it can be concluded that beyond a certain rainfall intensity threshold any increase in the intensity of the rainfall will not change the hydraulic conductivity of the surface layer. This threshold intensity is undoubtedly a function of the aggregate stability of the soil surface and the kinetic energy of the rainfall.

Kinetic energy of the simulated rainfall applied in the second experiment was calculated for one drop using:

$$K.E = 1/2\ m\ v^2 \qquad (1)$$

where: K.E = kinetic energy (j), m = mass of one drop = 10^{-4} (kg), and v = velocity (m s^{-1}). The velocity of a 3 mm drop falling a distance of 0.3 m is given by Laws (1941) to be equal to 2.3 m s^{-1}. The equivalent intensity of a natural rainfall was calculated from (Laws and Parson 1943):

$$K.E = 11.89 + 8.74 \log I \qquad (2)$$

where: K.E = kinetic energy (j mm^{-1} m^{-2}), I = intensity (mm h^{-1}), with the value of kinetic energy calculated from (1).

It was found that the simulated rainfall applied in the laboratory was equivalent in terms of its energy input, to a natural rainfall intensity of 27 mm day^{-1} which is a common rainstorm for the LFV area.

A comparison of the reduction in the hydraulic conductivities of columns A and D in Fig. 7 shows the importance of aggregate stability in the formation of the surface seal. The effective hydraulic conductivity of the soil from site 2 [agg. stability = (92 ± 2.5)%], after laboratory cultivation and application of the same number of rainfall events as for column A [agg. stability = (47 ± 4)%], decreased only from 7.0 x 10^{-5} to 1.5 x 10^{-5} m s^{-1}, without any sign of a surface seal being present at the end of the experiment.

1.4.1 Effect of Drying and Cover Crop on Seal Formation

Figures 8a and b show the result of drying on surface seal formation. In Fig. 8a drying was prevented by keeping the cultivation layer saturated at all times. At the end of the experiment the surface, while having the appearance of a seal, was extremely ineffective in reducing the flow rate. The resistance of the surface layer to flow was near zero, while an internal seal had formed as before. Fig. 8b shows the result of drying. The surface 5 mm after drying had a hydraulic conductivity in the order of 10^{-9} m s^{-1}.

The importance of drying on the formation and efficiency of the surface seal is in the creation of a suction force at the bottom of the surface layer. As pointed out by Morin et al. (1981), and Tackett and Pearson (1965), creation of this suction force causes orientation of the clay particles into a continuous and dense layer.

The effect of a cover crop on surface sealing was studied in the fourth experiment. Initially, the surface 5 mm had a hydraulic conductivity of 3.1×10^{-6} m s^{-1}. At the end of the experiment, this value was reduced only by a factor of two to 1.6×10^{-6} m s^{-1}, also, with no sign of an internal seal being present. It should be mentioned that the wheat provided full coverage of the surface. It would be of major interest,

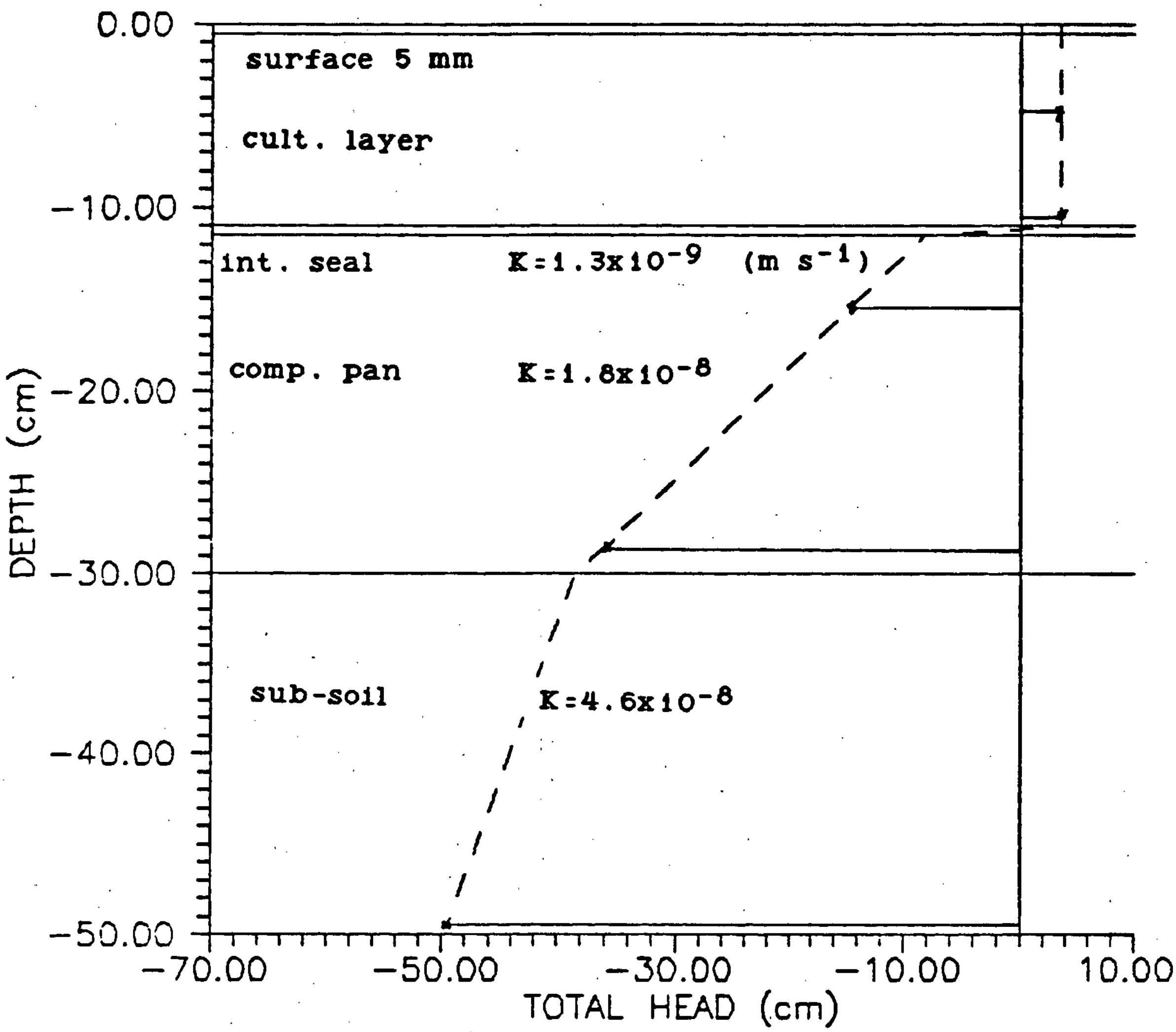

FIG. 8a TOTAL HEAD VS. DEPTH FOR COLUMN 'B' WHEN CULTIVATION LAYER WAS KEPT SATURATED. THE GRADIENT FOR THE SURFACE 5 mm AND THE CULT. LAYER WAS TOO SMALL TO ALLOW K TO BE MEASURED.

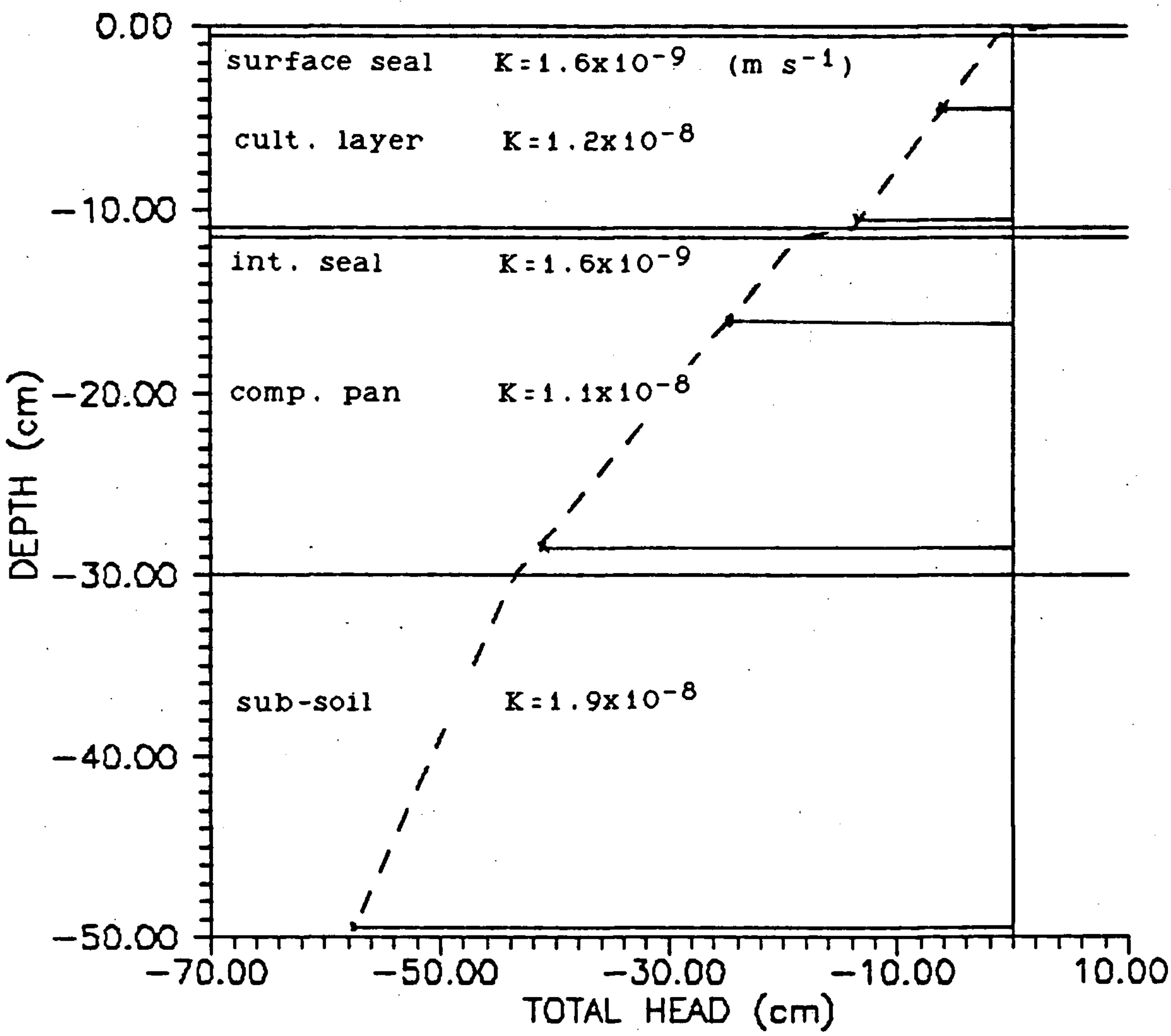

FIG. 8b TOTAL HEAD VS. DEPTH FOR COLUMN 'B' AFTER FORMATION OF A TENSION FORCE AT THE SURFACE.

however, to determine the minimum required coverage necessary for preventing the infiltration rate to decrease below a certain acceptable value.

1.4.2 Internal Seal

Calculating the hydraulic conductivity profile for the soil columns taken from the ponded depression prior to the laboratory cultivation, revealed an anomaly which was later attributed to the existence of an internal seal on top of the compacted pan. This anomaly was that the hydraulic conductivity of the layer between the two tensiometers installed below and above the surface of the pan was smaller than the hydraulic conductivity of the pan itself.

Fig. 9a shows the effective resistance between the tensiometers installed at one centimeter below and above the pan surface in the fifth experiment. This resistance increased with every rainfall application. An interesting observation is that the increase in resistance is roughly proportional to the rainfall intensity. Since resistance is additive, after subtraction of the resistances offered by the cultivation layer and the compacted pan, the resistance due to the internal seal alone was calculated and is also shown in Fig. 9a. The thickness of the internal seal was measured with a ruler to vary from 2 to 5 mm. Based on these two figures the hydraulic conductivity of the internal seal was calculated as shown in Fig. 9b. The last rainfall event was applied

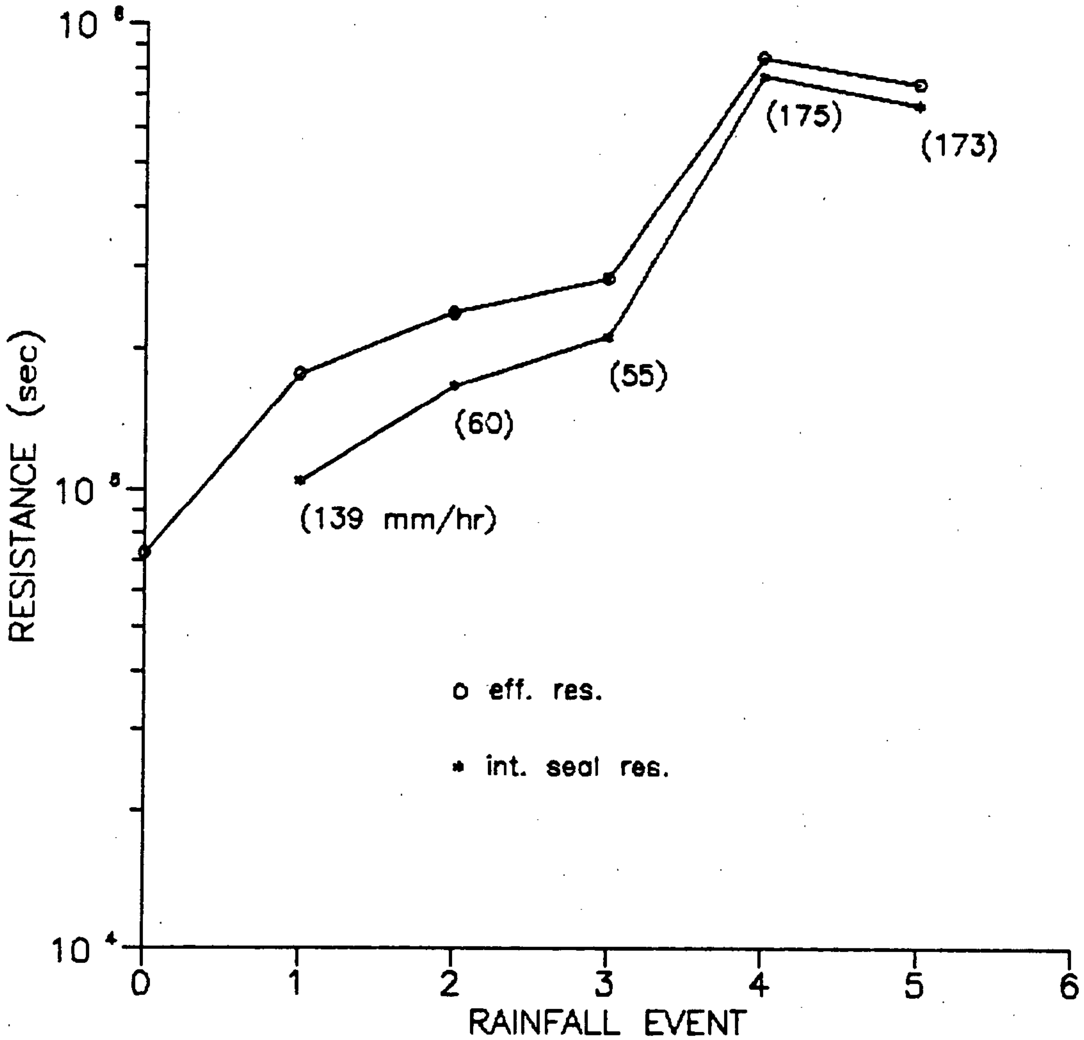

FIG. 9a RESISTANCE VS. RAINFALL FOR THE LABORATORY COLUMN. NUMBERS IN THE BRACKETS SHOW THE RAINFALL INTENSITY.

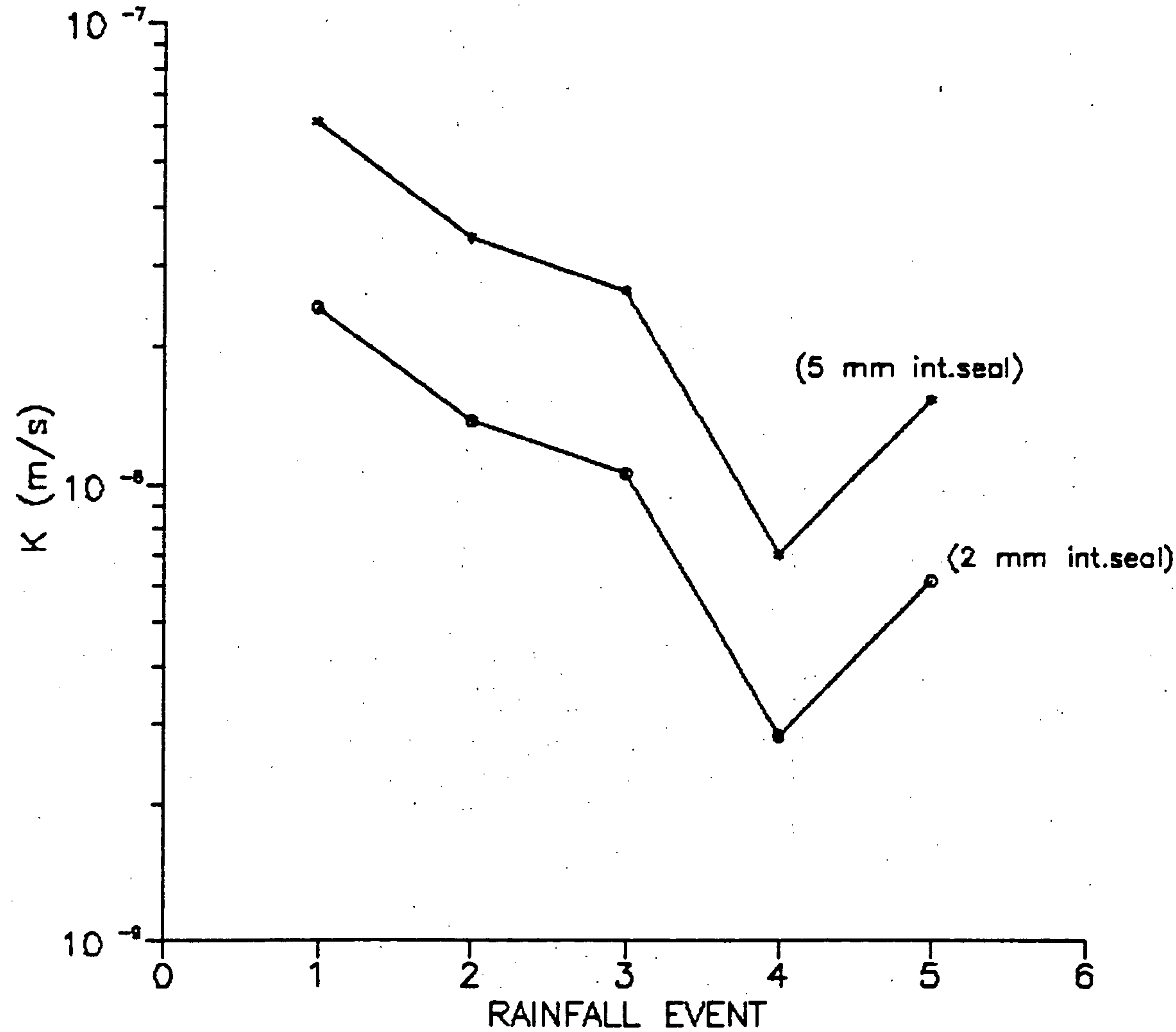

FIG. 9b HYDRAULIC CONDUCTIVITY VS. RAINFALL EVENT FOR AN INTERNAL SEAL FORMED IN LABORATORY COLUMN FOR TWO ASSUMED THICKNESSES OF THE SEAL.

after a prolonged drying period. It is believed that the reduction in the resistance of the internal seal is due to cracking of the seal.

After the experiment, the laboratory soil column was taken apart and the surface of the pan was photographed. Figs. 10a and b show close-up pictures of the internal seal. A seal can always be distinguished by a shiny surface when viewed from the top, and by a dense and thin band at the surface, when viewed from the side.

During the course of this experiment, movement of water into the soil profile was closely observed on application of each rainfall event. It was seen that a large amount of fine material moved through the soil profile along the cracks and macro-pores, settling at the bottom of closed cavities, or moving through and eventually settling on top of the compacted pan.

In the fall of 1987 the soil at site 1 was examined for any evidence of an internal seal. This examination, however, did not reveal the existence of any internal seal in a location where the soil surface had liquefied. It can be concluded that if the surface structure collapses prior to the formation of an internal seal, then this will prevent its formation. Structure of the soil surface can collapse during the very first rainfall event due to a severe structural instability. It is of interest to mention that the field under investigation had been sub-soiled with a conventional sub-soiler in the previous fall after harvest. Sub-soiling a)

b)

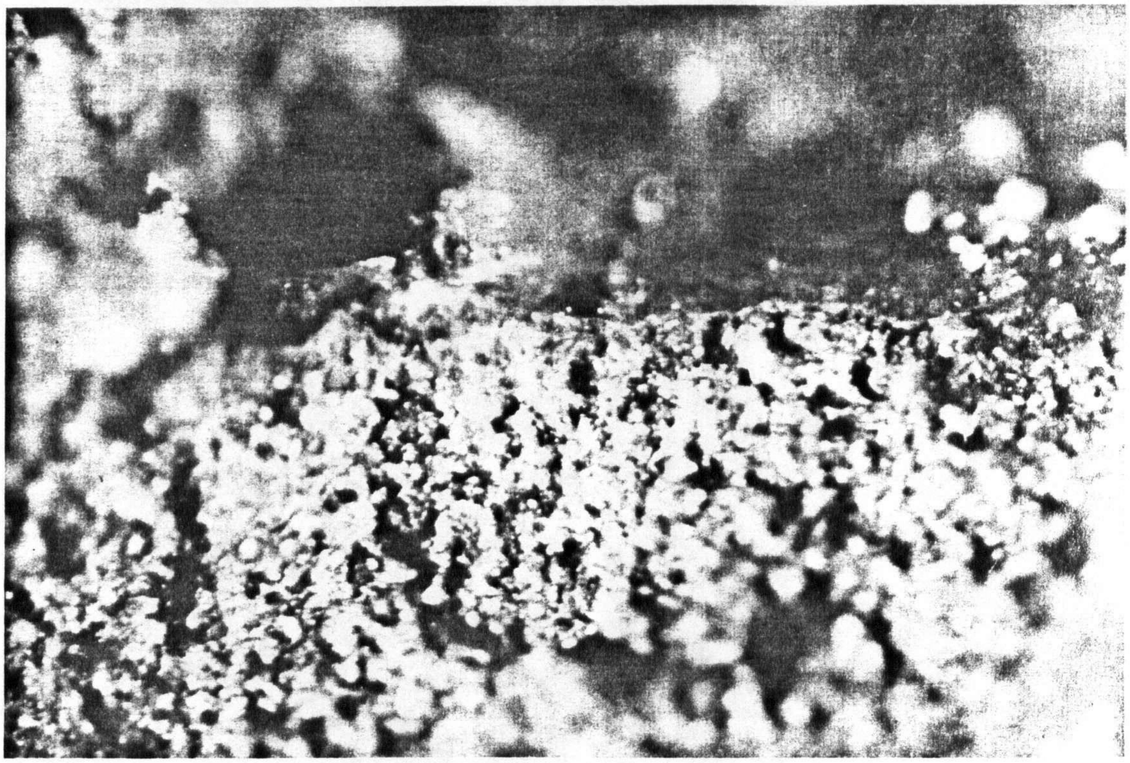

FIG. 10 THE INTERNAL SEAL FORMED ON TOP OF THE COMPACTED PAN IN LABORATORY COLUMN

a) top view
b) side view

has the undesirable side effect of bringing to the surface the weakly aggregated mineral sub-soil. When exposed at the surface, this material can easily slake as the result of a rainfall event. An essential process in the formation of the internal seal is the convective transport of fine sediments downward through the open cultivation layer. If such a flow is prevented, the formation of the internal seal will also be prevented. This argument is not contradicted by the result in Fig. 7 of the decrease in the hydraulic conductivity of the surface and the internal seal as a function of rainfall events.

A descriptive model of seal formation is discussed in chapter 3 as an extension of the mechanisms of surface and internal seal formation already discussed in the present chapter.

1.5 SUMMARY AND CONCLUSIONS

A series of laboratory experiments were conducted in order to investigate the mechanisms that reduce the hydrologic responsiveness of a Ladner soil. It has been shown that the cultivated Ladner soil suffers from a low aggregate stability, making it prone to disaggregation in response to rainfall events. The presence of a surface seal, due to its extremely low hydraulic conductivity, is the main cause of ponding which renders soil untrafficable at the beginning of the cultivation season.

Development of a suction force at the soil surface was shown to play an important role in the creation and efficiency of the surface seals.

A cover crop was shown to be an important management tool in preventing the formation of both surface and internal seals, thereby preventing soil hydrologic degradation as the result of raindrop impact.

An internal seal was observed to form in the laboratory on top of a compacted pan. A laboratory investigation demonstrated one mechanism for its formation. This mechanism was the transport of fine particles by convective flow through the macropores and the eventual deposition of the fines on top of the compacted pan.

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CHAPTER 2

USE OF SOIL STRUCTURE DESIGN PARAMETERS FOR OPTIMIZATION OF HYDROLOGIC RESPONSIVENESS

USE OF SOIL STRUCTURE DESIGN PARAMETERS FOR OPTIMIZATION OF THE HYDROLOGIC RESPONSIVENESS

2.1 ABSTRACT

The concept of managing soil structure according to a set of design hydrologic parameters is central in this chapter. It is based on the intimate connection between soil structure and the shape of the soil's partial hydrologic functions. A set of design hydrologic parameters is used which characterizes the shape of the partial hydrologic functions. A soil that is managed according to these design parameters meets both predetermined hydrologic response requirements, and corresponding time to workability requirements.

To develop the concept, a one-dimensional, numerical model involving flow through an integrated saturated-unsaturated system representing a two-layered soil is used to determine the time to trafficability and workability for a Lower Fraser Valley lowland soil. The soil is subsurface-drained. The soil structure is degraded in steps, from a freshly cultivated state by changing the design hydrologic parameters: saturated water content, saturated hydraulic conductivity, air entry pressure head, and a factor β which describes the shape of the retention curve beyond the air entry value. At each stage of degradation, the model calculates the time to trafficability and workability. The effect of changing the parameters on the time to trafficability and workability is examined to arrive

at a better understanding of the factors which control the hydrologic responsiveness of a soil.

2.2 INTRODUCTION

It was shown in chapter 1 that the structure of a cultivated soil is a dynamic entity. After harvest in the fall, it is common for Lower Fraser Valley lowland soils to be left in a bare and freshly cultivated state exposed to the destructive action of raindrop impact. This practice causes destruction of the surface aggregates which increases the bulk density, decreases the porosity, the saturated hydraulic conductivity and the air entry pressure head of the surface layer. The structure of the cultivation layer will also change to some extent as a result of consolidation and migration of fine particles. As the result of these changes in the soil structure, the hydrologic characteristics of the soil change, resulting in an increase in the soil response time. Response time is defined as the time required for a soil to reach a workable state from a flooded condition with the water table at the soil surface. A soil is considered workable if upon tillage it crumbles easily and forms a loose assemblage of relatively small, soft clods (Hillel 1980).

To carry out farming operations such as manure spreading, a soil must be trafficable (i.e, able to provide traction without being damaged structurally beyond limits for good crop growth), whereas workability is required for cultivation and seeding. From a hydrologic point of view, a soil is of good structure if it can provide farmers with adequate blocks of trafficable/workable days at the beginning of the cultivation season. Much work has been done to predict the effect of different factors on soil workability and trafficability. Wind (1976) used a model of non-steady unsaturated flow of moisture in analog and numerical models to investigate the influence of drainage on workability in spring. Paul and de Vries (1983a,b) investigated the effects of subsurface drainage on soil trafficability. van Wijk and Feddes (1986) developed a model to predict the effects of changes in water management by drainage on trafficability and workability in spring. Buitendijk (1985) calculated the number of workable days for harvest of sugar beet on a sandy loam soil in the Netherlands by application of a physical model of water movement in soils.

In all of the above, and in general in any model of the flow of water in an unsaturated soil, a good knowledge of the soil hydrologic characteristics is required. The partial water retention curve can easily be measured in the laboratory, but measurement of the unsaturated hydraulic conductivity is rather difficult, particularly for a structured or a loosely aggregated soil. Many methods have therefore been developed to represent the partial flow information on the basis of a function which describes the shape of the partial water retention curve (van Genuchten 1980; Campbell 1974).

A feature that most of the hydrologic functions have in common is a set of four parameters which can fully describe the hydrologic characteristics of a soil. These are: saturated water content (Θ_s), saturated hydraulic conductivity (K_s), air entry pressure head (h_a), and a parameter (β) which can characterize the water release ability of a soil, and therefore define the shape of the water retention curve. These parameters, referred to henceforth as hydrologic parameters, are all interdependent and change as the soil structure changes.

The central objective of this paper is two-fold: a) to model the effect of soil structure degradation on the hydrologic response time. Little attention has been given to the fact that hydrologic parameters are dynamic in nature, as most investigators have assumed a constant set of values in their models. b) To determine a set of design hydrologic parameters which produces a desired response time. In other words, to design a soil characterized by a set of design parameters. Such a soil would display the desired hydrologic behaviour. The objective of soil management can therefore be defined as to produce a soil with specified design parameters.

To achieve the above objectives, the upper and lower limits of the hydrologic parameters were estimated for a lowland soil at two extreme structural states, freshly cultivated (assumed to be the least degraded) and the most degraded. Further, degradation process was simulated by decreasing the Θ_s of the freshly cultivated soil in small increments. Assuming a reasonable shape for the partial retention curve at each stage of degradation enabled calculation of the values for β and h_a. Each set of parameters were combined with a range of K_s's and the time to trafficability and workability was calculated at each stage by a numerical model based on the flow equation through a two-layered subsurface-drained soil system.

2.3 MATERIALS AND METHODS

The soil used in this work consists of two layers. A 30 cm cultivated surface on top of an infinitely deep sub-soil. Drains are located at a depth of 120 cm. All the relevant information such as K_s and drainage behaviour is taken from the soil in site 2 as described in chapter 1.

The workability criterion was set at a water content equal to the lower plastic limit (Hillel 1980). The plastic limit of the Ladner soil was determined to be 0.28 kg kg^{-1} (n = 12, standard deviation = ±0.02). On a volumetric basis the plastic limit was calculated for the freshly cultivated soil to be equal to 0.30 m^3 m^{-3} for a bulk density of 1070 kg m^{-3}. This value of bulk density was the lowest value measured for the cultivation layer on April of 1987 (chapter 1, Table 1).

It is realized that as a soil degrades and the bulk density increases, the plastic limit expressed on a mass basis remains the same, whereas expressed on a volumetric basis it will increase. It can be calculated that for a porosity of

0.40 m^3 m^{-3} and a bulk density of 1590 kg m^{-3}, the plastic limit would be equal to 0.44 m^3 m^{-3}. It is not however physically possible for a saturated soil to be workable since it will puddle and liquefy upon being stressed and vibrated by the tractor wheels and the tillage implements. This indicates that expressing plastic limit on a volumetric basis loses physical meaning because it exceeds the porosity. To avoid this problem, the workability limit for different stages of degradation was assumed to be equal to 0.30 m^3 m^{-3}.

To set the trafficability criterion, a condition determined by Paul and de Vries (1979) is used in which a soil is considered trafficable if the pressure head in the top 5 cm is equal to or less than -50 cm of water. It should be kept in mind that this condition holds true only if the air entry pressure head of the surface is greater than (less negative) -50 cm of water.

To calculate the partial unsaturated hydraulic conductivity function a Campbell (1974) type approach was used because of its simplicity. It should however be mentioned that the flow of water in a structured soil is more complex than what is implied by the assumptions underlying Campbell's equation. These assumptions state that flow of water in a soil is controlled by the smaller of two pores in a sequence, only pores in a direct sequence contribute to the total hydraulic conductivity, and the pores in a porous medium fit together randomly (Childs 1969). Campbell (1974) states that if the moisture retention function can be represented by:

$$h=h_a(\Theta/\Theta_s)^{-\beta} \quad (1)$$

then the hydraulic conductivity is given by:

$$K=K_s(\Theta/\Theta_s)^{2\beta+3} \quad (2)$$

where: h = pressure head (cm of water), h_a = air entry pressure head (cm of water), Θ = water content ($cm^3\ cm^{-3}$), Θ_s = saturated water content ($cm^3\ cm^{-3}$), K = hydraulic conductivity (cm day^{-1}), K_s = saturated hydraulic conductivity (cm day^{-1}), β = a parameter referred to as "flatness factor" which describes the shape of the partial water retention curve; Θ_s, K_s, h_a, and β are the hydrologic parameters. The units indicated in brackets are used in the model for convenience.

A major difficulty in using equations 1 and 2 is the determination of the hydrologic parameters at each stage of soil degradation. As the structure of a soil changes, these parameters change. At every physical state of a soil, clearly there is only one set of values that can describe the characteristics of that soil. But the nature of the changes in these parameters with a change in structure is not yet clearly understood.

2.3.1 Determination of the Hydrologic Parameters

a) for the top soil

The partial water retention curve for the surface layer (Fig. 1) was determined in the laboratory with a tension table, for a freshly cultivated soil (highest Θ_s). A curve described by Eq. 1 was fitted to the measured retention curve and the value of β determined from it (Table 1).

Using a measured value of K_s = 864 cm day^{-1} (10^{-4} m s^{-1}) (chapter 1), Eq. 2 was used to calculate the partial flow curve (Fig. 2) for the freshly cultivated soil.

Conditions for the most degraded state were set at a saturated water content of 0.40 cm^3 cm^{-3} and an air entry pressure head of -150 cm of water.

Saturated hydraulic conductivity for the most degraded state was set equal to 8.64×10^{-2} cm day^{-1} (10^{-9} m s^{-1}) (chapter I). Characteristic curves for this state of the soil are also shown in Figs. 1 and 2. Values of the hydrologic parameters are shown in Table 1.

Using the characteristic curves for the least and the most degraded soil (Figs. 1 and 2) as upper and lower limits, and assuming a reasonable shape for the partial retention curve at each stage of degradation, a reasonable set of values was calculated for β and h_a (Table 2).

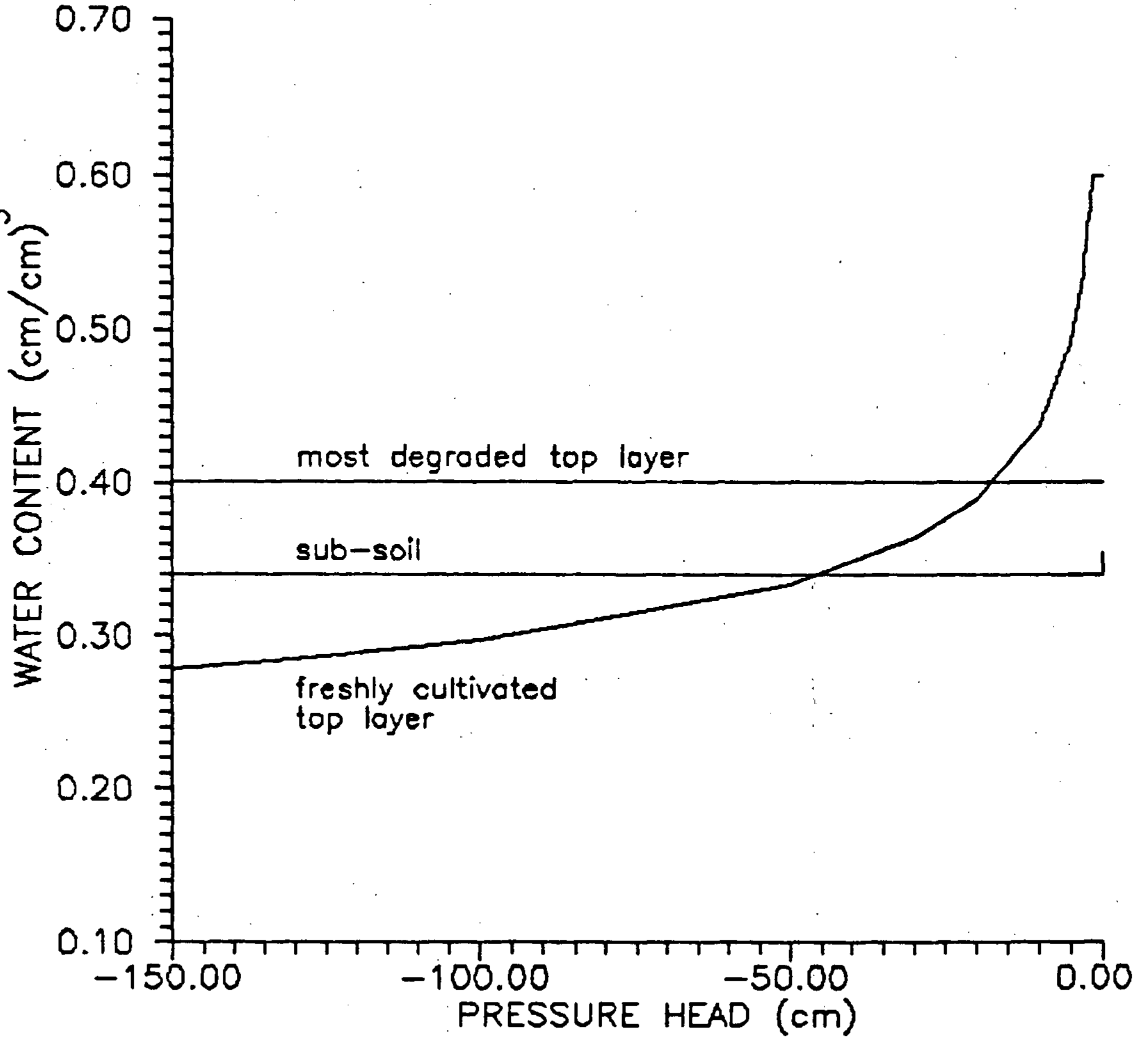

FIG. 1 PARTIAL WATER RETENTION CHARACTERISTIC CURVES FOR THE TOP 30 cm LAYER, AND THE BOTTOM 90 cm LAYER OF SUB-SOIL.

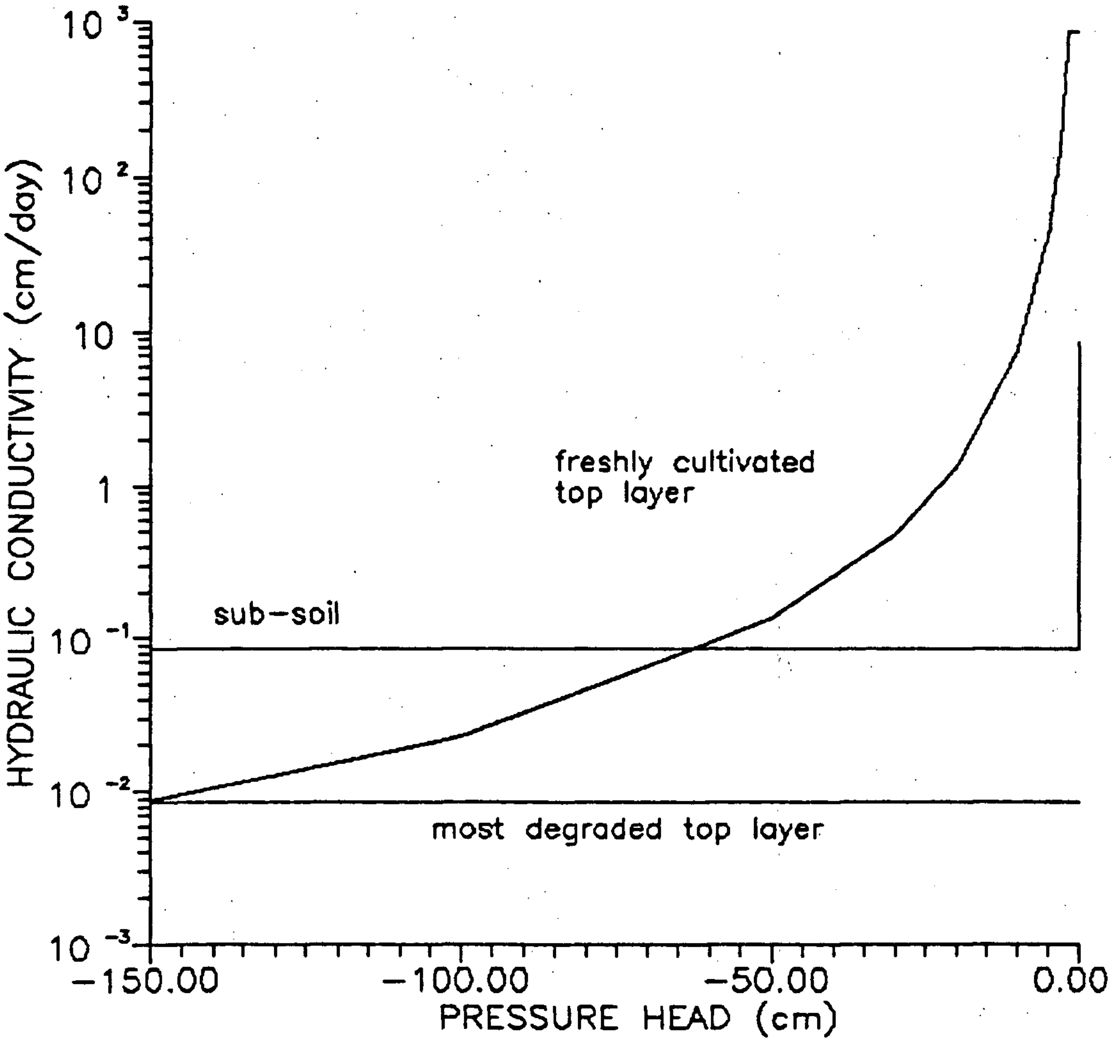

FIG. 2 PARTIAL FLOW CHARACTERISTIC CURVES FOR THE TOP 30 cm, AND THE BOTTOM 90 cm OF SUB-SOIL.

Table 1. Hydrologic parameters of the soil

	θ_s $cm^3\ cm^{-3}$	K_s cm day^{-1}	h_a cm	β
top 30 cm:				
freshly cultivated	.6	864	-1.5	6.0
most degraded	.4	.0086	-150	-
sub-soil	.35	8.64	0.0	0.0

Table 2. Values obtained for some hydrologic parameters by assuming a reasonable behaviour for the partial retention curves

Θ_s $cm^3\ cm^{-3}$	h_a cm	β
.59	-1.6	6.1
.58	-1.8	6.3
.57	-2.0	6.5
.56	-2.3	6.7
.55	-2.6	6.9
.54	-3.0	7.2
.53	-3.4	7.5
.52	-4.0	7.8
.51	-4.5	8.2
.50	-5.4	8.5
.49	-6.3	8.9
.48	-7.7	9.4
.47	-9.4	10.0
.46	-11.6	10.7
.45	-14.7	11.6

b) <u>for the sub-soil</u>

Characteristic curves for the sub-soil are assumed to remain unchanged during the off-season period because its structure does not change. These curves are shown in Figs. 1 and 2. The justification for this type of behaviour is based on the observations, where: 1. when saturated, most of the flow in the sub-soil was observed to take place through the stable root holes and, 2. when unsaturated, the matrix of the sub-soil was noted to have a relatively low hydraulic conductivity (chapter 1, Fig. 5). Also, since the contribution of the conducting channels to the porosity is negligible, the water content changes only slightly from saturated to unsaturated condition.

2.4 NUMERICAL MODEL

The soil water conservation equation for a one-dimensional, vertical, unsteady, unsaturated, and rigid porous material under isothermal conditions can be written (Richards' equation) as:

$$c(h)\delta h/\delta t = \delta/\delta z[K(h)\delta h/\delta z] + \delta/\delta z[K(h)] \qquad (3)$$

where: $c(h) = d\Theta/dh$ = specific water capacity (cm^{-1}), h = soil water pressure head (cm of water), t = time (day), Θ = volumetric water content ($cm^3\ cm^{-3}$), K = hydraulic conductivity (cm day^{-1}), z = depth (cm), positive upward with z = 0 indicating the surface.

For the saturated condition K(h) = constant, and c(h) = 0, therefore Eq. 3 reduces to:

$$\delta^2 h/\delta z^2 = 0 \qquad (4)$$

Derivation of these equations is detailed in Freeze (1969).

Fig. 3 taken from Freeze (1969) shows the mathematical model for continuous flow from the soil surface to the drains located at a depth of 120 cm below the surface. The model consists of a column of n_{max} nodes numbered vertically upward from the drain location.

Most soils exhibit a negative air entry pressure head (h_a) above which the values of hydraulic conductivity and water content are equal to their respective saturated values. Eq. 3 thus holds for all values of $h < h_a$ and Eq. 4 for all values of $h > h_a$.

The boundary condition at the elevation of the drain is:

$$\delta h/\delta z = [q/K(h)] - 1 \qquad (5)$$

where: q > 0 represents the rate of drainage discharge, and q < 0 indicates a recharge of the system. The drainage discharge rate is calculated by:

$$q = Ah_D \qquad (6)$$

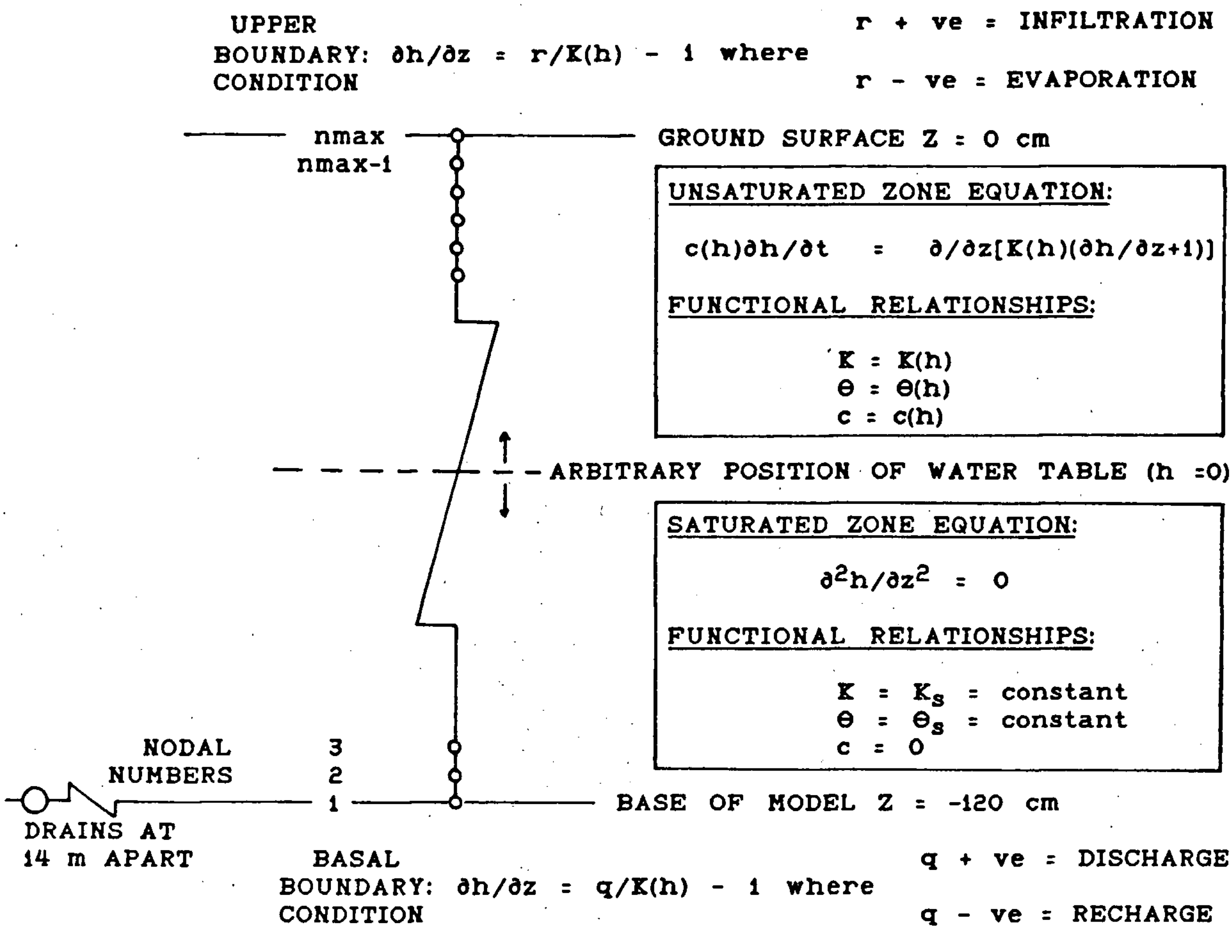

FIG. 3 MATHEMATICAL MODEL FOR ONE DIMENSIONAL, VERTICAL UNSTEADY INFILTRATION OR EVAPORATION.

where: A = drainage intensity (day^{-1}) (Wind and van Doorne 1975), and h_D = height of water table at midpoint between drains. Eq. 6 is based on Hooghoudt (1938), only holding midway between two parallel drains if the drainage resistance (1/A) is constant (Wind and van Doorne 1975). The value of A used in the model was obtained by the modified transient state Glover-Dumm equation:

$$A = \ln(1.16\ h_o/h_t)/t \qquad (7)$$

where: h_o and h_t (cm) are the initial and final heights of water table above drain depth midway between drains at start and end of the draw-down period, respectively, and t (day) is the length of draw-down period. Derivation of this equation is detailed in Paul and de Vries (1983). Values of h_o and h_t were obtained from water table recession data (provided from the Boundary Bay station plots by the B.C. Ministry of Agriculture) taken during a rainfree period t, which followed a heavy rainfall in March 1985.

It is assumed in the model that the water table can recede to a depth of not more than 30 cm below the drains early in the spring.

The boundary condition at the surface is:

$$\delta h/\delta z = [r/k(h)] - 1 \qquad (8)$$

where: r = the flow rate (cm/day) across the upper boundary. A positive r represents rainfall infiltration; a negative r represents evaporation. In the absence of any precipitation, an evaporation of $r = -0.1$ cm day^{-1} was assumed to take place early in the spring. Further it was assumed that the pressure head of the water in the surface layer does not decrease below -10^5 cm of water.

The problem described above is solved by numerical analysis, using a finite differencing procedure similar to that detailed by Whisler and Watson (1968). The only difference is that at the end of each time step (0.1 day) the value of the pressure head at the surface and at the drain depth was calculated according to the boundary conditions described by Eqs. 5 and 8.

To solve the numerical problem described above a computer programme was written in C language and it was run on an IBM microcomputer.

2.5 RESULTS AND DISCUSSION

Before presenting any results, a discussion of the data presented in Table 2 is warranted. It was discussed in chapter 1 that as the result of raindrop impact on a freshly cultivated soil, a disaggregation process takes place which increases the response time of a soil. This increase in the response time is due to the changes which takes place in the soil hydrologic characteristics, defined by the four hydrologic parameters. As soil aggregates break down and fill the pore spaces, the porosity of the soil and hence its saturated water content decreases. Furthermore, the diameter of the water conducting pores will decrease, restricting the flow of water and consequently lowering the saturated hydraulic conductivity. As a result of the reduction in pore diameter, the air entry pressure of the soil will also decrease along with an accompanying increase in the value of β. The hydrologic parameters change simultaneously as a result of soil structure degradation with relationships among them that are not well understood. To determine the effect of soil structure changes on the hydrologic parameters, the behaviour stated below is assumed for the partial water retention curves in response to soil degradation:

As a soil degrades and the saturated water content decreases, the partial water retention curves follow the behaviour shown in Fig. 4, where: a) the horizontal part of each successive curve must intersect the preceding retention curve b) each successive curve intersects the curve for the most degraded soil, at least, at h = -150 cm and c) each successive curve does not cross the preceding curve more than once (i.e., only at the horizontal part). It should be noted that as β increases the curves become flatter. The justification for the above restrictions is that at any given value of h, the water content of a more degraded soil should be higher than that of a lesser degraded soil for $h < h_a$. Table 2 shows the values calculated to meet the above

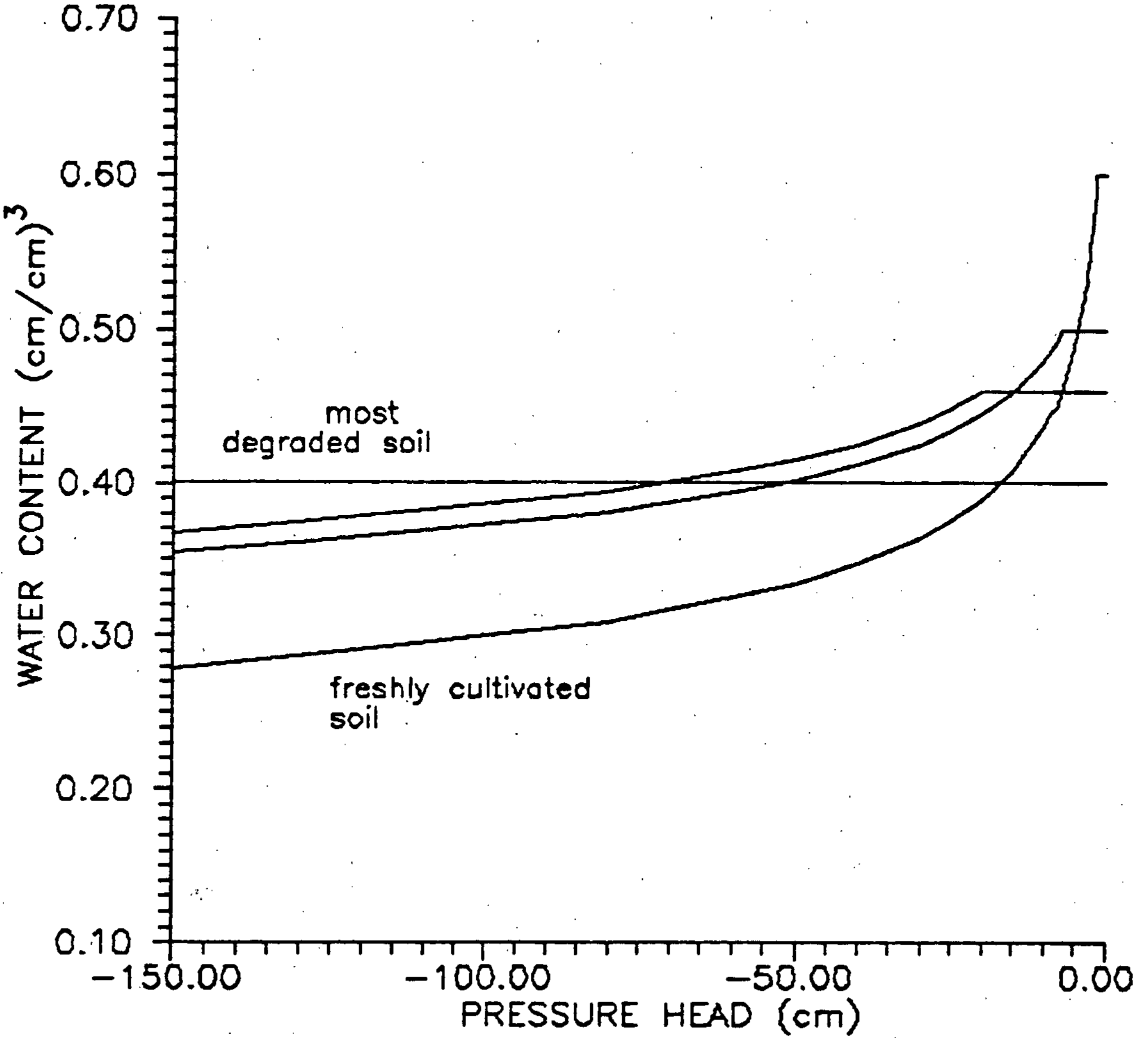

FIG. 4 PARTIAL WATER RETENTION CURVES AT VARIOUS STAGES OF DEGRADATION.

conditions. The model was run for some of the conditions in Table 2 combined with a range of saturated hydraulic conductivities (Table 3).

2.5.1 Model Response

Two different scenarios were run by the model. First, from an initial condition of flooding with the water table at the soil surface, time to trafficability and response time was calculated with an evaporation of 0.1 cm day^{-1} and zero precipitation. Second, using the pressure head distribution at the trafficable state of the first run as an initial condition, the model was run for a typical storm of 10 hour duration and 2 cm day^{-1} intensity which made the soil untrafficable. The time to trafficability and workability was calculated again from the time that the rainfall ceased neglecting hysteresis. Results are shown in Table 3.

Fig. 5 shows the response of the model to drying for condition 3a in Table 3 from a flooded condition to a trafficable state. Fig. 6 shows the response of the model to the above storm from an initially trafficable state.

Table 3 shows the response time and time to trafficability and workability for different soil conditions. It can be seen that as soil structure degrades the response time increases, whereas use of pressure head as an index of trafficability does not result in a consistent pattern. This inconsistency results from the definition of trafficability on the basis of

Table 3. Showing time to trafficability (tt), response time (rt), and time to workability (tw) for a number of possible hydrologic parameter combinations

case no.	K_s cm day^{-1}	θ_s cm^3 cm^{-3}	h_a cm	β	from a flooded condition: h-based* tt day	from a flooded condition: w.c-based** tt day	rt day	soil status index	after a 10 hr. storm of 2 cm day^{-1} intensity: w.c-based* tt day	after a 10 hr. storm of 2 cm day^{-1} intensity: tw day
1	864	.60	-1.5	6.0	6.4	6.5	10.6	1.0	2.4	5.8
1a		.60	-1.5	5.5	6.8	5.4	8.6	.8	1.6	4.6
1b		.60	-1.5	6.5	6.2	8.0	12.4	1.2	3.7	7.8
1c		.58	-1.8	6.3	6.7	7.6	12.1	1.1	1.8	6.4
1d		.57	-2.0	6.5	6.2	7.7	12.8	1.2	1.9	6.9
1e		.56	-2.3	6.7	6.3	8.7	14.7	1.4	2.0	7.7
2	432	.58	-1.8	6.3	6.3	7.2	11.1	1.0	2.5	7.4
2a		.57	-2.0	6.5	6.5	8.0	12.3	1.2	2.7	7.5
2b		.56	-2.3	6.7	6.3	8.7	14.7	1.4	3.1	7.7
3	86.4	.58	-1.8	6.3	6.2	7.0	12.1	1.1	6.1	10.2
3a		.57	-2.0	6.5	6.3	7.6	12.5	1.2	6.2	11.0
3b		.56	-2.3	6.7	6.1	8.1	12.8	1.2	6.5	11.2
3c		.54	-3.0	7.2	6.2	9.7	14.7	1.4	7.4	12.1
3d		.52	-4.0	7.8	5.8	11.5	17.1	1.6	7.4	13.2
3e		.51	-4.6	8.2	5.7	13.0	19.3	1.8	7.3	13.6
4	43.2	.56	-2.3	6.7	6.1	8.2	15.5	1.5	6.3	13.4
4a		.54	-3.0	7.2	5.8	9.1	16.3	1.5	7.9	14.5
4b		.52	-4.0	7.8	6.1	11.1	18.2	1.7	8.8	15.4
4c		.50	-5.4	8.5	5.7	13.1	20.2	1.9	12.0	19.0
5	8.64	.52	-4.0	7.8	6.4	12.8	33.1	3.1	11.1	31.9
5a		.50	-5.4	8.5	6.5	13.5	35.5	3.3	12.1	33.0
6	4.32	.53	-3.4	7.5	5.8	14.4	50.6	4.5	16.5	49.2
6a		.52	-4.0	7.8	7.2	17.2	52.4	5.0	17.6	51.9

*Based on a pressure potential of -50 cm at a depth of 5 cm.

**Based on a volumetric water content (v.c) of 0.33 cm^3 cm^{-3} at a depth of 5 cm.

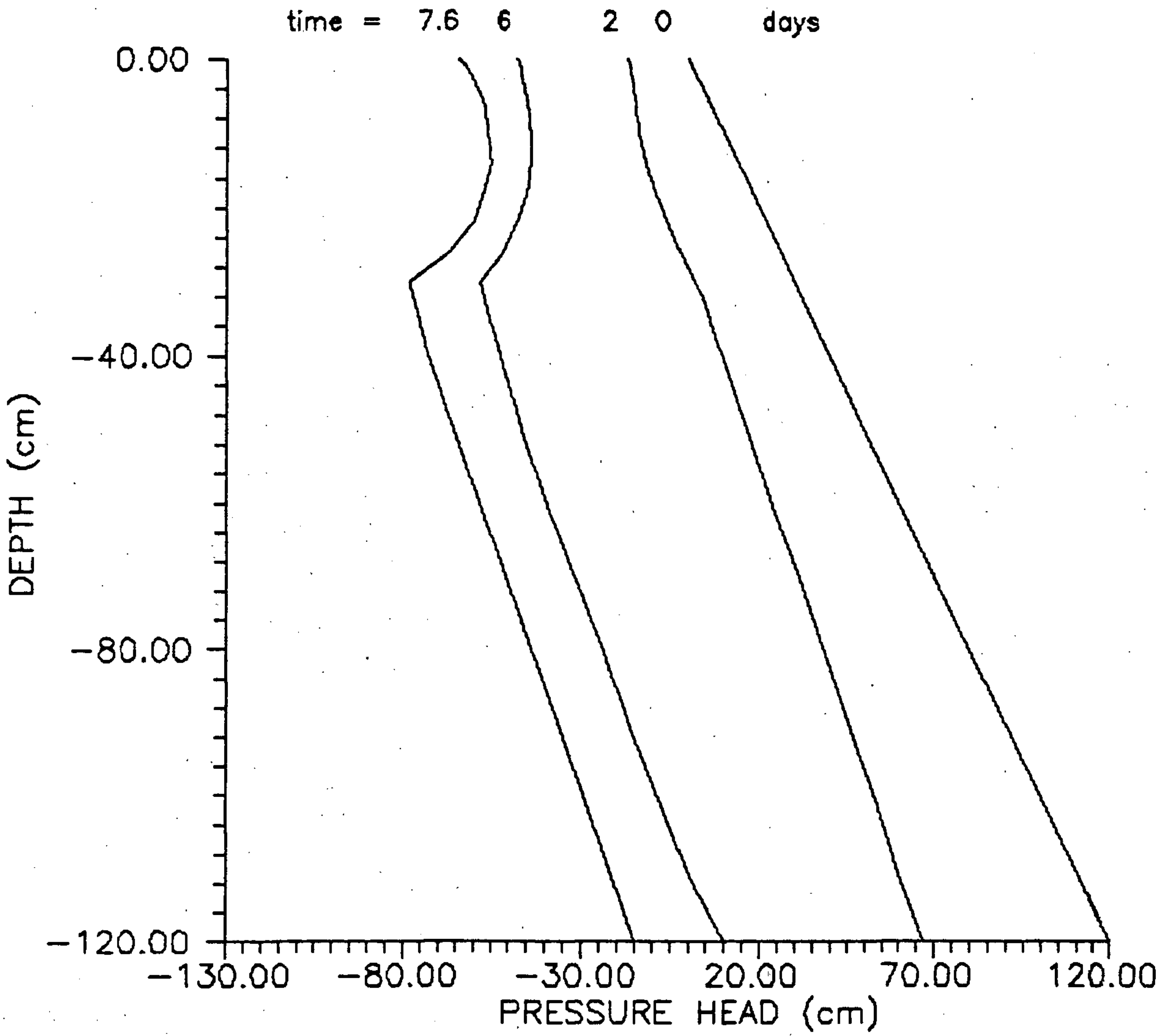

Fig 5. SHOWING THE PROCESS OF DRYING FROM AN INITIALLY FLOODED CONDITION FOR CASE 3a IN TABLE 3.

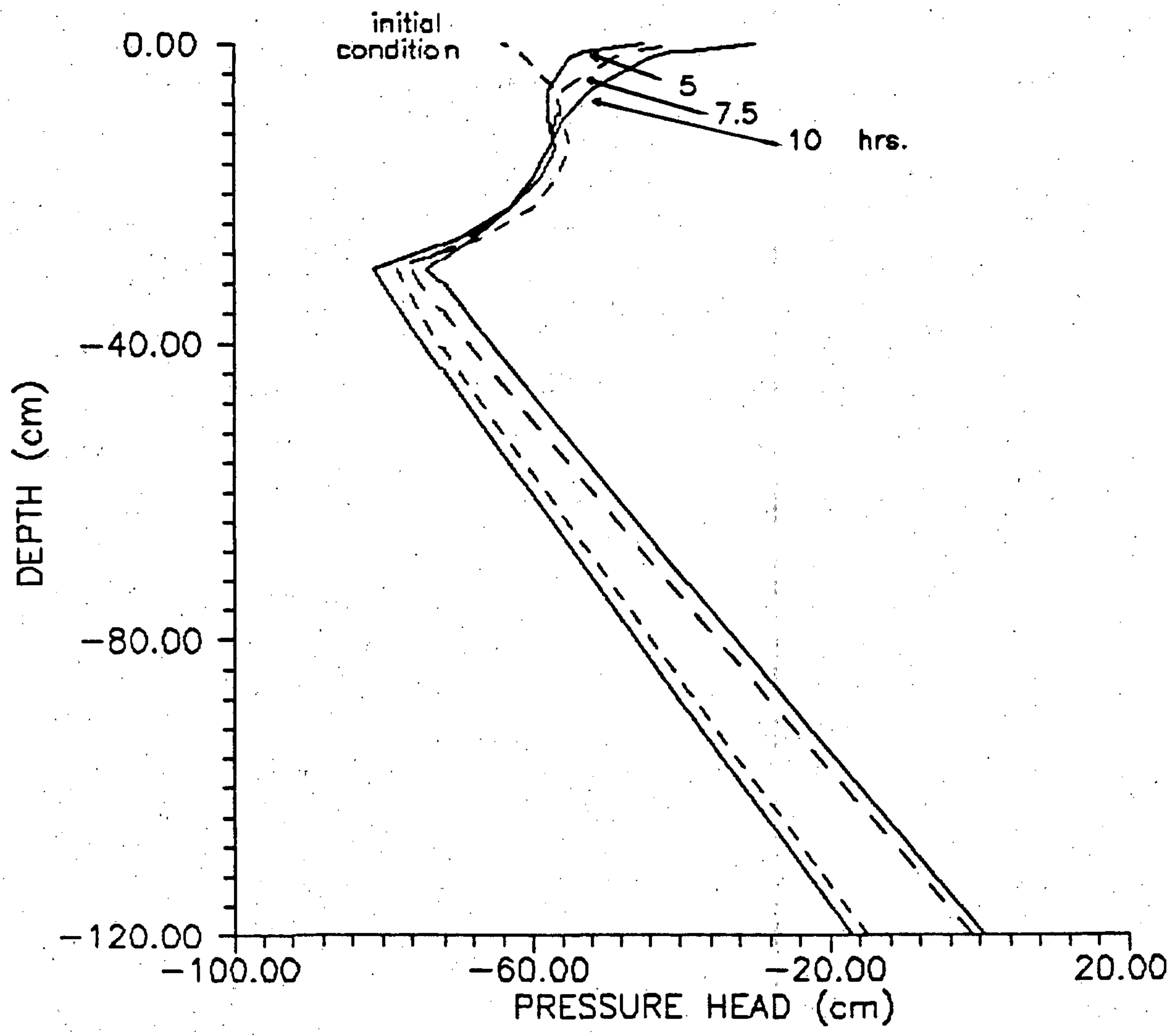

FIG. 6 SHOWING THE PROCESS OF WETTING FROM AN INITIALLY TRAFFICABLE STATE (AT t=7.6 DAYS FIG. 5) IN RESPONSE TO A STORM OF 10 HR. DURATION AND 2 cm/day INTENSITY.

pressure head. In accordance with the restrictions imposed on the behaviour of the retention curves, as the soil degrades, the water content at which the pressure head reaches -50 cm of water increases (Fig. 4); hence the time to trafficability may actually decrease for a more degraded soil. This finding indicates that using pressure head as an index of trafficability may not be adequate. A set of alternative values for time to trafficability was calculated on the basis of water content as shown in Table 3. This water content was assumed to be 0.33 $cm^3\ cm^{-3}$.

Since all the hydrologic parameters are interdependent and change simultaneously as a soil structure degrades, it would not make physical sense to keep one parameter constant while changing the other ones. This fact restricts the way in which the results in Table 3 can be interpreted. For example a comparison of the conditions 1c and 2 indicates that as K_s is reduced by half, the response time decreases by 1 day. This is contradictory. A more meaningful comparison however would be between 1c and 2a or 2b.

There is one important factor which leads to over conservatism in the results presented in Table 3. This factor which is not considered in the model, is the formation of tension cracks at the soil surface. Formation of these cracks speeds up the process of drying by increasing the evaporating surface (Ross and Bridge 1984). Also, in the case of a heavy rainfall event water can be conducted rapidly in the cracks bypassing the soil matrix (Bouma and De Laat 1981). Therefore a cracked soil could reach a workable stage at a much shorter time than that indicated in Table 3.

Setting an arbitrary upper limit of 20 days on the response time, the data in Table 3 show that the values of Θ_s, K_s, h_a, and β should not be worse than 0.50, 43.2 cm day^{-1} ($5x10^{-6}$ m s^{-1}), -5.4 cm, and 8.5 respectively. These are the so called design values for the hydrologic parameters. The objective of a soil and water management programme for the Ladner soil should therefore be to produce a soil with the above hydrologic parameters. To achieve this, the effect of management practices such as cultivation techniques and addition of organic matter on the hydrologic parameters should be investigated.

It should be emphasized that the values of the design hydrologic parameters should be chosen to optimize the response time and not to minimize it. Plants need a soil with good water retention capacity. The soil also must have good water release ability for an optimum response time.

By assigning unity to the response time of the freshly cultivated soil, an index for the hydrologic status of a soil can be defined as shown in Table 3. An index value of larger than 1.9 therefore, will not meet the criterion of a 20 day limit on the response time.

It was seen that the existing trafficability and workability criteria are not adequate in situations where soil structure changes due to degradation. It is suggested that further research should be done to determine how these criteria should change with soil degradation. The concept of plastic limit also is ambiguous with regard to degradation and warrants further research.

In the light of the recent advances in waste treatment practices, many by-products are being considered for use as soil amendments. Addition of organic waste to the soil will change its water release ability and hence the value of β. Table 3 shows that increasing the value of β by 0.50 for the freshly cultivated soil ($\Theta_S = 0.60$), increases the response time by almost 2 days. Keeping in mind that at the beginning of the cultivation season, it is a block of workable days which is important rather than a single workable day, this increase in the response time is very significant. Therefore it is recommended that the short and long term effects of any organic waste being considered as a soil amendment, on the water releasing ability of a soil be carefully investigated.

2.6 SUMMARY AND CONCLUSIONS

The central concept of this paper is quantification of soil structure and thereby soil management, in terms of the hydrologic behaviour of a soil.

A mathematical model is used to determine the response time and time to trafficability for a Ladner soil. A Campbell (1974) type approach is used to calculate the partial flow function from the partial water retention curve. Determination of the effect of structure degradation on the hydrologic parameters was carried out by assuming a reasonable behaviour for the partial water retention curves in response to degradation.

A set of design parameters are determined for a desirable hydrologic responsiveness. The goal of soil management for the Ladner soil considered, should be to achieve and maintain these design parameters. Further investigation is required to determined the effect of different soil management practices on the hydrologic parameters.

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CHAPTER 3

DESCRIPTIVE MODEL OF SEAL FORMATION

AND

MANAGEMENT MODEL

DESCRIPTIVE MODEL OF SEAL FORMATION AND MANAGEMENT MODEL

3.1 ABSTRACT

A descriptive model for the formation of a surface and an internal seal is offered for a Lower Fraser Valley (LFV) lowland soil. The seal formation mechanism suggested is a description of the dynamic changes which occur in the structure of the surface layer of a bare soil as the result of rainfall events. Some of the processes leading to the formation of a surface seal are: surface disaggregation, soil splash, sedimentation in ponded depressions, and development of a suction force at the bottom of the surface layer.

A management model is proposed with the objective of improving soil hydrologic responsiveness. The model comprises a systematic checking of conditions which lead to the development of a surface seal, and provides appropriate management remedies.

3.2 INTRODUCTION

Formation of a surface seal is an important process because of its adverse effects on infiltration and seedling emergence. Surface seals are formed through the impact of water droplets from rain or sprinkler irrigation, and by slaking of the surface aggregates in a flooded condition. Surface seal formation is a complex process and has been extensively studied during the last four decades.

McIntyre (1958 a & b) described the process of surface sealing and observed that deposition of fine particles, the washing of these into the soil matrix, and compaction caused by rain drop impact were involved. He noted two distinct layers at the surface: a skin seal 0.1 mm in thickness, and a "washed-in" region 1.5 to 2.5 mm thick. Other investigators however, failed to verify the existence of a washed-in layer.

Tackett and Pearson (1965), and Evans and Buol (1968) studied surface seals formed by simulated rainfall on a sandy loam. They found the seals to be very dense, and stated that clay particle orientation plays an important role in the sealing phenomenon.

Falayi and Bouma (1975) investigated the effect of different management practices on the hydraulic conductivity of the surface seal. They found that different tillage practices, and crop rotation had significant effect on the conductance of the surface seal. They also concluded that conductances of surface seals formed under short-term high-energy experimental rainfall were not significantly different from those formed under natural conditions. However, they noticed a significant difference between the morphology of surface seals formed under different conditions.

Morin et al. (1981) hypothesized that the sealing efficiency of a surface seal is enhanced by suction forces which cause the clay particles to be arranged into a continuous dense skin. The suction forces at the soil-seal interface are created as a result of the large differences in hydraulic conductivity between the seal and the underlying soil. The suction mechanism accounts for the stability of the seal and the similarity in values of seal hydraulic conductivity between soils varying greatly in their texture and mineralogy.

Bonsu (1987) offers a physically-based model describing a mechanism for surface sealing in the context of aggregate stability. He shows the saturated hydraulic conductivity of the cultivation layer to be positively correlated with the aggregate stability and negatively correlated with the mineral matter content.

The objective of this chapter is to suggest a single descriptive model of the processes which contribute to the formation of a surface and an internal seal. This model is based in part on the experiments and observations of chapter 1 and those which have been reported in the literature.

A management model is also presented with the objective of preventing formation of the seals and improving soil hydrologic responsiveness.

3.3 MECHANISMS OF SURFACE AND THE INTERNAL SEAL FORMATION

In describing the mechanisms of surface and internal seal formation, the initial condition is a cultivated bare soil at the end of the cultivation season. The process of sealing begins with the first rainfall event and continues throughout the off-season period. Therefore, we begin with what is called an open soil model (Fig. 1). As time proceeds and the soil conditions change, different models are introduced. These models are referred to as the surface seal model, internal seal model, and the cracked soil model. The term model is used to indicate a set of processes, and the entire picture in Fig. 1 is referred to as the mechanisms of seal formation.

It is assumed that the mechanisms of seal formation are the same in the field as in the laboratory. In this chapter the results of the experiments in chapter 1, conducted in the laboratory, are extended to the field condition.

In Fig. 1 each box describes a process. The lower box simply shows some of the important dependent variables of the upper box. For example, the effect of raindrop impact is a function of the rainfall energy.

3.4 DISCUSSION

The mechanism of surface seal formation can be divided into five stages: 1. Pre-overland flow as described by Tarchitzky et al. (1984). 2. Post-overland flow, formation of a pond in the depressions. 3. Settlement of the suspended load in the ponded depressions. This stage may or may not contain early recession of the pond, depending on whether or not an effective seal is already present. If an effective seal is not already in place and the cultivation layer is saturated,

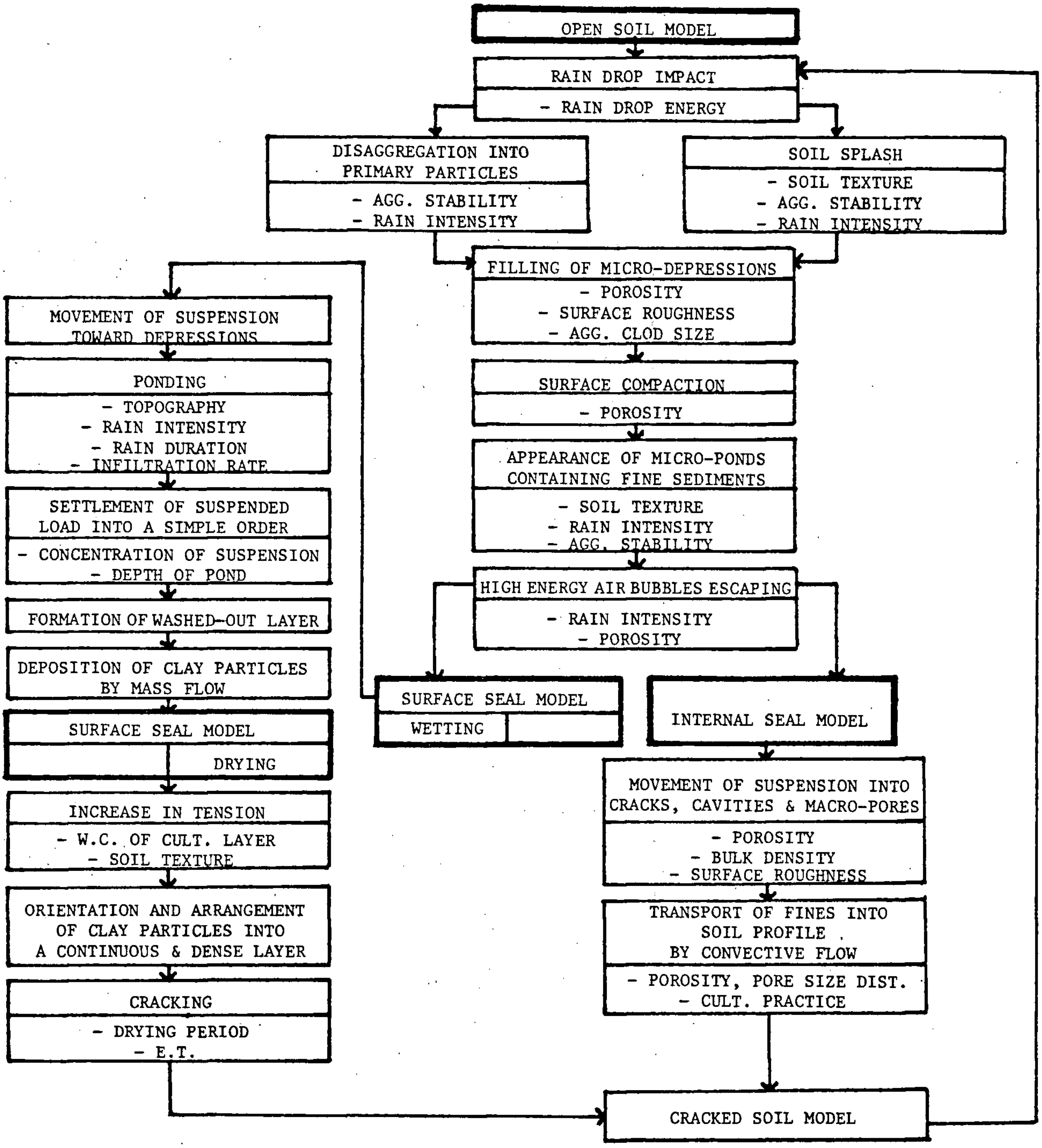

FIG. 1 DESCRIPTIVE MECHANISMS OF SEAL FORMATION

then the fourth stage is: 4. Recession of the pond and the formation of a suction force at the bottom of the surface layer. 5. Formation of tension cracks as soil dries further. It was discussed in the first two chapters that formation of these cracks will dramatically improve the hydrologic behaviour of the soil.

In the first stage of surface seal formation (open soil model) two important mechanisms are responsible for generating the source material for the formation of the seals. One is the destruction of the aggregates by the rainfall impact and the other is the soil splash which distributes the fine particles across the surface (Al-Durrah and Bradford 1982; Bubenzer and Jones 1971).

As shown in chapter 1, the most important factor in controlling the course of events in this stage is the aggregate stability of the soil. Aggregate disintegration and the consequent splash lead to the filling of micro-depressions, causing a reduction of the surface porosity and consequently causing surface compaction due to the raindrop impact (Tackett and Pearson, 1965; Mitchell and Jones, 1978). Close observation of the generation of the surface seal in the second experiment of chapter 1 revealed that as infiltration rate decreases, micro-ponds containing suspended fine particles appear at the surface. As a layer of free water covers the surface, some of the entrapped air within the soil profile escapes in a violent manner (based on the observations of the experiments in chapter 1), further breaking up the aggregates and putting fine sediment into suspension (Fig. 1). These processes create the source material necessary for the formation of a seal, and set in motion the sealing process.

The second stage consists of the beginning of overland flow and the creation of a surface pond in the depression areas (wetting process of surface seal model, Fig. 1). Much work has been done to describe the process of overland flow in terms of its potential for causing erosion and transporting fine particles. This process is fully described by Tarchitzky et al. (1984), Gabriel and Moldenhauer (1978), Epstein and Grant (1967), and many others. In chapter 1 the source material for the generation of the surface seal (experiment 2) was created in-situ as the result of disintegration of local aggregates alone. In the field, however, source material is also transported into the depressions, where the most effective surface seals are often formed.

In the third stage, the important process of particle settlement in the ponded depression takes place. The author is not aware of any studies describing this stage of the surface seal formation. Originally the arrangement of the particles in the soil is very random. Fine and coarse particles co-exist randomly. The conglomeration of particles into aggregates consists of fine and coarse particles together. But upon rainfall, when the aggregates break up into primary particles which are then put into suspension, this randomness in arrangement is lost.

Upon settlement, as governed by Stoke's law, the larger particles settle first, followed by finer and finer particles. This simple arrangement, where finer particles block the pore spaces in between the coarser particles, reduces the porosity and therefore the infiltration rate. A layer of coarse particles was observed immediately below the surface seals, when viewed under a microscope. Figs. 2a,b show two such seals, where the coarser layer is identified by the lighter colouring.

Next step is the deposition of clay particles by mass flow, as the pond recedes, to form a so-called McIntyre "skin layer" (McIntyre 1958 a & b). Studying magnified pictures of surface seals did not reveal McIntyre's "washed-in" layer. This also was the conclusion of Tarchitzky et al. (1984).

Formation of a suction force is thought to develop in the fourth stage of the mechanism of the surface seal formation (drying process of surface seal model, Fig. 1). However, in reality a suction develops at the surface during the initial stages of the sealing process. In a non-saturated condition, this suction force at the surface is determined by the suction at the wetting front (Morin et al. 1981). In chapter 1 (experiment 3), the formation of a suction force was prevented from occurring by keeping the entire cultivation layer saturated at all times. The result shows that a surface seal did not form until the soil was allowed to dry.

In the third experiment of chapter 1 the drying process occurs during the period when the water table is lowered to the base of the column and the pressure head distribution a)

b)

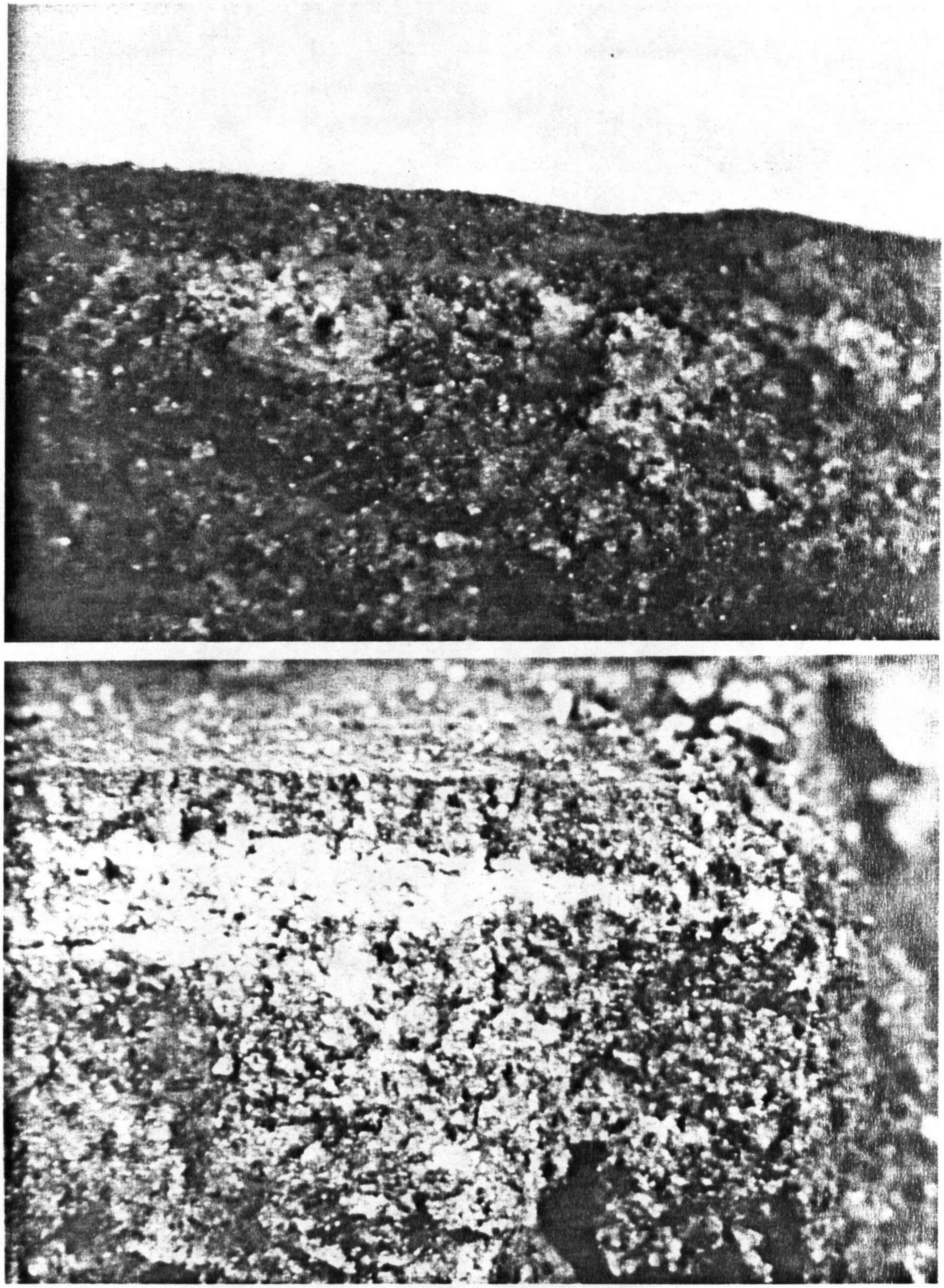

FIG. 2 SHOWING SIDE VIEWS OF TWO SURFACE SEALS. A COARSE LAYER AT THE BOTTOM OF EACH SEAL TOPPED WITH FINER PARTICLES CAN BE IDENTIFIED.

approaches equilibrium. As drainage commences, a suction force develops at the bottom of the seal, while the seal itself remains tension-saturated due to its large (negative) air entry value. Development of this tension force within the seal causes: 1. arrangement of particles into a more continuous and denser configuration and, 2. orientation of clay particles into a more ordered arrangement (Morin et al. 1981; Tackett and Pearson 1965).

Evans and Buol (1968), studied the micromorphological features of surface seals formed under different conditions. They reported observing numerous horizontally oriented plate-like particles in the surface seals. Morin et al. (1981), attribute the sealing efficiency of a surface seal to suction forces which develop at the bottom of the surface layer. The third experiment in chapter 1 showed the development of a suction force to be an essential factor in the formation of a surface seal.

The process of internal seal formation can be divided into two stages: 1. Downward movement of water carrying fine particles. 2. Deposition of the fine particles on top of a compacted pan.

In the simulated soil column (fifth experiment in chapter 1), it was observed that the downward flow of water through a freshly cultivated soil carried a large amount of suspended load to the top of the compacted pan. These fine materials were generated either by the disintegration of the surface aggregates due to the rain drop impact, or they were generated as a result of the cultivation practice. At the top of the pan, fine sediment particles were deposited forming an internal seal. In fact, during the simulated cultivation (second experiment in chapter 1), and at the time of the dismantling of the simulated column referred to above, close observation of the soil structure showed that small and very localized micro-seals had formed throughout the cultivation layer at dead end pores and at the bottom of closed cavities. But this effect was much more pronounced at the interface between the tilled layer and the undisturbed compacted pan.

3.5 SOIL MANAGEMENT

The hydrologic objective of soil management should be to prevent the formation of an effective surface and internal seal. For this purpose, a set of "design parameters" (chapter 2), controlling the soil hydrologic behaviour, should be specified according to the requirements of a region. Management practices should then be designed in order to meet the criteria as specified by these design parameters.

It was shown in chapter 1 that if a soil is left in a loose, bare and therefore unstable state after the fall harvest, its structure will degrade as the result of raindrop impact. There are a number of steps that can be undertaken in the area of soil management that could stabilize the structure of the soil surface and therefore minimize the reduction in the hydrologic responsiveness.

These management practices are described in the model presented in Fig. 3 and are discussed below in terms of pathways numbered 1 to 7. Each pathway consists of one or more soil and water management problems and suggested remedies.

Pathway 1. The model starts at the top with the question, "Is free water present at the soil surface?" Because of the nature and frequency of off-season rainfall events, it is not always economically feasible to meet the drainage requirement for all rainfall events and thereby prevent free water from ever being present on the soil surface (B.C. Agricultural Drainage Manual, 1986). But for pathway 1. which is the "ideal soil and water condition pathway", after an exceptional rainfall event that causes flooding, free water on the surface will recede quickly, and the water table will drop quickly to the design depth, returning the soil to a trafficable state within a few days. In such a soil a functioning drainage system is present and a proper cover crop or crop residue for off-season surface protection exists. The soil is of good tilth and has a stable structure. This optimum and therefore desirable pathway is depicted in the centre of Fig. 3, from top to bottom. Any deviation from this pathway can be remedied and ultimately looped back to the ideal path.

Pathway 2. If free water is present on the surface and no drainage system is present, the remedy is to install a drainage system. Depending on the requirements and conditions of a field, a surface, or sub-surface, drainage system or

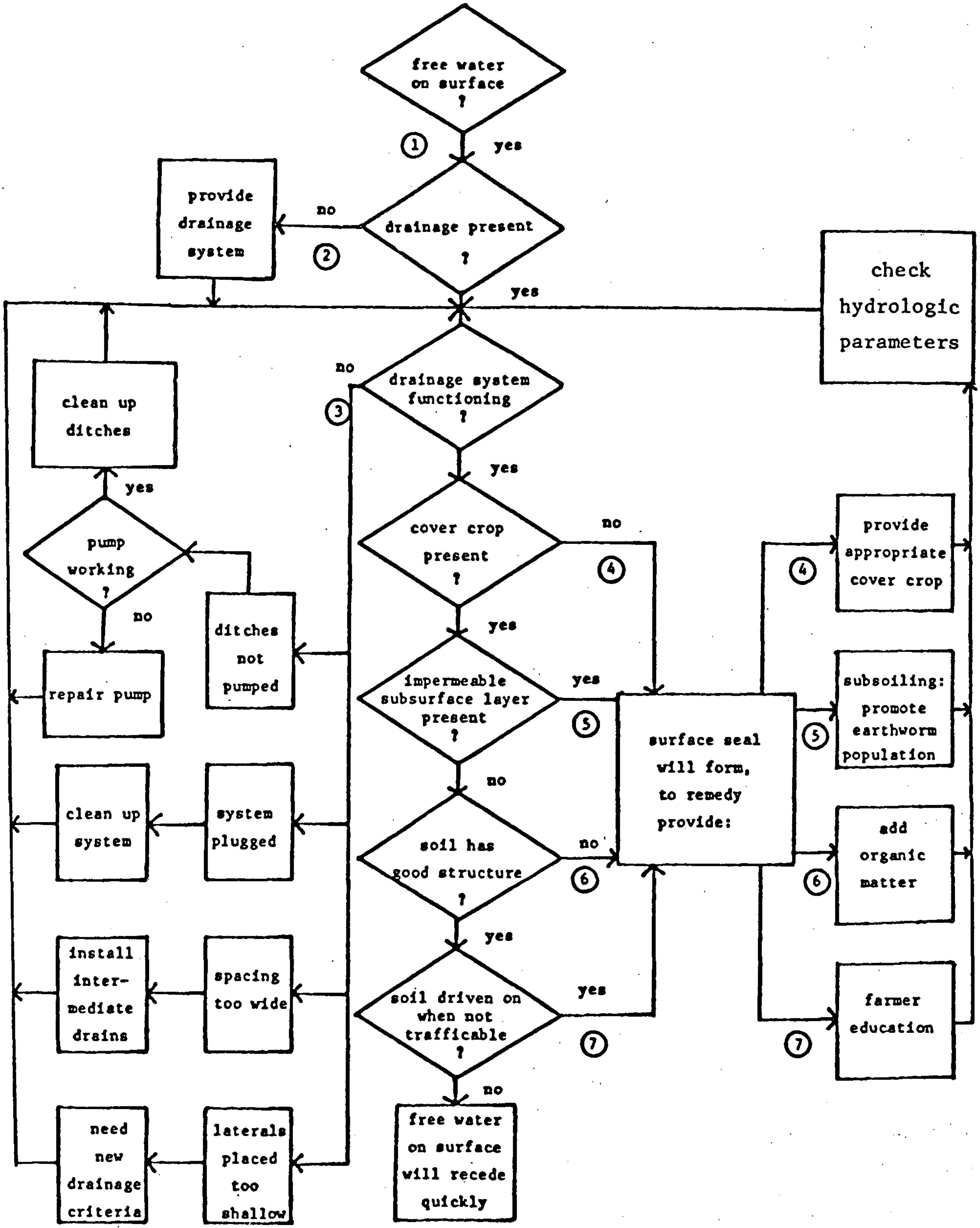

FIG. 3 A DESCRIPTIVE MANAGEMENT MODEL FOR LOWER FRASER VALLEY LOWLAND SOILS. DEPICTED AT THE CENTRE IS AN IDEAL SOIL AND WATER MANAGEMENT PATH.

both, may be considered.

Pathway 3. Relative to this path, Fig. 3 is self explanatory. If a sub-surface drainage system is present but it is not functioning, the cause(s) must be determined by a systematic checking procedure as indicated in Fig. 3. Control of the water table is a direct means of controlling the trafficability of lowland soils (Paul and de Vries, 1979).

Pathway 4. The presence of a cover crop dampens the pounding action of the rain drops, keeps the soil surface open, and helps meet the infiltration requirement. This requirement is met if rainfall does not result in ponding. It should be used in management as a tool to reduce soil erosion and degradation. More research is required in this area in order to determine the type and amount of cover crop needed to prevent surface seal formation. In the absence of a cover crop, proper management of crop residue after harvest can provide an effective alternative.

Pathway 5. Under a condition where a sub-surface drainage system is in place, but where a traffic pan is present, water may remain perched on top of the pan, or on the internal seal after recession of the water table to the design depth. The management remedy for this condition is sub-soiling. It is preferred that sub-soiling be done with the paraplough, which opens up the natural cracks in the soil without transferring the sub-surface soil to the surface (J. de Vries, personal communication 1987).

Pathway 6. Appropriate cultivation methods along with the supply of organic matter to the soil as well as maintenance of a cover crop and earthworm population would improve the soil structure.

Pathway 7. When a soil of good tilth is driven on and/or cultivated under untrafficable/unworkable conditions, compaction/puddling will result, which in turn will result in the accumulation of rain water on the soil surface and the triggering of surface seal formation. For this pathway, in particular, the remedy is education of the farmers.

To ensure the effectiveness of the above management practices, soil hydrologic parameters should be measured at the end of each season and compared with the design parameters.

The above management model has the potential to be used as an algorithm for devising an expert system for the purposes of soil management. An expert system is a data base which contains the opinions and experience of many different experts.

3.6 SUMMARY AND CONCLUSIONS

A descriptive model is presented showing the mechanisms that contribute to the reduction of the hydrologic responsiveness in a lowland soil. A new phenomenon referred to as internal seal was identified as forming at the top of the compacted pan, and one mechanism for its formation is offered based on laboratory experiments (chapter 1).

The mechanism of the seal formation developed in this chapter is in reality a description of the dynamic changes which occur in the structure of a bare soil in response to rainfall events. As soil structure changes, soil parameters which govern the soil hydrologic behaviour will also change. Therefore, any model which is designed to predict soil hydrologic behaviour over a long period of time, should take these changes into account to avoid serious errors.

To prevent formation of the surface and the internal seal, a management model is presented. Practicing the recommendations made in this model will ensure the maintenance of an optimum hydrologic responsiveness and a short response time for the purposes of timely cultivation and seeding/planting in the spring.

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CONCLUSIONS AND SUMMARY

Laboratory experiments were carried out to determine the causes of a low hydrologic responsiveness in a lowland soil in the Lower Fraser Valley of British Columbia. The results are presented in three chapters.

In chapter 1, hydraulic conductivities were measured on undisturbed soil columns removed from a ponded depression in a cultivated soil in west Delta. The results were compared with another soil column removed from an uncultivated soil in an adjacent field. It was found that the cultivated soil contained high resistance layer at the surface (surface seal) and on top of the compacted pan (internal seal). No seals, however, were observed in the uncultivated soil.

Cultivation was simulated on both columns and simulated rainfall was applied in an attempt to regenerate the seals under close observations. A disaggregation process, leading to the formation of the seals was identified as the main cause of the low hydrologic responsiveness.

In chapter 2, the process of soil degradation observed in chapter 1, was quantified in terms of the parameters which govern the hydrologic behaviour of the soil. This quantification was used to assign a set of design parameters to soil structure. The objective of soil and water management for the Ladner soil is therefore to achieve and maintain a soil structure as defined by the assigned parameters.

In chapter 3, a descriptive mechanism of seal formation is presented along with a management model. The mechanism of seal formation based on the observations in chapter 1 and a literature review, is divided into five stages.

The management model depicts an ideal soil and water management path and offers a remedy for each deviation. This model can be used as an algorithm for development of an expert system for the soil and water management of the Lower Fraser Valley lowland soils.