NPo-forskning
fra Miljøstyrelsen

Nr. B19 1990

Field Investigations of Preferential Flow Behaviour

Miljøministeriet **Miljøstyrelsen**

Danish Research Programme on Nitrogen, Phosphorus and Organic Matter (NPO)

The aim of the NPO Research Programme is to gather knowledge on the decomposition of Nitrogen (N), Phosporus (P) and organic matter (o) in the soil, and on their impact on lakes, watercourses, inlets, groundwater and the sea.

This report is one of a total of about 50 reports to be issued in connection with the implementation of the NPO Research Programme. The National Agency of Environmental Protection (NAEP) is responsible for the programme, under which about 70 NPO projects have been launched, carried out at 25-30 institutions.

In the 1970's and the beginning of the 1980's there was a growing awareness of the threats to life in watercourses etc. presented by discharges of nutrients – and of the risk of nitrate contamination of groundwater. In 1984 a report was prepared, synthesising existing knowledge in this field. The report, known by the name of NPO Report, was published by the NAEP.

To follow up this report the Dansih Parliament took the first steps in 1985 to reduce pollution with nutrients – laying down requirements for storage and application of farm yard manure in the agricultural sector.

For the purpose of improving our knowledge on the impact of nutrients in nature, the Danish Parliament also reserved 50 million DKK for the research programme, running from 1985 to the end of 1990.

The significance of the NPO Research Programme was further underlined with the Danish Parliament's adoption of the Action Plan on the Aquatic Environment in 1987. The results of the NPO Research Programme will play a vital role in the evaluation of the effects of the Action Plan.

To safeguard the technical and economic interests relating to the research activities a steering group was set up, having the overall responsibility for the implementation of the NPO Research Programme. Furthermore, three coordination groups were formed, each of them responsible for one of the three fields: soil and air, groundwater, and surface water.

The reports are published in the series »NPo-forskning fra Miljøstyrelsen« (NPo Research in the NAEP), divided into three sections:

A: reports on soil and air
B: reports on groundwater
C: reports on watercourses, lakes and marine waters.

The NAEP has been secretariat for the research programme. The reports published in this series are edited by the Agency with the assistance of the coordination groups.

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Field Investigations of Preferential Flow Behaviour

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Sammendrag

Klorid blev anvendt i et tracerforsøg for at påvise makroporestrømningsfænomener på markskala. Feltarealet er beliggende i oplandet til Syv Bæk, Sjælland og består af et stykke (0.2 ha) drænet landbrugsjord. Jordprofilet er udviklet på lerholdig moræne med tydelige tegn på strukturelle porer stammende fra lodrette ormehuller og rodkanaler i de øverste jordlag og fra interaggregate sprækker i de nedre jordlag. Klorid blev tilført jordoverfladen i fast form ($CaCl_2 \cdot 2H_2O$) i 2 m brede striber langs drænet, som befandt sig i ca. 1.3 m's dybde. Drænudstrømningen og kloridkoncentrationen blev kontinuerligt og automatisk registreret i perioden efter udlægningen. To uafhængige forsøg på separate arealer blev udført. Vandtilførsel fra regn blev mod slutningen af forsøg 1 og gennem hele forsøg 2 suppleret med kunstig vanding, eftersom drænflowet var ved at ophøre. En brat stigning i drænflowhastigheden i begge forsøg umiddelbart efter en stærk vandtilførsel på relativ fugtig jord (ca. 10 mm/time), der førte til begyndende overfladeafstrømning, blev taget som udtryk for makroporestrømning. Dette blev understøttet af en samtidig stærk stigning i kloridkoncentrationen i det andet forsøg. Klorid er således blevet ført fra overfladen med den kortsluttede strøm direkte til drænet. At klorid ikke blev genfundet i drænvandet i forsøg 1 kan forklares ved, at klorid var blevet tilført jordoverfladen næsten 30 dage inden det skarpe strømningsgennembrud og formentlig var diffunderet ind i de mindre porer i jordmatricen og derfor blev forbigået under makroporestrømningen. I forsøg 2 var klorid blevet udlagt samme dag som gennembruddet og derfor stadig tilgængeligt for transport i de større porer. Kun en mindre mængde (0.3 %) af det tilførte klorid blev genfundet i drænafstrømningen i forsøg 2. En del er imidlertid formentlig forsvundet til jordlag under drændybde, p.g.a. de små hydrauliske gradienter hen imod drænet sidst på drænsæsonen, hvorfor et skøn over makroporestrømningsfænomenets kvantitative betydning på dette grundlag er vanskelig. En udvaskningsrisiko er imidlertid påvist at eksistere ved udbringning af stoffer i umiddelbar forbindelse med kraftig nedbør. Yderligere undersøgelser er påkrævet til belysning af indflydelsen af mere naturlige nedbørsforhold, jordfugtighed og tracerens form ved tilførsel (fast kontra flydende form).

Summary

Chloride was used in a tracer study to document and qualitatively evaluate the effects of preferential flow at field scale. Very fast response of a subsurface drain at 1.3 m depth upon surface application of water and solute that can not be explained by a displacement flow mechanism was taken as an indication of

preferential flow. Further documentation was obtained from distinct bypass flow manifesting itself in two ways, one being surface applied water free of chloride bypassing a soil matrix with high chloride content, the second being surface applied chloride bypassing a soil matrix with little chloride content. The implication of preferential flow for leaching of surface applied fertilizers and pesticides is discussed.

Introduction

Preferential flow

Preferential flow is an established term and a recognized phenomenon in water and solute transport in soil systems. Preferential flow refers to a flow mechanism where transport of water and dissolved or suspended substances is primarily associated with a smaller fraction of the total soil pore volume. There is a whole spectrum of possible flow situations. One extreme is that the majority of the soil is totally bypassed by the fluid, and active transport only occurs in unhindered flowpaths, the intermediate being a random distribution of flowrates throughout the porous medium, to the other extreme being a uniform flow field. This range of flow situations is determined by the soil physical properties as well as the scale of observation. At the smallest scale, the pore scale, water will always move preferentially in the center of the soil voids. If the soil is texturally homogeneous and uniform, these microscopic effects will average out when the observation scale increases and macroscopic approaches using Darcy and Fick's law will be applicable in the flow description (Nielsen et al. 1986).

If, however, the soil exhibits heterogeneity or discontinuity in the soil physical properties at the larger scale the simple macroscopic approach is no longer sufficient. It has been proposed to include stochastic and geostatistic methods in the traditional approach to account for the randomness of soil and hydraulic properties (see e.g. reviews by Warrick and Nielsen, 1980, and Dagan et al., 1988). However, preferential flow represents a further degree of complexity. Discontinuities in the soil characteristics give distinct different flow behaviour, and the traditional one-domain macroscopic approach (applied either in a deterministic or stochastic sense) seems inadequate.

Two causes of preferential flow

Preferential flow can be related to discontinuities in poresize, meaning that water and solutes will be transported primarily in relatively large and continuous pores or openings (macropores) in the soil whenever the conditions are favourable.

Macropores can be indigenous to the soil like cracks in desiccating clay soils, or interpedal voids between surface aggregates or subsurface structural blocks or peds, or they can be created biologically by borrowing soil animals (e.g. earthworms and ants) or roots.

A distinct definition of a macropore has been proposed based on an equivalent diameter (see e.g. Luxmoore et al., 1990), but it is arbitrary since many other factors influence the potential of a pore to promote preferential flow, i.e. its continuity and orientation, its tortuousity, its surface characteristics, its connection to the surface and its stability.

Another flow mechanism that is responsible for preferential flow is due to wetting front instability. Rather than the movement being associated with isolated channels or macropores, water and solutes move in finger-like pathways through the soil matrix. The discontinuity promoting fingering, as it is also termed, has been found to be interfaces between soil layers of contrasting texture transversely to the flow direction, usually the case when a fine textured soil is overlaying a coarser soil (Glass et al., 1988, Glass et al., 1989). Other researchers report that soil hydrophobicity can result in flow concentration and fingering (Hendrickx et al., 1988, van Ommen et al., 1988).

The effect of preferential flow

The effects of preferential flow have been observed in numerous field and laboratory studies (for references see Thomas & Phillips, 1979, Beven & Germann, 1982, White, 1985). In laboratory experiments involving soil cores accelerated initial breakthrough of surface applied substances with asymmetrical long tailed breakthrough curves have been attributed to preferential flow phenomena. Also the non-homogeneous wetting of soil cores is associated with a bypass flow mechanism. Preferential flow caused mainly by macropore flow is usually observed in intact and undisturbed soil whereas fingering can be simulated in a repacked soil in the laboratory.

In field situations it has been possible to detect surface applied substances at depth far in advance of the time corresponding to a leached amount of one pore volume, indicating preferential flow. Sampling has been done through subsurface drains (Everts et al., 1989), lysimeters (Andreini & Steenhuis, 1990) or porous suction cups (Jardine et al., 1990).

The two first-mentioned works also describe the noted effect on chemicals with adsorbing properties, namely a decreased retardation in the soil matrix with increasing dominance of preferential flow. The implications of these findings is that fertilizers and pesticides applied to the soil surface might be carried below the root zone and into drains or shallow aquifers with a contamination of surface and groundwater systems and little intended crop related benefit as a result (Barraclough et al., 1983). The direct conduits to drains and groundwater might also be relevant in the consideration of atmospheric acidic deposition. With little residence time and hence contact possibilities with neutralizing agents in the soil the rainwater will be transported fairly unaffected to receiving water bodies (Potter et al., 1988 and Shanley & Peters, 1988). Increased infiltration associated with macropores in the soil surface reduces the risk of soil erosion in erosion prone areas due to less surface runoff, whereas slope stability might be affected positively or adversely depending on the drainage possibilities (Cheng, 1988). Rain or irrigation water will be more or less available for plants compared to a less-macroporous soil depending on whether or not the macropores extend beyond the rootzone (van Stiphout et al., 1987).

Modeling of preferential flow

Recognition of the prevalence of preferential flow and especially its effects on spreading of substances related to human activity has led to an intensified research on quantifying and modeling this flow phenomenon.

Earlier studies used a two-domain approach in which one domain is responsible for the fast and preferential flow while slow or no transport is associated with the second domain. An interaction term describes flow and diffusion of water and solute between the two domains. Examples of this modeling approach for water transport are found in Edwards et al. (1979), Hoogmoed & Bouma (1980), Beven & Germann (1981), Davidson (1984, 1985, a, b), Beven & Clarke (1986), and for solute transport in Yeh & Luxmoore (1982) and van Genuchten et al. (1984). These first generation models tested and expanded our conceptual understanding of the flow processes. Yet they were fairly simplistic and not amendable to application to field conditions. Generally they were single-pore models and assumed à priori knowledge of the geometry of the flow field.

Less geometrically based two-domain models are the CRACK-model of Jarvis (1989) and the mobile-immobile model of Skopp & Warrick (1974), van Genuchten & Wierenga (1976) and Skopp et al. (1981). The mobile-immobile model which is an adaptation of the traditional convective-dispersion equation model has been applied with varying degree of success to data from heterogeneous soil columns (e.g. Herr et al., 1989, Wierenga & van Genuchten, 1989 and Khan & Jury, 1990). In further studies it has been suggested that macropore flow is not restricted to the largest and non-capillary sized pores (Germann & Beven, 1981) and that the flow domain should be considered as a multitude of pore size classes (Jardine et al., 1990). Such a modeling approach has been attempted by Steenhuis et al. (1990) using the method of characteristics.

The less mechanistic transfer function model suggested by Jury (1982) and refined by Jury et al. (1986) describes solute transport based on the probability density function of solute travel times from the soil surface to some reference depth. Since soil heterogeneity and preferential flow is lumped into the variance of the residence times, limited physical meaning can be given to the calibrated parameters (van Ommen et al., 1989b). Beven & Young (1988) have recently suggested an approach related to the transfer function model, the so-called aggregated mixing zone model, which is stated to be more flexible in the description of preferential flow (Beven & Young, 1988).

The problem of parameter interpretation and estimation is not unique to the less mechanistic models. In the convective-dispersion equation model the dispersivity is shown to increase with the scale of observation (Gelhar & Axness, 1983 and Wheatcraft & Tyler, 1988) and the degree of soil structure (Parker & van Genuchten, 1984). Calibration of parameters might be possible for individual observations. However, the correlation of the parameters with the scale of observation and the soil structure must be inferred if the models are to gain any general and predictive value.

Untackled problems

The complex nature of preferential flow implies additional difficulties in the modeling endeavour. In field and laboratory experiments the extent and effect of macropore flow have been observed to depend on factors such as rainfall intensity or solute application rate and soil moisture conditions. An increase in application rate (Trudgill & Coles, 1988, Kanchanasut & Scotter, 1982 and Kluitenberg & Horton, 1990) as well as moisture content (Trudgill & Coles, 1988 among others) generally favours preferential flow which is in accordance with the conceptual picture of the flow mechanisms. Flow into larger voids in the soil surface is initiated when the infiltration capacity of the surrounding soil matrix is exceeded or ponding occurs. For an initially dry soil the macropores will be less effective because of lateral loss to the soil matrix. However, the effect of soil moisture is ambiguous. It has been reported that fast response in initially dry soil could be associated with hydrophobic conditions of the soil surface and worm hole channels (Edwards et al., 1989), and with clay cracks that swell upon wetting (Reid & Parkinson, 1984). To account for these factors modeling approaches that can accept highly variable and multi-pulse inputs are necessary. Furthermore, the physical relations responsible for preferential flow need further systematic investigation in order to find more quantitative descriptions.

Large-scale effects

The effect of preferential flow is typically related to the hydrological response of larger areas and diffuse contamination sources.

Hence in gaining further insight into the problem a relevant observation scale is equivalent to the extent of such contamination. In agricultural aspects it could be a field or an ensemble of fields. A practical and convenient way of observing flow responses is by means of subsurface drainage systems which was pointed out by Richard & Steenhuis (1988). In Denmark this is feasible since extensive areas already have artificial drainage facilities. The spatial variability of preferential flow which might be pronounced on a smaller scale (Andreini & Steenhuis, 1990) will be integrated to give a spatially averaged response. Also for distributed catchment models such as the SHE-model (Abbott et al., 1986) the unit grid size is principally equivalent to the field size making parameter determination at this scale important.

In this paper the preliminary results of a tracer study on the intake area of a single drain are presented. The purpose is to examine the effect of preferential flow at field scale and especially the influence of water application rate and soil moisture condition. Furthermore, the application timing for a conservative tracer is studied in relation to the retaining capacity of the soil. The hydrological response of a larger area, encompassing this field site, is investigated in terms of preferential flow effects by Engesgaard & Jensen (1990).

Field site

The field site is located within the farmland of Syv Creek catchment in the central part of Zealand, Denmark (Fig. 1). The drainage system consists of 40-50 year old tile drains (diameter 5.5 cm) installed at 120-140 cm depth and at individual spacings of about 20 m. The topography is rather flat with a slope less than 1 percent. The field site had been cropped with wheat during the season prior to the experiment which took place in the spring of 1990.

The total intake area of the drain involved in the tracer study was approximately 0.2 ha. For reasons explained later the site was divided into two experimental plots which were investigated separately (Fig. 2).

The soil type was described from two excavations located outside the tracer application areas, supplemented with soil samples from 28 handdrilled bore holes. Location of bore holes are shown in Figure 2. Soil type is a pseudo gley brown earth with the gley development evident below approximately 80 cm indicating partly imperfect drainage. Two geological profiles along the two plots based on the observation points have been constructed (Fig. 3). The boundary of the B-C horizons determined by soil structure

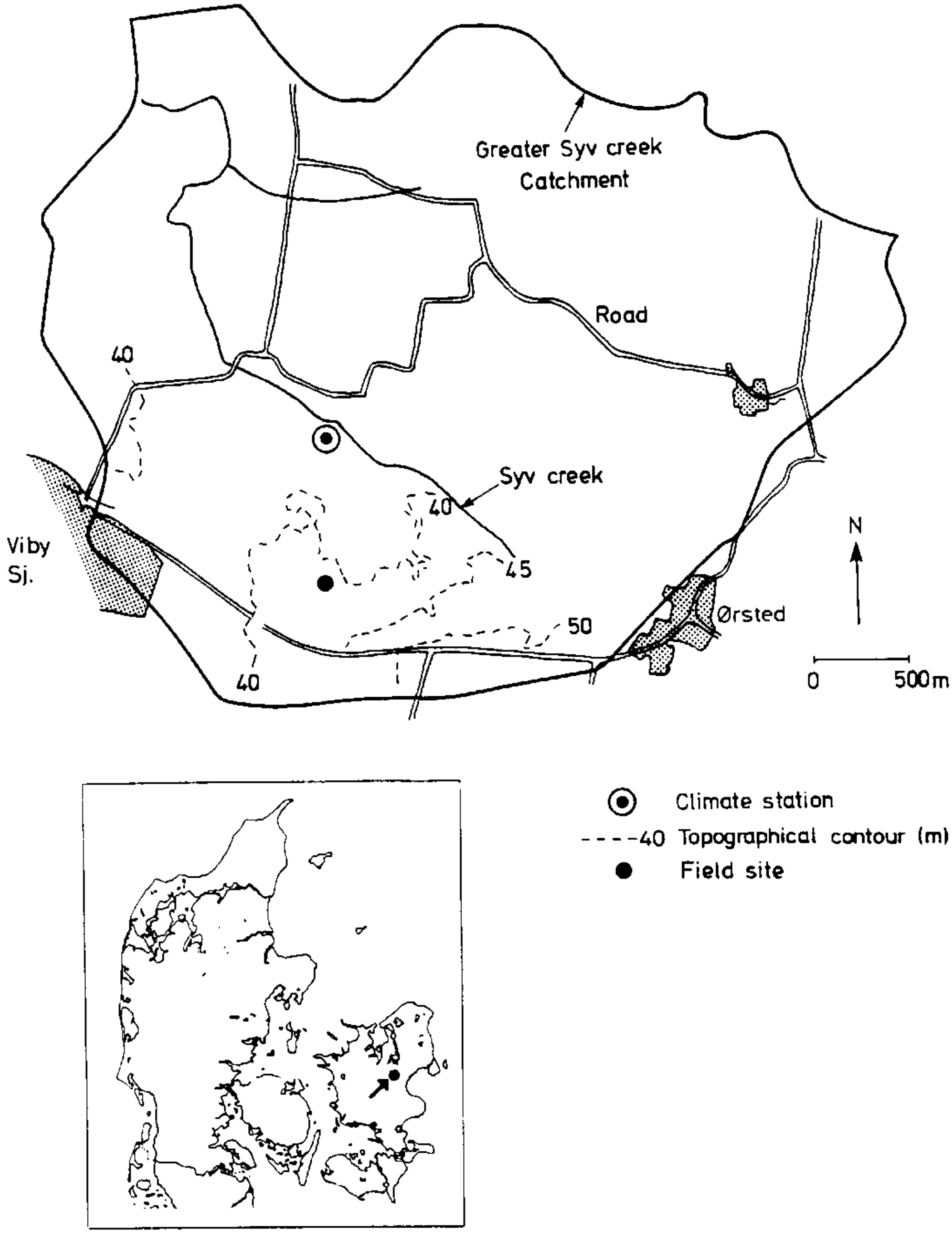

Fig. 1 Location of field site.

and colour is found in 90-150 cm depth, deepest where sandy till occurs. The upper limit of calcareous soil do in most part follow the B-C horizon boundary. The clayey till (approx. 20 % clay) is dominating and sandy till occurs only as isolated bodies at around 1 meter depth. Direct connection between the sandy till bodies and the nearby drain is a possibility in part of the field, hence making the horizontal part of the flow path to the drain relatively fast in these areas.

From the excavated soil profiles visual macrostructure in the form of worm holes and root channels in the upper soil layers and peds of different order and size in the lower layers was noted. Worm holes and root channels were predominantly cylindrical and vertical with diameters of 1-3 mm and with an intensity in a horizontal plane of approximately 5 per 10 cm^2. Between 40 and 120 cm depth distinct peds of 1-5 cm were seen.

Chloride application

The chloride-ion was chosen as an appropriate tracer. It has transport properties equivalent to the nitrate-ion which is of major concern in relation to contamination from fertilizers, yet it is practically chemically stable and biologically inactive. Furthermore, detection via a chloride specific electrode made continuous monitoring of the tracer in the drainage outflow possible.

The chloride tracer was applied as flakes of 77/80% $CaCl_2 \cdot 2H_2O$ by manually spreading on the soil surface, attempting a high degree of uniformity. An amount of 0.75 kg Cl/m^2 was applied in 2 m wide and approximately 50 m long strips around the drain line leaving a 1 m chloride-free zone to each side of the drain. This was done to minimize chloride movement through soil that might have been disturbed by the tile installation (Fig. 2). For plot 2 chloride was only applied to one side of the drain since results from Plot 1 showed that a lateral flow away from the drain could be responsible for chloride loss.

The two experimental periods were as follows with the first date indicating the day of chloride application:

Plot 1:	8/3 - 12/4
Plot 2:	26/4 - 28/4

It is seen that the first plot was monitored almost twelve times longer than the second.

Monitoring program

Instrumentation for monitoring flow rate and chloride concentration of the drainage water was installed in a collector well at the lower end of the field site (Fig. 2.). Water level in a 60 l container were measured at 5 minute intervals and converted to flow rate. An automatic pump released the water to the downstream end of the drainage system whenever the container was filled. The ion selective electrode was placed in a separate much smaller (40 ml) container that continuously received drainage water from the bottom and was equipped with continuous stirring. The data were collected by a datalogger.

Piezometres were placed inside as well as outside the plots (Fig. 2) to follow the groundwater level fluctuations.

Soil profile samples were taken (Fig. 2) prior to and after the experimentation periods for a mass balance analysis of water and chloride. Sampling was done at depth increments of 20 cm with a 6 cm diameter hand auger to a depth ranging from 80-150 cm, depending on accessibility and groundwater level. Water extracts from these samples were analysed photometrically using flow injection analysis, except for final soil samples from Plot 2, which were analysed by the argentometric method.

Precipitation data on an hourly basis were obtained from a climatological station located less than 1 km from the field site.

Results

The field installation of the ion selective electrode together with unreliable performance of the datalogger posed problems in the beginning of the experiment. Satisfactory implementation of the chloride measurement was not obtained till the end of the first experimental period which means that the chloride data from Plot 1 reported here originate from grap samples taken at irregular times, but with higher frequency during high flow periods (Fig. 4). Ground water levels were monitored in conjunction with the water sampling.

Plot 1

As seen from Fig. 4 chloride was applied to Plot 1 prior to an increase in drainage flow. No breakthrough of chloride was detected over the 28 day period that followed. At that time drainage flow had ceased due to an insufficient supply from rain and an increase in evapotranspiration. Water was then applied artificially from two hoses which could be moved manually over the plot including a zone of 1 m around the edges. The irrigation

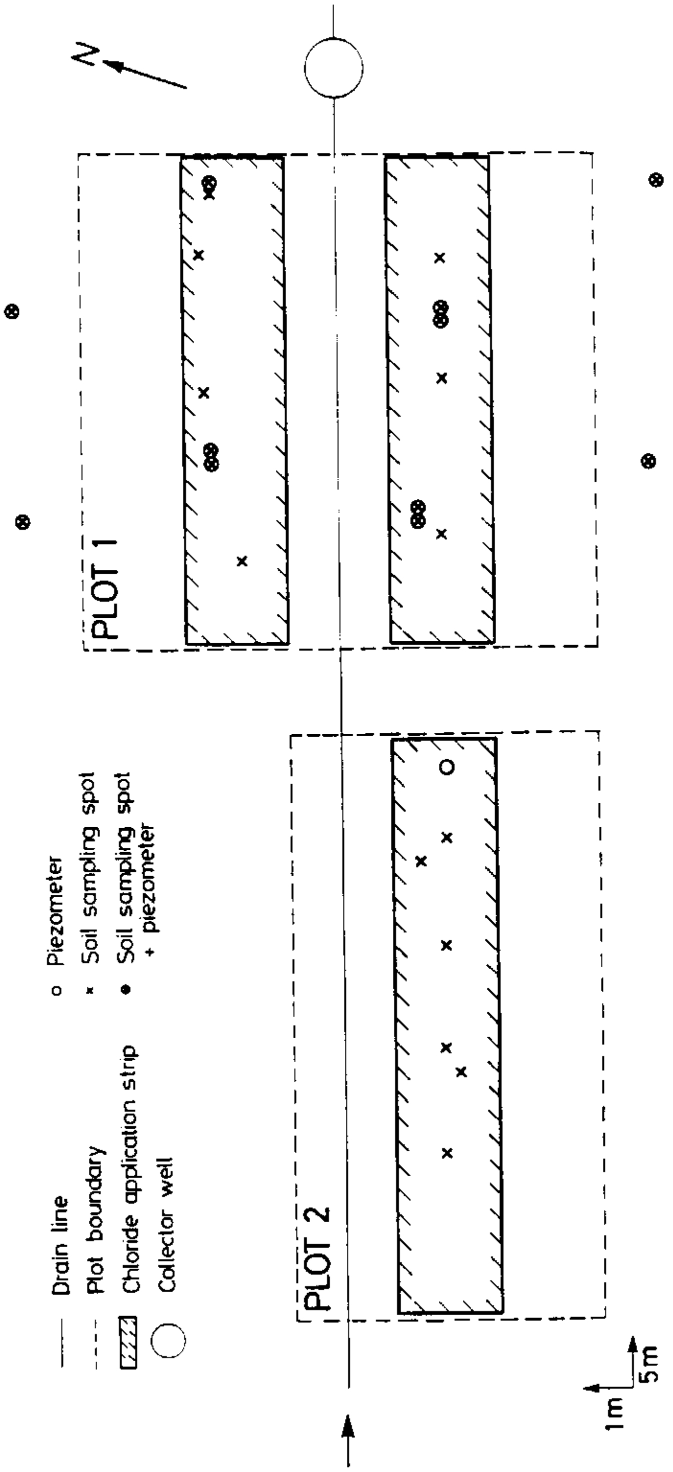

Fig. 2 Schematic plane view of the experimental field.

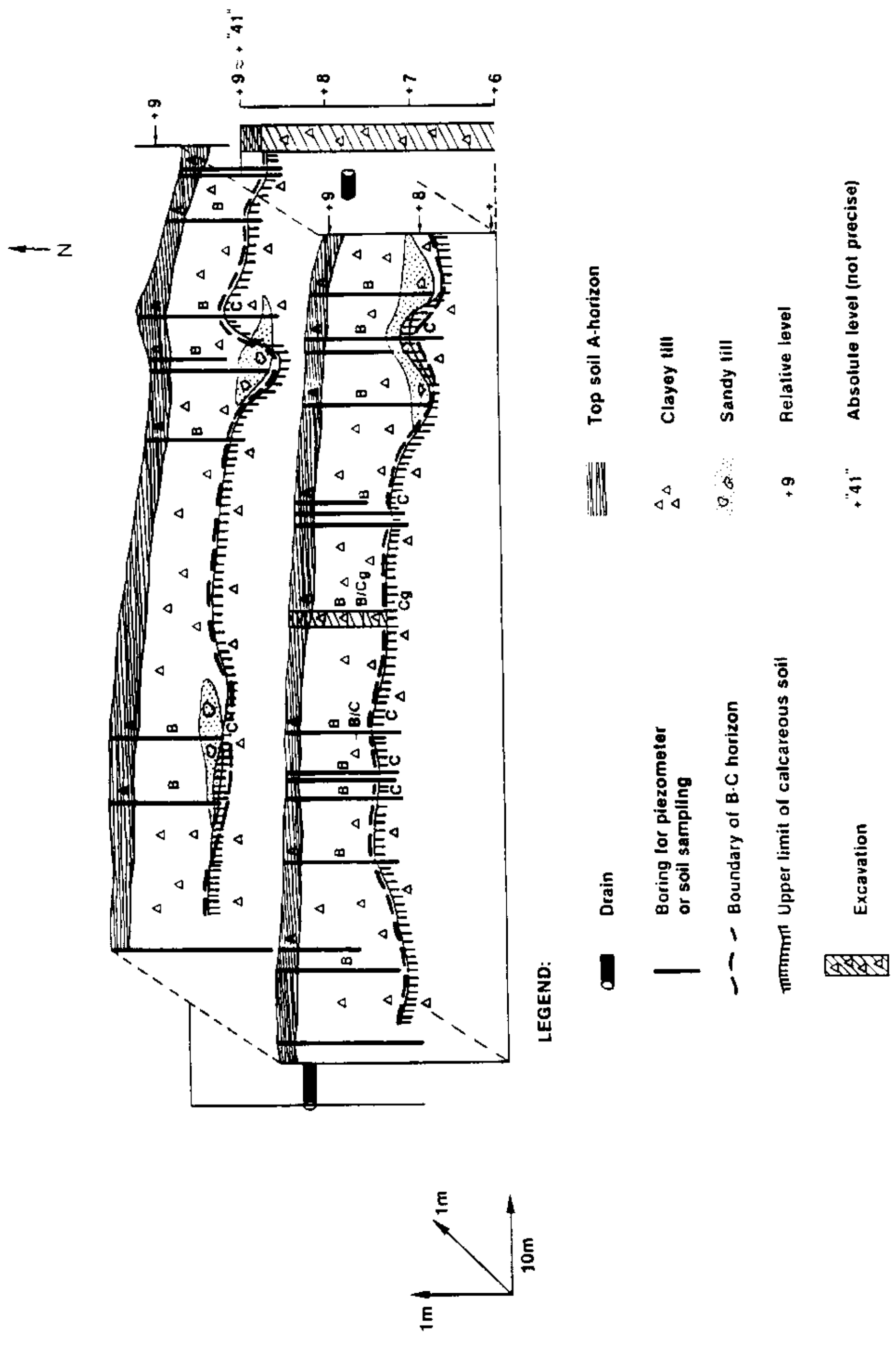

Fig. 3 Geological profiles on each side of the tile drain.

intensity was approximately 6 mm/hr, and irrigation was carried out over a two day period, about 3 hrs each day. Surface ponding during irrigation was observed while surface runoff was restricted to distribution of water within the microrelief of the nearby soil surface. A sudden rise in drainage flow was observed 2.5 hours after the irrigation was started on the second day. This flow peak was, however, still not associated with an increase in the chloride concentration.

An interpretation based on these findings is that the chloride initially applied at the soil surface had infiltrated into the soil matrix together with the rainwater and a percolation and diffusion process had distributed the solute in the upper soil layers. The gradual rise in drainage flow in the beginning of the experiment is likely to be caused mainly by a displacement type of flow. For the irrigated period the rise in flow was abrupt indicating that preferential flow paths through the soil profile were activated. This is supported by the fact that the drainage water was practically chloride-free and hence must have originated from water bypassing the chloride in the soil matrix.

Plot 2

The tracer experiment was repeated on Plot 2 with the aim of detecting the preferential flow directly, that is by a rapid breakthrough of the chloride. Water was mainly supplied by intermittent irrigation and again at fairly high intensities (approx. 11 mm/hr). Plot 1 was covered with a plastic sheet to avoid interference from this plot in case of natural rain. A moveable perforated hose that could be controlled from outside the irrigated area was used to minimize soil surface disturbance which may have been significant during the first experimental period. Again surface ponding, but minimal surface runoff was observed. Chloride was applied when the drain had started running again and just prior to an irrigation event (Fig. 5). The peaky appearance of the drainflow as before suggests preferential flow. In this case it is supported by the fact that chloride is also transported to the drain practically instantaneously, again an indication of a bypass mechanism. Hence a fraction of the surface applied chloride was not retained in the soil matrix and leaching occurred.

Condition for preferential flow

From this study it can be inferred that relatively high water application rates and possibly surface ponding are necessary to initiate preferential flow. Rates of 4 mm/hr which corresponds to the heaviest rain during the start of the first experiment did not produce distinct signs of preferential flow whereas an intensity of 6 mm/hr did. However, the existence of a distinct threshold value of application rate is not stated, since other factors are influencial.

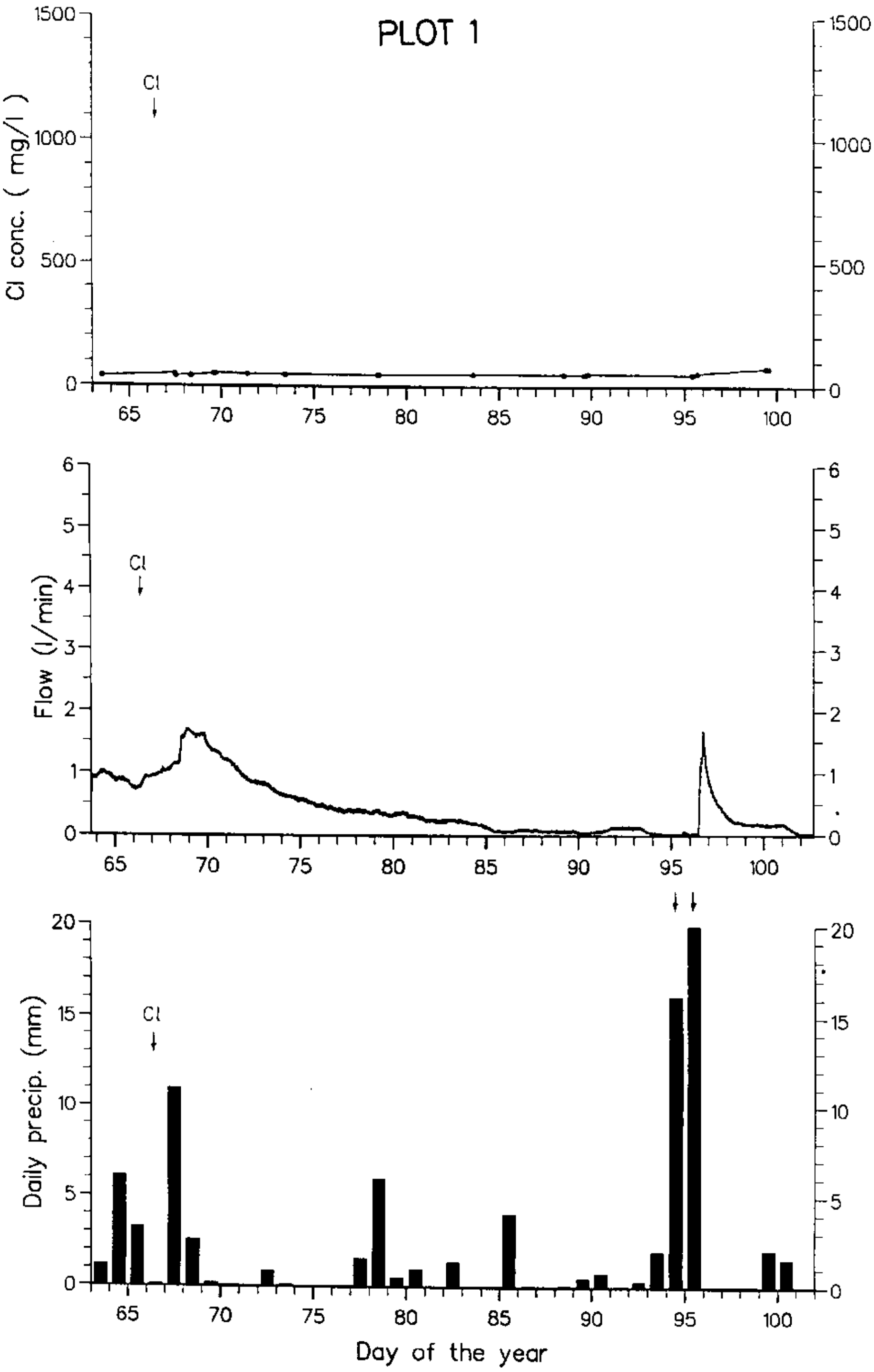

Fig. 4 Chloride concentration and flow rate in drain water outflow and daily precipitation for Plot 1. Arrows indicate application of chloride and water.

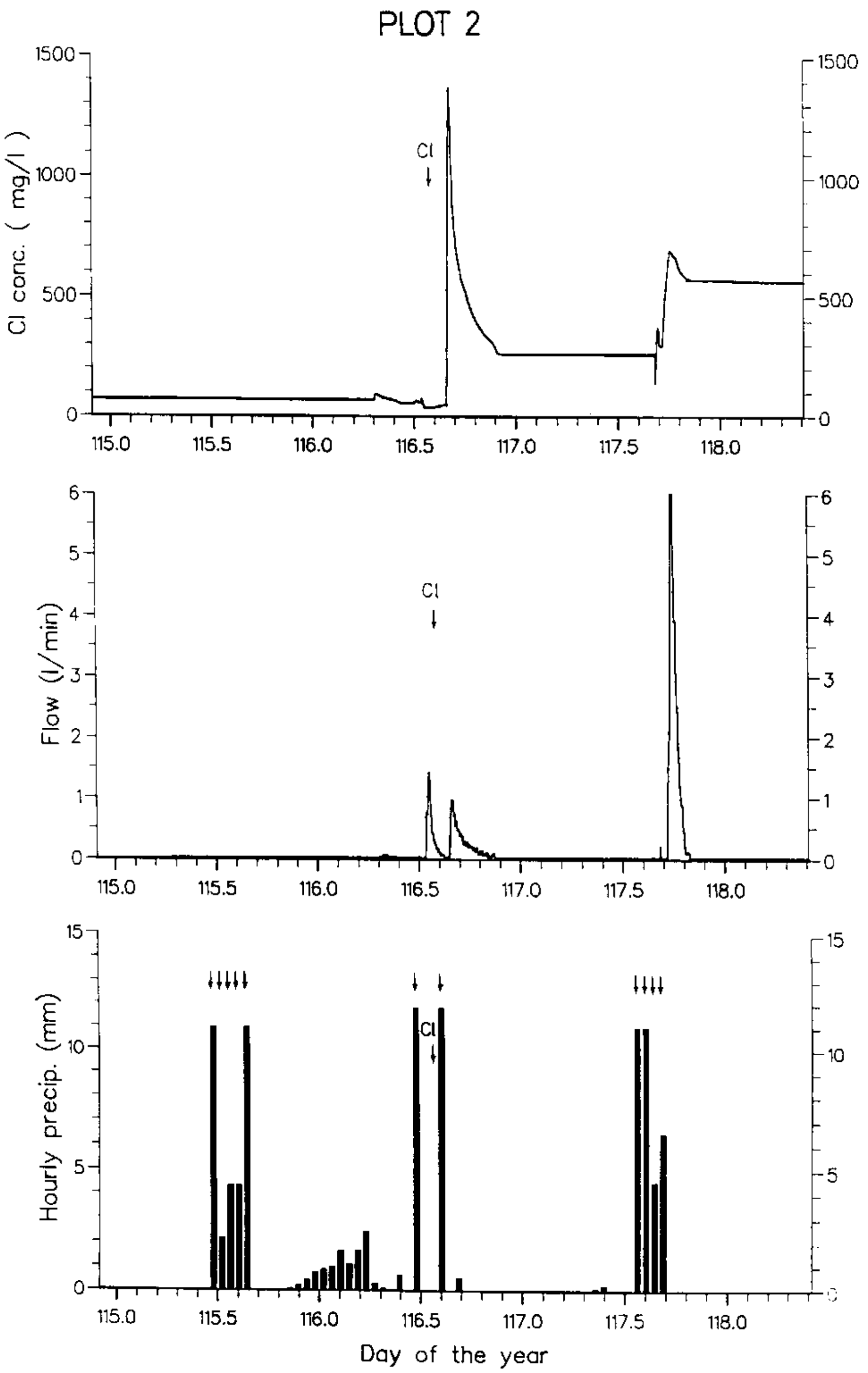

Fig. 5 Chloride concentration and flow rate in drain water outflow and hourly precipitaion for Plot 2. Arrows indicate application of chloride and water.

If the drain was not running prior to high intensity application no immediate response in drainage flow was observed. Parts of the applied water could be conducted in preferential flow paths through the mainly unsaturated soil profile with lateral loss to the soil matrix and recharge to the ground water below the drains leading to drainage flow once the ground water level reached the drains. The exact mechanism for flow under ponded yet unsaturated conditions can not be evaluated from this experiment.

Condition for leaching

Preferential flow and fast breakthrough of water is associated with leaching of surface applied substances if the application is carried out just prior to the occurrence of preferential flow. A second peak in the chloride concentration was observed in the second experiment when one day had elapsed since the tracer application, indicating that some chloride was still free to move in preferential flowpaths. White et al. (1985) and Trudgill & Coles (1988) have likewise called attention to the timing of surface application in relation to subsequent flow conditions. Besides the application time in relation to flow conditions factors such as the application method could be important for the leaching potential of surface applied substances. Application of chloride in dissolved rather than solid form might have generated a different leaching pattern. This issue is addressed by Kanchanasut & Scotter (1982), but no experimental work has to the authors' knowledge been published on the matter.

Mass balance analysis

A chloride mass balance was attempted to get indications of the relative fate of the applied tracer. Also, a water mass balance was carried out to evaluate the recovery of water and hence indirectly of chloride. The results for the two plots are presented in Figure 6 and Table 1 for chloride and water, respectively. The amount of chloride accumulated in the soil profile is calculated as the difference in chloride content prior to and after the experiments. Areally averaged values for each depth increment of 20 cm are used.

In Plot 1 and Plot 2 50% and 82%, respectively, of the total amounts of chloride applied at the soil surface were detected as drainage outflow and an increase in the soil storage. The amount of chloride not accounted for can likely be attributed to variability and uncertainty in the quantifications. The figure associated with greatest uncertainty is the amount of accumulated chloride in the soil, partly because of the large spatial variability over the plot and partly because of lack of soil sampling of the very top soil layer mainly consisting of organic matter. The average chloride concentration in this layer could be substantially larger than just a short distance below. This is emphasized by the obtained chloride profiles at both plots after the experiments (Fig. 7).

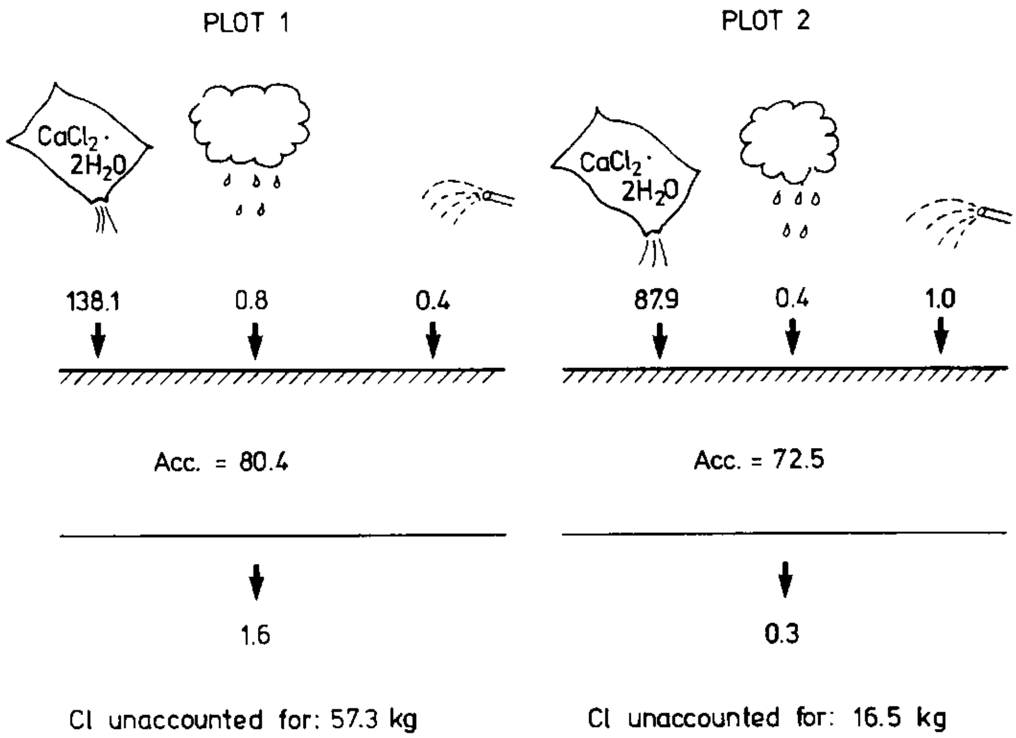

Fig. 6 Chloride mass balance. Figures in kg.

Chloride and water profiles

The chloride concentration after the experiments decreases sharply with depth with a maximum concentration at the first soil sample depth. Of the total chloride content in the soil profile to a depth of 140 cm an estimated amount corresponding to 77% and 64% were found in the upper 40 cm of the soil in the two plots, respectively. The lack of an apparent maximum in the chloride concentration at depth could be explained by a more continuous supply of chloride at the soil surface, rather than a pulse-type application. This is possible if the $CaCl_2$-flakes were not dissolved during the first irrigation event after application. It could also explain that a secondary peak in the chloride concentration was observed when preferential flow started drainage flow a day later during the second experiment. A similar pattern in tracer concentration with several individual peaks coinciding with high input rates were found in a comparable study (Richard & Steenhuis, 1988). This further underlines the importance of additional investigation into the effect of surface application method.

Tabel I Water balance. Figures in m^3.

	Plot 1	Plot 2
Rain	112	25.3
Irrigation	14	19.7
Drainage	25	0.5
Balance	101	44.5
	~ 1 mm/day	~ 7 mm/day

Other fates of chloride not accounted for in the mass balance could be uptake by vegetation, loss to deep percolation and to lateral flow out of the field site. Piezometer measurements outside Plot 1 indicated that water flow could be transverse to and away from the drain. Plant uptake was probably minor, even though it was not confirmed by measurements. Van Ommen et al. (1989a) report a 3% loss of bromide tracer in a drainage study due to plant uptake. Loss to deep percolation could be significant especially since the drain is barely actively flowing during the experiments, and hence the hydraulic gradient towards the drain is small. During no-drainage flowsituations water is directly routed to below drain depth. To support the chloride loss due to these sources the water balance also indicate loss of water (Table 1). A larger loss per day for the second experiment could be explained by an increase in evapotranspiration with denser plant cover and more loss to deep percolation since drainage flow was more discontinuous than in the first experiment. In agreement with this, the water content in Plot 1 was fairly uniform throughout the soil profile and practically equal before and after the experiment. In Plot 2 more variation is seen, and the water content after the experiment is smaller (Fig. 8).

The chloride detected in the drainage water amounted to 1.2% and 0.3% of the total amount of chloride applied to the soil surface in the two experiments, respectively, while the amount of drainage water from the plots corresponded to 20% and 1%. This means that the drainage water from the second plot was five times as chloride enriched as the water from the first plot, another way of detecting that leaching from surface applied chloride occurred preferentially in the second plot.

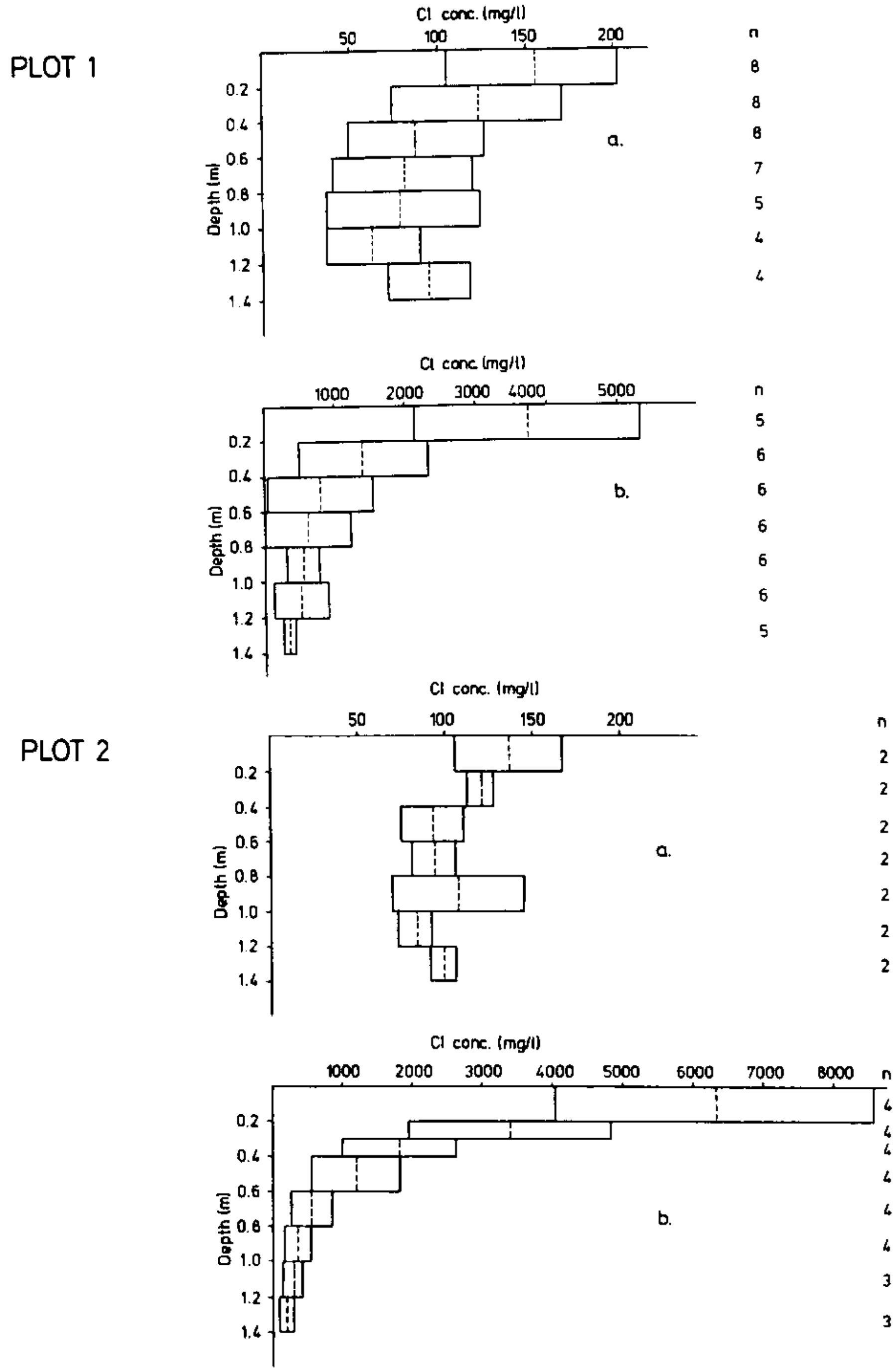

Fig. 7 Chloride concentration profiles, (a.) prior to, (b.) after the experiments. n indicates number of samples.

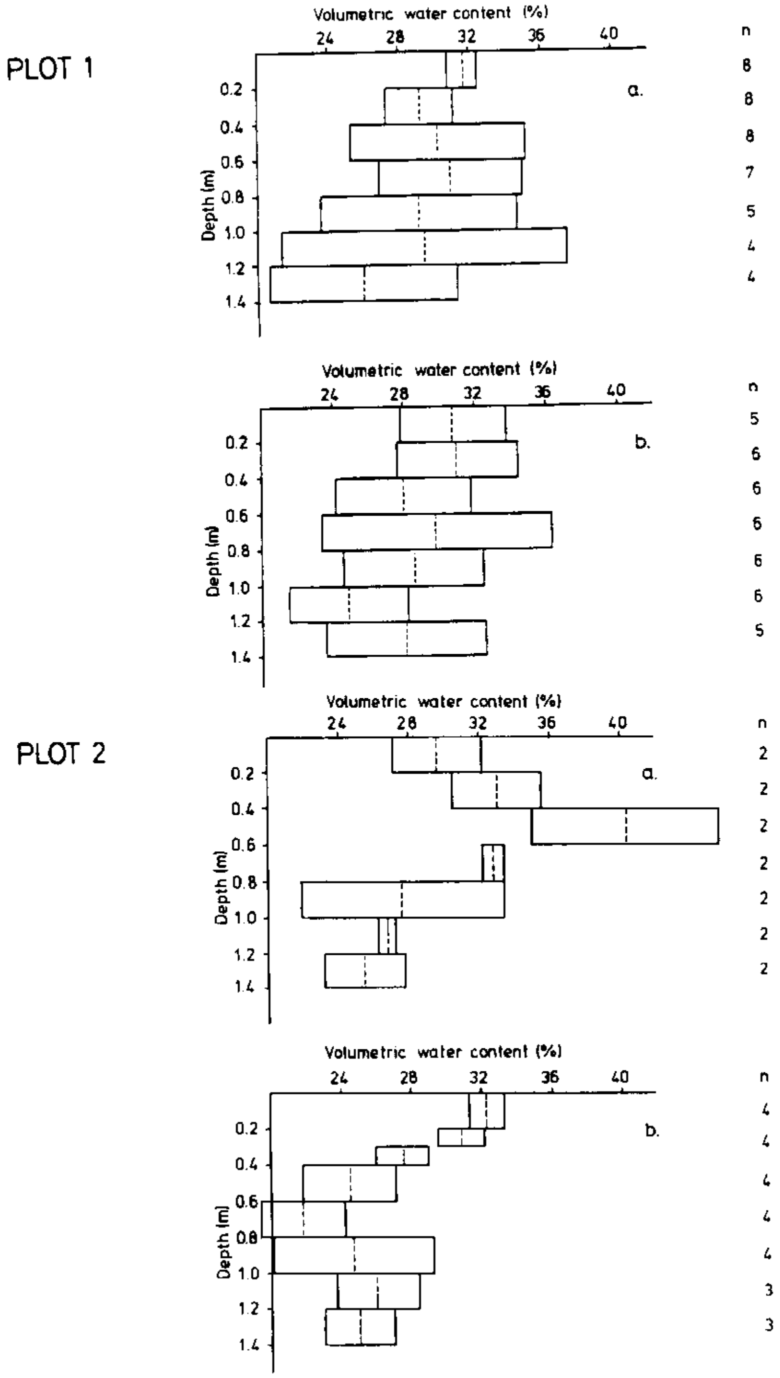

Fig. 8 Volumetric water content profiles, (a) prior to, (b) after the experiments. n indicates number of samples.

Discussion

The importance of preferential flow

The extent and the importance of the leaching of surface applied substances primarily caused by preferential flow is difficult to judge from this preliminary study. Based on figures of retrieved tracer amounts in the drainage water of less than 1% of the applied amount the significance appears to be minor. However, some aspects related to the experimental conditions might be crucial to this statement and need further investigations.

Need for further studies

Firstly, this experiment was carried out at the end of the natural yearly drainage season and the drain system was barely active during the experiment where preferential flow was observed. It was stated that a loss of chloride from preferential flow to deeper soil layers is possible, but quantification has not been attempted. Performing the tracer study during a longer period of larger and more reliable flow in the drain could give a better measure of the extent of leaching due to preferential flow.

Secondly, a more intensive and preferably continuous monitoring of the groundwater level to a depth below the drain along with soil water content measurements would yield further inside into the hydrological response of the system.

Thirdly, the application method of the tracer might show to be important as pointed out in this study. Controlled experiments that can be reproduced under different application conditions need to be carried out to shed light on this aspect.

Conclusion

Preferential flow effects at the field scale have been observed in a combined tracer/drainage study. High water application rates leading to surface ponding conditions excites the preferential flow mechanisms. Unfavourable drainage conditions made the evaluation of the extent and importance of leaching of surface applied substances by preferential flow inconclusive. However, it appears that the greatest risk of loss of surface applied substances, such as fertilizers and pesticides caused by bypassing is prevalent when a heavy rain succeeds the application within a relatively short time, in this study found to be of the order of one day. Further research is needed to evaluate the effect of soil moisture conditions and surface application method.

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Abstract:
In a tracer study preferential flow at field scale was documented. Very fast response of a subsurface drain upon surface application of water and chloride was taken as an indication of preferential flow. Further documentation was distinct bypass flow of surface applied chloride-free water through a soil matrix with high chloride content and bypass of chloride through a soil matrix with little chloride content. The implication of preferential flow for leaching of fertilizers and pesticides is discussed.

Terms:
leaching; soil types; drainage; surface runoff; analytical methods; soil structure; transport; chemical substances

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Resumè:
I et tracerforsøg er makroporestrømning blevet eftervist på markskala. Et hurtigt gennembrud i et markdræn af vand og klorid tilført jordoverfladen blev taget som indikation på makroporestrømning. Yderligere dokumentation var en sidestrømning af kloridfrit infiltrationsvand forbi en jordprofil med højt kloridindhold og af klorid forbi en jordprofil med lavt kloridindhold. Betydningen for udvaskning af næringssalte og pesticider er diskuteret.

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