Analyzing soil water repellency phenomena

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Preface

In April 2001, the research project interurban was initiated. The project is a cooperative effort of the Technical University of Berlin and the Free University of Berlin, combining the departments of soil sciences, soil chemistry, water quality control, environmental chemistry, microbiology, soil zoology, and applied geophysics. The project is sponsored by the German Research Council (DFG) as research group 409, "Water and Organic Matter in Anthropogenic Soils: Dynamics and Processes". This project was formed in order to study the dynamics of water and materials at urban locations while giving special consideration to spatial heterogeneity, organic soil substance, and soil-biological transformation processes.

The aim of the subproject “soil” is the analysis of the water flow and solute dynamics in heterogeneous urban areas. One of the main objectives of the study at hand within the framework of the project was to examine the soil physical and chemical characterisation of the sites, including the analysis of the spatial distribution of the hydraulic functions (saturated / unsaturated conductivity), bulk density, as well as the availability of heavy metals and nutrients, pH value, organic matter content, the desorption characteristics and water repellency. In the case of concerted samplings, these parameters were provided for all sub-projects and the experiments were complemented by the detailed chemical and biological analysis of the other subprojects.

Another focal point of the study was the installation and maintenance of the measurement areas at the research sites. These areas were equipped with automated TDR- devices and tensiometers, providing continuous water content and tension readings, so that the water movement through the soils could be observed with high spatial and temporal resolution.

Apart from the information about water and solute transport in the soils, we worked on the improvement of non-destructive soil-physical and geophysical methods, such as GPR, geoelectrics and NMR, making it possible to detect and observe small-scale rapid water content changes in the soils. For this aim, these geophysical measurements (which are commonly used on a bigger scale) were calibrated by the TDR- and gravimetric water content measurements.

The two main research sites were the Tiergarten park in the centre of Berlin and the former sewage fields at the northern city limit. The Tiergarten park is an example for a highly frequented park and recreation area in an urban environment. The former sewage fields show the rapid ecological adaptation processes due to land changes. This site is indicative for the problems of intensive commercial use and pollution.

From the start of the project in April 2001 it became clear that our research sites show a very interesting behaviour: water repellency. We detected sharply zoned moisture patterns in the topsoil, easily visible by the dark colour of the moist and wettable soil and the light colour of the dry and water repellent soil. Water repellency leads to time depending preferential flow with large impact on the solute transport. The repellent parts of the soil remain dry also during rainfall events and are excluded from the flow regime in the soil. This phenomenon drew my attention and I tried to characterize the factors which influence the occurrence of water repellency. The studies of this work were carried out on the research site Berlin Buch – a former sewage farm land.

1. Introduction

1.1 Impact of water repellency on water movement in soils

Water repellency is a wide spread phenomenon and numerous papers were published on its hydrological impact and occurrence in the soil. Water repellent soils were reported all over the world, e.g. in the Netherlands by Ritsema and Dekker (2003), in Spain by Moral Garcia et. al (2003), in the USA and Columbia by Jaramillo et. al. (2000), in South Africa by Scott (2000), in the United Kingdom by York and Cannaway (2000), and in Germany by Buczko et al. (2005).

The water repellent spots at our research sites were found in the topsoil, mainly in the humus-rich root zone at a depth of 10-30 cm. The soil in this layer is either wettable or strongly water repellent. The wettable areas appear as dark spots, the water repellent areas as dry spots (Fig. 1.1). The water repellent soil regions are not accessible for water; they stay dry for long periods. The rewetting process in these water repellent areas takes a few days or weeks. Thus, the amount of water - accessible soil volume and, consequently, the plant-available water in the root zone, which is already low in that sandy soil - is more restricted. Due to the texture and water repellence of the topsoil, the rainfall infiltrates the soil in unstable wetting fronts, bypasses most of the soil matrix in flow-fingers, and seeps into the deeper layers. Water repellent soils have been associated with preferential flow decades ago (Jamison, 1945; Bond, 1964). Preferential flow paths create a spatial variability in soil moisture, effecting the plant growth, solute transport and ground water recharge (Dekker and Ritsema, 1994).

Fig. 1.1: Wet (dark) and dry (light) spots of the potentially water repellent soil in Berlin Buch. Horizontal section at a depth in 15 cm (left) and vertical section (right).

Additionally, the water repellent topsoil causes a run-off of water after rainfall events even in regions which are only slightly sloped. In this way the water repellency increases water shortage for the vegetation on such sites.

Preferential flow allows a much faster transport of water and solutes, creating a greater risk of groundwater contamination. Most of the pollutants on our research sites (eg. heavy metals and organics) were found in the topsoil. The pollutants show a high affinity to the organic matter. The sandy soil itself has a very low cation exchange capacity. But in the topsoil, were pollutants could be retained, the cross-sectional area is reduced and the transport is accelerated.

1.2 Objectives of this thesis

Due to the big impact water repellency has on the water distribution and transport on our sites, the predominant part of my work dealt with the phenomenon of water repellency.

The objective of this study was a general description of the degree of repellency, the occurrence on the research sites and a phenomenological description of sample - wettability and the parameters which decide about wettability of a soil.

When does a soil become water repellent? It appears that the water content of the soil presents the main criterion. Many studies try to distinguish between dry, repellent soil samples and wet, non-repellent ones. The degree of repellency depends mainly on the soil water content. Therefore, Dekker and Ritsema (1994) established a transition zone or a critical soil moisture zone, defined by two water content thresholds; a critical water content below which every sample is repellent and a second one above which every sample is wettable. The reported water contents for these thresholds vary widely if different samples are analysed. Doerr and Thomas (2003), for example, measured a transition zone of 0.14 to 0.22 $g \cdot g^{-1}$. Dekker et al. (2003), Dekker et al. (2001) and Ziogas et al. (2003) found transition zones within a range of 0.05 to 0.06 $cm \cdot cm^{-1}$, if the soil was sampled in fine layers. The transition zone and its critical water thresholds is an important parameter for flow and transport models of water repellent soils (Ritsema and Dekker 2003). By measuring the actual water content of the soil samples, these models use the transition zone i.e. the critical water content to predict the soil water repellency. However, a differentiation between wettable and repellent samples using the critical water contents leads to a high number of unclear or wrong cases.

The aim of my work was to improve the understanding of the transition zone in order to achieve a distinct separation between repellent and wettable soil samples using the water content as the cut-off criterion. For this aim, several thousand field-moist samples were taken with high spatial resolution and analysed subsequently. In addition to the water content and water repellency, the samples were analysed for other properties. The results are presented in chapter 2 of this work.

Supplementary to the work on the transition zone, the dynamics of water repellency and its hydrological impact on our research sites was of interest to us. To this end we have conducted several samplings on our sites during different seasons and, consequently, at different actual soil moistures. The aim was to quantify the seasonal dynamics of preferential flow under field conditions. The 'effective cross section' is introduced as a new parameter to describe the area share of the flow paths and the water repellent soil volume. The quantification of the parameter's seasonal variation allows the effect of water repellency to be included into seasonal modeling of water and solute movement. For this purpose I compared the results of a complex sampling campaign consisting of 32 single samplings at different seasons and different locations on our research site with the moisture content readings of a TDR array recording the soil moisture contents continuously at one site. The effective cross section was determined for a cross sectional area in 20 cm depth by two different approaches: the visible area share of the wettable soil in that depth (sampling approach) and the analysis of the TDR-readings after rainfall events (TDR-approach). The results of this work are presented in chapter 3.

In April 2002 we started to conduct a tracer experiment. One objective was to verify the effective cross section approach and to collect information about the spatial alteration of flow fingers. Based on the chemical characterization of the samples we took on our sites, we were

convinced that changes in the flow finger position must take place. No significant difference in soil properties was measurable between wettable and water repellent samples.
A time delayed double tracer experiment was conducted in order to study the solute transport. Two inorganic conservative tracer solutions were applied at two different times on the surface of a 5 m² plot. The first tracer – a bromide tracer – was applied in April 2002. At that time – just before the growing season - a soil reaches the highest saturation, the effective cross section is at a maximum, the flow conditions can be assumed as nearly piston flow. In October 2002 a second tracer - chloride - was applied on the same plot. In January 2003 the samples were taken and the concentrations of the two tracers were analyzed. Although the tracer experiment gave us no information about a possible shifting of flow fingers, the dynamics of water repellency were ascertained and the soil regions of the tracer profile were classified into main flow path, moderate flow path, sparsely flow path and no flow region. We established a strong evidence for spatial alteration of flow fingers from the TDR readings which were collected continuously at a neighbouring site. The hourly recordings of the TDR-measurements showed that the flow paths remain stable in consecutive precipitation events. When comparing long time intervals, e.g. autumn 2002 – autumn 2003, a spatial alteration of the flow fingers was observed. The results of these experiments are presented in chapter 4.

1.3 Study site Berlin Buch

The two main research sites are the Tiergarten park in the centre of Berlin and the former sewage fields at the northern city limit. The Tiergarten park is an example for an highly frequented park and recreation area in the urban environment. The former sewage fields show the rapid ecological adaptation processes due to land changes. This site is indicative for the problems of an intensive commercial use and pollution. Since the 1990's the sewage farm land was investigated in different projects with participation of the dep. of soil science in order to develop and preserve this contaminated site. Assessing the risks originating from this site was the focus of the past projects. The amount and release of pollutants, esp. the release of heavy metals by mineralization of organic matter and the transport into the ground water were examined. Hoffmann (2002) measured rapid turnover processes of organic matter and an increased leaching of heavy metals and nitrate. Small scale heterogeneities and the water repellency on the site remained unsolved problems of recent studies. The following chapters present results based on experiments and samplings on the site Berlin Buch.

General

The study site Berlin Buch is located at the northern city limit of Berlin (13°30' western longitude and 52°40'). The climate is mild-temperate with an annual average temperature of approximately 9.3°C and an annual rainfall of 580mm. The rainfall is evenly distributed over the year. During spring and summer the water uptake and the evapotranspiration lead to a negative water balance – the soil dries out. In autumn and winter the water balance is positive - a recharge of the soil pore water takes place. The site is part of the marl sediments ground moraine of the 'Barnim' – a remnant of the Saalian glacial epoch in the Pleistocene, 230.000 – 110.000 years ago. The marl sediments are overlaid by fluvial sands of the Frankfurt stage of the Weichselian glacial epoch, 15.000 years ago. The thickness of the fluvial sands on the site ranges from 4 to 6 m. These fluvial sands dominate the soil-properties of the site.

History

In 1905 our research site became part of the approximately 13000 ha of sewage farm land around Berlin. Untreated municipal and industrial wastewater was applied on the sewage fields. During the first decades these sewage farms were used for agricultural production, following the principle of a closed nutrient cycle proposed by Justus von Liebig. The fields were irrigated through furrows and vegetables, fruits and pasture were cultivated. Later, rising amounts of wastewater and the accumulation of pollutants such as heavy metals made it necessary to infiltrate wastewater without taking agricultural targets into account. In the 1960's the walls of the sewage fields basins were raised and up to 10000 $mm \cdot a^{-1}$ of waste water were applied.

In 1985, when the wastewater treatment plant Schönerlinde was connected, the wastewater application was stopped abruptly. The basin walls of the sewage fields were levelled and an effort was made to afforest the site. Most of the trees died, mainly due to water shortage during summer time, nutrient deficiencies and heavy metal contamination (Schlenther et al., 1996).

Site properties

Today, dry grasslands (mainly couch grass: *Elytrigia repens*) can be found (Fig. 1.2). The topsoil shows an unnaturally high and very heterogeneous organic matter content originating from the organic compounds of the untreated wastewater. Today the soil, a hortic anthrosol, consists of 30 - 60 cm organic topsoil upon medium sized sand. The organic matter content of the topsoil horizon ranges mainly from 0.04 to 0.06 $g{\cdot}g^{-1}$, rarely up to 0.3 $g{\cdot}g^{-1}$. Below the A-horizon it is lower than 0.01 $g{\cdot}g^{-1}$. The basic effect of the relatively high organic matter content is a high CEC. The pH (H_20) on the site ranges between 4.8 and 6 in the topsoil. Except for its organic matter content, the sand is homogenous up to a depth of 5m. No visible layering or small-scale texture changes were be observed. Therefore, particle size distributions were obtained only at selected locations. The clay content in the non-calcareous medium sized fluvial sand is less than 0.01 $g{\cdot}g^{-1}$. Basic properties of the investigated soil are listed in tab. 1.1.

Fig. 1.2: The experimental site at Berlin Buch

Tab. 1.1: Basic soil properties of the investigated soil

	Texture [%]			Conductivity [cm/d]		Bulk density [g/cm³]	Water content [m³/m³] at		C_{org} [g/g]	pH [-] (CaCl$_2$)	CEC [cmol$_c$/kg]
	sand	silt	clay	k_s	at 63 hPa		63 hPa	15 000 hPa			
Topsoil 0-40 cm	94.3	5.4	0.3	275	0.1	1.3	0.215	0.05	0.066	4.8	22.6
Subsoil >40 cm	96.1	3.3	0.5	695	-	1.5	0.10	0.008	0.005	4.5	10.8

The soil has an extremely high saturated hydraulic conductivity, which decreases drastically under unsaturated conditions at pF 1.8 by about three powers of ten. The distribution of pore sizes in the soil is marked by a high portion of large pores and a low portion of medium and fine pores, which leads to an overall low water supply of the plants.

Due to the afforestation efforts, parallel furrows every 3.3 m draw 20 - 40 cm deep troughs through the site and give the surface a sinus-like shape. The bulk density up to a depth of 20 cm is about 0.9 – 1 g cm^{-3} in the upper parts of the undulated surface (see Fig. 3.2, distance 40 –120 cm). In the lower parts (Fig. 3.2, distance 120-180 cm) the bulk density of the topsoil is 1.2 g·cm^{-3}.

More details on the site, results of the small scale heterogeneities in the soil, water and solute transport are described in Hoffmann (2002). Based on the results of these experiences we became aware of the importance of water repellency for transport processes.

Site arrangement and permanent installations

Most of the work on the former sewage farm land was carried out on a 160m x 80m plot. The sampling campaigns were performed on that site. Areas were pegged out for the regular collective samplings of the research group every three months.

Automated measurement devices were installed permanently on the plot. One device recorded the climatic parameter temperature, relative humidity and rainfall at intervals of 5 minutes. A TDR-device measured the soil moisture at different depths at intervals of 1h (for more details see cap. 3.3.2). Fig. 1.3 shows the profile before the installation of the TDR probes.

Other subprojects also made permanent installations. The Subproject Geo (geophysics), for example, performed geo-electric and geo-radar measurements.

Fig. 1.3: The soil profile before the installation of the TDR array. The typical soil profile with the undulation (wavelength of 3.3m)

2. Part I - Determination of Repellency Distribution Using Soil Organic Matter and Water Content

2.1 Abstract

The aim of this study is to investigate the effect of soil moisture and soil organic matter content on the water repellency of a former sewage field. A topsoil block (40x 80x 30 cm) and a soil transect (300 cm x 100 cm) from a former wastewater infiltration site near Berlin were sampled with a high spatial resolution for this purpose. Actual and potential water repellency were measured using the Water Drop Penetration Time (WDPT) test. Gravimetric water content and soil organic matter (SOM) were determined for each sample; a total of 864 soil samples were analysed. The investigations were carried out in January 2003. Water repellency occurred in the top soil even during this winter period. The spatial distribution of water content and water repellency clearly showed preferential flow paths. Water repellency was measured in field moist samples (actual repellency) and in dried samples (potential repellency). The transition zone for distinguishing between water repellent and wettable regions was determined to be 0.15 $g \cdot g^{-1}$. Therefore, a calculation of the wettability by water content alone is not possible. We suggest a new approach by calculating a so called ‘critical water content’ (Θ_{crit}) as a function of the amount of soil organic matter (SOM). The function Θ_{crit} ($g \cdot g^{-1}$)= 1.12 SOM ($g \cdot g^{-1}$) +0.037 $g \cdot g^{-1}$ leads to a better prediction of wettable and non wettable soil regions for the entire soil profile. The distinction between these regions is necessary for the calculation of the water and solute transport in a 2 or 3 dimensional numeric model.

2.2 Introduction

Many studies have been conducted on the occurrence, importance and the hydrological impact of water repellency in soils. Water repellency can be found in soils all over the world (Franco et al. 2000, Scott 2000, Jarmillo et al. 2003, Doerr et al. 2003, Dekker et al. 1999). The occurrence of preferential flow and fingering is one of the main impacts of water repellency. In most cases the repellency is not permanent but vanishes during autumn and winter (Dekker and Ritsema, 1994).

Most studies use the Water Drop Penetration Time (WDPT) test as a measure for the stability of the repellency (Letey et al. 2003). It can be used on field moist samples for the actual repellency or on dried samples for the potential repellency. With the aid of this test, dry repellent soil samples can be separated from wet non-repellent ones. The degree of repellency depends mainly on the soil water content. Dekker and Ritsema (1994) established a transition zone or a critical soil moisture zone. This zone is defined by two water content thresholds. The lower one determines a limit below which the soil is water repellent, the higher one determines the water content above which the soil is wettable. Within this zone, the soil can be wettable or water repellent. The reported water contents for these thresholds vary widely. Doerr and Thomas (2003), for example, measured a transition zone of 0.14 to 0.22 $g \cdot g^{-1}$. Dekker et al. (2003), Dekker et al. (2001) and Ziogas et al. (2003) found transition zones within a range of 0.05 to 0.06 $cm \cdot cm^{-1}$, if the soil was sampled in fine layers. Ritsema and Dekker (2003) pointed out that the critical water threshold is an important parameter for flow and transport models of water repellent soils. It can be used to distinguish between water repellent and wettable soil regimes.

There are some studies that deal with the spatial distribution of water repellency and preferential flow paths. Ritsema et al. (1998) described the spatial variability of repellency, water content, pH, and the concentrations of a Bromide-tracer. Gerke et al. (2001) found hardly any spatial structures in mine soils, because different soil materials (severely repellent as well as not repellent) occur in the same soil profile. In most cases, preferential flow paths are visible and coincide with the measurements of actual water repellency. Moral Garcia et al. (2003) describes the influence of organic matter on the degree of potential water repellency for two sandy soils, a bare soil and a stand of pine trees. Samples with less than 0.06 $g \cdot g^{-1}$ SOM were slightly up to severely water repellent, samples with higher contents of organic matter were severely to extremely repellent. Dekker and Ritsema (1994) did not find a significant relation between the persistence of potential water repellency and the organic matter content. The connection between critical water content and soil organic matter has not been investigated until now.

This study examines the influence of soil organic matter on the critical water content. The aim is to get a better description of the soil moisture regime, and to gain what is called a ‘critical water content’ in order to predict water repellency in soils. Furthermore, the degree of water repellency in the winter time is quantified and the relation between preferential flow paths and potential water repellency is studied.

2.3 Material and Methods

2.3.1 Soil sampling

The soil samples were taken on January 22nd, 2003, along a 3 m transect down to a depth of 1m with a vertical resolution of 10 cm and a horizontal resolution of 6 cm. Close to the transect, a topsoil monolith of 40x 80x 30 cm was sampled with a resolution of 5 x 5 cm at depths of 15, 21 and 27 cm. The actual water repellency of the field moist disturbed samples was measured. Afterwards, the gravimetric water content, amount of organic matter, and potential water repellency were determined. A total of 864 soil samples, 480 for transect at 10 depths and 384 in the monolith, were investigated.

2.3.2 Laboratory measurements

The actual water repellency was determined with the Water Drop Penetration Time (WDPT) test as described by several authors (e.g. Krammes and DeBano, 1965; Dekker and Jungerius, 1990). In order to establish the actual repellency, three drops of distilled water were placed on the smoothed surface of a field moist soil sample using a standard glass pipette. The time that elapsed before the drops were absorbed was measured. Subsequently, the potential water repellency was tested at the same samples after drying at 35° C for two weeks. Dekker and Ritsema (1994) described the potential water repellency as the most appropriate parameter for comparing water repellency of soils, because differences in water content are eliminated.
A repellency index was applied allowing a quantitative description of the severity of water repellency as described by Dekker and Jungerius (1990). Seven classes of repellency were distinguished, ranging from wettable with WDPT less than 5 s to extremely water repellent with WDPT of more than 6 h (see Tab.2.1).

Tab.2.1: Classes of WDPT used in this study

Classes	Class 0	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
WDPT	< 5 s	5 – 60 s	1-10 min	10-60 min	1 – 3 h	3 – 6 h	> 6 h
	wettable	slightly	strongly	severely	extremely		
		water repellent					

The water content of all samples was determined gravimetrically by drying at 105° C. Afterwards the dry samples were used to measure the content of organic matter by igniting the samples for 5h at 550°C. The difference between the dried and ignited samples was taken as the organic matter content, since the samples are non - calcareous; the pH (H_20) on that site ranges from 4.8 to 6 (Hoffmann 2002).

2.4 Results and Discussion

2.4.1 Actual and potential water repellency

The actual water repellency in the topsoil (0-40 cm) was very high; nearly 50 percent of the samples showed extremely high water repellency (Fig 1). Only 30% of the soil samples in the top 40 cm of the profile were wettable. The number of samples showing extreme water repellency was lower in the top 10 cm (33% compared to 50% between 10 and 40 cm). It has to be pointed out that soil sampling took place at the end of January. Between a depth of 40 and 50 cm the water repellency decreased drastically. Below 50 cm soil depth water repellency no longer occurred. The soil organic matter content ranged from 0.04 $g{\cdot}g^{-1}$ to 0.1 $g{\cdot}g^{-1}$ in the top 30 cm of the profile and decreased from 30 to 60 cm depth. Below 60 cm the SOM content was about 0.005 $g{\cdot}g^{-1}$ (see Fig. 2.1).

The water repellency at this site is very persistent, with water repellent spots existing partly until spring. Ritsema and Dekker (1994) reported a vanishing of the water repellent, dry spots during wintertime.

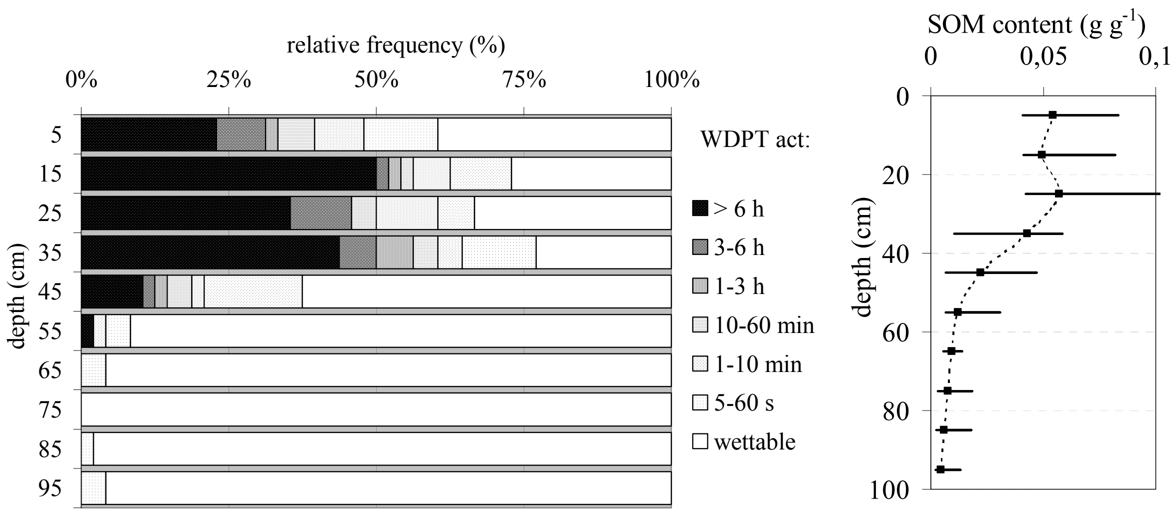

Fig.2.1 Relative frequency of actual repellency in soil horizons of the transect (left) and the vertical distribution of SOM (right), 22. Jan 2003, n=480.

Figure 2.2 visualises the effect of drying on the water repellency for the top soil. Most of the samples of the subsoil were wettable even after drying and were, for that reason, not included in Figure 2.2. The actual repellency of the topsoil samples shows a bimodal distribution with a high number of wettable and a high number of extremely repellent samples. The samples were arranged in classes of 0-6 according to their actual repellency. For each of these classes the frequency and degree of the potential water repellency after drying was calculated separately. Most samples show higher penetration times for potential repellency than for actual repellency. But for some of the extremely repellent samples a decrease in the penetration time was observed (see actual repellency class 5 and 6). Generally, it is not possible to calculate the actual repellency of a single sample on the basis of the potential water repellency measurement of that sample. However, differences occurred in the degree of potential water repellency between the actual wettable and actual water repellent samples. Only 4% of the actual wettable samples showed a potential water repellency of more than 6 h, whereas more than 50% of the actual repellency classes 1 - 6, even when only slightly repellent, had a potential WDPT of more than 6 h.

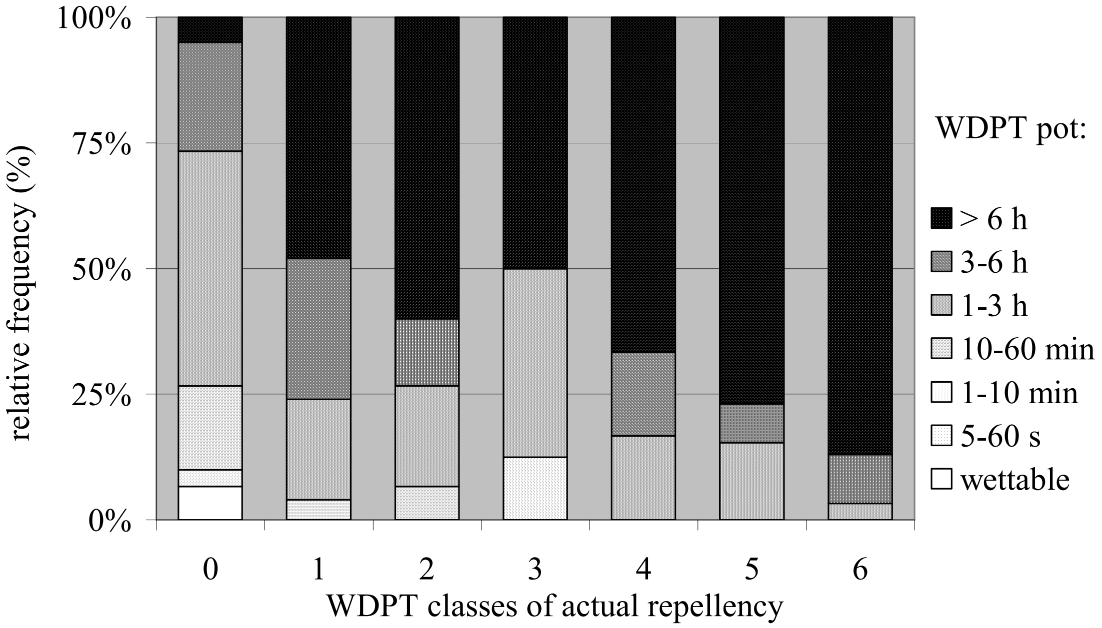

Fig.2.2: The topsoil samples are arranged in groups according to their actual repellency 0 -6. The pattern visualises the potential repellency after drying, n=206.

2.4.2 Spatial distribution and preferential pathways

Soil moisture patterns can easily be identified in the field by the light and dark contours of the soil. The water content in the dry, repellent regions ranged mostly from 0.04 to 0.09 $g \cdot g^{-1}$. In the directly neighbouring wet regions the water content ranged from 0.07 up to 0.24 $g \cdot g^{-1}$ in the topsoil (see Fig. 2.3 a). The mean water content for the subsoil was 0.06 $g \cdot g^{-1}$ with a minimum of 0.025 $g \cdot g^{-1}$ and a maximum of 0.11 $g \cdot g^{-1}$. No textural changes related to the water repellent and the wettable regions were observed.

The water content and actual water repellency maps (Fig. 2.3 a, b) clearly show five preferential flow paths along the transect. Regions with high water contents represent wettable areas in the water repellency map. The highly water repellent areas inhibit infiltration. Between them the water percolates in flow fingers towards the subsoil (Fig. 2.3 a, b).

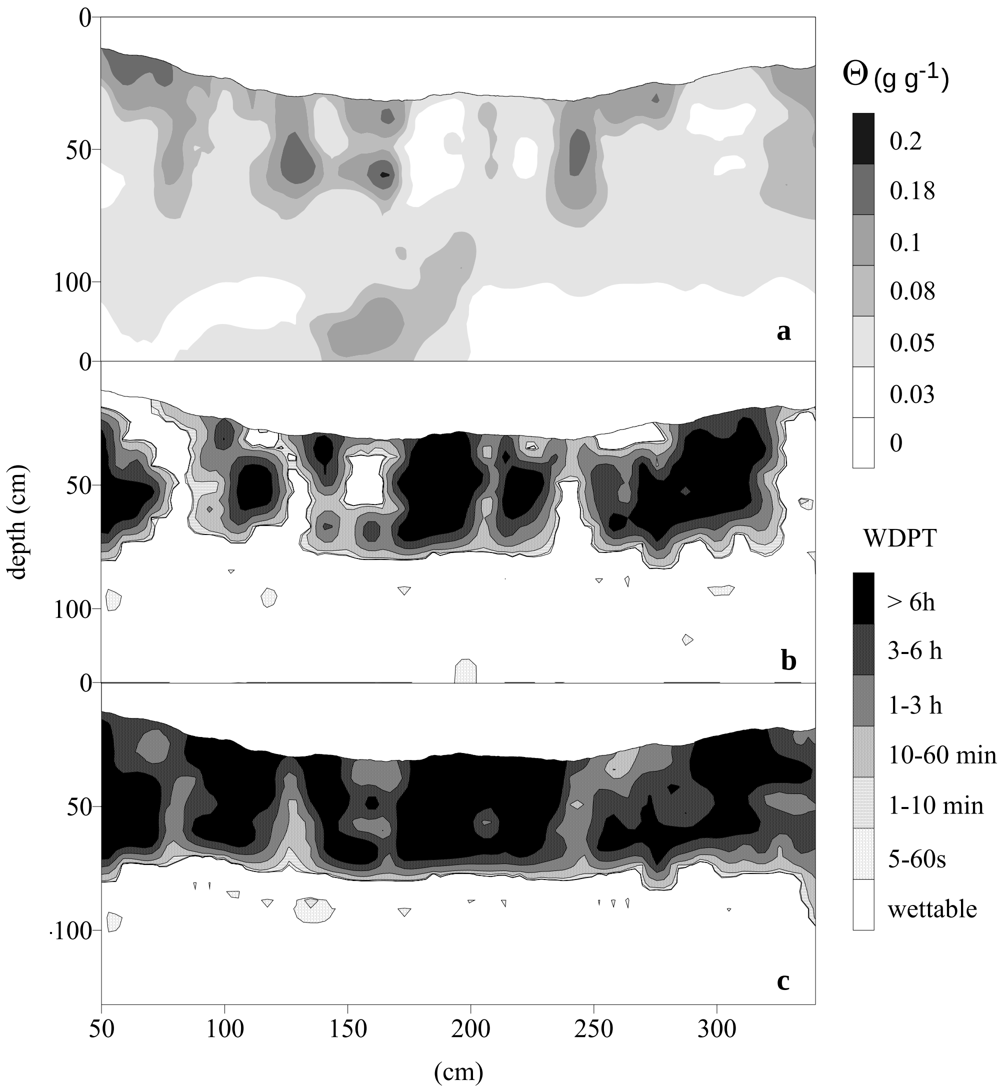

Fig. 2.3: Map of water contents (top), actual (middle) and potential water repellency (bottom).

The flow paths are also visible in the map of the potential water repellency (Fig. 2.3 c). In the regions between the flow paths the penetration times for the potential repellency are mostly above 6 h. The penetration times within the flow paths are lower.

2.4.3 Transition zone and influence of soil organic matter

If the actual WDPT is plotted against the water content for a group of repellent and wettable samples, the resulting figure is similar to fig. 2.4. Every point presents one field moist sample with its water content and the associated penetration time. The water repellent samples can be found at lower water contents with high penetration times and the wettable samples at higher water contents and penetration times < 5 s. The transition zone is the water content range where some samples repel while other samples are wettable. It is limited by the critical soil water content below which a soil is water repellent and the content above which it is wettable (Dekker et al. 2001, Ritsema et al. 2003). In some studies the transition zone shows wide ranges of more than 0.2 $cm \cdot cm^{-1}$ (Doerr and Thomas 2003). Sometimes the zone is narrow and shows ranges of less than 0.05 $cm \cdot cm^{-1}$. These sharply defined transitions appear when samples were taken at thin, defined layers (Ziogas et al. 2003). The transition zones vary for different depths (Ritsema and Dekker 1994, Dekker et al. 2001, Dekker et al. 2003).
Figure 2.4 shows the WDPT for actual repellency in dependence on the gravimetric water content for the whole profile. Considering all samples, the transition zone ranges from 0.03 $g \cdot g^{-1}$ – the lowest water content of a wettable sample - up to 0.18 $g \cdot g^{-1}$- the highest water content for a repellent sample. Most of the repellent samples show water contents between 0.04 and 0.1 $g \cdot g^{-1}$.
Samples with a SOM content higher than 0.065 $g \cdot g^{-1}$ were found to be still repellent at higher water contents of 0.1 – 0.15 $g \cdot g^{-1}$. Wettable samples occur at water contents higher than 0.03 $g \cdot g^{-1}$. However, for wettable samples with an intermediate SOM content, the smallest water content is 0.053, for samples with a SOM content >0.065 $g \cdot g^{-1}$ it is 0.098 $g \cdot g^{-1}$. The organic matter content of the samples seems to influence the water content range where repellency occurs. To prove the effect of organic matter on the wettability it is necessary to find a cut off criterion – the critical water content.

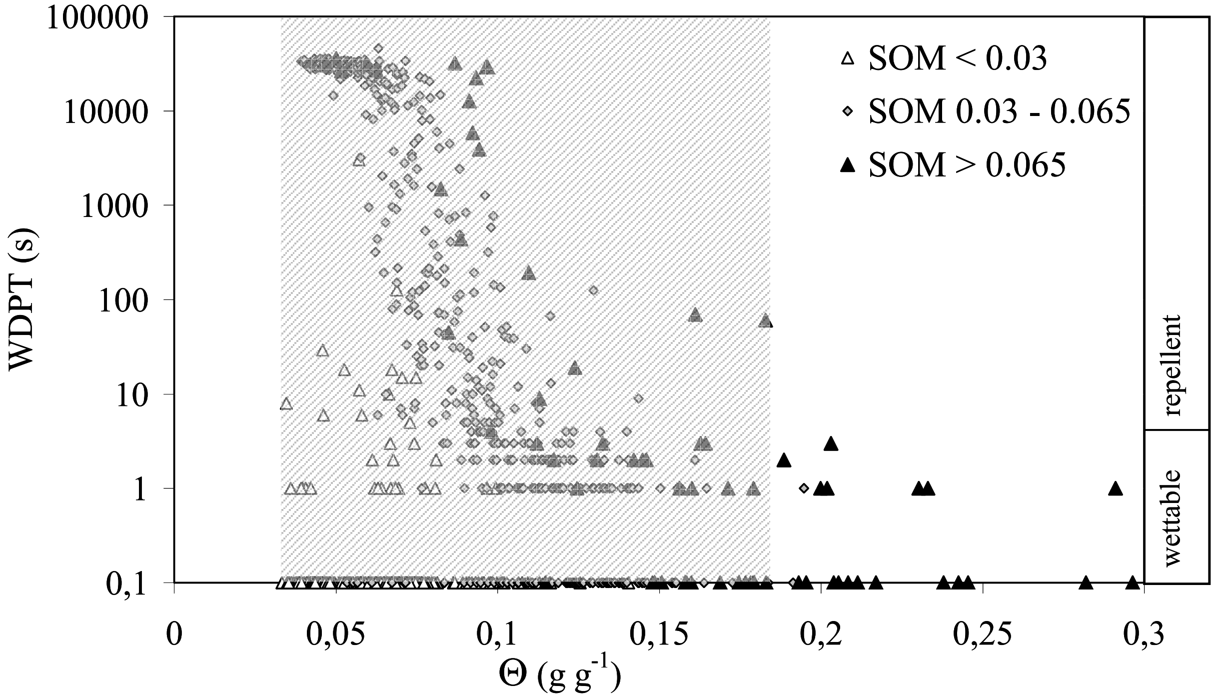

Fig. 2.4 Relationship between the soil water content and actual water repellency for all samples taken on Jan. 22nd with consideration of the SOM ($g \cdot g^{-1}$); the grey tone indicates the transition zone, n=864.

The following paragraph describes the procedure of establishing a critical soil moisture threshold for distinguishing between wettable and repellent states. The critical water content Θ_{crit} is used to predict the wettability status: wettable if the water content is higher than the critical water content, repellent if it is lower. The predicted values were compared with the measured results (wettable for WDPT < 5s, repellent for WDPT ≥ 5s). Using one constant critical water content to separate all top- and subsoil samples into a group of repellent samples and a group of wettable samples leads to a high number of wrong predictions (see Tab. 2.2). A prediction failed if samples with water content lower than Θ_{crit} are still wettable or if samples with water contents higher than Θ_{crit} are repellent. The critical soil water content Θ_{crit} was shifted until the residual sum of squares of the wrongly predicted samples converged; the number of wrong predictions decreased to a minimum. We derive:

case one: constant Θ_{crit}, without influence of SOM

(1) $\Theta_{crit} = \Theta_0$ with $\Theta_0 = 0.07\ g \cdot g^{-1}$

The influence of the organic matter on the transition zone and the critical water content of the samples are shown in fig 2.5. The samples were split into 10 groups of different organic matter contents. The critical soil water content and the range of the transition zone were calculated for each group using the procedure described above. The resulting critical soil water contents for each SOM classes respectively the transition zones show a clearly rising trend.

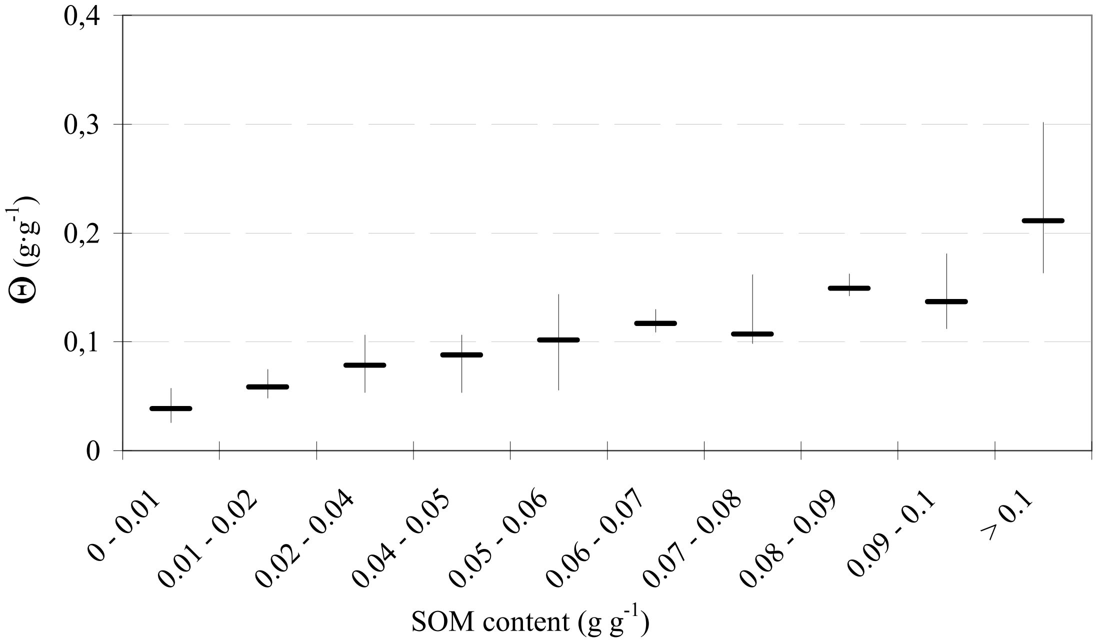

Fig. 2.5: Θ_{crit} (horizontal bar) and transition zone (vertical bar) for SOM groups, n=864.

The trend of fig. 2.5 suggests applying a linear function for a better prediction of Θ_{crit} for each sample as a function of SOM content with Θ_0 and a as fitting parameters. Θ_0 and a were calculated by optimising the sum of squares of the deviation. We obtain:

case two: Θ_{crit} linear dependent on SOM

(2) $$\Theta_{crit}(SOM) = a \cdot SOM + \Theta_0$$ with a = 1.12 ; $\Theta_0 = 0.037\ g{\cdot}g^{-1}$

For a fix Θ_{crit} value of 0.07 $g{\cdot}g^{-1}$ without consideration of the organic matter, 327 of 864 samples show different results than predicted; they are wettable at lower water contents or repellent at higher ones. 188 of the wrongly predicted samples are close to the calculated value for Θ_{crit}, the difference is less than 0.02 $g{\cdot}g^{-1}$. In 139 cases the difference is greater than 0.02 $g{\cdot}g^{-1}$. The use of equation (2) with Θ_{crit} (SOM) decreases the number of wrong predictions to 100. Only 13 of the wrong predicted samples show a deviation higher than 0.02 $g{\cdot}g^{-1}$ from the calculated threshold.

Tab. 2.2: Prediction of repellency by water content using a constant Θ_{crit} for all samples (case 1) or an individual Θ_{crit} for each sample as a function of the SOM content (case 2), n=864, 319 of them repellent.

	Θ_{crit}=f(SOM)	Θ_{crit}= const.
total number of wrong predictions	100	327
wrong predictions with a deviation > 1 Θ_m%	35	218
wrong predictions with a deviation > 2 Θ_m%	13	139

Figure 2.6 visualises the three parameters SOM, water content and water repellency within one picture. The lines characterize the threshold for the fix Θ_{crit} and the linear dependent Θ_{crit} (as a function of SOM content). The shape of the WDPT-classes may suggest a quadratic approach. The use of a quadratic function did not, however, lead to better results. Note that the WDPT classes for water contents smaller than 0.03 g·g^{-1} are a result of interpolation.

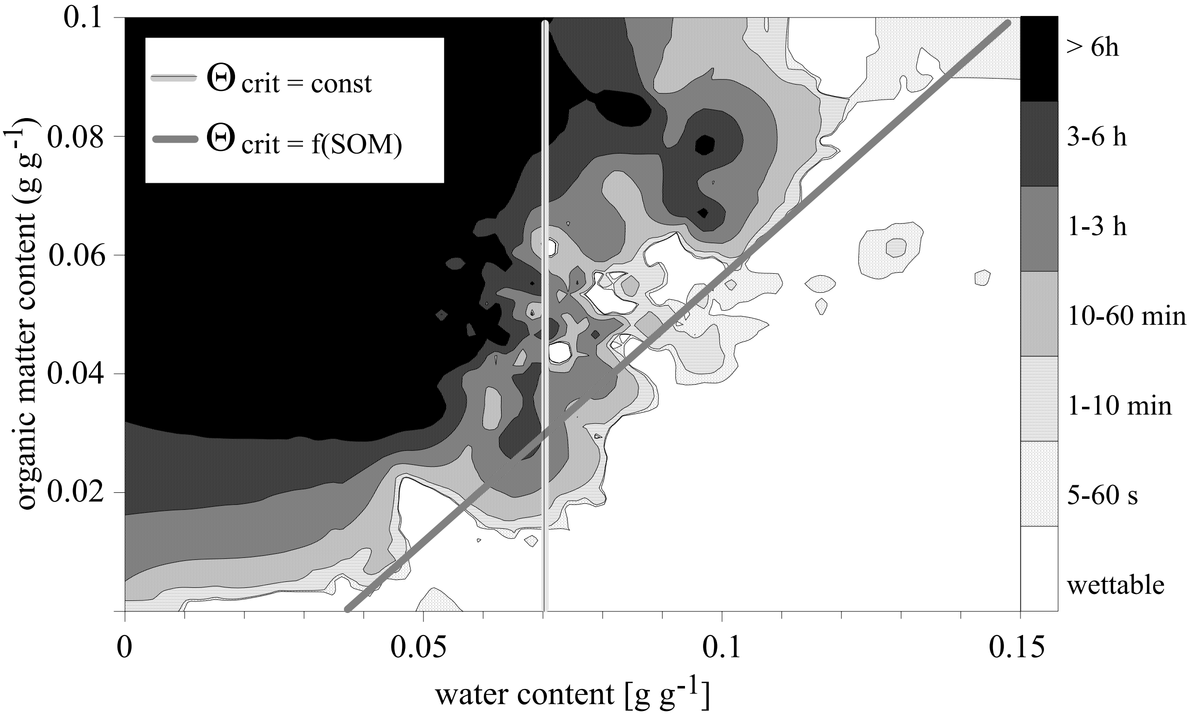

Fig. 2.6 Organic matter – water content – WDPT – relation, n=864.

3. Part II - Seasonal dynamics of preferential flow in a water repellent soil

3.1 Abstract

The temporal dynamic of water repellency in soils has a strong influence on water flow and the appearance of preferential flow paths at potentially water repellent sites. To quantify this effect, field investigations were conducted at a sandy site near Berlin, Germany. A large number of soil samples were collected at 32 different times over a 3-year period. Additionally, a TDR-array with 63 probes measured water contents hourly along a transect of 130x60 cm. Based on these sampling campaigns, the area share of water repellent soil regions was measured. Water content changes were observed with the TDR devices at a high spatial and temporal resolution after several rainfall events. Heterogeneities in water content changes were analyzed. To quantify the heterogeneity (i.e. the degree of preferential flow) we proposed the use of an effective cross section, ECS, for water flow. This parameter was calculated by fitting the beta function to the cumulative values of the water content change over a horizontal cross section at a depth of 25 cm. Sampling and TDR measurements showed similar seasonal dynamics of preferential flow, with the highest occurrence in summer and early autumn and a maximum accessible soil volume in the spring. Preferential flow in the winter month was enhanced not only by water repellency, but also by freezing and melting. We also tried to calculate the effective cross section from climatic data. It was possible to calculate the effective cross section using a linear relationship with the initial soil moisture at 10 cm depth, the duration and amount of precipitation, and the potential evapotranspiration rate.

3.2 Introduction

Water repellency is a widespread phenomenon that can affect water flow in soils significantly. Water repellency occurs on most continents and for a variety of land uses and climatic conditions. Repellency can occur naturally, as reported by Dekker et al. (1999), Harper and Gilkes (1994) and York and Canaway (2000), or can be affected by fire (Doerr et al., 1996). Repellency may impact surface runoff significantly and can lead to reduced wetting rates of dry soils. Water repellent soils tend to restrict water flow, creating fingerlike wetting fronts, which leads to a reduction in plant-available water and limits solute transport to relatively narrowed flow channels. Pollutants and nutrients consequently have shorter residence times in the affected soil layers and move much faster through the vadose zone. The effects can be observed as irregular moisture patterns or tracer distribution in the soil (Ritsema and Dekker, 1998; Arbel et al., 2005), patchy growth of plants, or erosion in sloping regions (Witter et al., 1991). Water repellency is not a permanent property. Soils become water repellent when they desiccate during dry periods in the summer, with water repellency often diminishing or vanishing when the soil becomes wet in the autumn or during wintertime (Dekker and Ritsema, 1994).

The process of water repellency has been analyzed since the 1960s. Its spatial variability and the creation of preferential flow paths in particular have recently received much attention. For example, Wang et al. (2000) conducted infiltration experiments on water repellent and wettable soils in the laboratory. They used the saturated hydraulic conductivity and an air entry value of the matric potential as conditions for unstable infiltration fronts. Clothier et al. (2000) studied infiltration experiments under unsaturated conditions in the laboratory and in the field. They observed an increase in the infiltration rate after 100 min, after which the water repellency broke down. Selker et al. (1992) derived the size of flow fingers from the unsaturated hydraulic conductivity, the air entry value, and the flow rate. Wang et al. (1998) reported finger diameters between 2 and 23 cm. An approach for calculating the finger size is included in the one-dimensional model SWAP (van Dam et al., 1996). Most experiments involved infiltration into dry soils. Glass et al. (1989) and Liu et al. (1993) found that the distribution of water contents and flow paths was strongly influenced by earlier infiltrations with fingered flow. Previous finger paths were preserved because of hysteresis in the soil moisture retention.

Dekker and Ritsema (1994) established the concept of a transition zone, or a critical soil moisture zone, to distinguish between water repellent and wettable conditions. The soil becomes water repellent when the water content decreases below a certain critical value, and it becomes wettable again when its water content exceeds another critical water content. Water contents for these two thresholds have been found to vary widely for different soils (Doerr and Thomas, 2003, Dekker et al., 2001, Ziogas et al., 2003). Täumer et al. (2005) described the influence of soil organic matter content on the critical water content.

Doerr et al. (1996) determined the spatial variability of water repellency in forestry soils in Portugal. Ritsema and Dekker (1998) analyzed the 3 dimensional distributions of water repellency, bromide and pH values, while Dekker and Ritsema (2000) described the water repellency of a clay soil. Using several sampling campaigns, they showed the high spatial variability and temporal nature of water repellency.

Most field investigations of water repellency have been conducted on disturbed or undisturbed soil samples. The disadvantage of this method is that it destroys the soil. Only few investigations have used non-destructive methods. Ritsema et al. (1998) used an array of TDR probes to demonstrate the occurrence of fingering after three rainfall events; however, they did not determine seasonal changes in preferential flow.

Without information about the seasonal dynamics of preferential flow, water and solute transport in a water repellent soil can not be fully described. Therefore, the objective of this study is to quantify the seasonal dynamics of preferential flow under water repellent field conditions. The 'effective cross section' is introduced as a new parameter to describe the area share of the preferential flow paths and the water repellent soil volume. Quantifying seasonal variations in this parameter allows the effects of water repellency to be included in the seasonal simulations of water and solute movement.

3.3 Materials and methods

3.3.1 Soil sampling

From April 2001 to April 2004 about 3000 soil samples were taken at 32 different times, in most cases as disturbed samples. The sampling positions were spread over a plot of 25 x 150 m. The TDR transect was also part of the plot. Soil samples were taken eight times with a high spatial resolution along a transect or in a grid (10 x 10 or 5 x 5 cm). The samples allowed an excellent description of the spatial variability of several soil properties. Special attention was given to the area share, the degree of water repellency, and the water content at a depth of approximately 20 - 30 cm depth. The actual water repellency was measured on field moist samples using the Water Drop Penetration Time (WDPT) test as described by Krammes and DeBano (1965). At the other 24 sampling times, the area share of the water repellent profile was estimated from the visible pattern of lighter and darker color, associated with dry and wet parts of the soil (Fig. 3.1). The area share was estimated directly from observations of the profile or from photographs of the trench. The sampling data, especially the water content and WDPT, were used to quantify the spatial variability. The spatial analyses of the water content from the first sampling campaigns helped to determine the optimal setup for the TDR array.

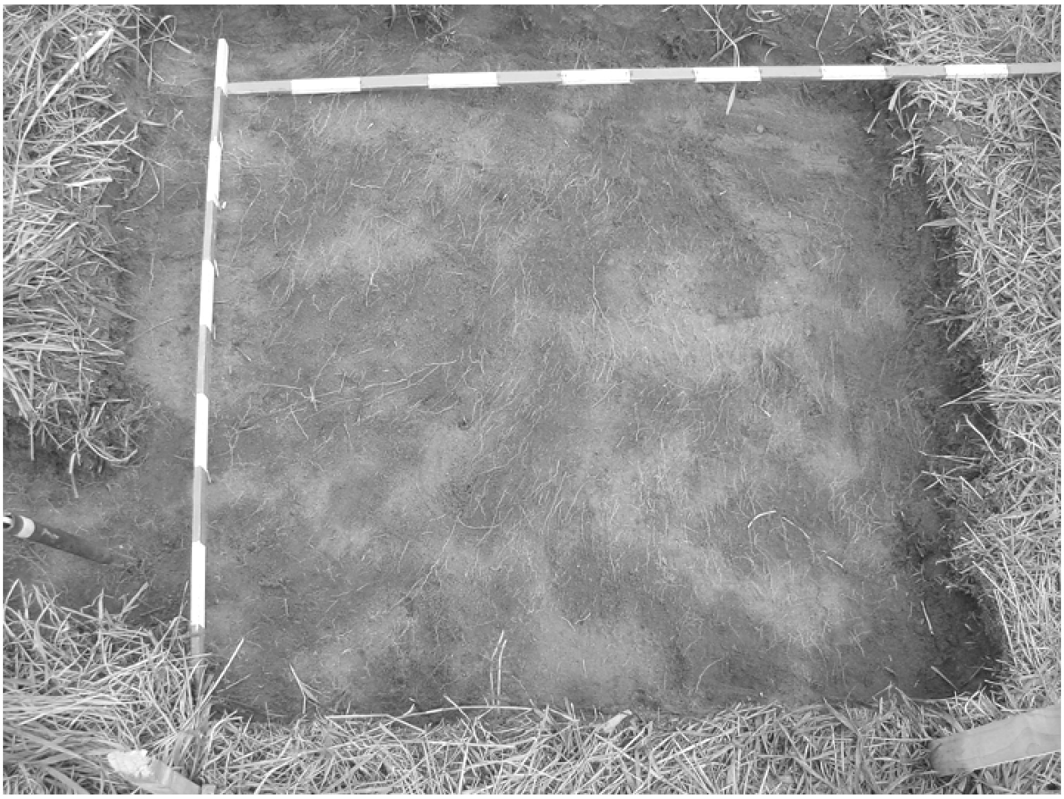

Fig. 3.1: Patterns of the soil moisture showing the relatively dry water repellent areas (light color) and moist, wettable areas (darker color).

3.3.2 TDR measurements

In order to monitor short term moisture changes in the topsoil, a TDR transect using D-LOG/mats (EASY TEST Ldt., Lublin, Poland) device was installed permanently. The device operates using a needle pulse type generated electromagnetic waves with 300 ps rise time and electromagnetic radiation with a frequency range from 30 MHz up to 1.6 GHz (Malicki and Skierucha, 1989). The D-LOG is designed for a periodic recording of instantaneous soil moisture profiles at selected time intervals. To switch between the probes, the D-LOG unit contains a built-in first level microwave switch and 8 second level switches. Each second level switch is connected to 8 TDR probes.

The TDR probes consist of a thin-wall PVC body that is 2 cm in diameter and 15 cm long. The probe has two parallel 10-cm long waveguides. The waveguides are stainless steel rods (diameter 2 mm) which are 16 mm apart. The region of influence of the sensor is approximately a cylinder with a length of 12 cm and a diameter of 5 cm. Outside of this region the electromagnetic wave of the TDR probe has little or no influence on the velocity.

In order to obtain the correct probe positions, the soil surface and horizon boundaries were copied onto plastic foil, which was fixed onto the profile wall. Since the surface undulated, a reference depth of zero was made to the smoothed soil surface. After removing the foil with the topography of the profile, the 63 TDR probes were installed horizontally into the profile wall through pilot bore holes of 15 cm. The TDR transect covered the complete topsoil for a representative area, from the top of the elevation to the middle of the lower profile range. In view of results of the spatial analyses, the probes were spaced at 10 cm in the humus-rich topsoil. A smaller spacing could result in interactions between the single TDR probes and lead to a higher disturbance of the surrounding soil. A larger spacing, on the other hand, would not reflect the heterogeneities in water content changes. After the installation the trench was refilled carefully with the original soil

Each probe represented a 10-cm compartment, except for the top probes (at 10 cm depth). A depth range between 0 and 15 cm was established for these probes. 13 probes were installed at each depth to analyze the heterogeneities. Fig. 3.2 shows the positions of the TDR probes in the profile. A measurement of the entire profile took about 2 ½ minutes. The measurements were usually taken at regular intervals of one hour. Water contents were calculated by using the calibration function of Roth et al. (1992).

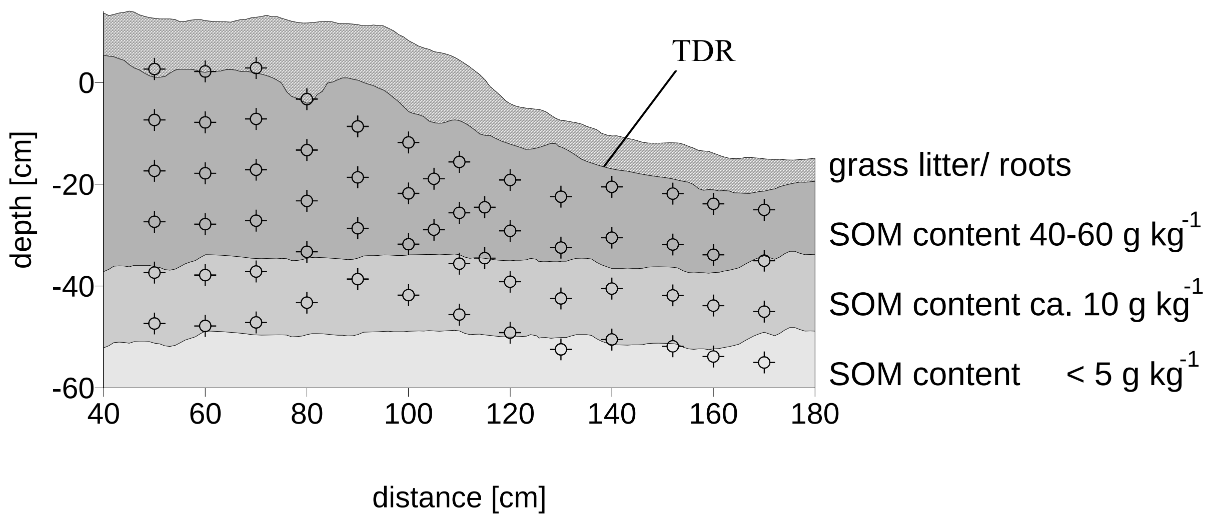

Fig. 3.2: Cross-section of the soil profile and positions of the TDR-probes.

3.3.3 Specifying preferential flow from TDR measurements

For water repellent soils, the area share of the flow paths is an important value reflecting the preferential flow paths for water and solutes. The flow paths can be identified by determining profile positions where the TDR readings show a high change in water content during single rainfall events. An index for the degree of preferential flow is necessary to compare different flow events. The index should be unambiguous for comparing and contrasting different distributions of changes in the soil water. We used an approach based on the Beta function. The standard Beta function (p) is defined by Bronstein and Semendjajew (1987) as

$$p(x;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \cdot x^{\alpha-1}(1-x)^{\zeta-1} \quad ;$$
$$for\ \alpha > 0,\ \zeta > 0,\ 0 \le x \le 1 \quad ; \qquad [1]$$

where G is the Gamma function (or Euler's integral of the second kind) and a and z are free parameters. The Beta function is defined over the interval [0, 1].

3.3.4 Calculation of the 'effective cross section'

We point out that the effective cross section concept is only useful for finger flow in the soil matrix, not for rapid flow through soil macropores. In the latter case, the TDR probes would not be able to measure the water content changes. At our site we found that the flow paths had typical dimensions in the range of decimeters. The TDR readings were examined for single rainfall events. A typical rainfall event and the corresponding response in water content changes for the whole soil profile is shown in Fig. 3.3. The water content change in the soil was delayed after the rainfall. Small differences existed between the amount of rainfall measured at this site and the amount of water recovery in the profile. Differences could be caused by interception and by higher water contents in the top 10 cm, above the first TDR probes.

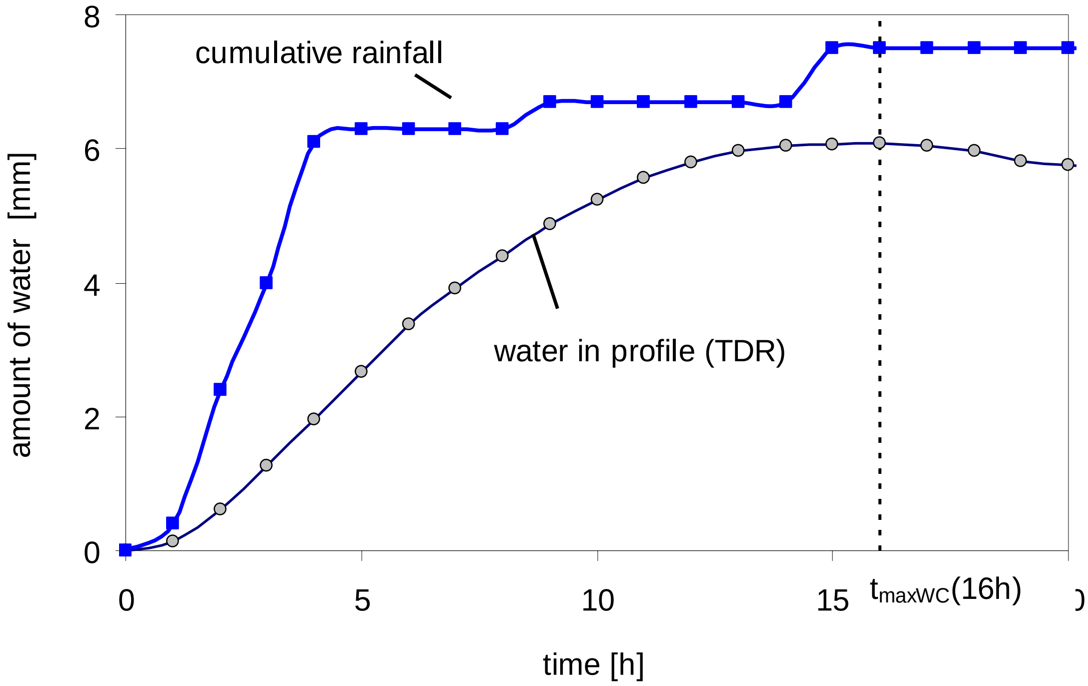

Fig. 3.3: Measured cumulative rainfall and water content changes for the entire profile as derived from TDR readings. The time of the maximum water content t_{maxWC} is 16 h

Only single rainfall events were analyzed in order to keep the share of stationary flow (flow without changes in water content) as low as possible. A single rainfall event is defined here as a rainfall event with a dry period of at least 3 days before the event.

The time (t_{maxWC}) of the maximum water content in the profile was determined for each rainfall event. For the example displayed in Fig. 3.3, t_{maxWC} was established as 16 h. The gain in water content (θ) from the beginning of the rainfall (t_0) until t_{maxWC} was calculated for each TDR probe at position x and depth z. The ratio $f_{x,z}$ between the water content change at position x and the total change in water content in that layer was calculated for each probe using

$$f_{x,z} = \frac{\theta_{x,z}(t_{\max WC}) - \theta_{x,z}(t_0)}{\sum_{x=1}^{x=13}\left[\theta_{x,z}(t_{\max WC}) - \theta_{x,z}(t_0)\right]} \qquad \text{with} \quad \sum_{x=1}^{x=13} f_{x,z} = 1 \quad . \qquad [2]$$

Afterwards, the values of $f_{x,z}$ for that layer were ranked in descending order. Each probe represented a section equivalent to 1/13th of the transect. Fig. 3.4 shows a plot of the cumulative ratio $f_{x,z}$ against the cumulative cross-sectional area. The Beta function was fitted to the data by optimizing the parameter α and ζ. The function expresses the share of the water content changes as a function of the area share. We now define the **effective cross section** as that fraction of the total area that realizes 90% of water content change as measured by the TDR probes at a certain depth. We used this value to quantify the heterogeneity in water flow in the soil.

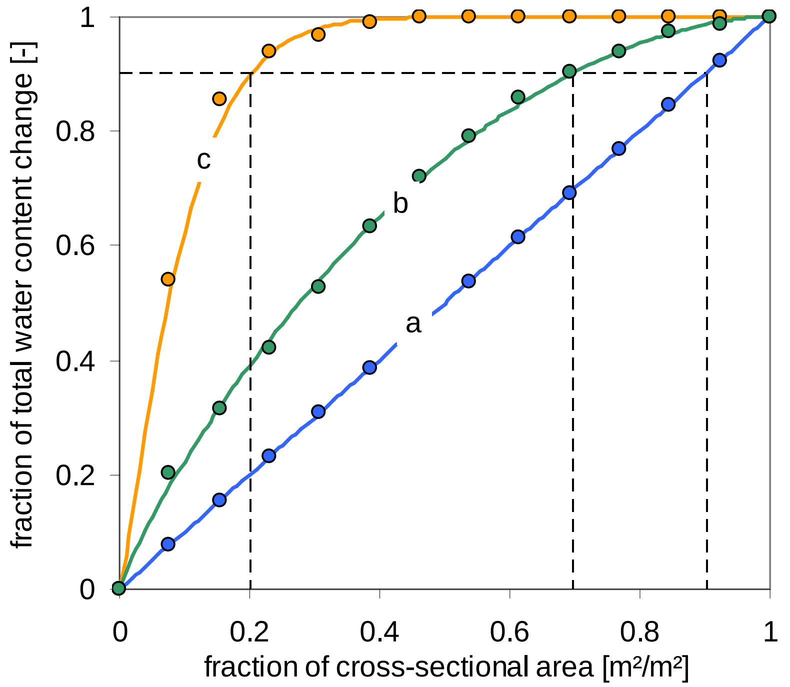

Fig. 3.4: Cumulative water content changes for (a) homogeneous flow, and flow affected by relatively (b) low and (c) high degrees of heterogeneity. The Effective Cross Section, ECS is 0.9 for case a, 0.7 for case b and 0.2 for case c.

Case a in Fig. 3.4 shows the hypothetical situation of having a uniform distribution with every compartment contributing the same amount to the water content change (piston flow). 90 % of the water content change takes place on 90% of the cross-sectional area. Case b and c shows non-uniform distributions on the basis of measured values. The graphs in those cases are curved. Every measurement represents an area of 10x10 cm. The first compartments in Fig. 3.4 have a higher share of the water content change than later ones, which leads to a deflection of the curve. For case b, 90% of the water content change occurred in approximately 70% of the cross sectional area. The shape of the curve reflects the degree of heterogeneity. The more the data points and the fitted beta distribution depart from the 1:1 line, the higher is the extent of preferential flow. A very high degree of preferential flow can be seen in case c, where the two compartments with the highest change realize 85% of the total water content change in that layer. Only 20% of the cross-sectional area is responsible for 90% of water content change. The concept of effective cross section can be used to quantify the area share that actually takes part in the water flow and appears most useful for making comparisons between different rainfall events.

3.4 Results and Discussion

3.4.1 Soil sampling - spatial distribution of the soil water content

Fig. 3.5 shows the distribution of the water content and actual water repellency (WDPT) of a transect sampled on Jan. 22nd, 2002, during a mild weather period following a strong frost. The soil layers at this position were found to be similar to the layers of the TDR transect (Fig. 3.2). The soil moisture distribution in the topsoil was clearly very heterogeneous. The higher water contents coincided with the wettable areas, while the dryer ranges were related to the water repellent areas. No differences in bulk density or particle size distribution were found for these adjacent wet and dry regions. We also excluded non-uniform water uptake by plant roots as a cause of the observed differences in soil moisture, since the sampling was carried out in the middle of winter, outside the vegetation period (April to October). No differences in root penetration were found between wet and dry areas. We did find a strong relation between the actual water repellency (which triggers the preferential flow process on the site) and the water content and the organic matter content (Täumer et al. 2005).

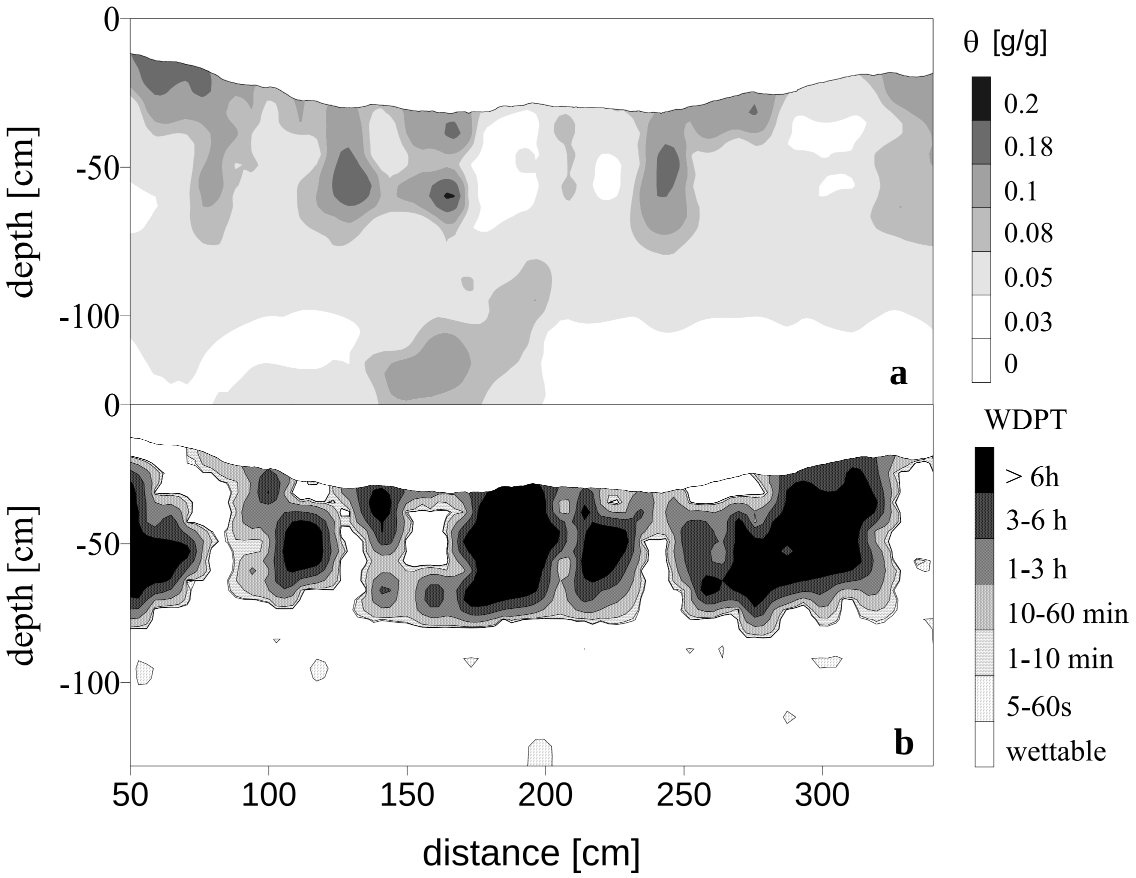

Fig. 3.5: Spatial distribution of (a) the gravimetric water content and (b) the Water Drop Penetration Time (WDPT) for a vertical profile. Samples were taken every 6 cm in the horizontal direction (51 samples per layer) and with a vertical resolution of 10 cm.

We analyzed the data geostatistically to quantify the range of spatial correlation. Experimental semivariances were calculated in a horizontal direction, separately for the topsoil and subsoil samples. Fig. 3.6 shows the semivariance in water content for samples taken at depths of 30 cm and 90 cm. The variance for the topsoil shows a steep increase in the first 20 cm. A local minimum is visible every 40 cm, indicating a recurring property at a regular spacing, i.e. the average distance between the flow channels or the dry spots. This spacing was not found for the subsoil, where no preferential flow paths were found. The water contents range from 0.039 g g^{-1} to 0.242 g g^{-1} in the topsoil and 0.026 g g^{-1} to 0.116 g g^{-1} in the subsoil. Therefore, the value of the variance for the subsoil was 3-4 times smaller than for the topsoil. A spherical model (blue solid lines in Fig. 3.6) was applied to the data:

$$\gamma_s(h) = \begin{cases} A \cdot \left[\frac{2}{3} \cdot \left(\frac{h}{b} \right) - \frac{1}{2} \cdot \left(\frac{h}{b} \right)^3 \right] & for\, h \leq b \\ A & for\, h > b \end{cases} \quad [3]$$

where A is the sill [%], h the distance [cm] and b the range [cm]. The range b was 26 cm at 30-cm depth. The range for the subsoil (90 cm depth) was significantly larger (76 cm). The analysis of other soil samplings at this site showed similar results.

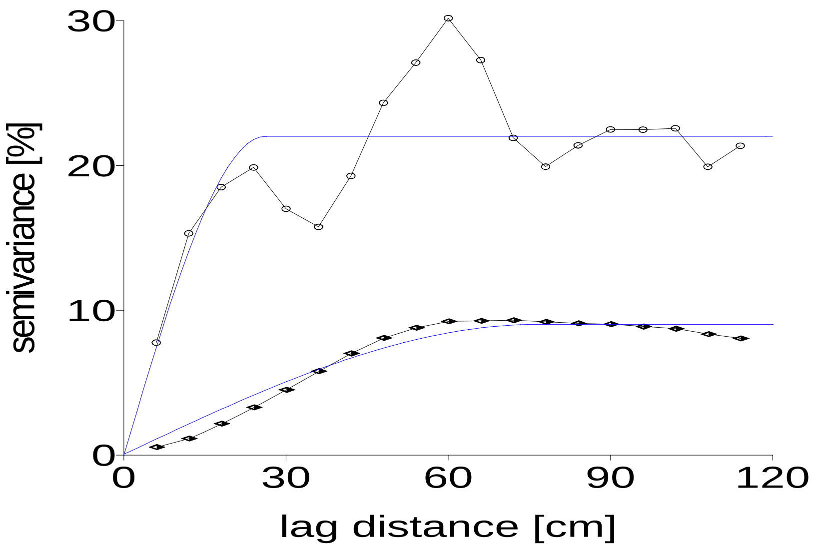

Fig. 3.6: Semivariogram of the measured gravimetric water content for samples taken at 30 and 90 cm depth.

Results of the spatial analysis of the TDR transect data suggested the need for a different experimental setup for the topsoil and the subsoil. To observe the rapid spatial changes in water content, the spacing between the TDR probes should be smaller than the range. With the selected grid of 10 cm between neighbouring TDR probes, additional probes were installed at distances of one half to one third of the range.

3.4.2 TDR data

The moisture contents were measured from April 2002 until April 2004 excluding some periods where the measurements failed due to problems with the TDR device or power supply. Fig. 3.7 shows data for two typical time frames from five neighboring TDR probes, each at 10 cm depth. The measurements show the drying of the topsoil in spring 2002 (Fig. 3.7a) and the rewetting after summer (Fig. 3.7b). Different responses to rainfall events are apparent during the two periods. While some of the TDR probes indicated high changes in water content, others did not react at all. Rainfall events caused an abrupt increase of the water content at some positions of the profile. After these abrupt increases, the water content decreased quickly within the first hours after the rainfall event, due to rapid drainage into deeper soil layers.

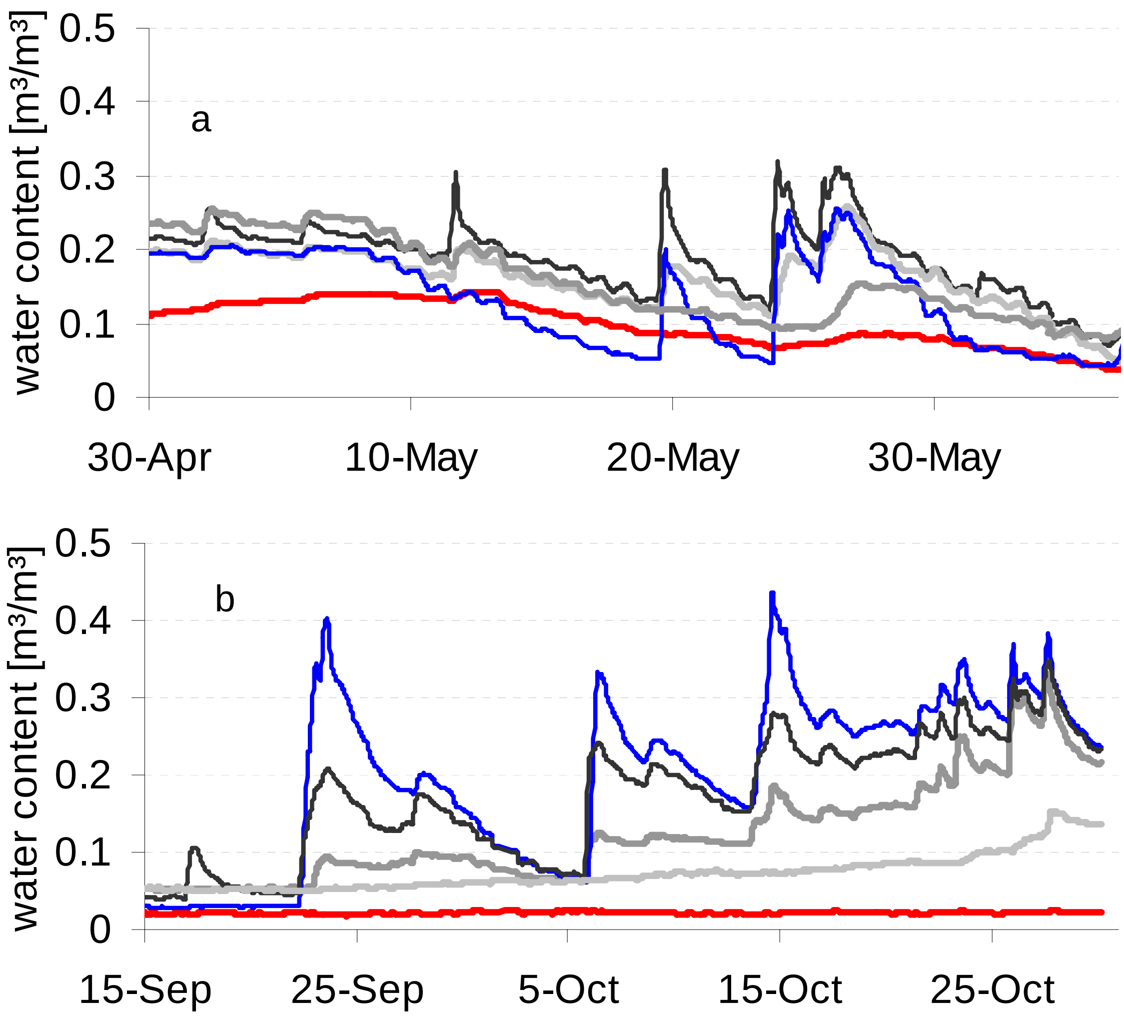

Fig. 7: Water content measurements during spring (top) and autumn (bottom) 2002 for 5 neighboring TDR probes at 10 cm depth. The probes in the flow paths show very abrupt reactions, while probes in the water repellent regions show little or no reactions.

In the springtime we observed a decrease in water content from the end of April to the beginning of June. On average, the water content of the top soil layer decreased from 0.18 $m^3 \cdot m^{-3}$ to 0.06 $m^3 \cdot m^{-3}$ during that time. During rewetting in the fall, especially at the end of September, large differences occurred in the TDR-readings between the different probes. At the end of October more probes reacted than at the beginning of September. Water content at several positions remained constant after the rainfall events, thereby indicating the water repellent areas of the soil.
We also observed some diurnal variations in water content, especially during the dry periods in May. Such diurnal changes in water content were caused by evapotranspiration during the day and water redistribution during the night. Temperature effects may also have been present (Stoffregen, 1998; Parlange et al., 1998).

Fig. 3.8 shows the moisture distribution along the transect at the start of a rainfall event on Sept. 22, 20002, and 9 h, 24 h, and 44 h afterwards. The evolution of flow paths and the influence of the undulated soil surface are clearly noticeable on the plot. The upper part at the right side of the profile stayed much drier than the lower part (left side); whereas several water repellent areas without much or any changes in the water content were present. Probes that showed strong reactions to rainfall events (e.g. position 140/10cm depth) at the beginning of rewetting also showed strong changes at subsequent events. Apparently, once a flow path is established, it will be followed during subsequent rainfall events. Regions between the flow paths showed no or only slight changes in water content (e.g. 130 cm/10 cm depth). Some of these dry regions were very persistent. Several rainfall events were necessary to overcome the water repellency and to rewet most of the profile. In time the number and size of the flow regions increased as well.

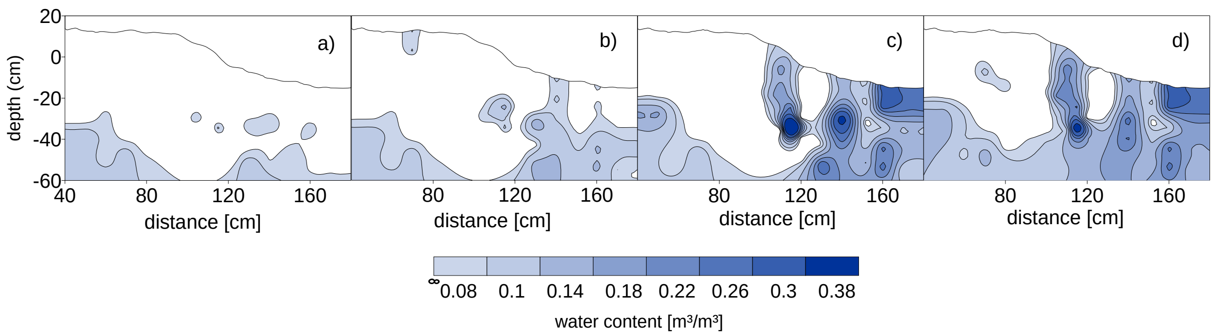

Fig. 3.8: Plots showing changing moisture distribution in the topsoil (a) initially and (b) 9h, (c) 24h and (d) 44 h, after a rainfall event on Sep. 22, 2002

3.4.3 Heterogeneity

The wettable areas estimated from the sampling data as well as the effective cross sections, ECS, from the TDR data clearly showed a seasonal trend. They reached minimum values in summer and maximum values at the beginning of spring (Fig. 3.9). Note that the sampling data (yellow and orange squares) was collected under varying conditions, mostly a few days after a rainfall event. The effective cross sections were always calculated from the TDR measurements (blue triangles) directly after rainfall events. Therefore, TDR data never showed a totally water repellent soil, while for the sampling data these conditions sometimes occurred in summer time.

From February to the beginning of April almost the complete profile was wettable; the area share of the water repellent spots at that time was mostly smaller than 10%. At the beginning of the growing season in April/May the water content in the topsoil decreased. The evapotranspiration rate at that time was higher than the precipitation rate. During prolonged dry periods the entire topsoil dried out and became water repellent. Rainfall events caused incomplete wetting; with the effective cross section being reduced to 20-40% of the total cross sectional area.

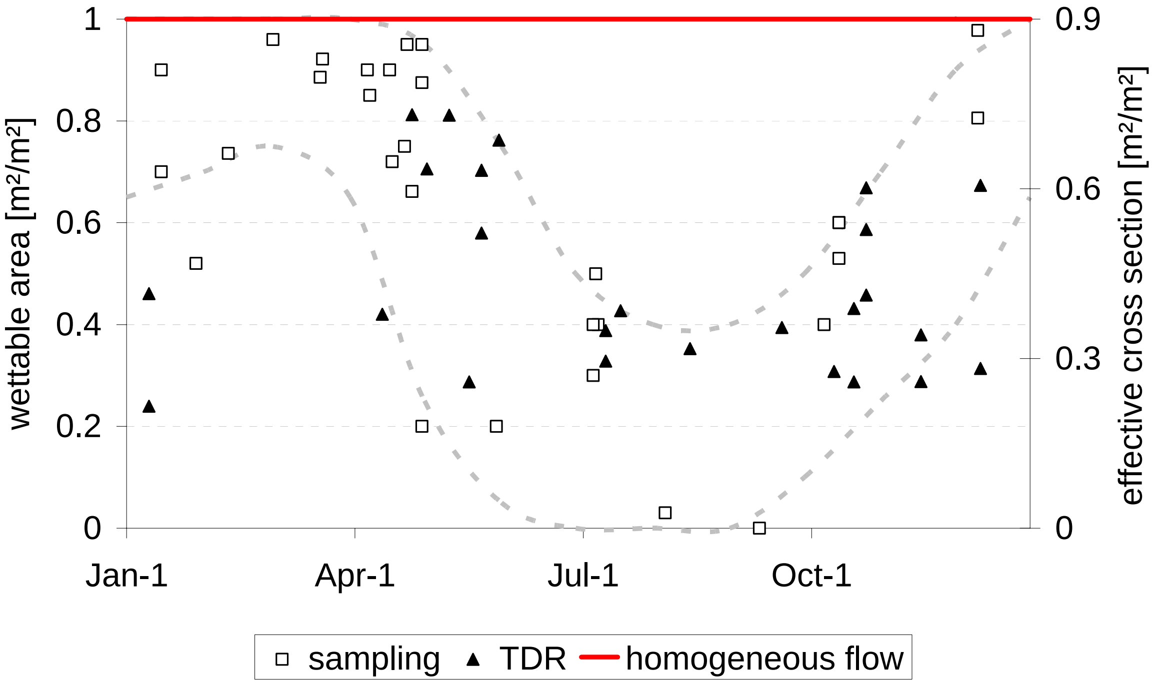

Fig. 3.9: Seasonal changes in the wettable area as estimated by soil sampling (squares) and in the effective cross section as derived from the TDR data (triangles). The grey dashed lines indicate the range of values during the year, excluding frost periods.

With decreasing water demand by the plants and lower temperatures in the fall the soil water balance slowly became positive. This caused a rewetting of the soil and hence an increase of the effective cross section. Especially at the beginning of May, the TDR data and sampling results showed an extremely high variability. The variability was caused by the variation in the climatic conditions. The year 2002 (820 mm annual precipitation) was unusually wet, while 2003 (410 mm) was very dry, especially during the first part from February to June.

Values of the TDR measurements in January were influenced considerably by the occurrence of frost. Sealing of the soil surface due to frozen parts caused runoff and preferential flow when the snow melted. Frozen water has a much lower dielectric constant than liquid water. Therefore, the time at which the soil thaws can be detected by the TDR measurements. Differences in the melting time between neighboring profile positions at the same depth were observed for several hours up to two days. In the soil sampling, on the other hand, this effect cannot be detected by measuring the water repellent area share.

3.4.4 Predictions of preferential flow

In the next research stage we examined the dependence of the effective cross section area on climatic parameters and water content. Data from periods with frost in the soil profile were excluded from the analysis. An important factor for water repellent soils is the initial moisture in the topsoil. A drier soil generally has a higher probability to become water repellent and, therefore, poses a higher risk of preferential flow. Several climatic conditions seem to favor the creation of preferential flow. For example, short intensive rain showers tend to trigger preferential flow, while long, steady rains tend to moisten the soil more uniformly. Fig. 3.10 displays the relation between the effective cross section and the average initial water content at a depth of 10 cm. A general dependence can be seen, although the regression coefficient r2 is only 0.35. Notice that the results differ as a function of the average intensity of the rainfall event. For lower (<0.35 mm h-1) and medium intensities we found a higher correlation, while no correlation was found for higher intensities (>0.9 mm h-1).

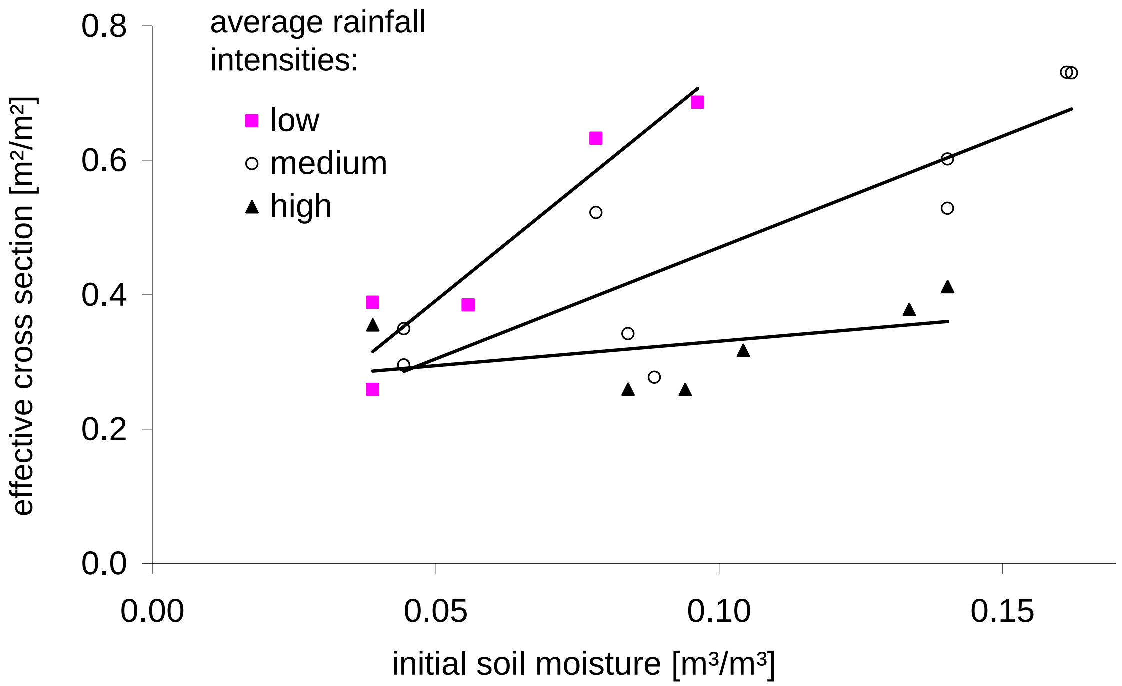

Fig. 3.10: Effective cross section and initial soil moisture at 10 cm depth for relatively low (squares), medium (circles) and high (triangle) average rainfall intensities.

The effective cross section calculated from the TDR data was found to be a function of several parameters. We examined several empirical correlations to predict the effective cross section using results of 20 rainfall events during one year. The factors we used in the prediction were the initial water content at 10 cm depth, the amount, intensity and duration of rainfall, the potential evaporation rate and the climatic water balance (precipitation minus potential evapotranspiration) for different periods before the rainfall events. Different functional dependences (linear, quadratic, power function, hyperbolic) were tested. To this end, the sum of square roots between calculated and measured effective cross sections were optimized by using a numerical solver.

The initial soil moisture at a depth of 10 cm (at the beginning of the rainfall event) was found to have the greatest influence on the occurrence of preferential flow. Good results were achieved using the linear relationship

$$ECS = 3.9*\theta_{10} - 0.24*I + 0.0020*E_p + 0.0072 * R \qquad [4]$$

where ECS is the effective cross section ($m^2 \cdot m^{-2}$), θ_{10} is the average initial water content at 10 cm ($m^3 \cdot m^{-3}$), I is the average intensity of a particular rainfall event ($mm \cdot h^{-1}$), E_p is the potential evaporation over a 24-d period (mm) and R is the rainfall amount (mm).

Fig. 3.11 shows a comparison between the effective cross sections calculated from TDR measurements and the predicted values from Eq. [4]. The use of quadratic equations gave only slightly better results, while hyperbolic or power functions produced worse results.

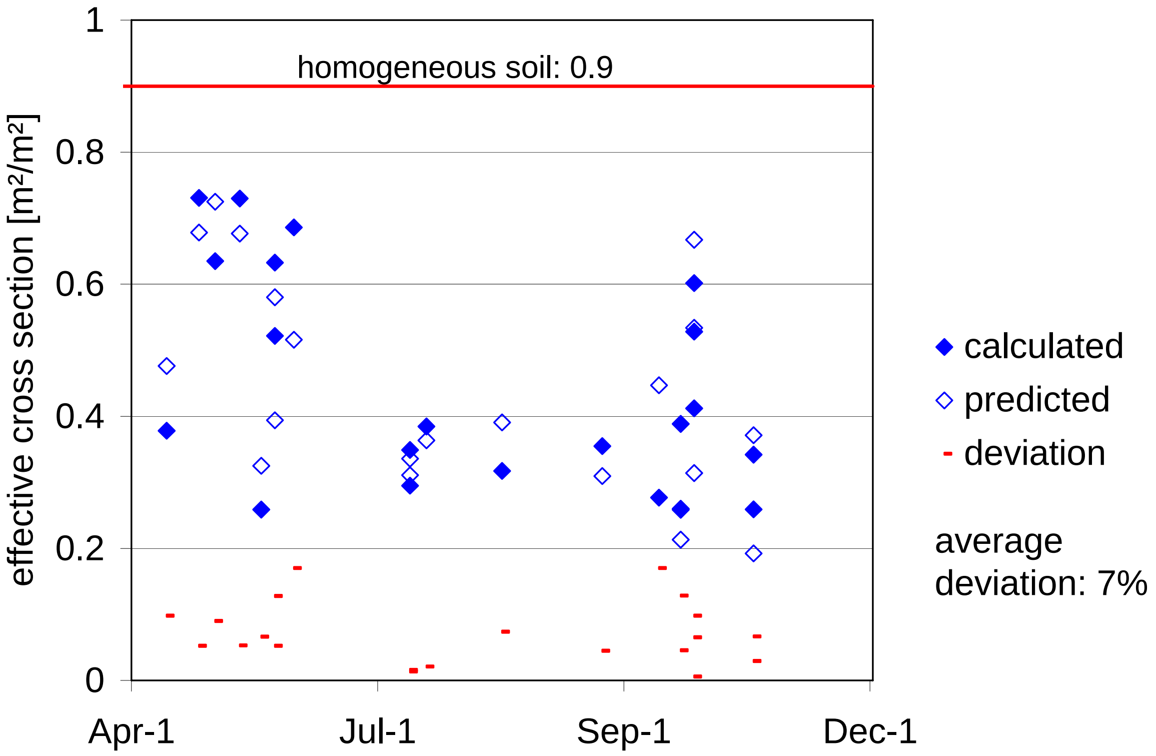

Fig. 3.11: Values of the effective cross section, ECS, calculated from TDR measurements, and predicted values with Eq. [4].

4. Part III - Stability of flow patterns in water repellent soils - conclusions of a time delayed double tracer experiment and TDR measurements

4.1 Abstract

In order to examine the stability of flow paths, a time-delayed double tracer experiment was conducted on a water repellent sandy site by applying two different tracers on one plot at various points of time (a bromide tracer in the spring of 2002, a chloride tracer during autumn of 2002). Additional TDR-measurements were carried out on an adjacent plot in hourly intervals. After a travel time of 328 (bromide) i.e. 87 (chloride) days the profile was excavated and small-scale soil samples were taken by disturbing the site along a set pattern.

The chloride tracer which was applied during autumn showed a distribution typical for fingering. The bromide tracer, which had already been applied during spring, was highly concentrated in dry, wetting-resistant areas, indicating that a transport into these areas must have taken place during the spring time. A different flow regime must have been predominant. Although the tracer experiment did not allow conclusions as to whether the flow paths always remain constant during the passages in spring and autumn, but they can be categorized. About 10% were classified as main flow paths, 45% as moderate flow path, 40% as sparsely flow paths, and in about 5% of the area no tracer was transported. The hourly recordings of the TDR-measurements showed that in consecutive precipitation events the flow paths stay the same. When comparing long time intervals, e.g. autumn 2002 – autumn 2003, a spatial alteration of the flow fingers was observed. Therefore, the formation of flow fingers is also a random event of the rewetting process.

4.2 Introduction

Water repellency is a widespread phenomenon that can have a significant effect on water flow in soils. It is not a permanent property. Soils become water repellent when they desiccate during dry periods in the summer, with water repellency often diminishing or vanishing when the soil becomes wet in the autumn or during wintertime (Dekker and Ritsema, 1994; Greifenhagen et al., 2006). The fact that water prefers the same flow paths after consecutive precipitation events is well described in literature and in our own experiments. Glass et al. (1989) and Liu et al. (1993) found that the distribution of water contents and flow paths was strongly influenced by earlier infiltrations with fingered flow. Previous finger paths were preserved because of hysteresis in the soil moisture retention. Soil seems to have some sort of memory for flow paths. However, it has not been examined as yet if these flow paths remain stable or if they vary during the seasons. Täumer et al. (2006) showed that the tendency towards preferential flow takes a clear seasonal course. The resulting effective cross sections vary: high effective cross section – the infiltration is homogenously distributed, low effective cross section – only certain regions of the soil participate in the flow events (Fig 4.1). The seasonal course is caused by climatic factors and by plant growth i.e. water uptake of roots. The best parameter to reflect the tendency toward preferential flow is the amount of water available in the upper soil. It is typical that a sufficient water supply during the winter months results in a low tendency towards preferential flow. Dryness during the summer period, on the other hand, encourages a high development of preferential flow. The water demand of the vegetation during autumn and winter is low and the evaporation amounts to 15-0% of the total annual evaporation (Renger and Wessolek, 2000), so that flow paths do not dry out completely and can be used again for the next event. Dry patches in the soil are gradually moistened. Ritsema et al. (1998) used an array of TDR probes to demonstrate the occurrence of fingering after three rainfall events; however, they did not determine seasonal changes in preferential flow.

Various tracer experiments have been carried out in soil science to mark preferential flow paths. Conservative tracers like bromide and chloride have been used as well as dye or fluorescence tracers. One disadvantage of dye tracers is the temporal decay of the tracer. Therefore, most of the shorter experiments with irrigation have been carried out using dye tracers (Vanderborght et al., 2002; Forrer et al., 2000), while in long term experiments inorganic anions like bromide or chloride predominate (Dyck, 2003; Kohne et al., 2005; Hammel et al., 1999). Bromide is the most suitable tracer in the group of inorganic anions

(Flury and Wai, 2003), because of its low concentration in natural soils. Ritsema and Dekker (1998) and Arbel et al. (2005) conducted tracer experiments to mark preferential flow paths in water repellent soils.
Multi-tracer experiments were used in several studies (Kung et al., 2000; Kasteel et al., 2003; Wang et al., 2002; Koschinski et al., 2006). Hangen et al. (2005) applied a tracer cocktail consisting of bromide, terbuthylazine, and deuterium to the soil surface of a potentially water repellent lime soil and subjected it to natural infiltration. Tracer concentrations in drainage waters were analyzed for a period of about 10 months. They determined a sectional drainage area in 110 cm depth of 71% in spring and 35% in autumn. The results for bromide and deuterium were comparable, the absence of terbuthylazine indicates the absence of rapid flow in the soil. Several authors showed that bromide is adsorbed slightly in the soil (Brooks et al., 1998; Clay et al., 2004). Until now, time delayed double tracer experiments in order to mark the flow path at different seasons had not been conducted on water repellent soils.

The aim of our study was to detect preferential flow paths during different seasons. For this purpose we performed a double tracer experiment using bromide in early spring and chloride in autumn. The bromide is intended to mark the areas of flow paths during spring and summer time, the chloride those of autumn. Excavations during the dry summer periods showed that the complete soil was dry and extremely resistant to wetting. Differences in the inhibition of the wetting, caused by earlier flow paths, or in the moisture levels could not be determined (Täumer et al., 2005). According to these experiences, the memory for certain flow paths i.e. patterns did not outlast the summer. Should a change in flow paths occur, it will not happen during consecutive precipitation events during winter or spring but during the rewetting period in autumn. This hypothesis holds true only if the soil dries out completely in the summer and the “flow path memory” has been deleted. In order to test the hypothesis, a study was carried out with two different tracers (bromide and chloride) that were applied at different points of time. The bromide tracer was applied twice during spring with the aim of recording the old flow regime. The second tracer (chloride) was applied once after the first precipitation events in autumn. According to our hypothesis, new flow paths can only be formed during this season and this rewetting phase if there were dry phases during the summer.

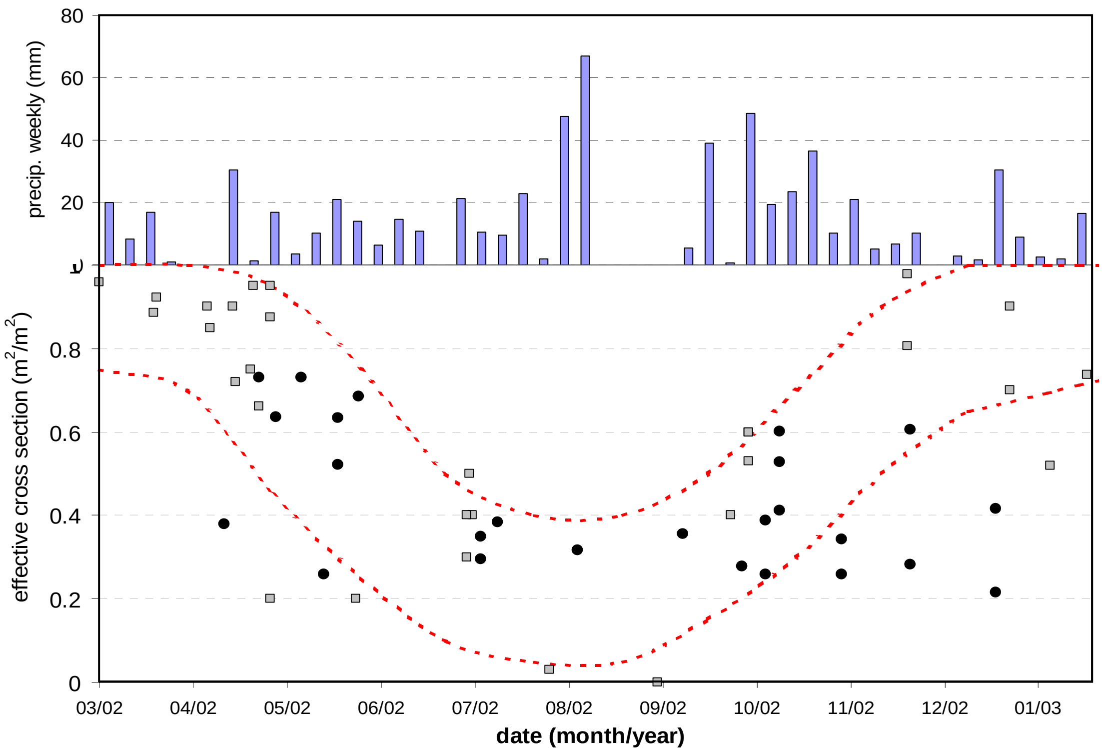

Fig. 4.1: Weekly rainfall during the experiment and effective cross section (measured by TDR (■) and soil sampling (□)) during the tracer experiment.

4.3 Material and methods

4.3.2 Laboratory measurements

Actual water repellency was determined with the **W**ater **D**rop **P**enetration **T**ime (WDPT) test as described by several authors (e.g. Krammes and DeBano, 1965; Dekker and Jungerius, 1990). In order to establish the actual repellency, three drops of distilled water were placed on the smoothened surface of a field moist soil sample using a standard glass pipette. The time that elapsed before the drops were absorbed was measured. The potential water repellency of the same samples was also tested after drying them at 35° C for two weeks. Dekker and Ritsema (1994) described the potential water repellency as the most appropriate parameter for comparing water repellency of soils, because differences in water content are eliminated.

A repellency index was applied allowing a quantitative description of the severity of water repellency as described by Dekker and Jungerius (1990). Seven classes of repellency were distinguished, ranging from wettable with a WDPT of less than 5 s to extremely water repellent with a WDPT of more than 6 h (see tab 4.1).

Tab. 4.1: Classes of WDPT used in this study

Classes	Class 0	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
WDPT	< 5 s	5 – 60 s	1-10 min	10-60 min	1 – 3 h	3 – 6 h	> 6 h
	wettable	slightly	strongly	severely	extremely		
		water repellent					

The water content of all samples was determined gravimetrically by drying them at 105° C. Afterwards, the dry samples were used to measure the content of organic matter by igniting the samples for 5h at 550°C. The difference between the dried and ignited samples was taken as the organic matter content, since the samples are non-calcareous.

30 g of air dried soil were shaken for 2 hours with 50 ml distilled water. The concentration of the tracer elements chloride and bromide was measured with a liquid chromatograph Dionex DX-120.

4.3.3 Calculation of climate water balance and percolation rate

In order to reach a better understanding of the tracer transport, the climate water balance (precipitation minus potential evapotranspiration) and soil water flow quantities during the experiment were estimated roughly using a simple 1d-numerical simulation model without considering water repellency or hysteresis. The climate data was taken from the nearest climate station in Berlin Tegel, which is about 5 km away from the tracer site. The climate water balance and net infiltration rates were calculated on a daily basis. The necessary water retention and unsaturated hydraulic conductivity functions were derived by fitting the measured hydraulic data according to Mualem (1976) and van Genuchten (1980). The potential evapotranspiration was calculated using the FAO Penman-Montheith grass reference formula (Allen, 2000), the actual evapotranspiration following a modified approach of Rijtema (1968). The difference between measured cumulative precipitation and actual evapotranspiration was used to calculate net infiltration for the periods after tracer application. To get a first impression about the traveling depths of the bromide and chloride center of mass, the piston flow concept was used by dividing the percolation rate by the cumulative soil water content from a matric potential of pF 1.8.

4.3.4 TDR measurements and effective cross section.

A TDR transect was installed permanently to monitor the short term moisture changes in the topsoil. The device is designed for periodic recording of instantaneous profiles of soil moisture in chosen time intervals. Usually, the measurements were taken at regular intervals of one hour. The TDR probes were installed horizontally into the profile wall through a pilot bore hole of 15 cm. The TDR transect covers the complete topsoil for a representative terrain – from the top of the elevation to the middle of the lower profile range. The probes were spaced at a distance of 10 cm in the humus-rich topsoil.

A schematic view of the TDR-array is given in fig. 3.2. The 'effective cross section' (ECS) can be calculated on the basis of the TDR-measurements. The effective cross section ranges from 0 to 0.9 and gives the area share, in which 90% of the water content changes (indicating 90% of the water flow for a single rain event) take place. For homogeneous flow, the effective cross section will be 0.9. For preferential flow it will be below 0.9. The ECS was calculated from the water content changes of TDR probes in a depth from 20 to 30 cm. For more details see Täumer (2006).

4.3.5 Tracer application and soil sampling

The tracer solutions were applied at three different times, as listed in Tab. 4.2. First, the bromide tracer I was sprayed onto the soil surface on March 1st, 2002, with the aim of labeling the flow regions that are responsible for the water and solute transport during the spring of 2002. At that time, the soil water content was high at nearly pF 1.8 and the effective cross-section was about 0.8. In total, 582 mm rainfall was measured from the first tracer application until Dec. 6th. Due to the high amount of rain in March, a second bromide pulse (Bromide II) was applied on the same site at the beginning of April, to make sure that all active flow pathways had been labeled. At that time, the soil had started to dry out and the effective cross section was slightly reduced (by 5 %) compared to the first application. This second tracer percolated into the soil as a result of 536 mm rainfall until Dec 6th. The third tracer, chloride, was sprayed out on October 28th, 2002, in the rewetting phase after the summer dryness. The soil water content varied from 3 up to 25 percent due to a heterogeneous soil water distribution. The effective cross section was low, making up less than 50 percent of the experimental site. 56 mm precipitation fell from the time of the chloride application until a strong frost period, which began on Dec 6th and lasted until the middle of January. The tracer plot was covered with rock wool mats to prevent a deep freezing. On January 22nd, 2003, at temperatures above freezing point, the site was sampled along a 3 m transect down to 1m depth with a vertical resolution of 10 cm and a horizontal resolution of 6 cm. To complete the information of the tracer movement, 24 soil samples were taken at depths between 1m and 2m using a "Puerckhauer" auger. The gravimetric water content, the organic matter content, the actual water repellency and the concentrations of bromide and chloride were determined in the laboratory for all field moist samples. Altogether 864 soil samples, 480 from the soil surface to 1 m depth and 24 auger samples of deeper layers were investigated.

Tab. 4.2: Basic information on the tracer experiment

Tracer	Bromide I	Bromide II	Chloride I
Date of application	1.03.2002	4.04.2002	28.10.2002
Tracer application ($g \cdot m^{-2}$)	250	500	20
Date of sampling	22.01.2003		
Water content (m^3/m^3) at application time	0.18 – 0.22	0.13-0.16	0.03 – 0.25
Effective cross section at application time	0.8 – 0.9	0.75 – 0.9	0.45 – 0.65
Percolation time (days)	328	294	87
Precipitation* (mm)	582	536	56
Net infiltration** (mm)	239	217	47
Calculated depth of center mass*** (cm)	>300	>270	<30

*from date of application until sampling,
**net infiltration=precipitation minus actual evapotranspiration from the date of application until December 6th,
*** using piston flow concept for homogeneous flow conditions,

4.4 Results and discussion

4.4.1 Climate water balance and percolation during the experiment

On the whole, the year 2002 can be described as moist and warm, with a mean temperature of 10.3°C and a precipitation 821mm (annual weather report of the Humboldt University, Berlin). The month of August was particularly wet, with 120mm rainfall being recorded at the measuring site, which is about twice as much as the annual average. Starting in October, 2002, all values for the climatic water balance were positive, so that the profile was gradually rewetted. Fig 4.2 shows the climate water balance and the cumulative net infiltration. The results of the daily climate measurements were integrated into values per week in order to obtain the climate water balance (bars). The cumulative net infiltration was calculated from the daily precipitation and the actual evaporation as shown in chapter 2.3.

The grey areas mark a strong frost period. The dotted lines at the beginning of March and April indicate the application of bromide. The dotted line at the end of October shows the chloride application. It can be observed that almost no drainage occurred after the end of April. In the summer months there is usually no percolation, with August representing an exception due to extremely heavy precipitation. Starting in October, sinking evaporation rates led to positive water balance values, and percolation occurred again.

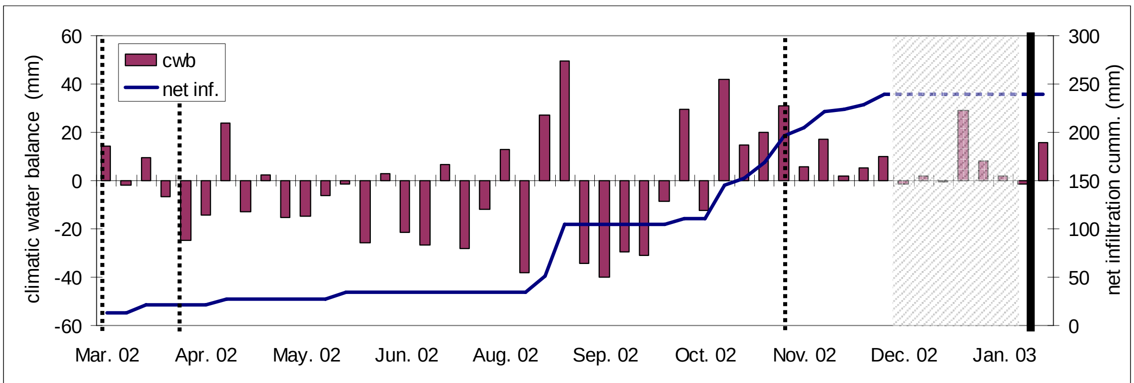

Fig. 4.2: Weekly climate water balance (cwb=rainfall minus potential evapotranspiration) and cumulative net infiltration during the tracer experiment. The dotted lines indicate the tracer applications. The frost period is shaded grey, sampling is indicated by the thick black line.

4.4.2 Results of TDR measurements, shift of flow paths

Fig. 4.3 demonstrates the shift of flow path using the TDR measurements. Three different rainfall incidents with similar amounts of precipitation caused the changes in water contents. The difference between the initial water content and the value 24 h after the onset of precipitation was calculated for each TDR-probe i.e. profile position. The areas participating in the flow events can be identified by rapid changes in water contents.

The following results were obtained by the TDR-measurements:

- It is nearly always the same set of probes that is activated after consecutive rainfall events. These positions identify the preferential flow paths. This arrangement of flow fingers remains constant over several months. For example, the most rapid increase in water content after precipitation events with high amplitude was seen at position 140 cm and 10 cm, a position corresponding to the category "main flow path" (s. below).
- Between probes showing high changes are those with no notable changes in water content following rainfall events over long periods of time (several weeks, months). For example in Fig.4.3b for the marked probes at a distance of 130 cm there were no changes of water content measured during the period from summer 2002 to autumn 2002.
- During the summer months, the number of probes which recorded an increase in water content after rainfall events was low. Percolation could be observed only in the sink and the main flow path (position 140 cm) of the profile.
- The micro-relief plays an important role in the infiltration process, since the wavy surface leads to runoff from the slightly elevated positions into the sinks, causing a lateral redistribution. This effect is more pronounced during the dry summer months than during the winter, when moist conditions prevail.
- The rewetting process during autumn gradually establishes additional flow paths, whereas the portion of dry areas that show no changes in water content after precipitation decreases.
- Fig.4.3c shows the situation in autumn 2003, in which a shift of flow paths occurred in the area of 100 – 130 cm. While in 2002 the area of 130 cm was characterized by a low change in 10 and 20 cm depth, the same area had a high change of water content during the autumn of 2003. In return, a low change existed in 2003 at 115 – 120 cm where there had been high changes in water content the year before. Therefore, some flow paths changed from autumn 2002 to autumn 2003, whereas others remain (e.g. at 140 cm).

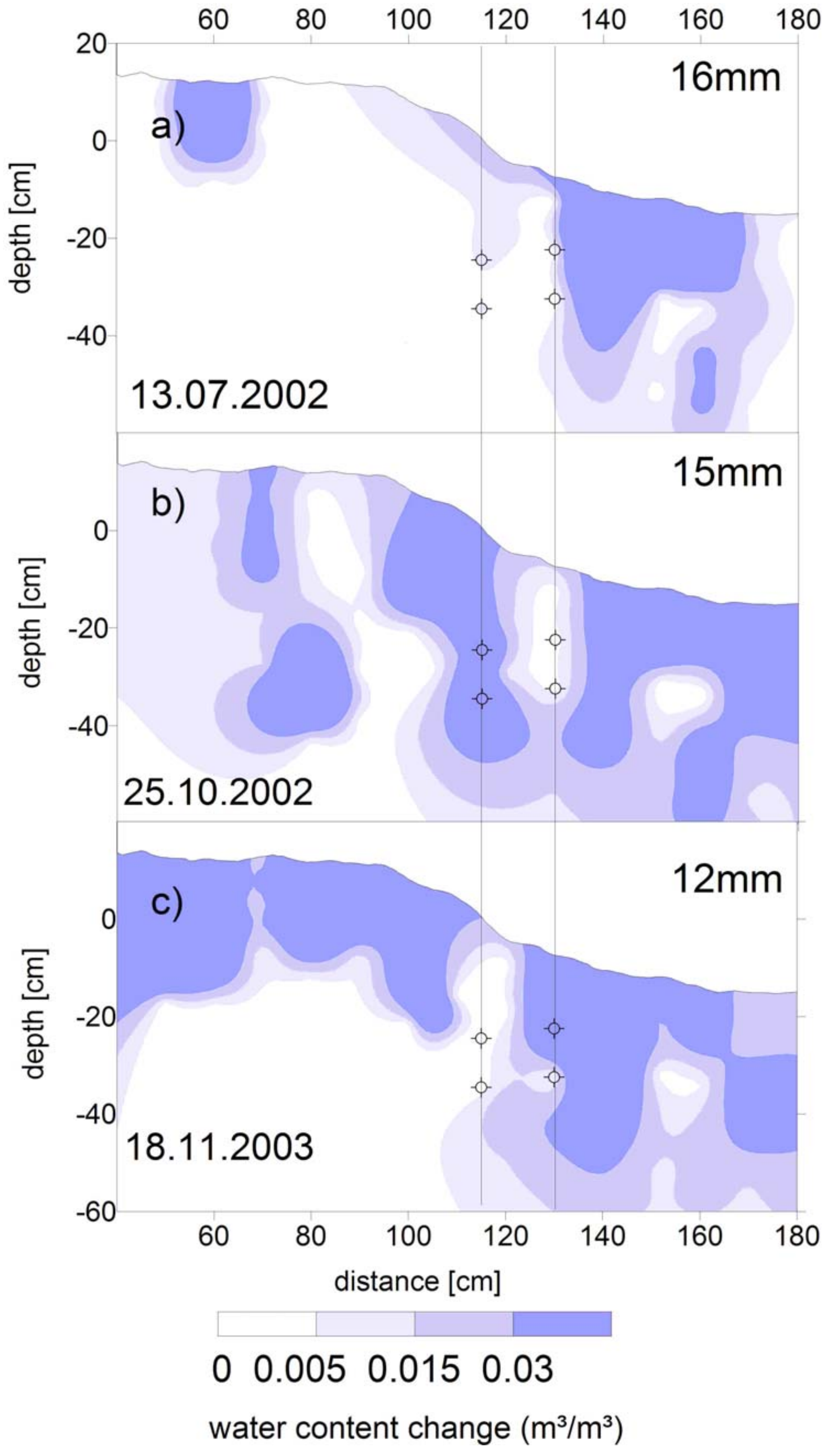

Fig. 4.3: Water content changes in the first 24 h after rainfall events at three different dates (amount of rainfall: 16, 15 and 12 mm). Preferential flow paths at 115 cm and 125 are changing, while the preferential flow paths at 140 cm is permanent. The diamonds mark positions of selected TDR probes.

4.4.3 Water content and water repellency

The results of the excavations in January 2003 showed the water contents and actual water repellency distribution at the time of the sampling. The profile showed a clear pattern of light (=dry) and dark (=moist) areas. At the time of the sampling, 51% of the samples at depths from 10cm to 30 cm were classified as extremely water repellent. The percentage of wettable soil was at a low 26%. The water content of the top soil varied between 0.04g g^{-1} and 0.24g g^{-1}. The areas with high water contents in Fig.4.4a correspond to the wettable areas in Fig.4.4b. Almost all samples taken from the subsoil were wettable. There were 7 regions with extreme WDPT times of more than three hours. On the other hand, there were seven wettable regions in the topsoil, indicating the flow paths. It has to be taken into account that the figure only displays a two-dimensional plane of a three dimensional soil.

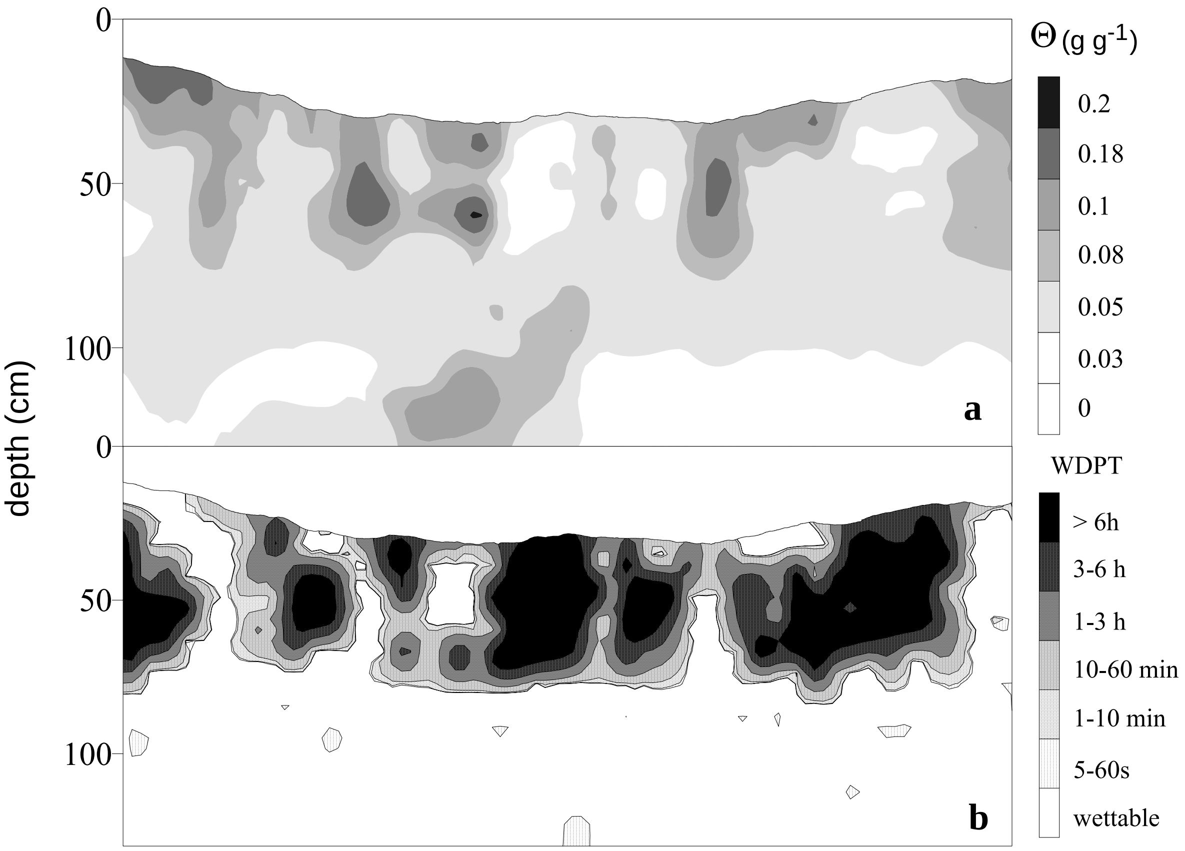

Fig. 4.4: Soil water distribution (top) and actual water repellency (bottom) at the date of sampling

4.4.4 Tracer transport

Chloride distribution

Even though the chloride tracer was applied at the end of October and the cumulative net infiltration amounted to only 47 mm (Fig.4.5), increased levels of chloride concentrations were found up to a depth of 200 cm in about 85% of the samples. The total recovery rate of chloride was 99%, the background concentration was about 3 $\mu g \cdot kg^{-1}$. The distribution is determined mainly by the preferential flow paths in autumn due to water repellency. The three following observations are typical for the chloride distribution:

- Large areas of the topsoil show no increased chloride concentrations. These areas correspond to the water repellent areas or lie directly below these areas (see Fig.4.5).
- The bulk of chloride is found at a depth between 100 and 200 cm, with a very large uninterrupted spot between the transect position 120 and 220 at a depth of 1 to 2 m. The recovery rates in this area were distinctly above 100%. The maximum of the chloride concentration is at a depth of 1.20 m below the soil surface, which is far lower than the calculations of a piston flow concept (s. Fig.4.5).
- The positions with high water contents in the top soil also have a high chloride concentration (Fig.4.4 and Fig.4.5). This shows that these areas participate in the flow events in autumn.

Bromide distribution

First of all it has to be pointed out that bromide was found in 99 percent of all samples. The background concentration was ~0.7 $mg \cdot kg^{-1}$. In 95 percent the concentration was higher than 5 $g \cdot kg^{-1}$.

In general, the bromide distribution in Fig.4.5 shows three concentration characteristics:

(i) a relatively low overall concentration,

(ii) spots with high bromide concentrations in the topsoil and

(iii) fingers in between with low bromide values.

The recovery rate of bromide refers to the sum of the applied tracers (bromide I and II). However, it is not possible to determine if a pattern is caused by the first or by the second bromide pulse. With values between 5 and 25% the recovery rate is low. We assume that the

largest portion of the bromide has already passed the maximum sampling depth; the calculated cumulative net infiltration corresponds with a centre of mass at about 3 m (Tab.2).
The remaining areas of high concentration are located in the topsoil down to a depth of 60 cm, mainly in dry, water repellent areas. The positions 120 and 240, where the recovery rates i.e. the concentrations were extremely low (about 5%), are of special interest, because they coincide exactly with the moist and wettable areas as shown in Fig 4.4. In these positions we assume flow paths, where the bromide was washed out almost completely due to the frequent flow-through. The “rest concentration” in these areas varied between 0.6 and 3 mg kg^{-1}.
There are two small spots in the topsoil (transect positions 44 cm and 215 cm, at 20-40 cm depth each) where neither chloride nor bromide was detected. These spots are in the centre of water resistant areas. We presume that no transport of tracer elements occurred in resp. through these areas. These are probably very stable water resistant areas, which were not rewetted during the complete examination period.
The results of the tracer experiments are not conclusive for the stability of flow paths, but they give indications for the changes of flow patterns. The tracer distributions do, however, confirm our understanding of the seasonal change in transport processes.

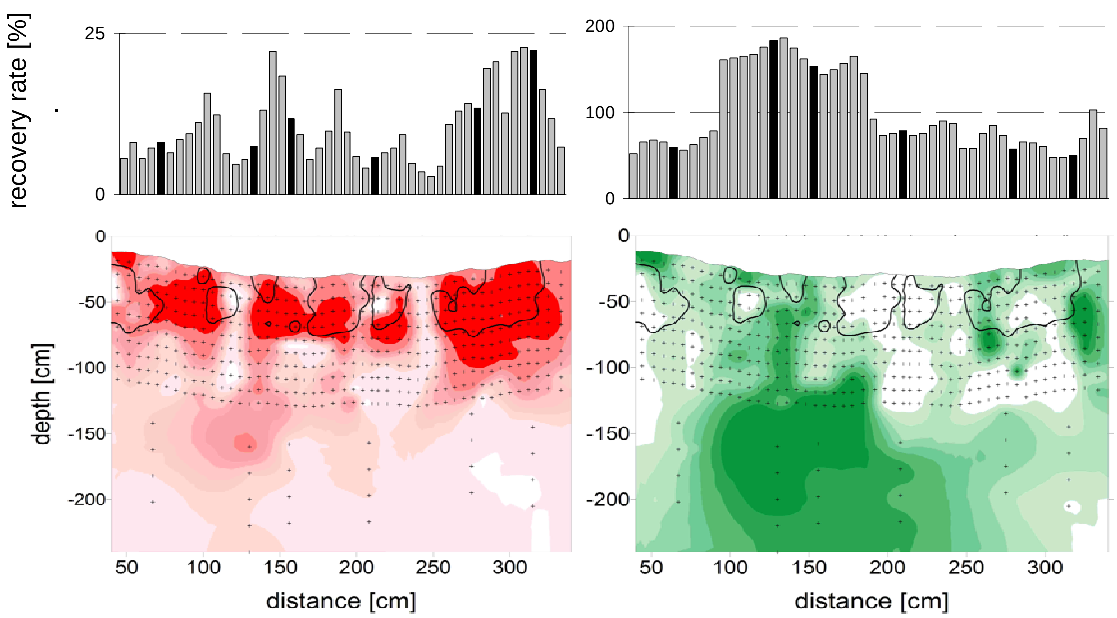

Fig. 4.5: Bromide (right) and chloride (left) distribution, sampling positions and recovery rate. Chloride marks the preferential flow path in autumn, while bromide retains in the water repellent areas in the top soil. Due to deep drainage the recovery rate of bromide in 0-2 m is much lower than of chloride.

Classification of flow paths

The sampling resulted in 48 depth profiles side by side with 10 samples each from depth of 5 cm to 95 cm. These depth profiles, showing a characteristic concentration change according to their position in the transect, are depicted in Fig. 4.6. Each of the 48 depth profiles was categorized in the following four categories, according to the tracer concentration and the distribution of water contents. Fig. 4.7 illustrates the area share and the temporal occurrence of the different flow categories.

- **Main flow paths (wettable)**: These are areas with above-average quantities and frequencies of percolation. Two positions in this transect (120 and 240 cm) were characterized as belonging to the main flow path. Samples from this region had high water contents of > 10%. From the surface up to a depth of 1m, the bromide concentration showed low values of about 7 mg kg^{-1}. The variation coefficients were comparatively low at 0.35. Furthermore, the areas are characterized by low chloride concentrations of < 5mg kg^{-1} in the upper 25 cm of soil, increasing to values > 10 mg kg^{-1} at a depth of more than 80 cm. The variation coefficients of 0.5 are higher than those of the bromide. Due to the low bromide concentration and the high water contents, it can be assumed that the tracer elements were, for the most part, washed out by the frequent flow-through. About 10% of the transect falls in this category.
- **Moderate flow paths (water repellent in summer)**: The flow of water in these sections is restricted, since the percolation as well as the frequency of flow-through is reduced. The areas can be found between water resistant parts at the transect positions 60, 90, 145, 150, and 320 cm, or on the peripheral of main flow paths. Contrary to the main flow paths, these areas are characterized by the highest chloride concentrations (> 8mg kg^{-1}) and high bromide concentrations (50 – 100mg kg^{-1}). The maximum concentration of bromide can be found at a depth of 15 – 35 cm, that of chloride at 25 – 55 cm. The variation coefficient for bromide is 0.45, for chloride 0.73. Since all depths of this area show increased water contents and chloride concentrations, it can be assumed that a transport of chloride has taken place. Since the concentrations of bromide were also high, it is probable that significantly less water is transported here than in the main flow paths. The area portion for moderate flow paths was determined as 45%.
- **Sparse flow paths (water repellent in summer and autumn)**: These profiles are characterized by extremely water repellent, dry regions in the top soil. The areas at a depth of 15 – 45 cm are probably a relict of the dry summer period, and have not yet been rewetted

during autumn. Their water content ranges from 4 to 9%, and they can be classified in the WDPT-class "extremely repellent". At depths of 15 – 35 cm, the chloride concentrations of <5 mg kg^{-1} are rather low, with variation coefficients of 0.4. Below this depth the chloride concentrations rise again to medium values. The low chloride values are in the range of the background concentration and confirm that no transport of chloride and, thus, of water has occurred in these areas during the autumn period. These sections make up 40% of the experimental area. The bromide concentration in these regions varies widely, with maximum concentrations reaching 380 mg kg^{-1}, and an average of 115 mg kg^{-1}.

- **No flow regions (water repellent during the whole year)**: There are two spots at 15 – 25 cm depth where bromide concentrations of 4 – 7 mg kg^{-1} were measured. It is possible that bromide and chloride were not transported into these spots. They have, therefore, been dry and water repellent over the complete experimental period. These spots represent 5% of the area share.

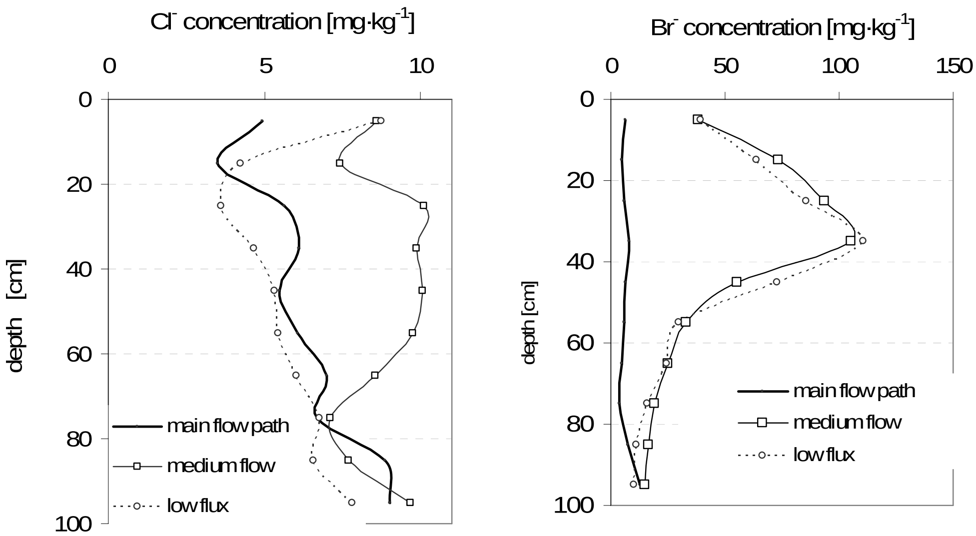

Fig. 4.6: Typical profiles of chloride- (left) and bromide (right) concentrations. The main flow paths are always active, the medium flow paths only during spring and autumn and the low flow paths only during spring.

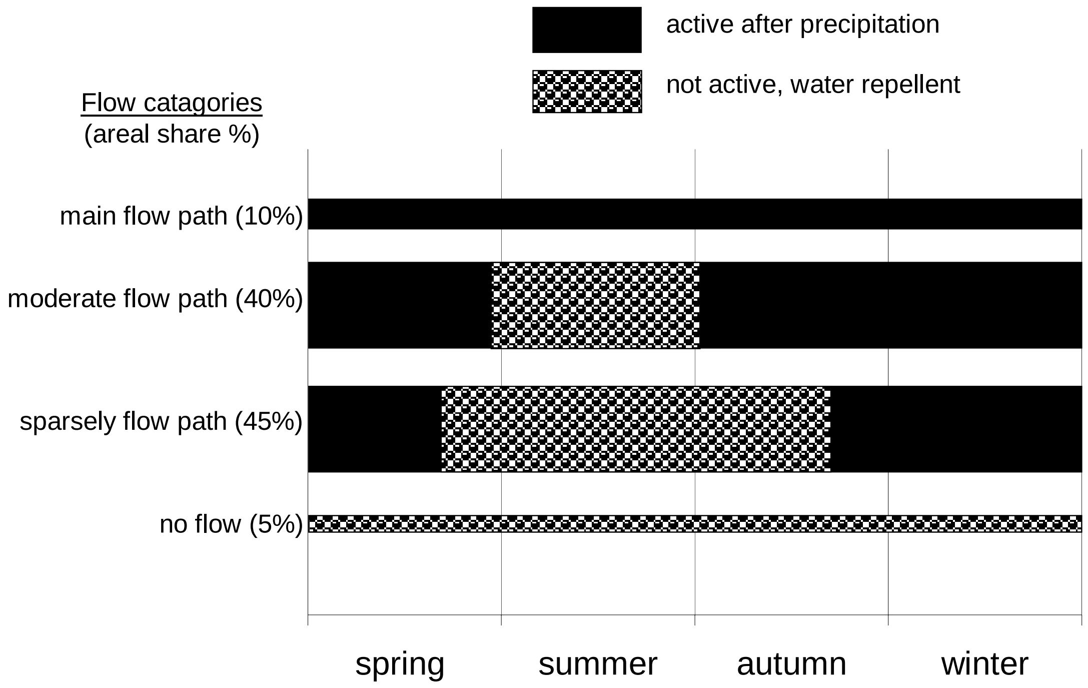

Fig. 4.7: The seasonal changes of the flow activities for different flow categories. The height of the bars represents the area share of category. The flow paths are inactive during the dotted time and active (after precipitation) during the rest of the time.

Reconstruction of flow events

In the following research we tried to reconstruct the flow regions regime of the tracer experiment during the seasons and to combine it with the effective cross section of the TDR transect (Fig. 4.8).

Spring

Fig. 4.8 presents a schematic reconstruction of the conditions for the tracer application. The tracer was applied during springtime (Fig. 4.8a). At that time the soil profile had almost reached field capacity. Except for a few spots in the top soil, the complete profile was moist and wettable. The infiltration and the transport of bromide into the top soil was relatively even (Fig. 4.8a). The effective cross section was comparatively high (Fig. 4.8d Graph a) and almost all regions of the soil participated in the flow events. The second bromide pulse was applied after the first had infiltrated the soil up to a depth of 30 cm (difference in net infiltration, Tab.4.3).

Summer

After the second application of bromide, the warmer weather led to a negative climatic water balance and the soil dried out due to a water uptake of the roots. Percolation did not occur any longer, so that the bromide tracer was not transported into other layers (Fig. 4.5). The soil dried out and became water repellent, as illustrated by the dotted area in Fig. 4.8b. High levels of water repellency in August led to runoff of water after heavy precipitation and to percolation along the main flow paths. The effective cross section was reduced to its lowest level of 20 – 50% (Fig. 4.8d, Graph b).

Autumn

Even during the rewetting period in autumn, the water flowed preferentially along the main paths. However, new flow paths were gradually formed, increasing the effective cross section (Fig. 4.8d, Graph c). A large portion of the bromide was washed out along the main flow paths, which coincides with the extremely low bromide concentrations and recovery rates in these areas.

At that time the chloride tracer was applied, illustrated by the green color in Fig. 4.8c. The chloride was transported rapidly into deeper layers along the existing preferential pathways. Other parts of the soil matrix were excluded from the transport of the tracer and remained dry until the sampling in January (see water content distribution in Fig. 4.4). They showed high concentrations of bromide, but almost no chloride (Fig. 4.5). The causal connections of these findings are listed in Tab. 4.3, the main criteria being the flow phenomena and their respective recovery rates and flow patterns.

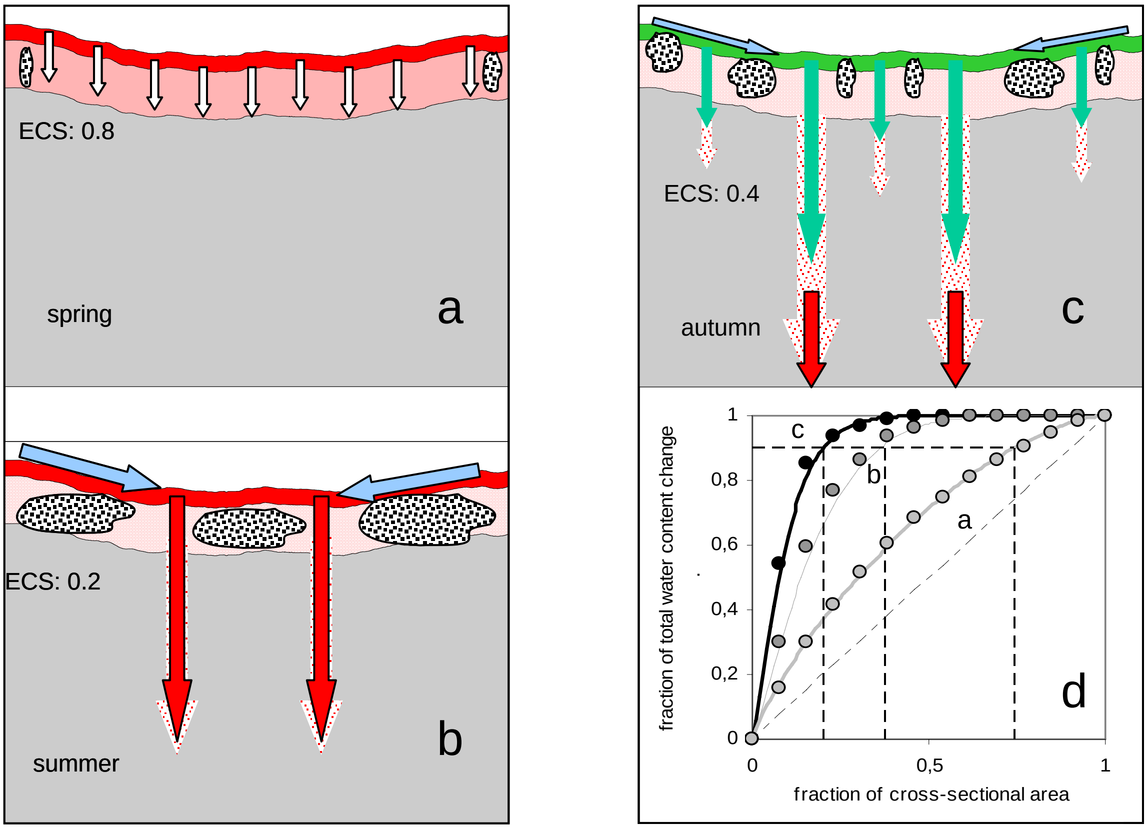

Fig. 4.8: Schematic distribution of water repellent areas (black dots) and preferential flow paths during the seasons. The effective cross section (ECS) is high in the beginning of spring (a), low in summer (b) and medium in autumn (c). The arrows mark the transport of bromide (red) and chloride (green).

Tab. 4.3: Criteria for interpreting the tracer distribution and recovery rates

Low tracer recovery rate (<<100%)	- tracer cannot penetrate the water repellent soil - tracer has passed the sample depth <u>Reasons:</u> - high precipitation and deep drainage - preferential flow - runoff - lateral water movement out of the sampled area
High tracer recovery rate (>100%)	- lateral tracer movement <u>Reasons:</u> dry and water repellent behavior of the topsoil in combination with micro relief conditions (runoff)
Irregular pattern of tracer distribution	- fingered flow, parts of the soil are excluded from transport processes <u>Reason:</u> water repellent spots with low water content

1. Conclusions

5.1 Part I - Repellency and moisture

At the former wastewater application site of Berlin Buch, water repellency has a main influence on the water flow, even during wintertime. On the one hand this leads to preferential flow paths, and on the other hand it reduces the amount of plant available water. The soil water availability during the vegetation period is decreased, which is one of the biggest problems for a successful afforestation on this site.

Water repellency has to be taken into account when simulating the soil water flow and solute transport. For this purpose, it is necessary to define a threshold or a function to distinguish between wettable and repellent regions. Our goal was to decide or to predict if a sample is wettable or water repellent by using an easily measurable parameter. A soil is always wettable when it is moist and can become water repellent when it dries out. Many studies try to use the water content as a measure for the moisture of a soil. The critical water content Θ_{crit} was used to predict the wettability status: wettable if the water content is higher than the critical water content, repellent if it is lower. The predicted values were compared with the measured results (wettable for WDPT $<$ 5s, repellent for WDPT $\geq$ 5s). Using a single constant critical water content to separate all top- and subsoil samples into a group of repellent samples and a group of wettable samples leads to a high number of wrong predictions .

Fig 2a shows the wettability of the soil samples according to the WDPT classes as established by Dekker and Jungerius 1990. Fig. 5.1b shows the predicted wettability using the a constant Θ_{crit} - the figure is more or less an inverse figure of the water content – areas with low water content appear dark, which means they are water repellent. Thus, a high number of predictions (327 of 864) were wrong. As shown in Fig. 5.1a, most of the repellent samples were found in the topsoil, whereas most of the subsoil in Fig. 5.1b was predicted to be water repellent.

Since the texture of the soil samples did not show any difference, we tested the content of organic matter for its relevance. We found a significant correlation between the water content, the content of organic matter, and the water repellency of a sample on this site.

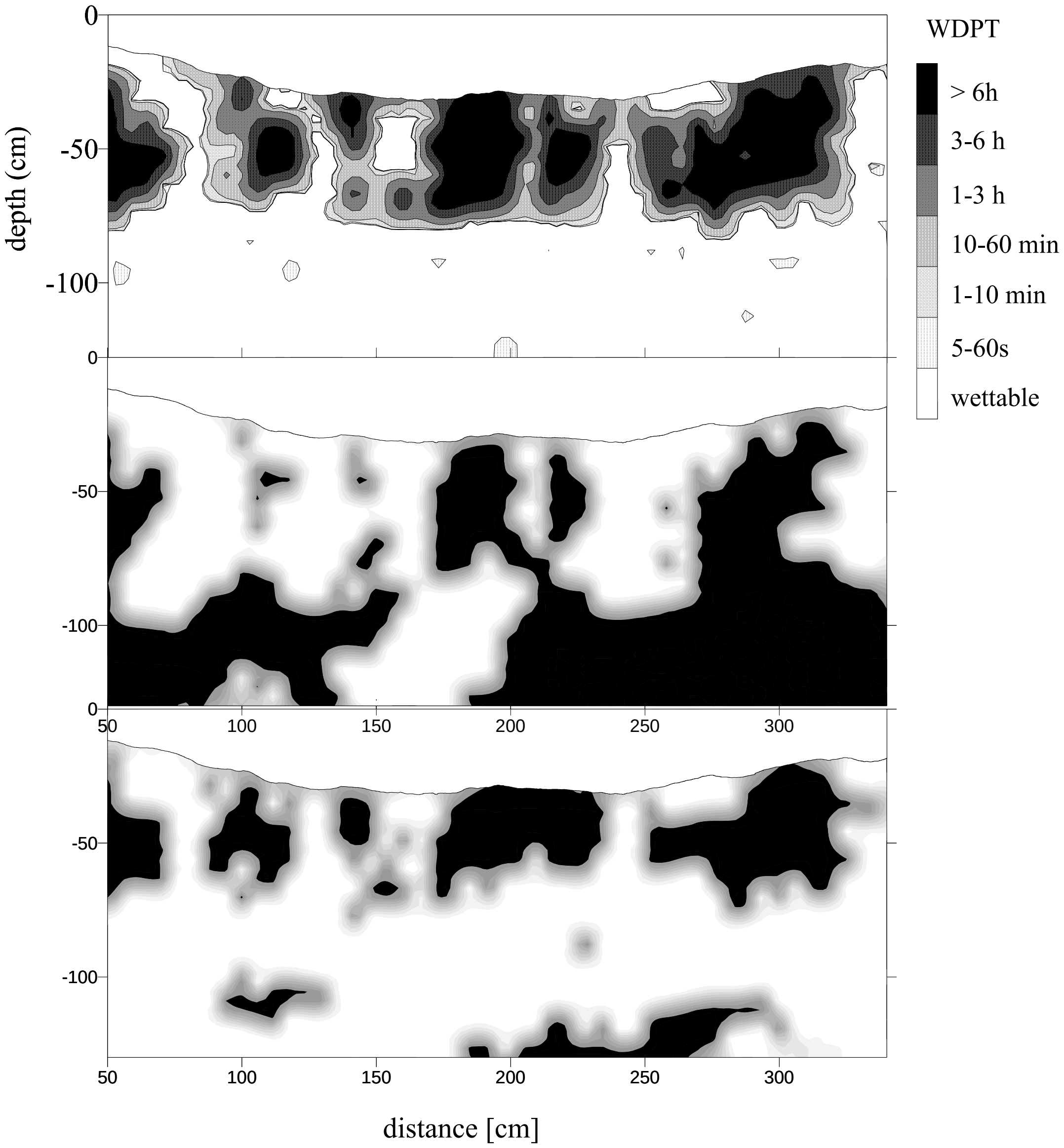

Fig. 5.1: Measured (top) and predicted WDPT of water repellent areas without (middle) and with the influence of soil organic matter content.

Using the linear approach

$$\Theta_{crit}(SOM) = a \cdot SOM + \Theta_0$$

with a = 1.12 ; $\Theta_0 = 0.037\ g{\cdot}g^{-1}$, the water repellency can be predicted for the whole profile with just one function. The prediction is shown in Fig 5.1c. Of course other parameters, such as the quality of the organic matter, texture and bulk density, may also influence the critical water content, so that an adaptation of the parameters a and Θ_0 would be necessary if this function was applied to other sites.

The patterns of the flow paths (see. Fig 5.1a) were not only found for the actual water repellency, but also for the potential repellency. It seems that there is some kind of memory behavior in the soil.

5.2 Part II - Appearance and vanishing of water repellency – the annual cycle

As described above, one of the main impacts of water repellency is the reduction of the water accessible soil volume. Water infiltration, as a consequence of precipitation events, results in unstable wetting fronts – the water infiltrates in flow fingers. The soil between these fingers remains dry and water repellent. Many excavations in the past years gave indications for this flow phenomenon. Looking from the top into a 20cm deep pit we saw irregular moisture patterns on a horizontal cross section, marked clearly by dark structures of the wettable and moist flow fingers and light structures of the dry and water repellent soil in between (see Fig. 3.2). The structures show a typical size of 10-20 cm. The samplings on this site were carried out at 32 different dates from April 2001 to April 2004. As a result we found a clear trend: in summer the area share of the water repellent spots was very high (>60%), after dry periods at the end of summer the whole profile was water repellent. During winter the water repellent spots seemed to disappear. Only single spots were found at the end of the winter with an area share of approximately 10%.

The samplings were complemented by the operation of an automated TDR-device on the same site. The question was if it is possible to see the effect of water repellency in the moisture readings of the TDR-device. The device measured the volumetric water content hourly with 64 probes which were installed permanently at regular distances in a soil profile / in a vertical array (for more details see cap. 3.3). After rainfall events, the water content in the soil profile increased. In order to compare the different rainfall events an index was introduced - the effective cross section (ECS). The effective cross section is the area share of a horizontal cross sectional area which realizes 90% of water content change after rainfall events at that depth. In the case of absolutely homogeneous flow the effective cross section would be 0.9, whereas in the case of preferential flow it would be smaller (for the exact procedure see cap. 3.3 ff). We calculated the ECS for a depth of 20 cm in order to obtain values comparable to the area share of the wettable soil which was obtained by soil sampling.

The results confirm the seasonal trend. The ECS indicated preferential flow in summer with values <0.4 and a nearly uniform infiltration at the end of winter with values of about 0.8. Fig. 3.9 compares the results of the wettable cross sectional area of the soil sampling and the calculated ECS from the TDR readings. Both approaches agree with the seasonal trend. Only the results for the wintertime show a discrepancy between the two approaches. This discrepancy is caused by frost, which also triggers preferential flow as seen in the TDR data.

ECS provides a useful quantitative measure of the extent of preferential flow during the seasons. This parameter can also be used for comparing numerical models and measurements for heterogeneous water flow. It was possible to calculate ECS using the average water content and climatic parameter. The average water content was found to have the strongest influence on the effective cross section. While the concept of effective cross section itself could be transferred to other sites, the parameters of Eq. [4] are limited to the examined site. The equation may be used in numerical models to predict the effective cross section for different climatic conditions. Our results are based on data from one year. Measurements during subsequent years may be needed. The use of the effective cross section as such and in numerical models may improve the current possibilities of estimating the amount of plant-available water and contaminant transport at particular sites.

5.3 Part III - Stability of flow pattern – shifting of flow fingers

Seasonal changes of the effective cross section have a great influence on transport events in the soil. During the winter months until spring (Jan. – April), an even distribution of moisture and percolation prevails and only few parts of the soil remain water repellent. This is contrasted by the effect of fingering, which is predominant during the summer months and autumn.

The formation of flow paths after a complete drying up of the top soil is random, but once a flow path is established it remains more or less stable until the next summer. During the rewetting phase new fingers might be added, which gradually grow wider in the course of the winter until the flow conditions can be described as piston flow.

According to our measurements, the established flow paths are used preferentially for the subsequent water transport. Consecutive rainfall events form similar patterns of dry and moist areas in the soil, so that the position of the dry spots i.e. flow paths remain the same. Over longer time periods (several months, years) these patterns change slowly. The flow paths “grow” under the moist winter conditions, and the dry spots become smaller and are rewetted to a large extent. Consequently, almost the entire soil can participate in the flow events. During the vegetation period, the soil dries out successively and becomes water repellent. The precipitated water infiltrates the soil preferentially along flow fingers. If the dry periods in the summer are prolonged, the complete top soil becomes water repellent, so that the water has to find new flow paths through the repellent material. On the basis of the TDR-data, a change i.e. shift in flow paths was substantiated. A dry spot, for example, which was registered during the complete experimental phase of 2002, changed into a flow path after the summer dryness.

The varying distribution of the bromide and chloride tracer makes it clear that different flow regimes predominated at the time of the tracer transport. Thus, a more or less consistent transport of bromide took place during spring, whereas the continuing desiccation and the negative water balance led to water repellency and preferential flow paths in the top soil, which stopped the bromide transport. The bromide was held in the dry, water repellent areas, while the water flowed past on preferential paths. During autumn the tendency towards preferential flow was high, so that the applied chloride tracer infiltrated the soil along the flow paths and was, therefore, transported quickly into deeper layers.

The TDR-readings affirm the existence of main flow paths showing high changes of water contents after each precipitation. These areas correlated with the tracer transect. The frequent water flow in these areas led to a washing out of the bromide tracer and a transport of chloride into depths larger than 1m. The chloride tracer did not flow into the water repellent areas.

The temporal change of the preferential flow complicates the numerical modeling of the contaminant discharge out of the areas. Since the exact position of the flow fingers under the same boundary conditions is random, whereas the seasonal course of the effective flow cross section shows a distinct calculable trend, it is possible to implement these processes in a model.

2. Synthesis and Outlook

The study at hand deals with three main aspects describing the phenomenon of soil water repellency and its impacts on the transport of water and solutes:

- distribution and arrangement of water repellent spots in the topsoil,
- water repellency – a dynamic property,
- stability of flow patterns

- **Distribution and arrangement of water repellent spots in the topsoil:** The water repellent areas in the topsoil show a characteristic distribution pattern with respect to size and arrangement, often described as „leopard's skin" in scientific literature. Even though the water repellent areas have an irregular structure, they show similar sizes of 10 to 15 cm (see Fig 4.6). The distribution i.e. expression of these water repellent areas depends first of all on the soil moisture. In this context, the wettability was described relatively well by combining the parameters water content and organic matter content.
- **water repellency – a dynamic property:** On the basis of a large number of samplings and quasi-continuous water content measurements using TDR-devices, it was established that these moisture patterns and, thus, the fingering phenomenon have no statistic significance for the transport processes in the soil. There is rather a seasonal course of appearance and disappearance of these areas as well as a water– and solute transport which is at times more preferential (summer) and at other times more homogenous (end of winter). Consequently, a parameter was derived describing the tendency towards preferential flow – the effective cross section. Based on this parameter was the attempt to derive this tendency towards preferential flow from easily measurable or generally available data. The following values seemed favourable:
  - θ_{10} - average initial water content at 10 cm ($m^3 \cdot m^{-3}$)
  - I - average intensity of a particular rainfall event ($mm \cdot h^{-1}$)
  - E_p - potential evaporation over a 24-d period (mm)
  - R - rainfall amount (mm)

  Good results were achieved using the linear relationship:

  $$ECS = 3.9*\theta_{10} - 0.24*I + 0.0020*E_p + 0.0072 * R$$

  The average deviation was 7%.

The impacts of the dynamic flow processes on the solute transport were confirmed by a time delayed double tracer experiment. For this purpose, two tracer solutions were applied to the same plot, so that information on the solute transport at different points of time was gained. About 10% of the cross sectional area of the plot were classified as main flow paths, 45% as moderate flow path, 40% as sparsely flow paths, and at about 5% of the area no tracer was transported.

We also established that unstable temperatures during winter, causing a freezing and thawing of the soil, lead to preferential flow on a similar scale (ECS) as during the summer months. These effects are, however, more difficult to quantify and require higher technical demands due to the unfavourable weather conditions.

- **Stability of flow patterns:** The formation of flow paths after a complete drying up of the top soil is random, but once a flow path is established it remains more or less stable until the next summer. During the rewetting phase new fingers might be added, which gradually grow wider in the course of the winter until the flow conditions can be described as piston flow.

The results of the laboratory and field experiments formed the basis for a better incorporation of these processes into numerical models and for a long-term modeling of the water and solute transport on our research areas. Fundamental concepts were considered and practical parameters developed which can be used for a consideration of fingering in these models. It seems possible to derive these dynamic parameters from easily determinable external conditions (marginal conditions).

This can lead to an improvement of existing models. The concept of the critical water content can be implemented in 2 or 3 dimensional numerical model. The concept of the Effective Cross Section makes it possible to validate the model. For one dimensional models, stream flow tubes or mobile/immobile water can lead to better predictions of plant available water or graoundwater recharge. The concept of mobile/immobile water depending on the water content is already implemented in the model SWAT (van Dam et al., 1996, Ritsema et al. 2005).

The experiments showed, the effects described above can also be observed on those areas of the Tiergarten Park which tend to be water repellent. It still remains difficult to transfer the locally obtained results to other areas without having information on its tendency towards

water repellency. Although the climatic influences mentioned above are a necessary factor for the development of water repellency, they alone cannot explain its emergence.
Water repellency has been of rising interest in the past years, posing the question of whether it is a new type of soil alteration due to changing land use, immissions situation (nano particles) or climatic factors, and will, therefore, become more important in the future, or whether it is a natural soil property that has always existed.

The search for the inner causes of water repellency will require research on the quality of humus, plant and soil animal exudates, and microbiotic processes, including their interactions. The subprojects HUMUS, MIKRO and FAUNA provide the first interesting results.
In order to regionalize the results, it will be necessary to find methods for transferring these results onto larger areas. It might be possible to use noninvasive geophysical methods to determine the water distribution, water dynamics and other important structural parameters. Perhaps it could be of help to use remote sensing techniques for detecting areas at risk and determining the effects of a regional water regime quicker and more effectively.

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