MOISTURE VARIABILITY RESULTING FROM WATER REPELLENCY IN DUTCH SOILS

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MOISTURE VARIABILITY RESULTING FROM WATER REPELLENCY IN DUTCH SOILS

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Proefschrift

ter verkrijging van de graad van doctor
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As early as 1910, Schreiner and Shorey described that some soils in California "could not be properly wetted, either by man, by rain, irrigation or movement of water from the subsoil, with the result that the land could not be used profitably for agriculture". Waxy organic substances were found to be responsible for the water repellency (Oswald Schreiner and Edmund C. Shorey, 1910. Chemical nature of soil organic matter. USDA Bur. Soils Bull. 74: 2-48).

This thesis is dedicated to ***VERA*** *and*
our children ***LEO***, ***BONNIE***, *and* ***STELLA***.

Front cover: Cross-section of preferential flow paths (dark areas) embedded in dry soil (light areas) at a depth of 15 cm in a water repellent sandy soil.

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STELLINGEN

1. Gronden met een afwijkend stromingsgedrag zijn meer regel dan uitzondering.
   - *Dit proefschrift.*

2. Veel vennen op de Veluwe danken hun voeding aan de toestroming van regenwater over het waterafstotende oppervlak van de zandhellingen in hun omgeving.
   - *Dit proefschrift.*

3. Het heeft heel wat voeten in aarde gehad om bodemkundigen te overtuigen dat in veel zandgronden natte vingers kunnen worden aangetroffen.
   - *Dekker L.W. and P.D. Jungerius, 1990. Water repellency in the dunes with special reference to The Netherlands. Catena Supplement 18: 173-183.*
   - *Dit proefschrift.*

4. Duinen hebben last van watervrees.
   - *Dekker, L.W., 1992. Waddenbulletin 27: 182-185.*
   - *Dit proefschrift.*

5. Zandzuiltjes in opgewaaid zand danken hun ontstaan aan preferente stroming van water, die optreedt als gevolg van verdichting van het oppervlaktelaagje door de eerste regenval.
   - *Dekker L.W. and C.J. Ritsema, 1994. Fingered flow: the creator of sand columns in dune and beach sands. Earth Surface Processes and Landforms 19: 153-164.*

6. De aanwezigheid van preferente stroombanen in zowel zand-, klei-, als veengronden vergroten de kans op verontreiniging van grondwater.
   - *Steenhuis, T.S., L.W. Dekker, J.-Y. Parlange en C.J. Ritsema, 1995. Hoe snelle stroming door preferente banen het grondwater kan verontreinigen.* H_2O *28(4): 118-121.*

7. Landsdekkende berekeningen naar de uitspoeling van meststoffen en bestrijdingsmiddelen naar het grondwater zijn weinig zinvol, zolang niet meer bekend is over het effect van waterafstotendheid van gronden op deze uitspoeling.

8. Er bestaat een wederzijds verband tussen het ontstaan van ijzerbanden en de stroming van water in zandgronden.
   - *Dekker, L.W., A.H. Booij en C.J. Ritsema, 1997. IJzerbanden en ijzerwanden in onze zanden. De samenhang ervan met de stroming van water. Stromingen 3(2): 29-40.*

9. Daliegaten bevatten een schat aan historisch bodemmateriaal met betrekking tot de landbouw in de Middeleeuwen.
   - *Dekker, L.W., 1974. Duizend jaar modderen in West-Friesland. Westfriese Oudheden XV. West-Frieslands Oud en Nieuw 41: 235-250.*
   - *Dekker, L.W., 1994. Daliegat: kleibron voor verbetering van veengronden. In: Historische landschapselementen in Nederland. Matrijs, Utrecht.*

10. Waterhardlagen in zandgronden zijn goede indicatoren van een voormalig veendek.
    - *Dekker, L.W., A.H. Booij, H.R.J. Vroon en G.J. Koopman, 1991. Grondboor en Hamer 45(2): 25-30.*

11. De aanwezigheid van potscherven in de teelaarde van landbouwgronden wijst niet alleen op menselijke invloed, maar ook op gerichte verbeteringsmaatregelen van de bodem.
    - *Dekker, L.W., 1980. Westfriese polders bezaaid met middeleeuwse potscherven. Westfriese Oudheden XX. West-Frieslands Oud en Nieuw 47: 237-245.*

12. Een kijkje in de bodem kan meer ophelderen dan onderzoek tot op de bodem.
    - *Dit proefschrift.*

13. De benamingen "jonge doctor" en "senior author" zijn verwarrend voor nietwetenschappers.

14. Een verrre vriend is beter dan een slechte buur.

15. Spreken is zilver, maar schrijven is goud.

Stellingen behorend bij het proefschrift van Louis W. Dekker "Moisture variability resulting from water repellency in Dutch soils".

Wageningen, 1 september 1998.

ABSTRACT

Dekker, L.W., 1998. Moisture variability resulting from water repellency in Dutch soils. Doctoral thesis, Wageningen Agricultural University, The Netherlands, 240 pp.

The present study suggests that many soils in the Netherlands, in natural as well as in agricultural areas, may be water repellent to some degree, challenging the common perception that soil water repellency is only an interesting aberration. When dry, water repellent soils resist or retard water infiltration into the soil matrix. Soil water repellency can lead to the development of unstable wetting and preferential flow paths. Preferential flow has wide-ranging significance for rapid transport of solutes, such as agrichemicals, towards the groundwater and surface water, making it essential to understand this phenomenon.

The persistence and degree of water repellency was examined in topsoils of nature reserves and cultivated soils, using the water drop penetration time (WDPT) and alcohol percentage tests. The severity of water repellency measured on dried soil samples, the so-called "potential" water repellency, can be used as a parameter for comparing soils with respect to their sensitivity to water repellency. In some cases, however, the severity of potential water repellency was found to be sensitive to the initial moisture content of the soil and the temperature during drying. Measurement of the "actual" water repellency on field-moist samples determines the soil fraction excluded from direct solute and water flow. However, preferential flow is a dynamic process, which is why the ratio between water repellent and wettable soil is time dependent. The "critical soil water content", below which the soil in the field is water repellent and above which the soil is wettable, was found to be a useful parameter in water repellency studies.

Spatial and temporal variability in volumetric soil water content was studied in vertical transects by intensive sampling with 100 cm^3 steel cylinders. Spatial variability in soil water content under grass cover was high, due to fingered flow. On arable land, vegetation and microtopography appeared to play a dominant role. This thesis provides examples of uneven moisture patterns in water repellent sand, loam, clay and peat soils with grass cover, and in cropped, water repellent sandy soils.

ACKNOWLEDGEMENTS

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Part of this study was supported by the Research Programme 223 *"Physical Soil Quality"* of the Dutch Ministry of Agriculture, Nature Management and Fisheries. Another part was supported by the Environment and Climate Research Programme of the European Union and carried out within the EU-project EV5V-CT94-0467 *"Analysis and improvement of existing models of field-scale solute transport through the vadose zone of differently textured soils, with special reference to preferential flow"*.

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PREFACE

Bij het gereedkomen van dit proefschrift wil ik iedereen bedanken die direct of indirect heeft bijgedragen aan de totstandkoming ervan. Allereerst wil ik Dr. Jan Klijn bedanken, die mij als eerste suggereerde om een boekje te maken van een aantal artikelen over de waterafstotendheid van gronden. Ook Prof. Dr. Pim Jungerius van de Universiteit van Amsterdam dank ik voor zijn hint om eens te denken aan een thesis over water repellency. Bovendien dank ik hem voor de prettige wijze waarop we samen over dit onderwerp hebben geschreven en voor de gezellige tochtjes naar de hydrofobe Nederlandse, Belgische en Franse duinen.

Prof. Dr. Jan Hendrickx bedank ik voor zijn advies om vooral veel monsters te nemen, zodat statistische bewerkingen en toetsen op de diverse bepalingen kunnen worden losgelaten. Jan, de bemonsteringen bezorgden ons weliswaar een zee aan bodemfysisch en chemisch werk, maar resulteerden dan ook in een reeks nationale en internationale publicaties. Met genoegen denk ik nog aan het bodemonderzoek met Coen Ritsema en Jan in de Amerikaanse nationale parken "White Sands" en "Sevilletta" en aan de monsterrit die we maakten door het (te) mulle zand van de Mexicaanse duinen.

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I am grateful to Prof. Dr. Nick Jarvis and Dr. Martin Larsson of the University of Uppsala in Sweden, as well as to Dr. Ole Wendroth and Dr. Wolfram Pohl of the ZALF Institute in Müncheberg, Germany, for the fruitful discussions and our joint research and publications. It was also a pleasure for me to discuss several aspects of my work with people attending the international conferences, among which I would like to mention Prof. Dr. Larry Boersma, Prof. Dr. Jaap Dane, Prof. Dr. Jan Hopmans, and Dr. Rien Van Genuchten, all belonging to the so-called "Dutch mafia" in the USA, as well as Prof. Dr. Jean-Yves Parlange from Cornell University, Dr. Frank Stagnitti from Australia, Dr. Brent Clothier from New Zealand, Prof. Dr. Jan Feijen from Belgium, Prof. Dr. Juan Giráldez from Spain, and last but not least, Prof. Dr. Peter Germann and Prof. Dr. Hannes Flühler from Switzerland.

De samenwerking met verschillende (ex) collega's en mede-auteurs van diverse publicaties heb ik als zeer prettig ervaren. Ik denk hierbij met name aan Obbe Boersma, Klaas Oostindie, Albert Booy, Pim Hamminga, Ing. Henk Vroon, Ing. Wim van der Knaap, Ing. Erik van den Elsen, Ing. Anton Heys en Dr. Evert Bisdom. Het zal niemand van hen verbazen dat mede-promovendus Drs. Coen Ritsema hierbij de kroon spant. Coen, cheers!

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CONTENTS

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

1.1 GENERAL INTRODUCTION

Normally, dry soils are easily wetted by rainfall and irrigation. The force of attraction between soil particles and water causes the water to lose its cohesiveness, i.e., the tendency to retain its droplet shape, allowing it to flow along the surfaces of the particles. The water thus disappears as a liquid drop, wetting the soil (Fig.1.1, left-hand panel). If the attractive forces are neutralised or absent, e.g. because of the presence of a water repellent coating, the water remains as a droplet and the soil is said to repel water (i.e., resist wetting). Such soils are considered to be water repellent and to exhibit hydrophobic properties, especially when they are dry. Before water will evenly infiltrate into or percolate through a soil, there must be a continuous film of water on the soil particles. Hence, the soil must first be wetted before water will flow. Any condition resisting the wetting of the soil particles will inhibit water infiltration (Fig.1.1, right-hand panel).

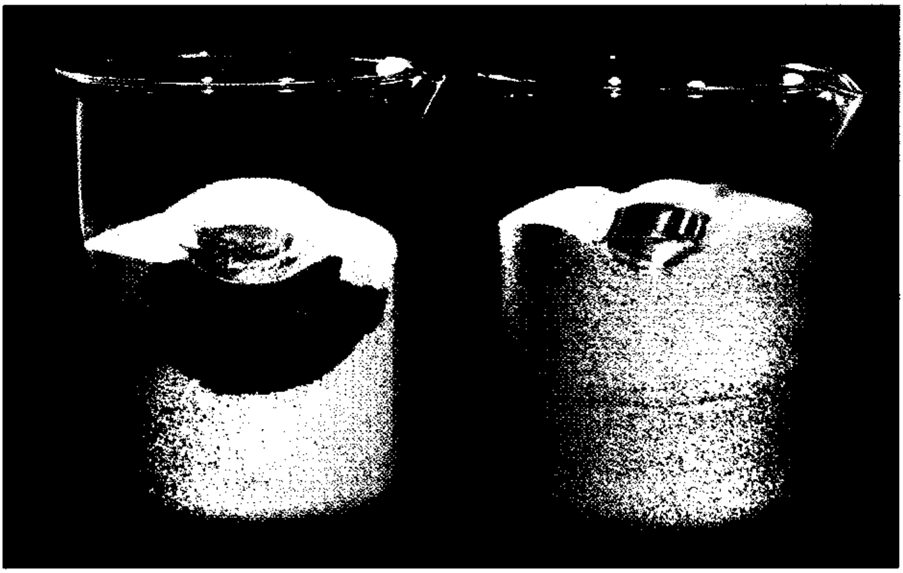


Fig. 1.1 *Water poured upon the surface of dry, wettable soil (left-hand side) infiltrates immediately, whereas it ponds on extremely water repellent soil (right-hand side).*

The assumption that water repellency does not occur is the norm in soil physics (e.g. Philip, 1969). Although an increasing number of researchers are aware of the occurrence and consequences of water repellency in a wide range of soils, it is still a neglected field in soil science. In the Netherlands for example, the occurrence, distribution and hydrological problems of water repellent peat soils have been known for many years (Hooghoudt, 1950; Domingo, 1950; Hooghoudt et al., 1960; Bennema en Van der Woerdt, 1952), but the phenomenon of water repellency in sandy soils and heavy clay soils has only been recognized in the last decade.

In the Netherlands, many grass-covered clayey peat and peaty clay soils are difficult to wet after a prolonged dry period, due to water repellency of the topsoil and the layer just below the topsoil (Van Wallenburg, 1976, 1977; Schothorst and Hettinga, 1977; Dekker, 1983). Soils that exhibit such characteristics have been indicated on several soil maps at different scales. They have been indicated and described on scale 1: 200,000 soil maps as soils with "poor properties of the organic matter of the topsoil: difficult to wet after drying" (e.g. Pons, 1965; Cnossen, 1971). Kloosterhuis (1958) made a detailed map of the distribution of peat soils, which are susceptible to drought, in polders in the western part of the Netherlands. But the national soil maps (scale 1: 50,000), also distinguish peat soils which "locally have layers in the topsoil which are susceptible to drought" (Stichting voor Bodemkartering, 1969, 1970, 1972).

Although the occurrence of water repellent sandy soils in the Netherlands is widespread, it was scarcely mentioned in the literature before 1985 (Dekker, 1985b). Dekker (1985a) reported on a dusty, dry sandy soil at Zuidlaren, in the northeastern part of the country, which he investigated on November 28, 1983. In the preceding 2 days, precipitation had amounted to more than 40 mm, and soils at an adjacent parcel were thoroughly wetted, while water was ponding on the surface. On the poorly wettable parcel, however, the soil was still dry to a depth of more than 40 cm in the middle of December, when sand columns were taken in 20 cm x 20 cm PVC cylinders for wetting experiments in the laboratory (Dekker, 1985b). Numerous applications of water to the surface of the columns over a period of 3 months only slowly wetted the sand, and most of the water moved through the columns via preferential flow paths, coming out at the bottom (Dekker, 1985a,b).

Subsequent water repellency measurements of samples taken from all around the country by Dekker (1988) revealed that approximately 70% of sandy agricultural topsoils in the Netherlands are slightly to extremely water repellent, and that more than 95% of the topsoils in nature reserves, including dunes, exhibit a strong to extreme water repellency. Dekker (1988) concluded that water repellency in Dutch topsoils is the norm rather than the exception, while the degree of repellency varies considerably among soils.

Water repellent soils have been reported in many other countries and may occupy large areas, such as the sandy soils of South and Western Australia (Bond, 1964). As early as 1910, Schreiner and Shorey referred to water repellent soils in California. Jamison (1946) reported that "large bodies of difficultly wettable soil" remained unwetted even during the rainy season under Florida citrus trees. DeBano (1969) described the 1960s as a decade of increasing interest in the problem of soil wettability. Much research was conducted at the University of California, Riverside, where an international symposium on the subject was held in May 1968 (DeBano and Letey, 1969). Research on water repellent soils in California remained active throughout the 1970s and interest spread to other states and countries. Although research into repellency has waned somewhat over the past two decades, there are now more than 200 papers on the topic (Wallis and Horne, 1992).

1.2 ASSESSMENT OF SOIL WATER REPELLENCY

The fundamental principles underlying the process of wetting show that a reduction in the surface tension of a solid substance which is to be wetted reduces its wettability. Conversely, a reduction in the surface tension of the applied liquid increases the wettability. The study of repellency development or its amelioration requires appropriate measurement techniques to be used. Such techniques allow reproducible measurements of phenomena whose genesis is not yet understood. Ideally, the technique should be simple and inexpensive and should provide a rapid quantitative measure of practical significance. Over the years many techniques have been developed to measure water repellency, during which time the understanding and definition of water repellency has evolved (Krammes and DeBano, 1965; Watson and Letey, 1970; DeBano, 1981; Wallis and Horne, 1992). One of the simplest and most common methods of classifying water repellency is the empirical

Water Drop Penetration Time (WDPT) test, already described by Van 't Woudt in 1959. Three drops of distilled water from a standard medicine dropper are placed on the smoothed surface of a soil sample, and the time that elapses before the drops are absorbed is determined (Fig. 1.2).

Fig. 1.2 *Water repellency measurement (WDPT test) by placing three drops of water upon the surface of a soil sample and determining the time to complete absorption.*

In general, a soil is considered to be water repellent if the WDPT exceeds 5 s (e.g. Bond and Harris, 1964; DeBano, 1981). This allows soils to be qualitatively referred to as being either wettable or water repellent. Classification into these categories implies an "either-or" situation, with a sharp demarcation line between the two properties. However, soil water repellency is a relative property, varying in intensity. An index allowing a quantitative definition of the persistence of water repellency was introduced by Dekker (1988) and was applied by Dekker and Jungerius (1990). They distinguished five water repellency classes, as shown in Table 1.1.

Table 1.1 *Classification of the persistence of soil water repellency.*

Class	WDPT (s)	Nomenclature
0	< 5	wettable; non-water repellent
1	5 - 60	slightly water repellent
2	60 - 600	strongly water repellent
3	600 - 3600	severely water repellent
4	>3600	extremely water repellent

Another common method is the alcohol percentage test, a technique first suggested by Letey (1969) and Watson and Letey (1970). Water containing increasing concentrations of ethanol is applied in drop form to the surface of soil samples until a concentration is reached where immediate infiltration occurs. At this concentration, the aqueous ethanol drop has a sufficiently low surface tension to overcome the surface water repellency restriction to infiltration. If a high concentration of ethanol is required for incipient infiltration, this is indicative of hydrophobic soils.

1.3 ORIGINS OF SOIL WATER REPELLENCY

It has been recognized for many years that the water repellency of a soil is a function of the type of organic matter contained in it (Puchner, 1896; Schreiner and Shorey, 1910; Albert and Köhn, 1926; Prescott and Piper, 1932). Organic matter induces water repellency in soils by several means. Firstly, irreversible drying processes in organic matter can induce water repellency, mainly in the surface layers of peat soils, which are difficult to rewet after drying (Hudig and Redlich, 1940; Hooghoudt, 1950; Van't Woudt, 1969). Secondly, organic substances leached from plant litter can induce water repellency in sandy and other coarse-grained soils (DeBano, 1981). Thirdly, hydrophobic microbial by-products coating a mineral soil particle may induce wetting resistance (Bond, 1964; Bond and Harris, 1964; Chan, 1992). Fourthly, mineral particles need not be individually coated with hydrophobic materials; intermixing of mineral soil particles with particulate organic mattter, like remnants of roots, leaves and stems, may also induce severe water repellency (DeBano, 1969; Bisdom et al., 1993).

Some debate has arisen over the question whether the repellent coating is within the humic or fulvic acid fraction of the organic matter. Humic acids have been regarded by numerous researchers as the origin of hydrophobicity (e.g. Savage et al., 1969; Tschapek et al., 1973; Adhikari and Chakrabarti,1976; Singer and Ugolini, 1976). However, Miller and Wilkinson (1977) found that the organic coating surrounding sand grains produced an infrared spectrum closely resembling those of fulvic acids. On the other hand, Roberts and Carbon (1972) found that it was the humic acid (HA) fraction and not the fulvic acid (FA) fraction of the organic coating which induced repellency when added to nonrepellent sand. Nakaya et al. (1977) added a range of soil HAs to a nonrepellent sand and found that all five HAs tested produced repellency in the sand.

Ma'shum and Farmer (1985) have provided evidence that it is the molecular orientation of organic matter which determines whether or not a soil is water repellent. Most forms of organic matter in a soil possess both hydrophilic and hydrophobic groups. The hydrophilic groups interact with water molecules when the soil is wet, but tend to interact with each other in dry soil. Furthermore freeze-drying converts a very severely water repellent soil into a readily wettable soil, while subsequent rewetting and oven-drying regenerates the original water repellency. These changes have also been ascribed to changes in the molecular conformation of the organic compounds (Ma'shum and Farmer, 1985). When the soil is oven-dried, the loss of water may induce the polar groups to interact with each other, and the organic matter then presents largely non-polar groups (e.g. methyl and mythelene) on its surface. Ma'shum et al. (1988) found that hydrophobic materials contain extensive poly-methylene chains, including both long chain fatty acids and esters. It was shown by Valat et al. (1991) that the humic polymers found in most decomposed peats contain polar as well as nonpolar sites, the former groups being hydrophilic and the latter hydrophobic. They claimed that in the drying process, polar groups associate with Fe and Al oxides and hydroxides, causing the system to become hydrophobic when dry. Capriel et al. (1995) investigated the hydrophobicity of organic matter in soils with widely differing textures and organic C contents, using diffuse reflectance infrared fourier transform spectroscopy (DRIFT) in order to establish relationships between the aliphatic C-H IR signal area (3000-2800 cm^{-1}) and certain chemical variables. They found that the organic matter of sandy soils contains relatively more alkyl C and less carbohydrates and proteins compared with the organic matter of clayey soils. In other words, the organic matter of sandy soils is more hydrophobic. The ratio of aliphatic C-H to organic C could serve to characterize the degree of hydrophobicity of the organic matter in soils. The hydrophobicity index (HI) was defined as the area of the aliphatic C-H infrared band in the 3000-2800 cm^{-1} spectral region divided by the organic C content. A high ratio indicates greater hydrophobicity. In general, one may assume that the hydrophobicity of the organic matter is caused by methyl, methylene and methine groups present in aliphatic and aromatic (olefinic) compounds (Capriel et al., 1995). The organic input into soils from plant residues and fertilizers contains compounds such as cellulose, hemicellulose, proteins, lignin, and lipids. The more hydrophylic ones (cellulose, hemicellulose, proteins) are metabolized far more easily by soil microbes to produce energy, new microbial biomass and metabolic products. Lipids contain predominantly hydrophobic aliphatic C-H units and are generally more recalcitrant to microbial decomposition (Dinel et al., 1990). The result of this selective degradation is an accumulation of lipids from the organic input and the formation of new lipids of microbial origin (Capriel, 1997).

1.4 FACTORS CAUSING SOIL WATER REPELLENCY

All primary parts of plants (except roots) are covered by a cuticle that constitutes the interface between plants and their environment. The cuticle is composed of soluble, hydrophobic lipids embedded in a polyester matrix (Holloway, 1994). The micro-relief of plant surfaces, mainly caused by epicuticular wax crystalloids, often results in effective water repellency (Barthlott and Neinhuis, 1997). Contaminating particles (dust, spores, etc.) on the waxy leaves are picked up by water droplets from rain, dew or fog, or they adhere to the surface of the droplets and are then removed with the droplets as they roll off the leaves, resulting in a cleaned surface (Neinhuis and Barthlott, 1997). This can be demonstrated most impressively with the large leaves of the sacred lotus *Nelumbo nucifera*, which is why this phenomenon has been dubbed "Lotuseffect" (Barthlott and Neinhuis, 1997). Plants with water repellent leaves can be found in any habitat and with all life forms, with a clear dominance among herbs (Neinhuis and Barthlott, 1997).

Many workers have recognized the importance of plants in contributing towards the development of water repellency in soils. Jamison (1942) associated water repellency with citrus trees in Florida, Van't Woudt (1959) with heath vegetation and coniferous trees in New Zealand, Bond (1964) with perennial pastures in South Australia, DeBano (1969) with chaparral brush in California and McGhie and Posner (1980), Burch et al. (1989) and Crockford et al. (1991) with dry sclerophyll eucalypt forests in Eastern and South Australian. In sports turf, thatch may be a contributing factor (Wilkinson and Miller, 1978; Rankin and Ross, 1982; Danneberger and White, 1988; Tucker et al., 1990; York and Baldwin, 1992). Thatch is the layer of partially decomposed organic material which comprises the uppermost layer of most turf profiles, and is widely believed by turf managers to be responsible for the development of repellency in turf (commonly called "dry patch" because of its "patchy" occurrence).

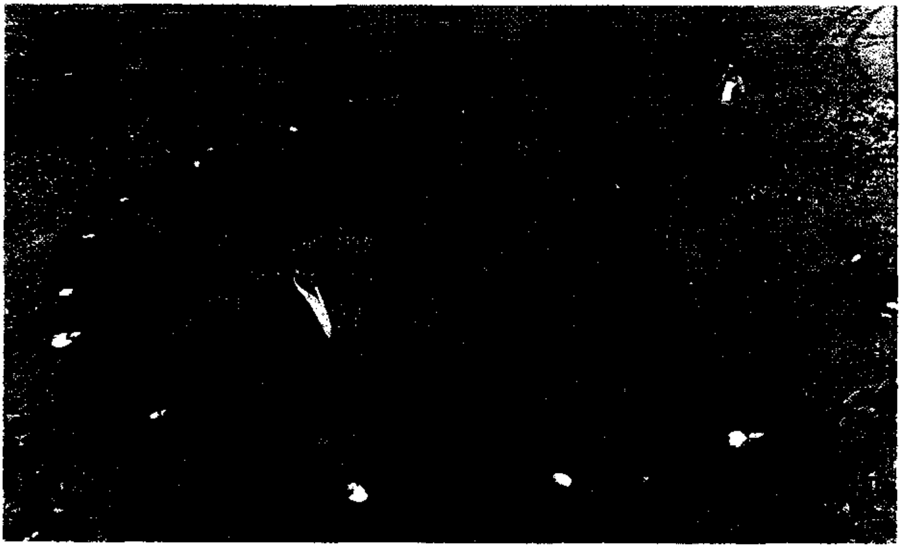


Fig. 1.3 *Fairy ring of mushrooms in Bunne, July 13, 1993 (photo by Bert Wieringa).*

Many studies have also associated soil water repellency with other factors such as the range of fungi associated with the remains of different plant species (Bond and Harris, 1964). Schantz and Piemeisel (1917) already showed that "fairy rings" in pastures and crops were due to basidomycete fungi, and that the presence of basidomycete mycelia was associated with poor soil water absorption. Dekker and Ritsema (1996a, b) examined an expanding fairy ring with a diameter of 12 m (Fig. 1.3) in grassland in the hamlet of Bunne in the northeastern part of the Netherlands on July 22, 1993. A total precipitation of 66 mm in the preceding two weeks had caused irregular moisture patterns inside the fairy ring. The sandy soil had been wetted to depths of more than 20 cm outside the fairy ring, whereas the soil was still dry at a depth of 3 cm in the 30 cm wide band with mushrooms inside the ring (Fig. 1.4). Towards the centre of the fairy ring, an irregular wetting pattern was present. In the zone with the mushrooms, as well as in the zone with stimulated grass growth, the relatively dry soil was actually water repellent. Compared with the soil outside the fairy ring, the degree of potential water repellency of the soil inside the ring was high, as a consequence of the hydrophobic fungal mycelium (Dekker and Ritsema, 1996b).

Fig. 1.4 *Dry, water repellent sand in the fairy ring at Bunne on July 22, 1993, after 66 mm precipitation had fallen in the preceding two weeks.*

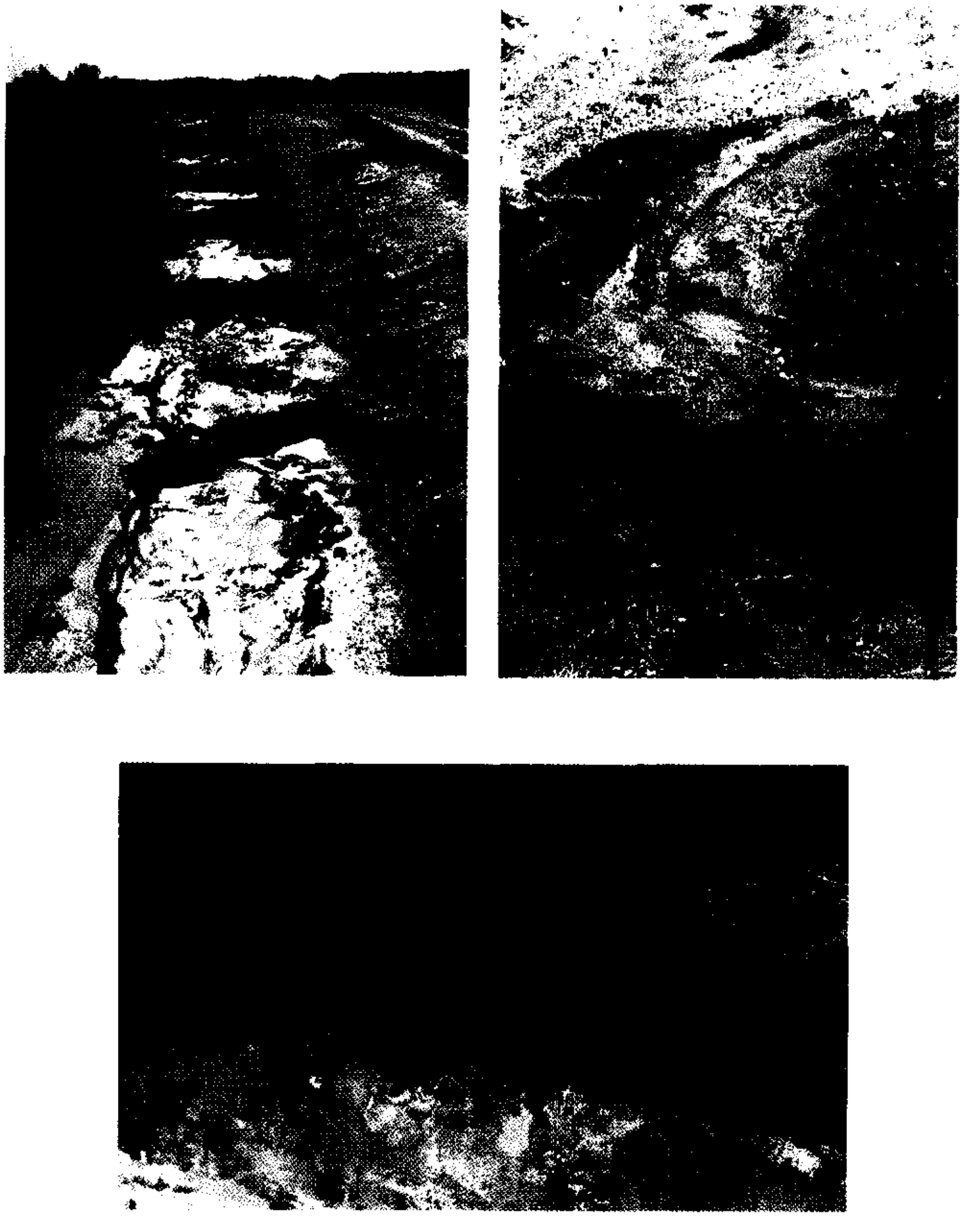


Fig. 1.5 *Erosion of sandy roads (A), sedimentary sandy and humic materials in lower places (B), and irregular wetting (C) in the water repellent sands of the Veluwe area.*

Fire can also induce severe water repellency (DeBano, 1969). Water repellency caused by wildfires in forests has been extensively reported by DeBano (1981), Imeson et al. (1992), and Doerr et al. (1996). After a fire has swept through an area, a water repellent layer of varying thickness often remains.

1.5 CONSEQUENCES OF SOIL WATER REPELLENCY

Infiltration and Erosion

In general, water movement is initially severely limited in dry water repellent soils. Infiltration rates into water repellent soils can be considerably lower than those into wettable soils (Meeuwig, 1971; DeBano, 1981; Rutin, 1983). During rain events after prolonged dry periods, water repellency of the topsoil may cause surface runoff, especially in sloping areas (Rietveld, 1978; McGhie, 1980; Jungerius and Van der Meulen, 1988). Water repellency is greater in dry than in wet soils, which may be the reason why runoff during the first rainstorm after a dry spell is larger than during later, comparable storms (Letey et al., 1975; Jungerius and Dekker, 1990; Imeson et al., 1992). Jungerius and Dekker (1990) described the influence of water repellency on erosion and sedimentation of sand for Dutch coastal dune sands. Dekker and Wösten (1983), and Dekker et al. (1984, 1997) studied the effects of a water repellent surface layer in sandy soils in the Veluwe area, in the eastern part of the country. Such layers were found to influence surface runoff towards fens, as well as erosion of sandy roads, and the sedimentation of sand and organic matter in lower places, including the fens (Fig. 1.5 A, B). Thus, water repellency tends to increase runoff and erosion and decrease the volume of water absorbed by the soil. With increasing rainfall, water infiltration proceeds and finally starts to break through the water repellent layer by creating irregular wetting patterns (Fig. 1.5 C) and/or vertical flow paths into the subsoil.

Preferential flow and accelerated transport

Knowledge of the movement of water and solutes through the unsaturated zone of field soils is essential for reliable predictions of pollution risks to groundwater and/or nutrient losses from agricultural soils. As intensive sampling is costly and time-consuming, characterization of the soil moisture state is often based on a limited number of samples or measurements, which may lead to an incomplete picture of the real flow mechanisms in field soils. Incomplete knowledge of the actual flow mechanism through the unsaturated zone may result in the development of inaccurate computer models, leading to practical consequences such as increased pollution risk to soil and groundwater. So far, most models simulating water and solute transport through the unsaturated zone have assumed homogeneous infiltration and a subsequent downward movement of the wetting front parallel to the soil surface. This type of stable flow, however, is uncommon in field soils (Bronswijk et al., 1990; Gee et al., 1991; Jury and Flühler, 1992; Steenhuis et al., 1995; Nieber, 1996; Scanlon et al., 1997). Deviations are caused by a variety of mechanisms, which in general are related to specific soil properties or soil characteristics. Firstly, preferential flow (or bypass flow) of water and solutes may occur in well-structured clay and/or peat soils owing to the presence of shrinkage cracks and/or channels left behind by decayed roots or soil fauna (biopores), providing pathways through which water and solutes migrate rapidly, essentially bypassing the buffering capacity of much of the unsaturated zone (Bouma and Dekker, 1978; Beven and Germann, 1982; Dekker and Bouma, 1984; Bouma, 1990; Booltink, 1993; Bronswijk et al., 1995; De Vos, 1997). Secondly, preferential flow may also occur in non-structured sandy soils, owing to the development of unstable wetting fronts (Raats, 1973; Philip, 1975a,b; Parlange and Hill, 1976; Diment and Watson, 1985). Perturbations in an initially flat wetting front may grow into "fingers" or "preferential flow paths", instead of flattening out by lateral diffusion. This occurs if (1) the hydraulic conductivity increases with depth, as is encountered in soils with a fine-textured layer covering a coarse-textured layer (Miller and Gardner, 1962; Hill and Parlange, 1972; Hillel and Baker, 1988; Baker and Hillel, 1990), or a densely packed sandy layer covering a loosely packed one (Ritsema and Dekker, 1994a); (2) the soil is water repellent (Raats, 1973; Ritsema et al. 1998a; Steenhuis et al., 1994); (3) air entrapment takes place during an infiltration event (Raats, 1973; Hillel; 1987; Selker et al., 1989; Glass et al., 1990).

Wetting patterns in water repellent soils can be quite irregular and incomplete after rain (Emerson and Bond, 1963; DeBano, 1969; McGhie, 1983; Yang et al., 1996; Ritsema et al., 1997a,b, 1998b; Ritsema and Dekker, 1998; Van den Bosch et al., 1998). Considerable soil water content variations in water repellent horizons have been reported by numerous authors (Jamison, 1945; Bond, 1964; Krammes and DeBano, 1965; Ritsema and Dekker, 1994b).

Solute leaching related to preferential flow in water repellent field soils has been studied by applying dye solutions or other coloring agents to the soil surface (e.g. Van Ommen et al., 1988, 1989; Hendrickx et al., 1988, 1993; Dekker and Jungerius, 1990). Visual observations of wetting patterns in trenches dug in a water repellent dune sand with grass cover by Dekker and Jungerius (1990) revealed that water moved downward through narrow channels, leaving the adjacent soil volumes dry and causing considerable variation in soil water content. They studied the penetration of rain into some dune sands by using the dyestuff staining technique described by Bond (1964). Trenches were dug after rains during the autumn and winter of 1988. The pit faces were dusted with a dry mixture of 1% Rhodamine B in finely ground kaolinite until the faces were uniformly covered with a white powder. Within a few minutes, the wet areas developed an intense red colour, while dry areas remained white. The patterns were photographed to provide a permanent record for comparison (Fig. 1.6).

Fig. 1.6 *Preferential flow paths in a water repellent dune sand visualized by using a dyestuff staining.*

Van Ommen et al. (1988) developed a technique similar to dye staining to visualize preferential flow paths. They applied an iodide solution to the soil surface and excavated the treated area layer by layer. Each layer was dusted with dry starch. After the thin starch layer had been wetted by the soil solution, the surface was sprayed with a chlorine solution. At places where iodide was present, it was oxidized to iodine, yielding a dark blue color. These experiments revealed the locations of the preferential flow paths. Once preferential flow paths have formed, the soil no longer impedes infiltration of water, so that additional precipitation tends to infiltrate through the existing preferential paths which have been wetted before. Thus, dry zones tend to persist due to their water repellent character and their low hydraulic conductivity. Field evidence of preferential flow of bromide through a water repellent dune sand soil, resulting in early arrival times and high bromide concentrations in the groundwater, were presented by Van Dam et al. (1990), Hendrickx et al. (1993), Ritsema et al. (1993), and Ritsema and Dekker (1998).

From a management point of view, it is essential to know where and when preferential flow may be expected in field situations and to what extent it may accelerate water and solute transport, in order to develop consistent strategies to minimize environmental risk to groundwater and surface waters.

1.6 IMPROVEMENT OF WATER REPELLENT SANDY SOILS

Crop and pasture production are seriously hampered in water repellent agricultural areas, and consequently research has attempted to find suitable amelioration techniques to reduce runoff and leaching processes, and to increase the crop and pasture production efficiency (Dekker 1983, 1988; Danneberger and White, 1988; Ma'shum et al., 1989; Blackwell, 1993). A number of different strategies have been applied to water repellent sands to either overcome or make use of water repellency to improve agricultural production on these problem soils. These include clay application, furrow sowing and band spraying of wetting agents, cultivation during rain and deep cultivation/subsoiling (Michelsen and Franco, 1994). None of these methods actually reduce the amount of waxes present in the soil; rather, they reduce the symptons. The use of microorganisms either already present in the soil or added to the soil to break down these waxes is another possible method for overcoming the problem (Roper, 1994). The use of microorganisms to break down undesirable compounds in the soil into compounds that do not cause problems is termed "biomediation". Biomediation can be achieved either by stimulating existing microorganisms in the soil (biostimulation) or by adding organisms to the soil that are more efficient at utilising the unwanted substance than existing organisms (bioaugmentation). Wax-degrading bacteria may be able to improve water repellent soils by removing water repellent substances from the surfaces of soil particles. Recent studies have indicated that soils contain a wide range of wax-degrading bacteria, and artificial stimulation of these bacteria might lead to better crop and pasture performance on water repellent soils (Roper, 1994).

According to Blackwell (1993), furrow sowing improves crop production on water repellent sandy soils. Rain is easily shed from ridges of water repellent sand, and the runoff accumulates, ponds, and infiltrates below the furrow. This "water harvesting" can increase opportunities for early crop and pasture establishment if seeds are sown in the furrow. This effectively increases the amount of rainfall reaching the seed, increasing the likelihood of succesful establishment even during brief autumn showers.

The application of surfactants and/or water-absorbing gels can also be considered as tools to improve crop and pasture performance on water repellent soils (Letey et al., 1975; Danneberger and White, 1988). Surfactants and related substances reduce the effect of repellency and can therefore increase plant growth and yield. When applied to the bottom of the furrow, the use of surfactants can result in better crop, pasture and fodder shrub establishment, and early plant growth (Blackwell, 1993).

Improved wetting of water repellent sandy soils in Australia amended with fly ash has been described by Roberts (1966), by Campbell et al. (1983) and by Aitken et al. (1984). The application of fly ash resulted also in an improved emergence and growth of clover (Roberts, 1966).

On water repellent sandy soils in Australia, Ma'shum et al. (1989) established that dispersive clay can correct water repellency by covering the non-wetting coatings on soil particles, leading to improved germination and increased storage of water available to the plant. Dekker (1988) noticed that clay amendments had been used successfully by Dutch farmers in the 1950s to improve the soil's water- and nutrient-holding capacity, to prevent wind erosion, and to reduce water repellency in dune sands in the vicinity of Ouddorp, in the southwestern part of the country.

Jamison (1945) indicated that water repellent topsoils can be improved by mixing them with wettable sand from the subsoil. In the Netherlands, large areas of water repellent grass-covered dune sand soils in De Zijpe, Callantsoog and Koegras have been converted to arable land for bulb growing; these were improved by deep ploughing, as well as by the addition of calcareous sea sand (Dekker, 1988).

Cultivating the soil after the first rain following a dry period stimulates further regular wetting (Jamison, 1969; Roberts and Carbon, 1972), an experience shared by the users of water repellent sandy soils in the Dutch districts of Goeree-Overflakkee and Voorne-Putten (Dekker, 1988).

Water repellency has also been a problem in intensively cultivated organic soils in Sweden, especially for the cultivation of potatoes, which are usually irrigated. If the potato ridges dry out, the water repellency will make the ridges very hard to rewet and subsequently cause water shortage (Berglund and Persson, 1996). Similar

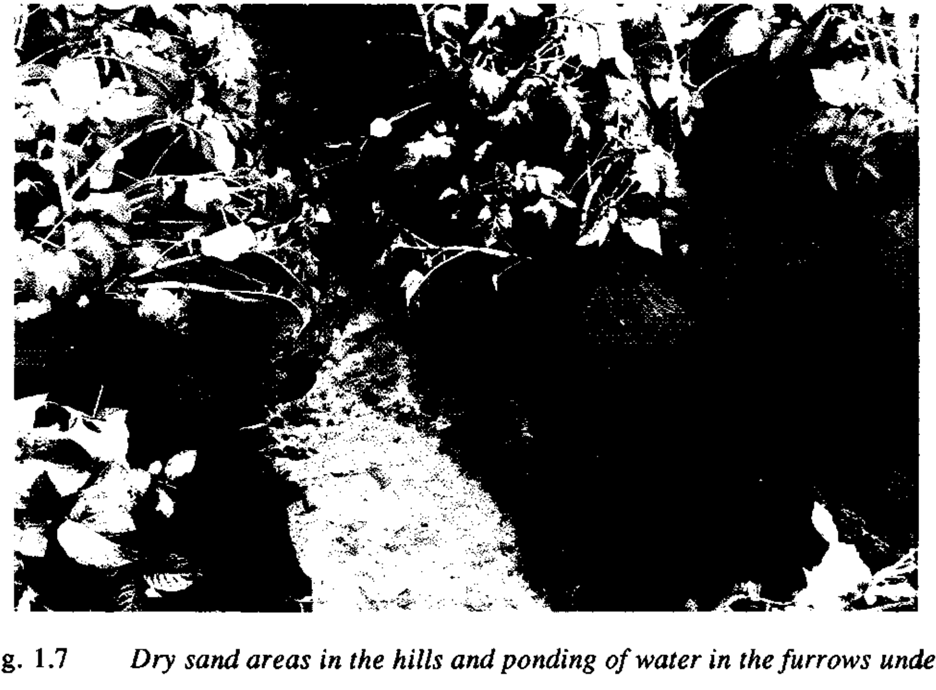


Fig. 1.7 *Dry sand areas in the hills and ponding of water in the furrows under a potato crop after 30 mm sprinkler irrigation.*

observations were made by Dekker and Ritsema (1996b) in a water repellent sandy topsoil at the Vredepeel experimental station. Sprinkler irrigation after a dry period resulted in ponding water in the furrows, leaving areas in the potato ridges dry (Fig. 1.7). Similar soil wetting patterns under potato crops have been found in Wisconsin in the USA (Saffigna et al., 1976). Correctly timed irrigation, may be able to prevent soils from becoming water repellent by keeping the soil water contents above the critical level above which the soil is wettable and below which it is water repellent (Dekker and Ritsema, 1994b). The success of this approach depends to a large extent on real-time monitoring of the soil water status at different depths and timely application of sufficient amounts of irrigation water. In this way, environmental damage and crop production losses may be prevented (Blackwell, 1993).

1.7 OBJECTIVES AND STRUCTURE OF THE THESIS

A few years ago, three Doctoral thesis studies were initiated, with the aim of increasing our basic knowledge regarding the occurrence of water repellent soils and the effect of soil water repellency on flow and transport processes. The present study, carried out by Louis W. Dekker, aimed at investigating the occurrence of water repellency in different soil types in the Netherlands and its effect on inducing soil water content variability. The second study, by Coen J. Ritsema (1998), aimed at unraveling the process mechanisms in water repellent sandy soils in relation to water flow and solute transport processes. The third study, performed by Hung V. Nguyen, is still in progress and aims to elaborate the findings of both previous studies; it mainly deals with simulating observed flow and transport processes.

The objectives of the research reported on in the present thesis were to:

1) investigate the occurrence, thickness and distribution of water repellent layers in major soils of the Netherlands, as distinguished by the Netherlands Soil Survey Institute;
2) identify a standard technique for water repellency measurement;
3) study and document the influence of land use and vegetation type on water repellency for major Dutch soils and determine its effect on wetting patterns, soil moisture variability and water flow.

This thesis describes detailed field and laboratory measurements of soil water content, dry bulk density and soil water repellency of a total of over 25,000 samples taken from Dutch sandy, loam, clay and peat soils.

In Chapter 2, results are presented of a detailed study of the variation in the severity of soil water repellency in a dune sand with a grass cover. The distinction between "potential" and "actual" soil water repellency and the assessment of the "critical soil water content" are introduced and highlighted in this Chapter.

Chapter 3 presents the results of a field survey, covering areas throughout the coastal dunes of the Netherlands, which sought to determine the occurrence and depth of soil water repellency and to study the effect of the type of vegetation on its severity.

Chapter 4 provides a detailed description of the effect of maize canopy and soil water repellency on moisture infiltration patterns in a black plaggen soil at the "Heino" experimental farm, located near the town of Zwolle. Special attention is given to the fact that the irregular wetting patterns did not induce development of preferential flow paths.

Chapter 5 presents evidence of the occurrence of flow through the matrix of a water repellent silt loam soil, located in the southwestern part of the Netherlands. Attention is also given to the influence of dry bulk density and water repellency on the moisture patterns observed.

Chapter 6 describes the water repellency of heavy basin clay soils as a function of land use. It further describes the variation in water content over short distances in a heavy clay with grass cover at the "De Vlierd" experimental farm, located near Zaltbommel, on ten sampling dates. Special attention is given to the relationship between dry bulk density and the volumetric water content of the clay.

Chapter 7 discusses evidence of the variability of soil water content over short distances in water repellent peaty clay and clayey peat soils, and relates the observed irregular wetting patterns to the process of preferential flow.

Chapter 8 concentrates on the effect of the drying temperature on the severity of soil water repellency, while Chapter 9 considers the influence of sample distance and sample volume on the detection of preferential flow paths in a water repellent dune sand. A summary, final conclusions and recommendations for further research are presented in Chapter 10 and Chapter 11 of this thesis.

CHAPTER 2

POTENTIAL AND ACTUAL WATER REPELLENCY

Adapted version of "How water moves in a water repellent sandy soil 1. Potential and actual water repellency" by Louis W. Dekker and Coen J. Ritsema, published in Water Resources Research 30: 2507-2517,1994.

2 POTENTIAL AND ACTUAL WATER REPELLENCY

Abstract

Water repellency is an important property of many soils. It causes rainwater to penetrate into the soil as preferential flow paths, and solutes can reach the groundwater more rapidly than in the case of a homogeneous wetting. Water repellency depends on several factors which are principally related to the characteristics of the organic matter of the soil. A distinction between "potential" and "actual" water repellency and the assessment of the "critical soil water content" are introduced and highlighted in this paper. Persistence and degree of potential water repellency of dried samples were examined from 10 trenches in a dune sand with grass cover using the water drop penetration time and the alcohol percentage tests. The spatial variability of water repellency and, therefore, soil wetting was extremely high. The actual water repellency was measured on field-moist samples to obtain critical soil water contents. The soil is wettable above and water repellent below these values. The critical soil water content varies between 4.75 vol% at 5-10 cm and 1.75 vol% at 45-50 cm depth in this sandy soil.

2.1 INTRODUCTION

Water repellency often occurs in surface soil horizons that frequently dry out. It is generally not recognized. One simple way to detect water repellency is to add a drop of water to the surface of a fairly dry soil. If, on initial contact with the soil, the water "beads up" into a spherical shape instead of quickly penetrating into the soil, the soil is water repellent, as shown in Figure 2.1.

Water repellency of a soil depends on its moisture content. An air-dry soil repels water the most. Wet soil might not be water repellent. The severity of water repellency is not the same for all dry soils and can be determined using two tests: water drop penetration time (WDPT) and alcohol percentage. These tests can be applied on dried as well as on field-moist samples.

Infiltration rates into water repellent soils can be considerably lower than those into wettable soils (Jamison, 1969; Meeuwig 1971; Van Ommen et al., 1988; Van

Dam et al., 1990; Hendrickx and Dekker, 1991). Moreover, wetting patterns in water repellent soils can be quite irregular and incomplete.

The objectives of this study are to examine the variation in water repellency over short distances in a water repellent dune sand with grass cover and to investigate the effects of water repellency on the variation in soil water content. A distinction is made between measurements on dried samples and measurements on field-moist samples, introduced here as "potential water repellency" and "actual water repellency", respectively.

2.2 MEASUREMENT OF WATER REPELLENCY

Persistence of Water Repellency

Persistence of potential water repellency was measuered on 5,000 dried dune sand samples using the water drop penetration time (WDPT) test described by several workers (e.g. Krammes and DeBano, 1965; Letey et al., 1975; Dekker and Jungerius, 1990). Three drops of distilled water from a standard medicine dropper (approximately 6 mm in diameter) were placed on a smoothed surface of a soil sample, and the time it took to penetrate the soil was recorded (Fig. 2.1). If the drops initially stand on the soil surface, they indicate that the liquid-solid contact angle is greater than 90°. Under such circumstances, the water drops should, theoretically, never penetrate. However, the water drops do eventually penetrate in some soil samples, which indicates that the liquid-solid contact angle changes and eventually becomes less than 90°. This is due to an interaction of soil surface and water, reducing the surface tension of the liquid (Van 't Woudt, 1959; Richardson, 1984). During the WDPT test, the water drops often become covered by a film of organic particles and also become more flattened. If the contact angle is less than 90°, capillary forces will draw water into the soil. Thus, in principle, the WDPT test will only divide soils into two broad categories: with contact angles greater and smaller than 90°. It does not further quantify the degree of repellency but does give useful information on the rapidity of the soil-water reaction. The longer the drops remain on the surface, the more stable or persistent the water repellency. Drops penetrating quite rapidly indicate that repellency is not so stable. In general, a soil is considered water repellent (contact angle >90°) if the water drop penetration time exceeds 5 s (e.g. Bond and Harris, 1964; DeBano, 1981; Dekker and Jungerius, 1990). The 5 s time period was selected for convenience and has no specific physical meaning (Richardson, 1984).

Fig. 2.1 *Water drops penetrate immediately into wettable sand and can remain for hours on the surface of extremely water repellent sand.*

Increasing the temperature of the water applied will reduce the surface tension, and in line with this the time required for wetting will be reduced, the actual reduction in time increasing with increased water temperature (Van 't Woudt, 1959; King, 1981). Therefore the temperature at the time of testing must be constant, for instance between 18^0 and 23^0C (Richardson, 1984). The relative humidity of the air in the laboratory also affects the penetration time of the water drops. Increasing the relative humidity increases the time that the drops remain on the surface (Bisdom et al., 1993).

Using the WDPT test on dried samples gives the persistence of the *potential* water repellency. In the field, some of these samples were dry, but others were moist or wet. Therefore, we also checked the persistence of the *actual* water repellency of field-moist samples from different horizons. Because we also measured the soil water content of these samples we could assess "critical soil water contents" for the distinct layers. The soil samples are water repellent below and wettable above these values.

Degree of Water Repellency

The fundamental principles underlying the process of wetting show that a reduction in the surface tension of a solid substance to be wetted reduces its wettability. Conversely, a reduction in the surface tension of the applied liquid increases wettability (Van 't Woudt, 1959). The liquid-solid contact angle is dependent on the surface tension of the liquid. In general, when the surface tension of the liquid decreases, the liquid-solid contact angle will also decrease. The liquid surface tension which wets a soil material with a 90° contact angle was proposed as an index of water repellency by Watson and Letey (1970). This 90° surface tension can easily and quickly be measured as follows. A series of aqueous ethanol solutions producing different surface tensions is prepared. A drop of each solution is applied to the soil surface, and the penetration time recorded. If the surface tension of the liquid applied to the soil is lower than the 90° surface tension, the drop will penetrate rapidly. If the surface tension is higher than the 90° surface tension, the liquid applied will be slightly retarded in penetration. Five seconds was arbitrarily chosen as reference time (Letey et al., 1975; Richardson, 1984).

Watson and Letey (1970) and Letey et al. (1975) expressed the degree of water repellency as a liquid surface tension (dynes per centimeter), whereas King (1981) and Ma'shum et al. (1988) used MED values (the molarity of aqueous ethanol solutions). We prefer to express the degree of water repellency, simply, as the lowest alcohol percentage of the solution that penetrates the soil in 5 s or less.

We measured the degree of potential water repellency of the 5,000 dried dune sand samples using the alcohol percentage test. Although we did not do so, this test can also be applied to field-moist samples to assess the degree of actual water repellency.

2.3 CHARACTERISTICS OF THE AREA OF INVESTIGATION

Experimental Site and Soil

The experimental site is located in Ouddorp in the coastal dune area in the southwestern part of the Netherlands. The spatial variability of water repellency and soil moisture content was examined on a dune sand parcel under grass which had probably never been ploughed. The sandy soil is classified as a Mesic Typic Psammaquent (De Bakker, 1979) and has a water repellent top layer. The soil consists of a 5-cm-thick humose top layer, with an intermediate layer to 9 cm depth, on top of a noncalcareous fine dune sand to 75 cm depth, overlying calcareous fine sea sand. The organic matter content of the humose top layer is approximately 20%, of the intermediate layer 4%, and below 9 cm depth it decreases to less than 0.5%. The clay content is less than 3%. The sand fraction mainly consists of grains of between 150 and 210 µm.

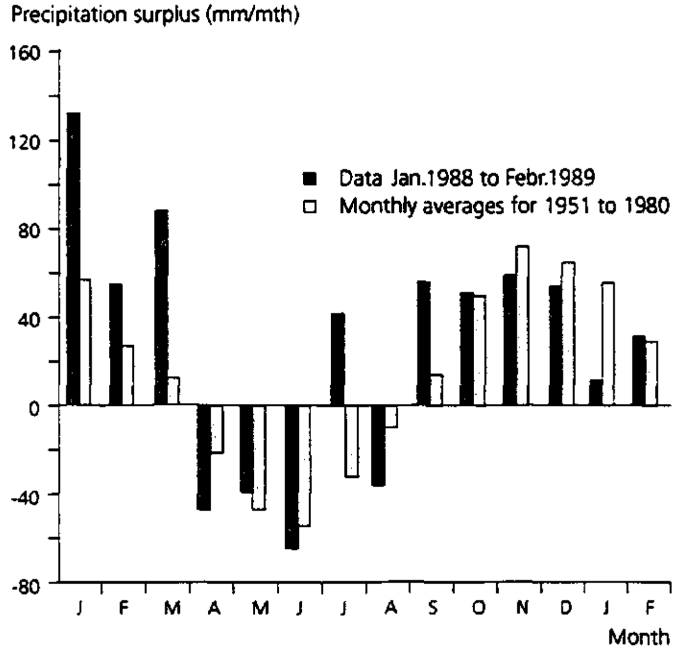


Fig. 2.2 *Monthly precipitation surplus during the period of the field operations in Ouddorp, the Netherlands. The monthly averages for 1951 - 1980 are also given for comparison.*

Climate

In the Netherlands, annual precipitation averages 765 mm and is more or less evenly distributed over the year. Potential evaporation averages 690 mm/yr. Mean monthly temperatures vary between 1.7°C in January and 17.0°C in July. During the growing season there is a small precipitation deficit; in autumn and winter, a precipitation surplus.

Monthly precipitation surpluses, that is, the difference between precipitation and 0.8 times the open water evaporation (P - 0.8 E_o), in Ouddorp in the period before and during the measurements and in comparison with monthly averages for 1951 - 1980 are shown in Figure 2.2. This diagram shows that January, February, March, July, and September 1988 were clearly wetter and the other months somewhat drier than the long-term means.

2.4 MATERIALS AND METHODS

Soil Sampling

Between April 1988 and March 1989, 10 sampling operations were carried out in a 0.05-ha experimental field. The samples were taken on April 8, May 24, June 21, July 12, August 30, October 4, October 11, November 10, and December 13, 1988, and on February 22, 1989. In each sampling operation the soil was sampled at five depths (5-10, 15-20, 25-30, 35-40 and 45-50 cm) using steel cylinders (100 cm^3) with a height and diameter of 5 cm. At each depth, 100 samples were taken in close order over a distance of 550 cm. The cylinders were pressed vertically into the soil, and layer after layer was sampled directly after removing the soil, to minimize evaporation of the soil sampled. The steel cylinders were emptied into plastic bags and used again, and the plastic bags were tightly closed. The wet soil in the plastic bags was weighed, dried for several days at 65°C, and weighed again to determine soil water content and dry bulk density. Each dried sample was also used to measure the persistence and degree of the potential water repellency using the water drop penetration time and alcohol percentage tests.

Two hundred samples were collected separately at each of the five depths on September 1, 1992, to measure the actual water repellency of field-moist soil and to obtain critical soil water contents for the different depths.

Organic Matter Measurement

The organic matter content was determined for the 500 samples taken out of the last trench, dug on February 22, 1989. The organic matter content was measured by drying the sample for 1 day at 105°C and igniting the dried sample for 4 h at 650°C. The weight difference between the dried and ignited samples was taken as the organic matter content.

Water Drop Penetration Time (WDPT) Test

The persistence of the potential water repellency of all 5,000 samples taken in the trenches was measured using the water drop penetration time (WDPT) test. After removing samples from the oven they were under controlled conditions stored at a constant temperature of 20°C and a relative air humidity of 50%. WDPT tests were deferred for at least 2 days to allow the samples to equilibrate with the ambient air humidity and temperature. We used the WDPT of the second drop (the median value) to classify the water repellency of the sample. We measured the water drop penetration time of the samples taken in trenches 1 to 9 up to 1 hour, and of those taken in the last trench up to 6 hours. The following classes were distinguished: wettable or non-water repellent (<5 s); slightly (5-60 s), strongly (60-600 s), severely (600-3600 s), and extremely water repellent (>3600 s).

The actual water repellency was measured using the WDPT test on field-moist samples taken on September 1, 1992. These measurements were done immediately after weighing their wet weight. The samples were divided into two classes: wettable or non-water repellent (<5 s) and water repellent (>5 s). After determining their soil water content a clear distinction was noticed between the two classes. All samples per depth were wettable above and water repellent below a certain soil water content, introduced here as the "critical soil water content".

Alcohol Percentage Test

We measured the degree of water repellency of all the samples taken in the 10 trenches using the following alcohol percentage test. We used bottles with solutions containing 1, 2, 3, 4, 5, 6, 8, 10, 12.5, and 15% and with increments of 2.5% to 35% of ethanol on a volume basis. Alcohol percentage tests were conducted on the dried samples, thus measuring the degree of potential water repellency. Because temperature and relative air humidity affect the obtained values, the measurements were performed under laboratory conditions with a constant temperature of 20^{0}C and a relative humidity of 50%. Alcohol percentage tests were deferred for at least 2 days to obtain samples in equilibrium with the ambient air humidity.

Contour plots of alcohol percentage distributions were obtained using the statistical package Genstat 5, release 2 (Lane et al., 1987).

2.5 RESULTS

Potential Water Repellency

The persistence of potential water repellency measured on all 5,000 dried samples using the WDPT test are summarized in Figure 2.3. Nearly all the samples from 5-10 cm and 15-20 cm, and 87% of the samples from 25-30 cm depth, show extreme water repellency, with water drops remaining for more than 1 hour on their surfaces. With increasing depth the dry soil becomes less water repellent and more variable. Even at the 45-50 cm depth, 65% of the dried samples repel water. Figure 2.3 represents the spatial variability of the persistence of potential water repellency for all samples taken.

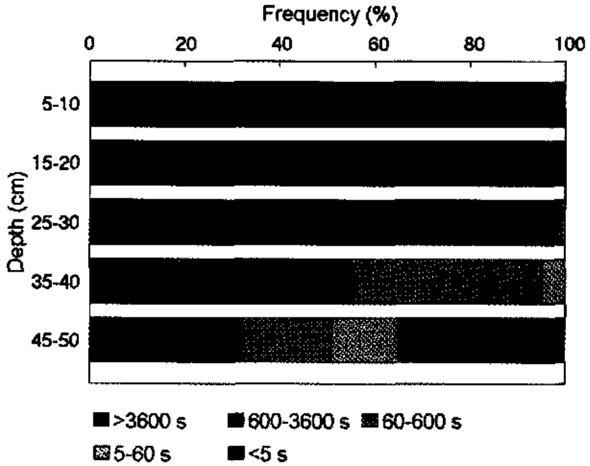


Fig. 2.3 *Relative frequency of the WDPT test on dried samples from five depths in the sandy soil of the Ouddorp site. For each depth the persistence of potential water repellency was measured on 1000 samples.*

To gain more understanding of the soil samples in which the water did not infiltrate in 1 hour, those which were extremely water repellent, we measured the WDPT of the samples of the last dug trench of February 22, 1989, for up to 6 hours (Table 2.1). It was quite remarkable that it was not the 5-10 cm layer, but the 25-30 cm layer which showed the most persistent potential water repellency. Deeper than 30 cm, persistence drops quickly. Table 2.1 also shows that there is a larger range in persistence within the extreme WDPT class at 5-10 cm and 35-40 cm depths, than at any other depth.

Table 2.1 *Frequency distribution of the persistence of potential water repellency of samples from the February 22, 1989, trench.*

Depth (cm)	**Number (*n*)**	**Water Drop Penetration Time**								
		< 5 s	**5-60 s**	**60-600 s**	**600-3600 s**	**1-2 h**	**2-3 h**	**3-4 h**	**4-5 h**	**5-6 h**
5-10	**100**	**-**	**-**	**-**	**1**	**3**	**11**	**38***	**31**	**16**
15-20	**100**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**84***	**16**
25-30	**100**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**68***	**32**
35-40	**100**	**-**	**-**	**-**	**4**	**2**	**15**	**29***	**31**	**19**
45-50	**100**	**11**	**10**	**32***	**22**	**25**	**-**	**-**	**-**	**-**

*** Median value**

Figure 2.4 shows a contour plot of the time that a water drop remains on the dry surface before infiltrating samples from the last dug trench. This vertical section shows areas in the top layer with WDPT values of 1-4 hours. On the other hand, locally more persistent pockets are found in this top layer, with WDPT values of 5-6 hours. Between 15 and 30 cm depth the greater part of the sandy soil has a potential water repellency of 4-5 hours, but locally vertical pockets with extreme persistences (WDPT >5 h) occur.

The degree of potential water repellency measured on the dried samples from this trench using the alcohol percentage test is presented in Table 2.2. The decrease in degree and increase in the variability with depth is quite striking. According to these measurements the severest repellency occurs in the upper layers. This is confirmed by Table 2.3, in which the results of the alcohol percentage test of all the samples from all the trenches have been summarized. The mean alcohol percentages in the 5-10, 15-20, 25-30, 35-40, and 45-50 cm layers were 22.5, 17.5, 12.5, 8, and 2, respectively. Table 2.3 also shows that the variability of the degree of potential water repellency is high at all the depths.

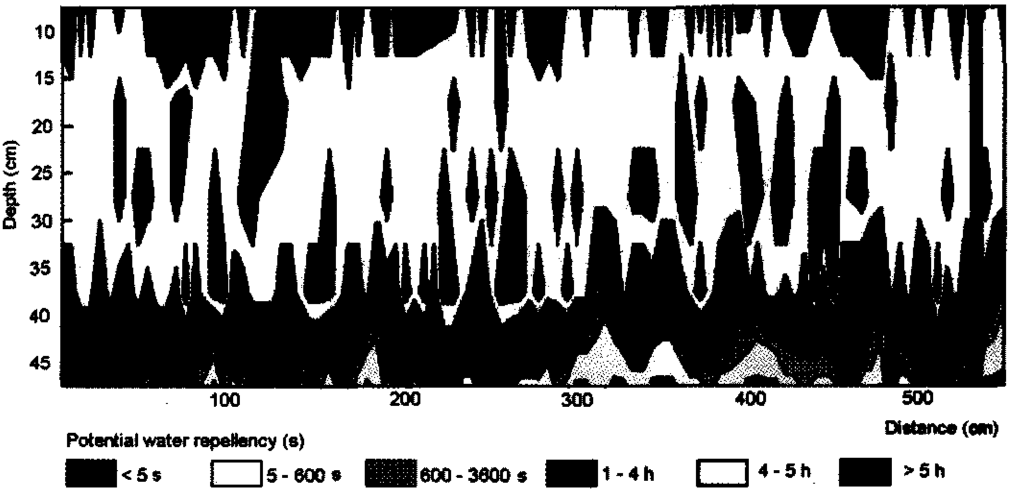


Fig. 2.4 *Contour plot showing the spatial distribution of the persistence of potential water repellency measured with the WDPT test on dried samples from the February 22, 1989, trench.*

Table 2.2 *Frequency distribution of the degree of potential water repellency of samples from the February 22, 1989, trench.*

Depth	Number	Alcohol percentage															
(cm)	(*n*)	0	1	2	3	4	5	6	8	10	12.5	15	17.5	20	22.5	25	27.5
5-10	100	-	-	-	-	-	-	-	-	-	-	-	1	22	72*	5	-
15-20	100	-	-	-	-	-	-	-	-	-	-	-	-	98*	2	-	-
25-30	100	-	-	-	-	-	-	-	-	-	35	19*	5	41	-	-	-
35-40	100	-	-	-	-	-	-	3	17	49*	26	5	-	-	-	-	-
45-50	100	11	4	8	19	14*	10	7	19	7	1	-	-	-	-	-	-

* Median value

Table 2.3 *Frequency distribution of the degree of potential water repellency of samples from the ten trenches.*

Depth (cm)	Number (n)	Alcohol percentage															
		0	1	2	3	4	5	6	8	10	12.5	15	17.5	20	22.5	25	27.5
5-10	1000	-	-	-	-	-	-	-	-	-	-	-	25	206	449*	294	26
15-20	1000	-	-	-	-	-	-	-	-	20	175	203	293*	286	22	1	-
25-30	1000	-	-	1	2	7	23	39	76	327	215*	171	87	52	-	-	-
35-40	1000	5	16	22	65	133	112	115	137*	224	122	37	12	-	-	-	-
45-50	1000	325	113	109*	98	100	97	65	75	17	1	-	-	-	-	-	-

* Median value

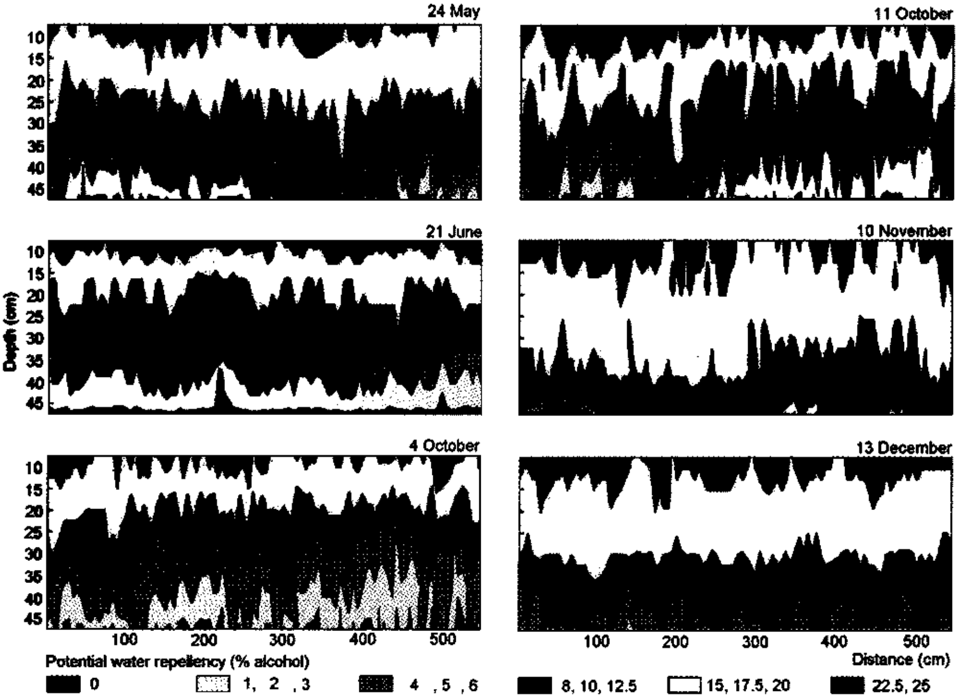


Fig. 2.5 *Contour plots showing the spatial distribution of the degree of potential water repellency measured with the alcohol percentage test on dried samples from six trenches.*

Figure 2.5 shows vertical sections of the degree of potential water repellency of six trenches. The irregular, fingerlike patterns, indicating short-distance variability are remarkable. Differences in the degree of potential water repellency between the trenches are relatively small.

Table 2.4 *Relationship between the degree and the persistence of potential water repellency of the 500 samples from the February 22, 1989, trench.*

Alcohol (%)	**Number (*n*)**	**Water Drop Penetration Time**								
		< 5 s	**5-60 s**	**60-600 s**	**600-3600 s**	**1-2 h**	**2-3 h**	**3-4 h**	**4-5 h**	**5-6 h**
0	**11**	**11***	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
1	**4**	**-**	**4***	**-**	**-**	**-**	**-**	**-**	**-**	**-**
2	**8**	**-**	**3**	**5***	**-**	**-**	**-**	**-**	**-**	**-**
3	**19**	**-**	**2**	**16***	**1**	**-**	**-**	**-**	**-**	**-**
4	**14**	**-**	**1**	**8***	**5**	**-**	**-**	**-**	**-**	**-**
5	**10**	**-**	**-**	**1**	**9***	**-**	**-**	**-**	**-**	**-**
6	**10**	**-**	**-**	**2**	**8***	**-**	**-**	**-**	**-**	**-**
8	**36**	**-**	**-**	**-**	**3**	**17***	**10**	**1**	**4**	**1**
10	**56**	**-**	**-**	**-**	**-**	**9**	**5**	**18***	**17**	**7**
12.5	**62**	**-**	**-**	**-**	**-**	**1**	**-**	**8**	**40***	**13**
15	**24**	**-**	**-**	**-**	**-**	**-**	**-**	**2**	**16***	**6**
17.5	**6**	**-**	**-**	**-**	**1**	**-**	**-**	**-**	**2***	**3**
20	**161**	**-**	**-**	**-**	**-**	**2**	**6**	**10**	**107***	**36**
22.5	**74**	**-**	**-**	**-**	**-**	**1**	**5**	**27**	**27***	**14**
25	**5**	**-**	**-**	**-**	**-**	**-**	**-**	**1**	**1**	**3***

*** Median value**

Table 2.4 presents the relationship between the degree and persistence of potential water repellency of the February 22 trench. As might be expected, there is a general trend of increasing severity, indicated by the alcohol percentage, with increasing persistence or stability of the water repellency, indicated by the WDPT. However, within all the WDPT classes a wide range of alcohol percentages occurs. For example, samples in the WDPT class 5-60 s have alcohol percentages of between 1 and 4, samples in the WDPT class 60-600 s between 2 and 6, and those in the 5-6 hour class even vary between 8 and 25. On the other hand, samples with the same degree often differ in persistence. For example, samples with an alcohol percentage of 8 can have a WDPT of between 600 s and 6 hours (Table 2.4).

Table 2.5 *Relationship between the persistence and the degree of potential water repellency of samples at different depths in the February 22, 1989, trench.*

Depth (cm)	WDPT	Alcohol percentage															Number (*n*)
		0	1	2	3	4	5	6	8	10	12.5	15	17.5	20	22.5	25	
5-10	5-6 h	-	-	-	-	-	-	-	-	-	-	-	-	1	12*	3	16
	4-5 h	-	-	-	-	-	-	-	-	-	-	-	-	3	27*	1	31
	3-4 h	-	-	-	-	-	-	-	-	-	-	-	-	10	27*	1	38
	2-3 h	-	-	-	-	-	-	-	-	-	-	-	-	6*	5	-	11
	1-2 h	-	-	-	-	-	-	-	-	-	-	-	-	2*	1	-	3
	600-3600 s	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1
15-20	5-6 h	-	-	-	-	-	-	-	-	-	-	-	-	14*	2	-	16
	4-5 h	-	-	-	-	-	-	-	-	-	-	-	-	84*	-	-	84
25-30	5-6 h	-	-	-	-	-	-	-	-	-	4	4	3	21*	-	-	32
	4-5 h	-	-	-	-	-	-	-	-	-	31	15*	2	20	-	-	68
35-40	5-6 h	-	-	-	-	-	-	-	1	7	9*	2	-	-	-	-	19
	4-5 h	-	-	-	-	-	-	-	4	17*	9	1	-	-	-	-	31
	3-4 h	-	-	-	-	-	-	-	1	18*	8	2	-	-	-	-	29
	2-3 h	-	-	-	-	-	-	-	10*	5	-	-	-	-	-	-	15
	1-2 h	-	-	-	-	-	-	-	-	2*	-	-	-	-	-	-	2
	600-3600 s	-	-	-	-	-	-	3*	1	-	-	-	-	-	-	-	4
45-50	1-2 h	-	-	-	-	-	-	-	17*	7	1	-	-	-	-	-	25
	600-3600 s	-	-	-	1	5	9*	5	2	-	-	-	-	-	-	-	22
	60-600 s	-	-	5	16*	8	1	2	-	-	-	-	-	-	-	-	32
	5-60 s	-	4	3*	2	1	-	-	-	-	-	-	-	-	-	-	10
	< 5 s	11*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11

* Median value

Table 2.5 shows the relationship between the persistence and the degree of potential water repellency for the different layers of the last sampled trench. The degree of water repellency of all the samples from the 5-10 cm depth is high, but the persistence of several samples is relatively low. The persistence of the samples with an alcohol percentage of 20 ranges between 1 hour and 6 hours at 5-10 cm depth, and between 4 and 6 hours in the 15-20 and 25-30 cm layers. Remarkable also are the 19 samples from 35-40 cm depth with alcohol percentages of only 8-15, but with persistences of 5-6 hours, indicating that a low degree can go hand in hand with a high persistence. The persistence or stability of potential water repellency considered in relation to its degree seems to increase with depth. The tendency of this persistence/degree ratio to increase with depth is undoubtedly related with the characteristic and content of the organic matter.

Organic Matter Content

The decrease in the degree of potential water repellency with depth is associated with reduced amounts of organic matter, which would be expected if soil organic matter were the source of the hydrophobicity. Figure 2.6 shows the relationship between the organic matter content and the degree of potential water repellency of the 500 samples taken at five depths in the February 22, 1989, trench. The alcohol percentage increases with increasing organic matter content, although above 3.5% organic matter it increases only slightly. All the samples with more than 1.5% organic matter have alcohol percentages of 17.5 or more. The spatial distribution

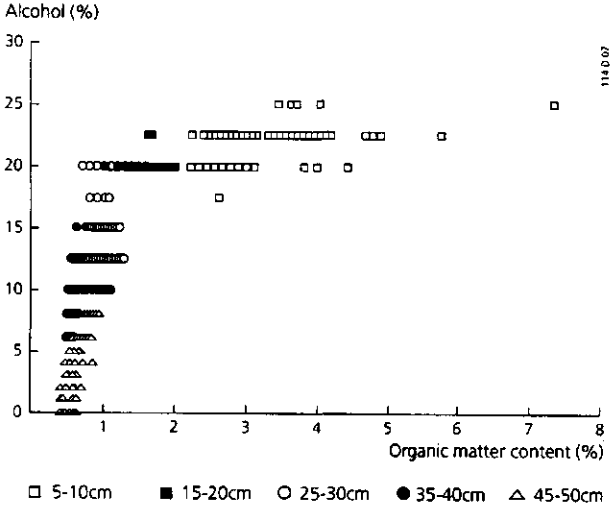


Fig. 2.6 *Relationship between the organic matter content and the degree of potential water repellency of samples from the February 22, 1989, trench.*

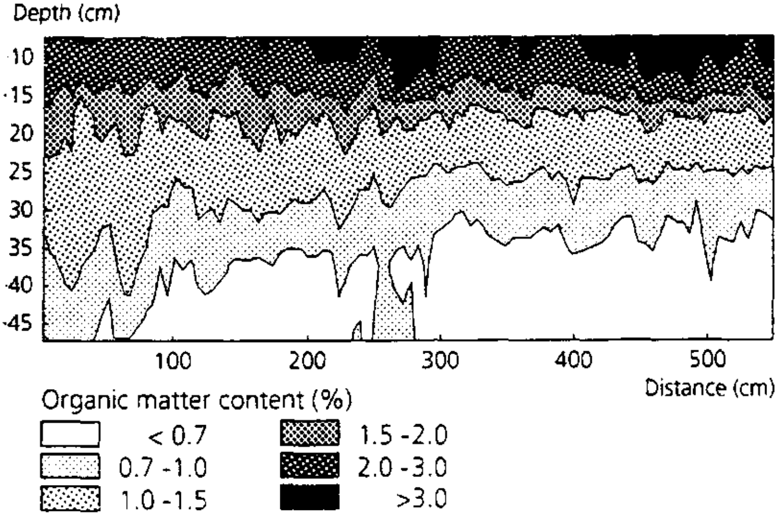


Fig. 2.7 *Contour plot showing the spatial distribution of the organic matter content from the February 22, 1989, trench.*

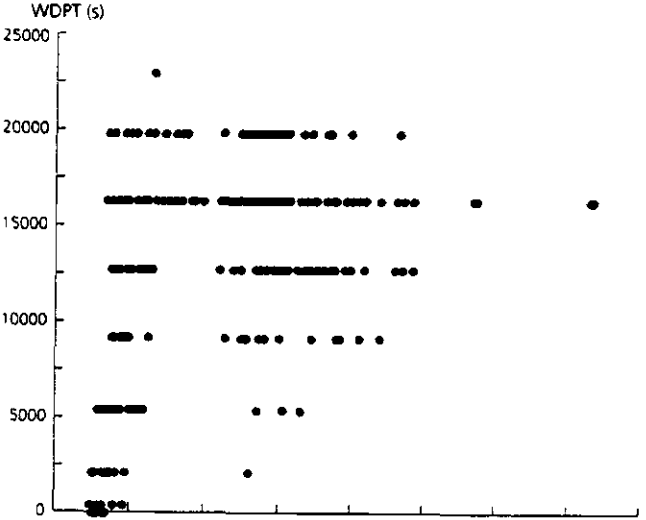


Fig. 2.8 *Relationship between the organic matter content and the persistence of potential water repellency of samples from the February 22, 1989, trench.*

of the organic matter content of this trench is shown in Figure 2.7. The rapid decrease of the organic matter content with depth is obvious.

As can been seen in Figure 2.8, there is no significant relationship between the organic matter content and the persistence of potential water repellency. This contradicts the findings of Scholl (1971), who found a positive relationship between organic matter content and WDPT for air-dry soil samples in central Arizona. Singer and Ugolini (1976) had taken samples from the major horizons of soils of Findley Lake, Washington, and found that the organic matter content highly correlated with WDPT on the air-dried samples using an exponential model. However, the organic matter content alone is not enough to predict the persistence of water repellency; apparently, the quality of organic matter, which is difficult to quantify, is also important. Biological decomposition of leaves, stems and roots, whereby different types of humus and organic substances are formed, will give different WDPT values (Bisdom et al., 1993). In general, fresh and partly decomposed organic matter will have a higher WDPT than further humified fragments. During this biodegradation of the biomass, organic macromolecules are broken down, and water repellency will be reduced. The affinity of soils to water can be reduced by water repellent organic materials which are either intermixed with the soil or form a coating around the mineral soil particles. Bisdom et al. (1993) found water repellent C horizons in dune sands, similar to those studied here, which had organic matter contents of less than 0.5%, and WDPT values exceeding 8 hours. Microscopical analysis revealed that these dune sand samples had thin organic matter coatings on their grains.

Actual Water Repellency and Soil Moisture

Water movement can be severely restricted by dry water repellent sandy topsoils. Rain that falls on the surface of water repellent sand does not penetrate evenly but moves downwards through narrow channels, leaving the intermediate soil quite dry and causing considerable variation in the moisture content of the sand. Figure 2.9 shows the soil moisture contents of samples from five depths of the August 30 trench. Variability is extremely high, especially in the upper layers. The peaks represent the wet sand of preferential flow paths and the valleys the dry, principally, still water repellent sand. The horizontal lines in the five diagrams indicate the critical soil water contents, which are different for each layer. Samples with water

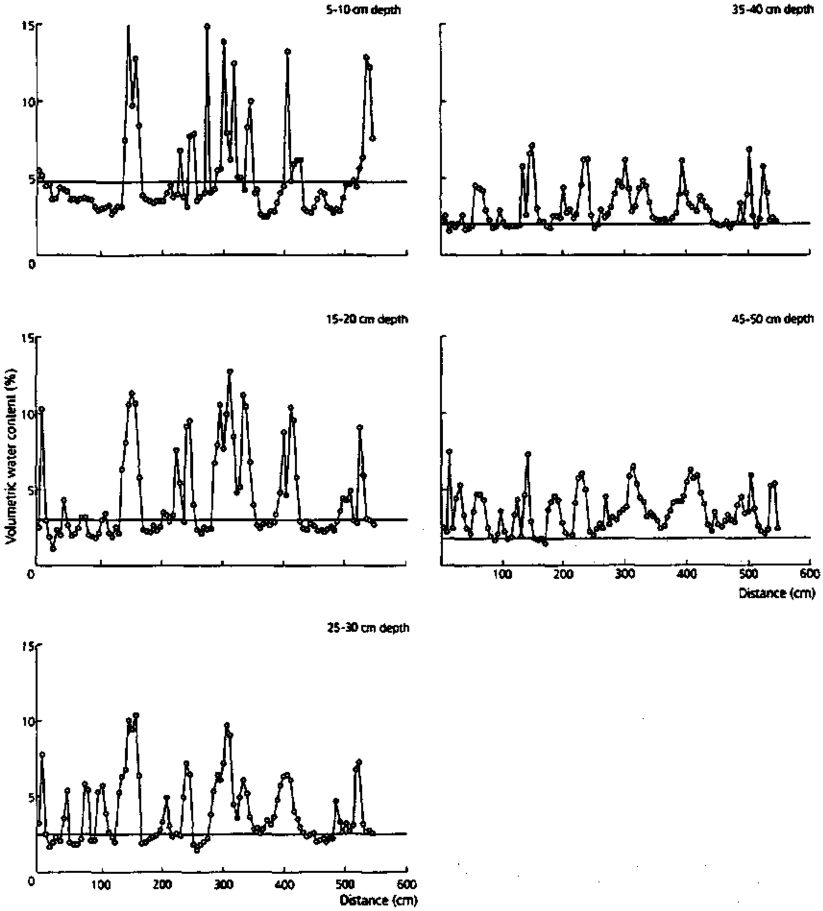


Fig. 2.9 *Measured volumetric water contents of soil samples in a 5.5-m transect at five depths on August 30, 1988. The samples with contents above the horizontal lines, representing the critical soil water contents, are actually wettable, and those below the lines are actually water repellent.*

contents beneath these lines are actually water repellent, and samples with higher contents are actually wettable. The critical soil water contents for the 5-10, 15-20, 25-30, 35-40, and 45-50 cm layers are 4.75, 3.0, 2.5, 2.0, and 1.75 vol%, respectively. In places where preferential flow paths have been formed, the soil becomes actually wettable, allowing the water to flow down through these paths. Between the preferential flow paths, dry, actually water repellent soil pockets or zones will persist.

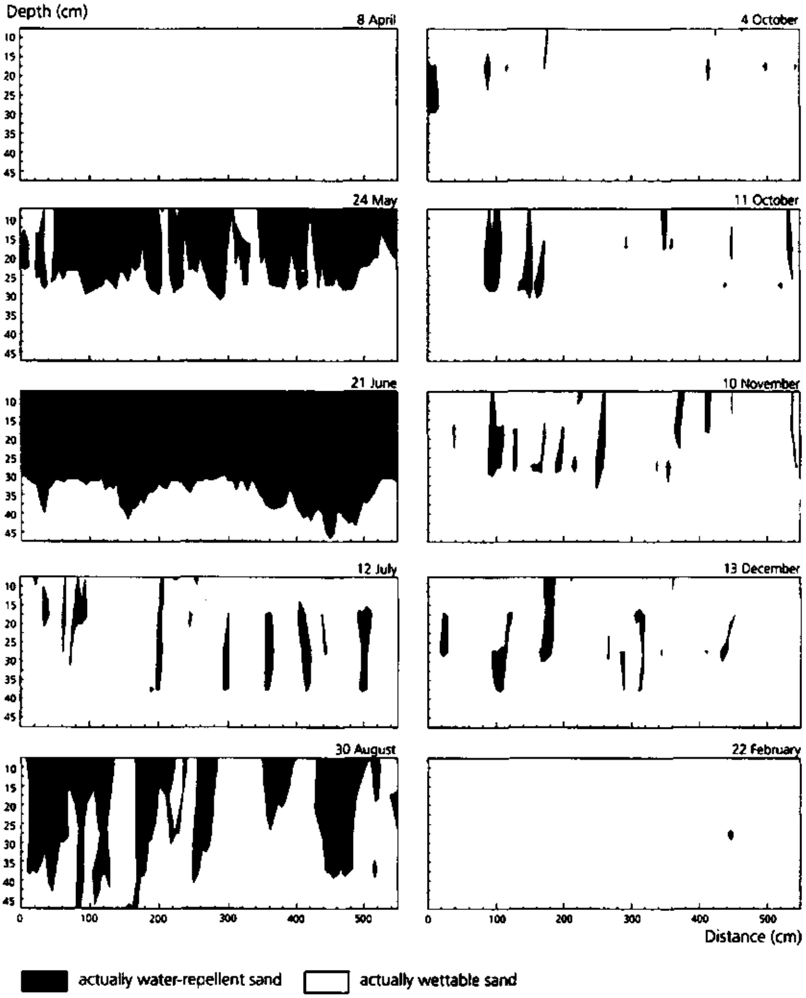


Fig. 2.10 *Contour plots showing the distribution of dry, actually water repellent sand parts in the 10 sampled trenches.*

Figure 2.10 shows cross sections of all 10 trenches with the distribution of actually wettable and actually water repellent sandy parts. The April trench is completely, and the February trench nearly completely, actually wettable. The soil of the June trench is completely actually water repellent to 30 cm depth, and locally to 45 cm depth. In all the other trenches, vertically orientated dry, actually water repellent sand areas occur between the moist and wet, actuallv wettable sand areas.

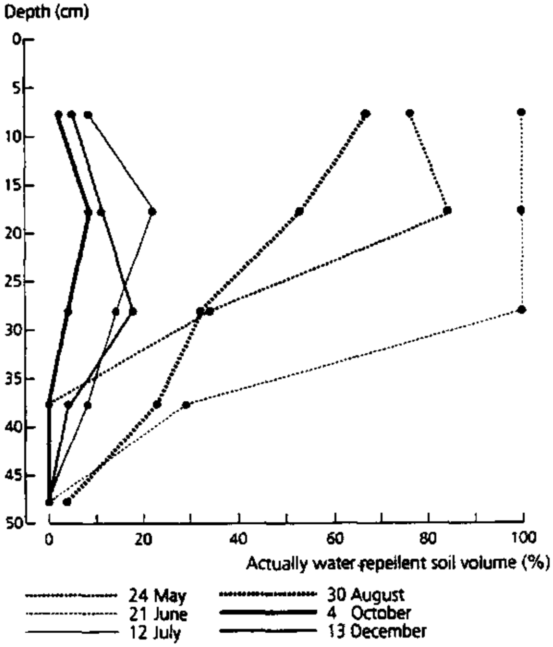


Fig. 2.11 *Relative frequency of the actually water repellent soil volume at five depths from six trenches.*

Figure 2.11 shows the percentages of the actually water repellent soil samples between 5 and 50 cm depth for six trenches. As might be expected, the percentages of actually water repellent samples decrease deeper in the profiles. The layers with the largest number of actually water repellent samples were 5-10 cm in August, 15-20 cm in May, July and October, and 25-30 cm in December, whereas in June in three layers all the samples were actually water repellent. The different percentages at different times are worthy of note. These percentages may be interpreted as percentages of soil volume which are unable to wet within several hours and thus may not be permeated by water in the case of a rainfall event. In fact, these actually water repellent soil volumes may wet only in the long run.

2.6 DISCUSSION AND CONCLUSIONS

Water repellency is an important, often neglected property of many soils and has its greatest effect in relatively dry soils. It has serious consequences for the wetting and water-holding capacity of the soil. Water and solutes often flow in these soils through preferential flow paths, the so-called "tongues" or "fingers". This phenomenon shortens solute travel time and increases the risk of groundwater contamination.

The degree of potential water repellency of soils can quickly be measured on dried samples using the alcohol percentage test. The persistence or stability of potential water repellency can be measured using the water drop penetration time (WDPT) test on dried samples, especially when these measurements are extended to several hours. Measurements of potential water repellency may give some information about the occurrence, depth, distribution, variability, degree and persistence of water repellency, and comparisons between soils can be made.

In the dune sand studied, the decrease in degree of potential water repellency with depth is closely related to reduced amounts of organic matter. On the other hand, there is no significant relation between the organic matter content and the persistence of potential water repellency. According to the alcohol percentage test the most severe potential water repellency occurs in the topsoil at 5-10 cm depth, and according to the WDPT test the 25-30 cm layer is the potentially most persistently water repellent one.

Water repellency is a time-dependent physical property of the soil, because resistance to wetting of a water repellent soil will decrease over time. This increasing wettability makes static measurements of water repellency inadequate. Therefore actual water repellency was measured using the WDPT test on field-moist samples. Because we also measured the soil water content of these samples, we could assess critical soil water contents for the different depths of the intensively sampled trenches. The effects of the potential and actual water repellency on the variability in soil moisture content, and the dynamics of the fingered flow in the soil studied, are discussed in a companion paper, in the same issue of Water Resources Research (Ritsema and Dekker, 1994b).

CHAPTER 3

EXTENT AND SIGNIFICANCE OF WATER REPELLENCY IN COASTAL DUNES

Adapted version of "The extent and significance of water repellent sands along the Dutch coast" by Louis W. Dekker, Coen J. Ritsema and Klaas Oostindie, submitted to Plant and Soil.

3 EXTENT AND SIGNIFICANCE OF WATER REPELLENCY IN COASTAL DUNES

Abstract

Depth, degree and spatial variability of water repellency were examined in the surface layers of dune sands along the coast of the Netherlands. Soil samples were collected at six depths of up to 50 cm at 865 dune sand sites in nature reserves. The potential water repellency was measured on dried samples using the water drop penetration time (WDPT) test. The vegetation at the sites consisted of marram grass, buckthorn, grey hair grass, pine, oak, other grasses, and heather. The 5190 samples were dried at the laboratory, after which the potential water repellency was measured using the WDPT test. 60-70% of the samples taken at several depths in the young dunes with a sparse vegetation of marram grass were wettable, whereas the other samples were slightly to strongly water repellent. The samples taken at a depth of 0-5 cm in the surface layer at the sites with different vegetations were all strongly to extremely water repellent. At all of these sites, the severity of water repellency decreased with depth. The decrease was most evident at the grey hair grass sites. No significant differences in severity of water repellency were found between the samples taken under a cover of buckthorn, pine and oak, other grasses, and heather. The large variability over short distances in the water repellency and water content of the soil in the dune sands is shown by the intensive sampling of soil blocks at the Ouddorp, Westduinen, Schoorl, and Zwanenwater sites. Drier as well as wetter soil areas were visualized in contour plots showing soil water content distributions in some transects. Large differences in wetting capacity between samples taken at several depths at the Ouddorp site were assessed by measurements of the wetting rate. In all cases, wetter samples wetted faster than their drier counterparts.

3.1 INTRODUCTION

Water repellency of surface horizons is often found in soils that frequently dry out and are not cultivated. When dry, they resist or retard water infiltration into the soil matrix. The simplest way to recognize water repellency is by applying a drop of water on the surface of a fairly dry soil. If upon initial contact with the soil, the water "beads up" into a spherical shape instead of quickly being absorbed into the soil, the soil is water repellent (Chapter 1, 2). Repellent soils can be found in many parts of the world, under a variety of climatic conditions (DeBano, 1981; Wallis and Horne, 1992; Doerr et al., 1996), and may occupy large areas, such as the sandy soils of South Australia, Western Australia, and Victoria (Roberts and Carbon, 1972; Bond, 1968; Blackwell, 1993). Water repellency of soils in the USA has been described by numerous researchers (e.g. Jamison, 1946; Krammes and DeBano, 1965; DeBano, 1981; McNabb et al., 1989). In the Netherlands, slightly to extremely water repellent topsoils occupy large areas of sand, loam, clay, and peat soils (Dekkers et al., 1986; Dekker, 1988; Dekker et al., 1991; Chapter 2, 4, 5, 6, 7). The surface layers in sands of nature reserves, including the coastal dunes, often exhibit strong to extreme water repellency (Dekker and Jungerius, 1990; Dekker, 1992; Dekker and Bisdom, 1992; Heijs et al., 1996).

Many workers have recognized the importance of various plant species in contributing towards water repellency in soils. Jamison (1946) associated water repellency with citrus trees, Bond (1968) with perennial pastures, Van 't Woudt (1959) with heath vegetation and coniferous trees, DeBano (1969) with the various chaparral brush species, and Crockford et al. (1991) with dry sclerophyll eucalypt forests. Water repellency can also be found in grasslands, agricultural lands, sports turfs, and on golf greens (DeBano, 1981; Danneberger and White, 1988; York and Baldwin, 1992). The cause of water repellency in sandy soils was found by Bond and Harris (1964) to be an organic coating on the sand grains produced by the growth of fungi. DeBano (1969, 1981) identified a direct contribution of partially decomposed plant parts to the development of water repellency in soils.

Infiltration rates into dry water repellent soils can be considerably lower than those into dry wettable soils, which can lead to runoff and erosion on hill and steepland soils (Bridge and Ross, 1983; Jungerius and Dekker, 1990; Witter et al., 1991; Wallis and Horne, 1992). After prolonged rainfall, however, the soil will start to wet, generally resulting in a very wet surface layer on top of a still dry subsoil. Water may flow laterally through this surface layer, the so called "distribution layer", to provide water to places where vertical flow paths are formed, the so called "fingers"or "tongues" (Ritsema and Dekker, 1994b; Ritsema et al., 1993). These vertically directed preferential flow paths facilitate the rapid movement of water and solutes to the groundwater (Ritsema and Dekker, 1995).

The purpose of the present study was (i) to investigate the occurrence, distribution, and depth of water repellent layers in the Dutch coastal dune sands, (ii) to measure the severity of water repellent layers in relation to the current vegetation, (iii) to draw attention to the hydrologic consequences of water repellency. Most importantly, it is hoped that the publication of the results will stimulate debate and research in an insufficiently recognized field.

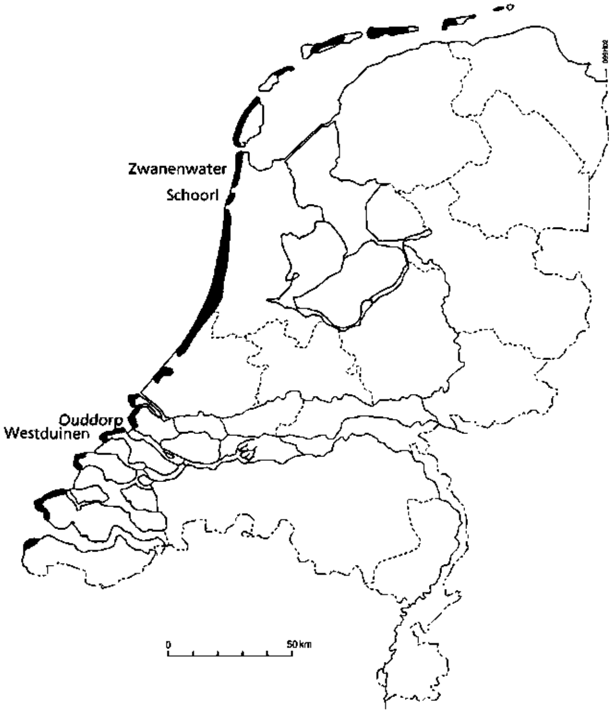


Fig. 3.1 *Schematic map of the Netherlands showing the distribution of coastal dune sands and the four sites studied.*

3.2 MATERIALS AND METHODS

Sampling Coastal Dune Sand Area

Soil samples were collected at 865 sites, distributed throughout the dune sand areas along the west coast of the Netherlands, including the North Sea Islands (Fig. 3.1). The samples were taken with an auger at depths of 0-5, 5-10, 10-20, 20-30, 30-40, and 40-50 cm. Sparse marram grass (Fig. 3.2) grew at 148 sampling sites, whereas grey hair grass and mosses occurred at 104 sites (Fig. 3.3). 93 sites had a vegetation consisting of buckthorn, 188 sites one of pine and oak, and 66 sites one of heather, whereas at 266 sampling sites the dune sand was covered by different grass types.

Fig. 3.2 *Sparse marram grass vegetation in a foredune along the North Sea coast.*

The 5190 samples collected were dried at the laboratory at an oven temperature of 65^{0}C, after which the persistence of potential water repellency was measured using the WDPT test (Chapter 1, 2). After drying, the samples were kept at a constant temperature of 20^{0}C and a relative air humidity of 50%, for at least two days, to allow the samples to equilibrate with the ambient air humidity, before the WDPT test was performed. The test involved three drops of distilled water being

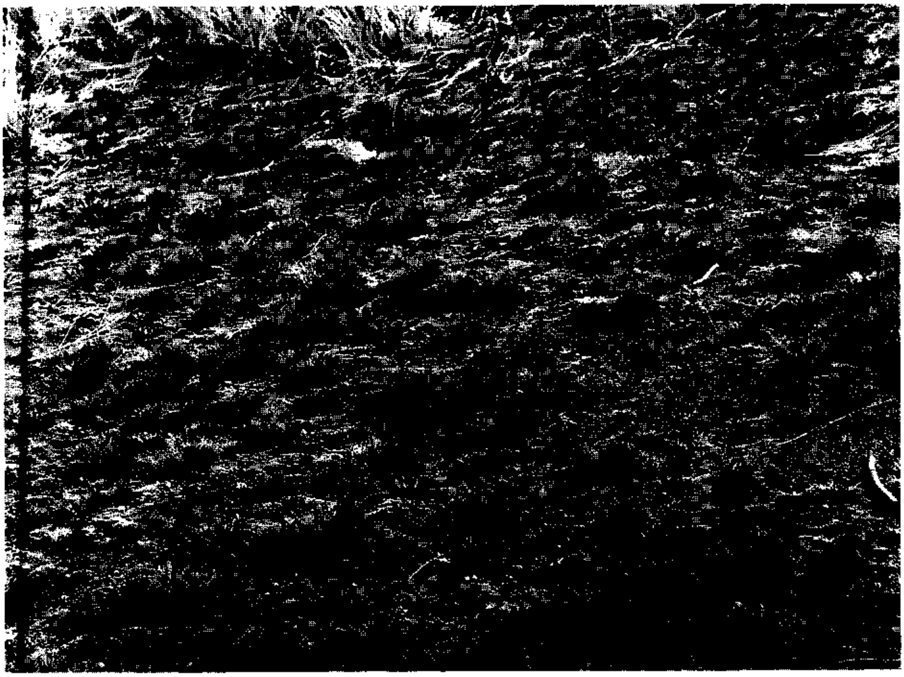


Fig. 3.3 *Dune sand occupied by grey hair grass and mosses.*

placed on the surface of a sample, after which the time required for infiltration was recorded. Five classes of water repellency were distinguished, based on the time needed for the water drops to penetrate into the soil: wettable, non-water repellent (infiltration within 5 s), slightly water repellent (5 to 60 s), strongly water repellent (60 to 600 s), severely water repellent (600 s to 1 h), and extremely water repellent (more than 1 h).

Soil Block Sampling at Four Dune Sand Sites

To study the variability of soil water content over short distances, and to obtain two- and three-dimensional water content patterns, samples were taken from 4 soil blocks in dune sands at Ouddorp, Westduinen, Schoorl, and Zwanenwater (Fig. 3.1). The dune sands of these sites are classified as mesic Typic Psammaquent (De Bakker, 1979). The Ouddorp site is grass-covered, is in use as pasture, and has not been tilled for at least several decades. The other three dune sands are situated in nature reserves. The Zwanenwater site is covered with a grassy vegetation, the Westduinen site with grey hair grass and mosses, and the Schoorl site by Pinus sylvestris.

Organic matter contents of 8.9 to 40.4 w% were found in the thatch layer of the Ouddorp and Zwanenwater sites, and in the uppermost layer, including some litter, of the Schoorl site. Grey sand at depths of 9-24 cm at the Ouddorp, and at depths of 7-26 cm at the Zwanenwater site, contained 0.7 to 1.3 w% organic matter, whereas the yellow sand, deeper in both profiles, and from 7 cm downwards at the Westduinen and Schoorl sites, contained only 0.2 to 0.6 w% organic matter.

The soils were sampled at different depths, using steel cylinders (100 cm^3) with a diameter and height of 5 cm. The cylinders were pressed vertically into the soil, emptied into plastic bags and used again. The plastic bags were tightly sealed to minimize evaporation from the soil. The field-moist soil in the plastic bags was weighed, the actual water repellency was measured, and water content and dry bulk density of the samples were calculated after drying at 65^0C.

Sampling dates and depths of the layers sampled are indicated in Table 3.1. At the Ouddorp site a large soil block was sampled and a total of 1680 samples were collected; 240 samples were taken at seven depths, in a regular grid of 40 by 6 samples. At the Westduinen, Schoorl, and Zwanenwater sites, smaller soil blocks were sampled and in these cases 75 samples were taken at each depth, in a grid of 15 by 5 samples.

Measurements of the actual water repellency were performed immediately after assessment of the wet weights. The samples were divided into two groups: wettable (< 5 s) and water repellent (> 5 s). The actual water repellency of the samples from the Ouddorp site was measured to be up to more than 6 hours. The samples from depths of 0-5 cm at the Ouddorp and Westduinen sites were split into two 2.5 cm parts. After drying at 65^0C, the potential water repellency of the samples was measured at the conditioned laboratory up to more than six hours.

Two- and Three-dimensional Visualization of Soil Water Content

Contour plots of the soil water content distributions were obtained using the Genstat 5 statistical package, release 2 (Lane et al., 1987). For the soil block from the Westduinen site, the water content values were ordered according to a prede-

Table 3.1 *Mean dry bulk densities and soil water contents at several depths at the four dune sand sites.*

Depth (cm)	Bulk density ($g.cm^{-3}$)	Soil water content Minimum (vol%)	 Mean (vol%)	 Maximum (vol%)
Ouddorp, November 28, 1995 (n = 240)				
0-5	0.90	18.6	30.5	38.3
9-14	1.42	1.9	6.2	14.3
19-24	1.42	1.5	4.6	11.4
30-35	1.49	0.7	4.4	10.0
42-47	1.49	1.0	3.4	7.9
55-60	1.48	1.0	3.8	9.0
69-74	1.47	3.9	7.4	9.6
Westduinen, August 16, 1996 (n = 75)				
0-5	0.88	4.9	11.1	23.7
7-12	1.49	1.1	3.1	6.1
14-19	1.54	0.9	2.8	10.6
21-26	1.53	1.0	4.0	7.2
28-33	1.53	2.3	5.4	7.4
35-40	1.54	3.9	6.0	8.3
Schoorl, November 4, 1996 (n = 75)				
0-2.5	0.61	17.3	37.3	71.7
2.5-5	1.38	7.3	14.7	41.5
7-12	1.51	4.4	7.0	10.7
14-19	1.49	1.4	4.8	10.9
21-26	1.53	1.0	2.7	6.8
28-33	1.53	0.7	1.9	6.6
35-40	1.58	0.6	1.3	4.6
Zwanenwater, October 30, 1996 (n = 75)				
0-5	0.28	22.8	34.1	43.7
7-12	1.21	2.8	10.8	22.6
14-19	1.46	1.2	4.1	9.0
21-26	1.48	1.0	4.3	9.1
28-33	1.48	2.2	6.3	10.6
35-40	1.48	4.7	7.9	12.6

-fined matrix system. This data set was used as a basis for visualizing the water content patterns. Visualization was done using the IRIS Explorer modular visualization software environment, on a SGI Indigo workstation (Heijs et al., 1996; Ritsema et al., 1997a). In addition to the visualization of a three-dimensional iso-surface, intersecting horizontal and vertical planes were also depicted in the graph.

Wetting Rate Measurements on Samples from the Ouddorp Site

Resistance to wetting was determined by measuring the wetting of field-moist samples collected at depths of 0-5, 7.5-12.5, 29-34, 42.5-47.5, and 50-55 cm at the Ouddorp site. The sand samples were taken with the help of steel cylinders (100 cm^3) with a height and diameter of 5 cm. These samples, within their steel cylinders, were subjected to a constant pressure head of -2.5 cm water applied to the bottom of the sample (see Chapter 8, Fig. 8.2). The experimental set-up was designed in such a way that water content increments of 0.2 vol% were recorded automatically over a period of one week.

3.3 RESULTS

Influence of the Type of Vegetation on Water Repellency in Coastal Dune Sands

Fig. 3.4 shows the severity of potential water repellency of the 5190 samples taken to a depth of 50 cm, distributed over 865 sites throughout the coastal dune sands. A remarkable feature is the slight to strong water repellency of at least 26% of the samples taken from the surface down to a depth of 50 cm in the yellow sands of the foredunes, which are sparsely vegetated with marram grass and have a low organic matter content. On the other hand, potentially wettable sand at depths of 0-5 cm was only found at the sites with marram grass, whereas at sites with different vegetation types the surface layer was always strongly to extremely water repellent. At the sites with different vegetation types the severity of water repellency decreased with depth, which is due to the reduced amounts of organic matter, the source of the hydrophobic materials. Although even at depths of 30-40 cm most sites exhibited water repellency, with the exception of the sites with a vegetation of grey hair grass and moss, where 70% of the samples at that depth were wettable.

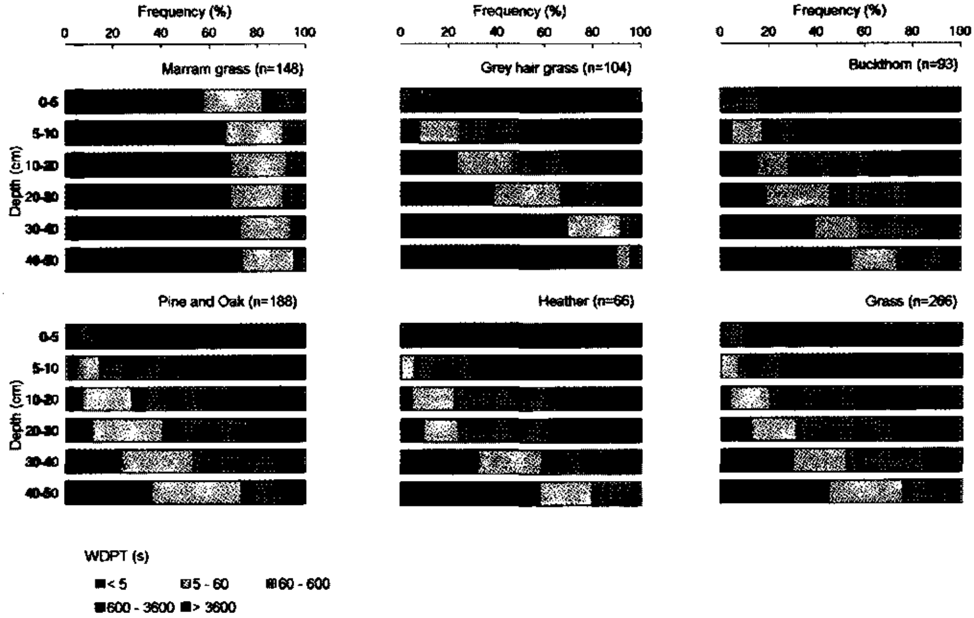


Fig. 3.4 *Relative frequency of the degree of potential water repellency of soil samples taken at six depths on numerous locations with selected vegetation types.*

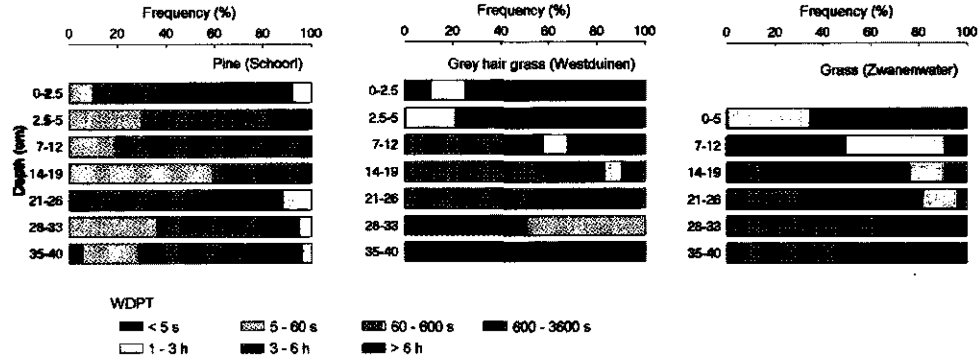


Fig. 3.5 *Relative frequency of the degree of potential water repellency of samples (n = 75) taken at several depths at the Schoorl, Westduinen, and Zwanenwater sites.*

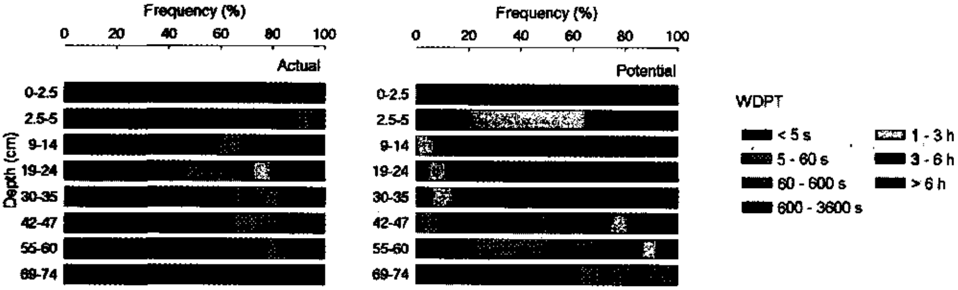


Fig. 3.6 *Relative frequency of the degree of actual and potential water repellency of samples (n = 240), at several depths in the dune sand at Ouddorp, sampled on November 28, 1995.*

Thus, the water repellent layer under a gray hair grass cover was generally found to be thinner than that under buckthorn, pine, heather, and various grass vegetations. The more rapid decrease of water repellency with depth under the grey hair grass cover is also due to lower organic matter contents at shallow depths.

Spatial Variability of Potential Water Repellency

The severity of potential water repellency differ from place to place under similar circumstances as regards the vegetation type. For example, potential water repellency varied from wettable to strongly water repellent in the topsoil and subsoil of the dune sands with a sparse marram grass vegetation (Fig. 3.4). Wettable to extremely water repellent sand was established at depths of 5-30 cm at the locations with grey hair grass. The locations with buckthorn, pine, heather, and grass vegetations also showed major variations in the severity of potential water repellency, especially in the layers at depths of 5-50 cm.

The spatial variability of potential water repellency was also high for samples taken within short distances of each other in the soil blocks of the Schoorl (pine), Westduinen (grey hair grass), Zwanenwater (grass) and Ouddorp (pasture) sites. For example, WDPTs ranged from 60 s to more than 6 hours over a horizontal area of only 0.19 m^2 at depths of 7-12 cm at the Westduinen site (Fig. 3.5). The Ouddorp soil block, with horizontal planes of 0.6 m^2, also showed a wide range of WDPT values (Fig. 3.6, right hand panel). As shown in this diagram, the most severe potential water repellency was found in the 9 to 35 cm zone. Deeper in the profile, potential water repellency decreased, although it could still be detected in the 69-74 cm layer. It seems likely that the most extreme water repellency found in the 9-14 cm soil layer obstructs infiltrating wetting fronts most effectively, causing instability at this depth.

Actual Water Repellency and Critical Soil Water Content

Water movement can be severely restricted by the dry water repellent dune sand topsoils. Rain that falls on the surface of water repellent sand does not penetrate evenly but moves downwards through narrow channels, leaving the intermediate soil quite dry and causing considerable variation in the moisture content and actual water repellency of the sand. Figure 3.6 (left-hand panel) shows the frequency of various classes of actual water repellency for all field-moist samples from Ouddorp (1920 in all), indicating that soil water repellency was restricted to the 2.5-60 cm zone at the moment of sampling. The highest degree of actual water repellency was found in the 9-14 and 19-24 soil layers. Even at depths of 55-60 cm, actual water repellency was distinct in approximately 60 of the 240 samples.

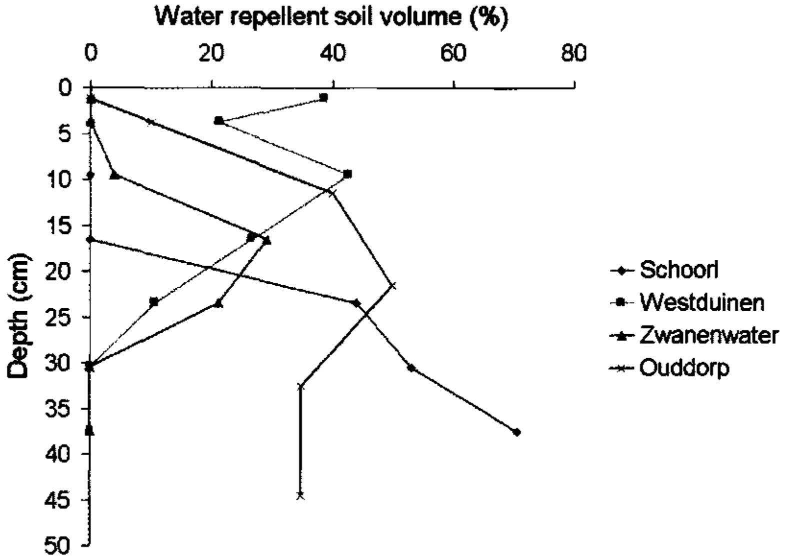


Fig. 3.7 *Relative frequency of the actually water repellent soil volume at several depths at the four dune sand sites.*

Water contents of the layers sampled at the Ouddorp, Westduinen, Schoorl and Zwanenwater sites ranged from 0.6 to 71.7 vol% (Table 3.1). Some of the samples, with relatively low water contents, taken at depths of 2.5-60 cm at Ouddorp, at depths of 21-40 cm at Schoorl, at depths of 0-26 cm at Westduinen, and at depths of 14-26 cm at the Zwanenwater site, were determined to be actually water repellent, whereas all or nearly all samples from the other depths were actually wettable. Figure 3.7 shows the relative frequencies of actually water repellent soil samples from the four dune sand sites at the moment of sampling.

A "critical soil water content" exists above which a water repellent soil layer becomes wettable (Chapter 2). These critical soil water contents were determined for each layer on the basis of the complete set of individual WDPT measurements carried out on field-moist samples from the Ouddorp site during several studies (Dekker and Ritsema, 1984b, Ritsema and Dekker, 1996b). Soil samples in each layer were divided into actually wettable and actually water repellent, and critical soil water contents were established, making use of the measurements of the present and previous studies (Fig. 3.8). At water contents to the left of the line, the soil is

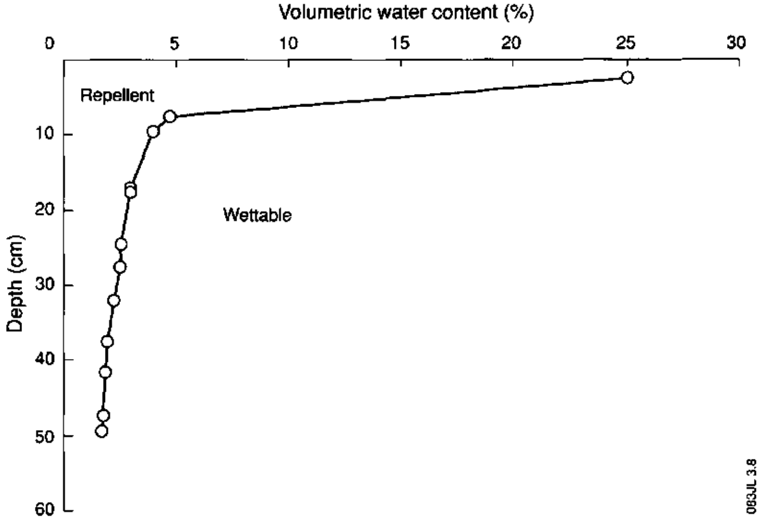


Fig. 3.8 *Critical soil water contents versus depth for the Ouddorp site, indicating actually wettable soil to the right, and actually water repellent soil to the left of the line.*

water repellent; to the right it is wettable. Water repellency depends strongly on water content, which varies with depth. Therefore, water repellency will affect water flow mainly in initially dry soil, and its influence will be less significant under wetter soil conditions.

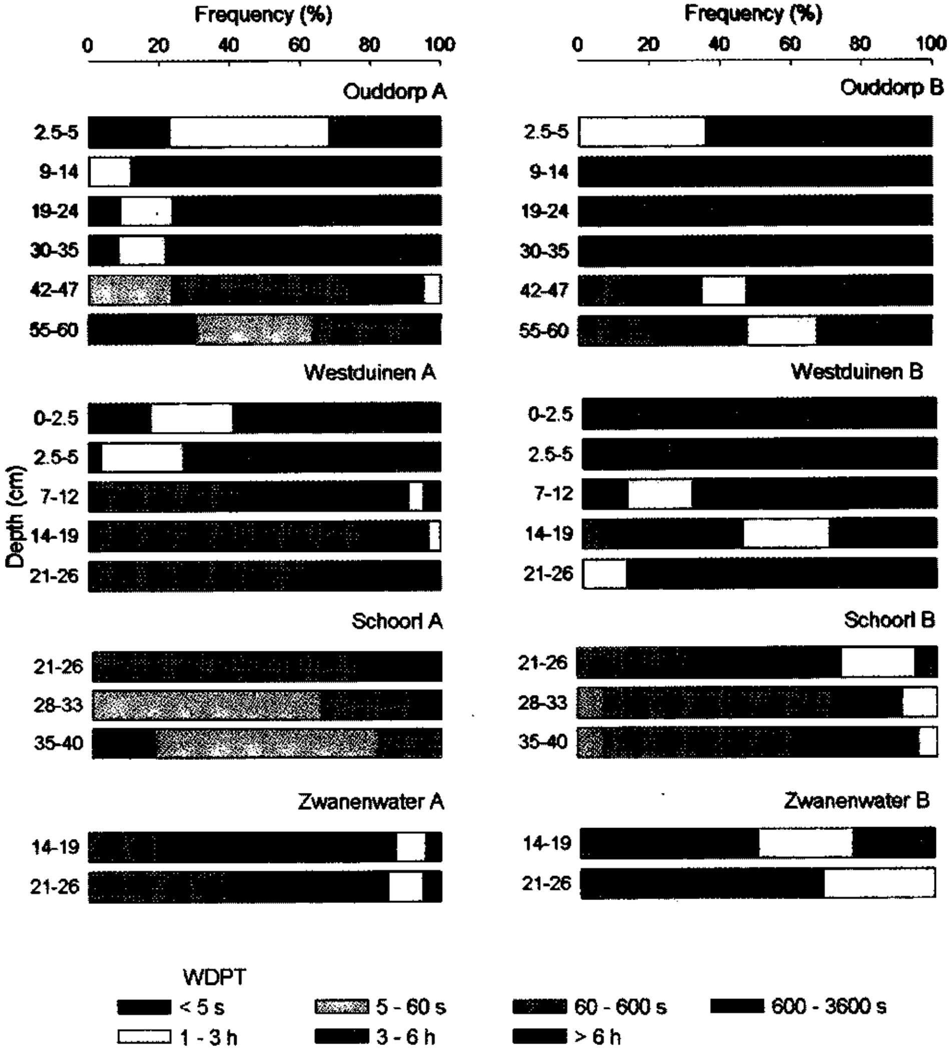


Fig. 3.9 *Relative frequency of the degree of potential water repellency of (A) initially wet (actually wettable) and (B) initially dry (actually water repellent) samples from several depths at the four sites.*

Actual Versus Potential Water Repellency

Spatial variations in the degree of potential water repellency might be caused by a heterogeneous distribution of water repellent humic substances within the soil. In contrast with the actual water repellency, which may change rapidly in time because of changing soil water contents, the potential water repellency is a more or less time-independent soil property, as much time is needed to change the quantity and/or quality of the water repellent humic substances within a volume of soil.

The left-hand diagram of Figure 3.9 shows that all actually wettable field-moist samples from depths of 2.5-47 cm at the Ouddorp site became slightly to extremely water repellent after drying. The right-hand diagram at the top of Figure 8.6 shows, however, that the potential water repellency of the actually water repellent samples was significantly greater.

The actually water repellent dune sand samples from the Westduinen, Schoorl, and Zwanenwater sites also exhibited significantly greater water repellency than the actually wettable ones after drying, as can be seen by comparing the right-hand with the left-hand diagrams in Figure 3.9.

Fig. 3.10 *Characteristic moisture patterns in a horizontal plane at a depth of 5 cm in a dune sand covered by grey hair grass and mosses.*

Moisture Patterns and Spatial Variabilty in Soil Water Content

Visual observation of wetting patterns in trenches dug in the water repellent dune sands revealed that water moved downwards through narrow channels, leaving the adjacent soil volumes dry and causing considerable variation in soil water content (Fig.3.10). The channels, tongues or preferential flow paths offer less resistance to wetting due to a lower degree of water repellency or to ponding on the surface in shallow surface depressions where the hydrostatic pressure aids water entry.

The variation in water content and the occurrence of irregular wetting patterns can be easily established by intensive soil sampling, as is shown for all four sites (Table 3.1). The mean water contents of layers sampled in the four soil blocks varied between 1.3 and 37.3 vol%. The highest water contents were found in the surface layers, which have higher organic matter contents and lower dry bulk densities. The difference between minimum and maximum water content was often high for all soil layers sampled (Table 3.1).

The variation in water content within short distances is shown by means of contour plots of horizontal and vertical planes for the Schoorl, Zwanenwater, and Westduinen sites (Fig. 3.11). Wet spots and dry spots can be distinguished in the contours of the top views, whereas wet preferential flow paths and adjacent dry soil bodies are evident in the side views.

The water content distribution within the soil block sampled at Westduinen, covered by grey hair grass and mosses, was visualized three-dimensionally (Fig.3.12). In addition to a water content iso-surface, a horizontal cutting plane at a depth of 20 cm and a vertical cutting plane were also visualized. The color legend indicates water contents ranging from 0.6 to > 8 vol%. Distinct fingerlike patterns were detected in this soil block, sampled on August 16, 1996. Visualizing different water content iso-surfaces allowed us to derive an optimum water content at which the finger flow patterns showed up clearly. Fig. 3.12 shows the 5 vol% moisture iso-surface. Higher moisture contents were observed above and within the "fingers", while drier soil, as low as 0.7 vol%, was found in between the fingers. The fingers formed at a depth of around 5 cm, which corresponds roughly with the boundary between the humose topsoil and the underlying dune sand, which contains less organic mattter.

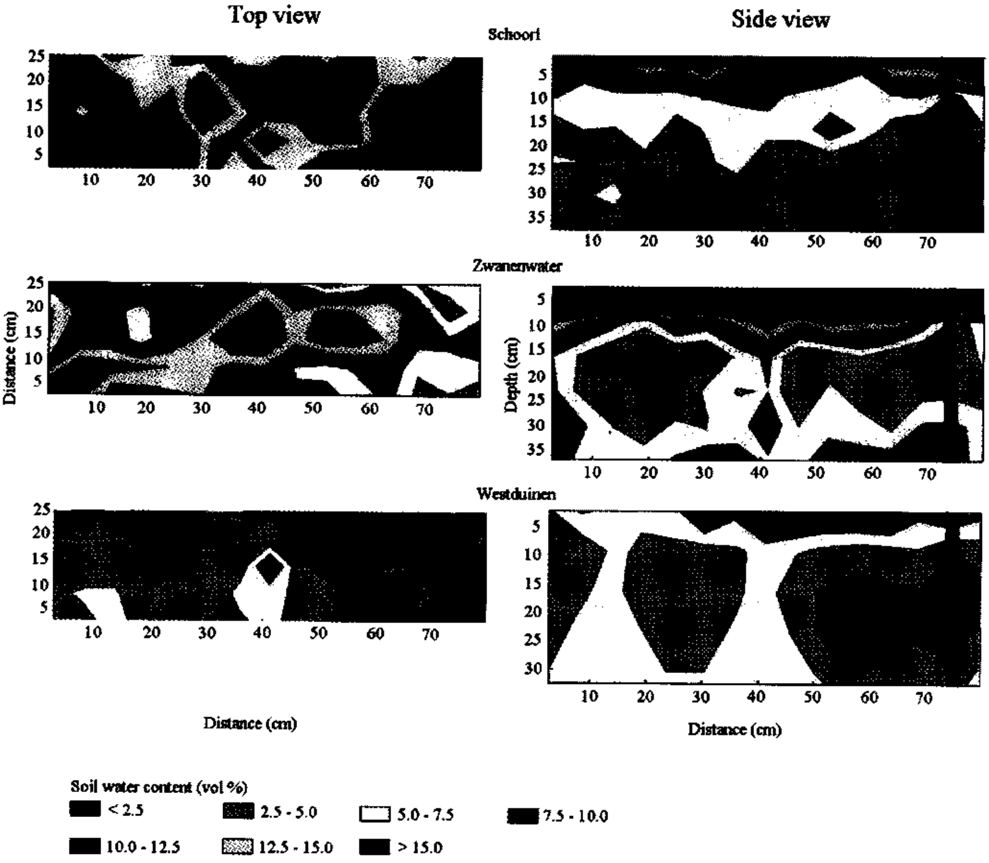


Fig. 3.11 *Contours of the volumetric soil water contents in horizontal and vertical planes at the Schoorl site on November 4, 1996, at the Zwanenwater site on October 30, 1996, and at the Westduinen site on August 16, 1996. The top views of the sites are situated at depths of 2.5-5, 7-12, and 14-19 cm, respectively.*

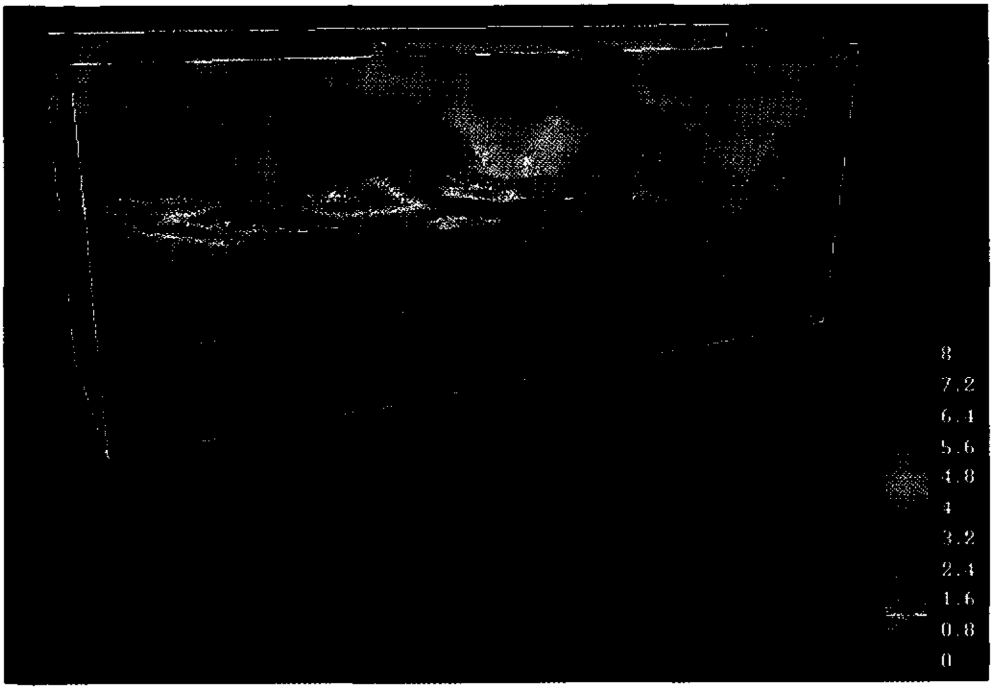


Fig. 3.12 *Three-dimensional soil water content distribution with intersecting horizontal and vertical planes in the soil block excavated at the Westduinen site on August 16, 1996. Values in the legend indicate volumetric water contents in vol%. The red color indicates dry soil with a water content of less than 1 vol%, while the purple color refers to a water content of around 7 vol%.*

Resistance to Wetting of Field-Moist Samples

The wetting rate of field-moist samples was measured for samples taken at depths of 0-5, 7.5-12.5, 29-34, 42.5-47.5 and 50-55 cm at the Ouddorp site. At each depth, samples were taken in duplicate, one in a wet finger and the other in between the fingers in the drier sand. The initial water contents of these samples are indicated in the diagram of Figure 3.13. It is evident from the curves in the diagram that wetting is faster and results in higher water contents, when the initial water content of sand is greater. The dry samples from depths of 7.5-12,5, 29-34 and 50-55 cm, with initial soil water contents ranging from 1.0 to 2.2 vol%, did not wet at all during the 7 day experiment.

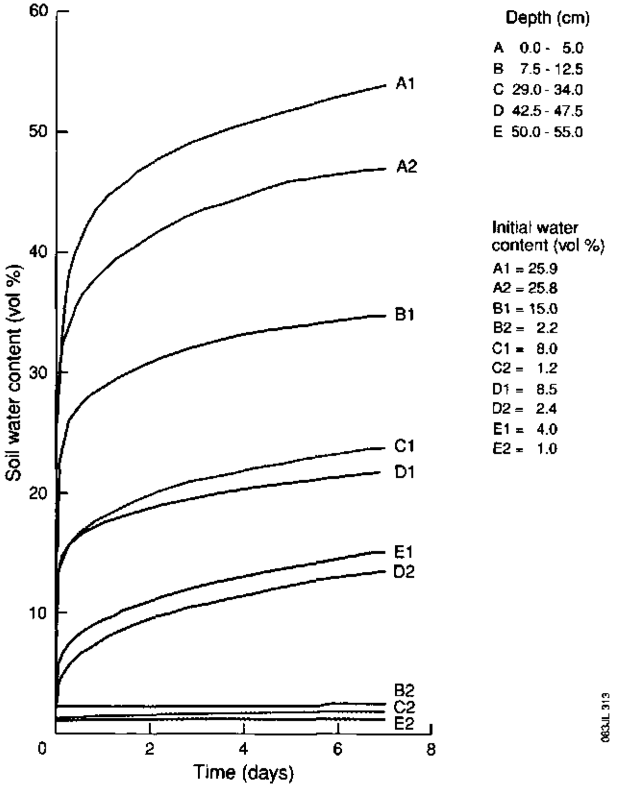


Fig. 3.13 *Volumetric water content versus time of field-moist dune sand samples taken at several depths at the Ouddorp site, and placed at a constant pressure head of -2,5 cm water applied to the bottom of the samples.*

3.4. CONCLUSIONS

The surface layer of nearly the whole coastal dune sand area in the Netherlands is water repellent during dry spells. Wettable sand was only found in the yellow sands of the foredunes, which are sparsely vegetated with marram grass and have a low organic matter content. The samples taken at a depth of 0-5 cm in the surface layer at the sites with different vegetations were all strongly to severely water repellent. At all these sites, the severity of water repellency decreased with depth.

The decrease was most evident at the sites covered by a vegetation of grey hair grass and mosses. No significant differences in water repellency were found between the other sites, which were covered by buckthorn, pine, oak, other grasses and heather.

The severity of potential water repellency differ from place to place under similar circumstances as regards to vegetation type. For example, the locations with buckthorn, pine, heather, and grass vegetations showed major variations in the severity of potential water repellency, especially at depths of 5-50 cm.

The spatial variability of potential water repellency was also high for samples taken within short distances of each other, as is shown with the soil blocks of the Schoorl (pine), Westduinen (grey hair grass), Zwanenwater (grass) and Ouddorp (pasture) sites.

The actually water repellent dune sand samples from these sites exhibited significantly greater potential water repellency than the actually wettable ones. The variation in soil water content and the occurrence of irregular wetting patterns can be easily established by intensive soil sampling.

CHAPTER 4

EFFECT OF MAIZE CANOPY AND WATER REPELLENCY ON MOISTURE PATTERNS

Adapted version of "Effect of maize canopy and water repellency on moisture patterns in a Dutch black plaggen soil" by Louis W. Dekker and Coen J. Ritsema, published in Plant and Soil 195: 339-350, 1997.

4 EFFECT OF MAIZE CANOPY AND WATER REPELLENCY ON MOISTURE PATTERNS

Abstract

Man-made raised sandy soils in the Netherlands are classified as "brown" or "black" plaggen soils. When dry, the brown soils are wettable, but the black soils are water repellent. For one growing season, transects were sampled in a maize cropped black plaggen soil at the Heino experimental farm. Due to interception and stemflow, water was concentrated near the roots of the maize. Between the maize rows, higher soil water contents were found in microdepressions, due to rainwater dripping to the ground from overhanging leaves. Redistribution of soil water from wet to dry areas was restricted by the water repellency of the dry sand. As a consequence, there was a distinct variation in soil moisture content. These irregular wetting patterns did not induce preferential downward flow, but widened over time; because the dry, water repellent subsoil impeded and resisted infiltration into the deeper subsoil.

4.1 INTRODUCTION

The transport of water and solutes through the soil is often much more complex than is assumed and formulated in traditional models (Philip, 1991; Jury and Flühler, 1992; Addiscott, 1993; Hillel, 1993). One of the main simplifications in simulation models is that water and solutes are equally distributed at the soil surface. In reality, spatial differences exist, which are due to a number of factors such as stemflow around trees and plants, water repellency, and distribution flow in the surface layer of the soil (Ritsema and Dekker, 1995).

Nonuniform distribution of precipitation beneath forest trees has long been recognized (Hoppe, 1896; Horton, 1919). Forest hydrologists have ackowledged the importance of interception, stemflow, leaf drip, and stem drip on the water economy of individual trees and of entire forests, and have examined the effects of nonuniform distribution on the induction of spatial differences in soil water content (Specht, 1957; Voigt, 1960; Rutter, 1964; Gersper and Holowaychuk, 1970a,b;

Crabtree and Trudgill, 1985; Neal et al., 1991).

Relatively few authors have examined the importance of stemflow in cropped soils. Wollny (1890) showed that 12-55% of the rainfall could be intercepted by maize and soybeans. Horton (1919) recognized that interception by mature crops may approach that of trees. Considerable amounts of stemflow have been recorded for maize (Kiesselbach, 1916; Haynes, 1940; Glover and Gwynne, 1962; Van Elewijck, 1989a,b; Parkin and Codling, 1990; Bui and Box, 1992), resulting in the positive effects of stemflow on soil moisture storage around the maize roots (Van Wesenbeeck and Kachanoski, 1988; Van Wesenbeeck et al., 1988).

Infiltration rates into dry, water repellent, sandy soils are low (DeBano, 1969; Dekker and Jungerius, 1990). Considerable variations in soil water content and irregular wetting patterns in water repellent horizons have been reported by Jamison (1945), Krammes and DeBano (1965), Bond (1964, 1972), Ritsema and Dekker (1994b), and Dekker and Ritsema (1994b, 1995, 1996b).

In the Netherlands, water repellent soils are widespread (Dekker, 1988) and they often show irregular moisture patterns, which may lead to accelerated transport of water and solutes to the groundwater and surface water (Hendrickx et al., 1993; Ritsema et al., 1993). These studies found rapid movement of water through a dune sand soil and early arrival of solutes in the groundwater. The soil concerned was water repellent to a depth of about 45 cm and the groundwater table fluctuated between depths of 60 and 150 cm below the soil surface. The present study was performed at the Heino experimental farm on a sandy soil with a thick, water repellent A horizon and with the groundwater table always below a depth of 2 m. The soil is a black, man-made raised, so-called plaggen soil, which for centuries has been fertilized with a mixture of manure and sods, litter or sand.

Measurements of differences in soil water content over short distances, as implemented for several soils by Dekker and Ritsema (1994b, 1995, 1996c,d) have never been performed in black plaggen soils.

Therefore, the objectives of the present study were to assess the variability of soil water content over short distances in a water repellent black plaggen soil growing a maize crop, and to relate the observed irregular wetting patterns to the processes of stemflow, leaf drip, soil water repellency and to microtopographical depressions.

4.2 ORIGIN AND DISTRIBUTION OF PLAGGEN SOILS

Plaggen soils have developed in the Pleistocene sandy areas of the Netherlands, Belgium and Northwest Germany as a result of a stabling system called "potstal" (Fastenabend and Von Raupach, 1961; Pape, 1970; Conry, 1974; Eckelmann, 1980). The system dates from the Middle Ages (Spek, 1992), when the sandy soils had to be manured for greater productivity and was used until the introduction of artificial fertilizers towards the end of the last century. Because these soils were too poor to recover through a fallow period alone, a management system was developed in which as much manure was gathered as possible. For this purpose the livestock - both cattle and sheep- were stabled at night to restrict manure losses. Because sheep produce more dung than cattle, few cattle were kept, catering only for the houshold's needs. Large amounts of litter and earth were used in the stables to absorb the liquid components of the manure in such a way that a tolerable bedding for the animals could be obtained. The litter used consisted of heather sods, grass sods, forest litter, peat and sand, and this dung-impregnated bedding of the stables was used to manure the arable land.

As a consequence, the arable fields were gradually raised, changing podzol soils into anthropogenic soils sometimes down to a depth of 1.5 m, the so-called plaggen soils (called Plaggenböden in Germany, and Plaggengronden in Belgium). In the Netherlands, there are more than 221,000 ha of plaggen soils, with a humose sand cover which is usually 50-80 cm thick (Fig. 4.1). The area of these soils represents approximately 6.5% of the country's surface area. In the American classification system (7th Approximation), plaggen soils are labelled as sandy, silicious, mesic, plaggepts, and are included in the order of the inceptisols. According to the system of soil classification used in the Netherlands, they are classified as "enk" earth soils (De Bakker, 1979). On the basis of the colour of the humose topsoil, the "enk" earth soils are classified further into brown and black plaggen soils, called brown and grey plaggen soils in the German system (De Bakker, 1979). In the Netherlands less than 10% of the plaggen soils are brown and more than 90% are black (so called because they are black when wet, though they are actually grey when dry).

It is generally assumed that the black colour indicates the deposition of manure mixed with heather sods. The black plaggen soils have a number of typical properties, as was described by Pape (1970) and Eckelmann (1980). The most important chemical properties are: (1) an organic matter content of about 5%; (2) a strongly acid reaction, pH of about 4; (3) a high total phosphate content of more than 100 mg P_2O_5 per 100 g soil, of which only 10-15% is available for uptake by plants; (4) a high C/N ratio of 18-22.

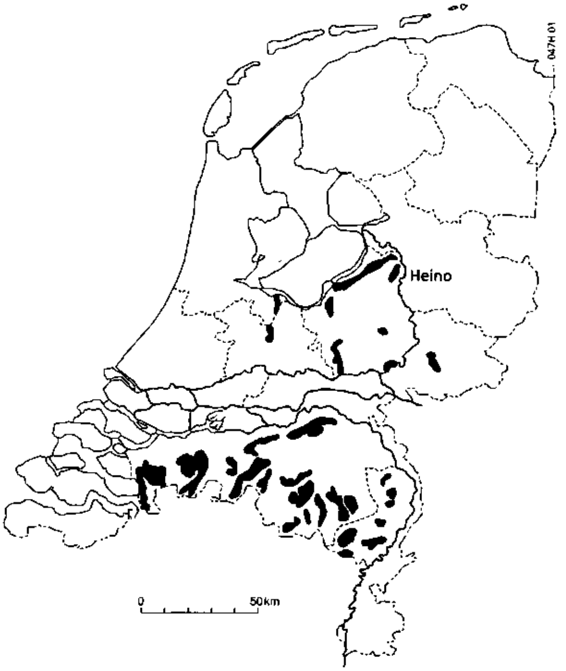


Fig. 4.1 *Schematic map showing the Heino site and the distribution of plaggen soils in the Netherlands.*

The brown plaggen soils are more clayey and loamy and have a lower C/N ratio (13-16) and a higher base saturation than their black counterparts. Pape (1970) showed that the higher clay contents are due to the use of clayey sods as plaggen material.

Dekker (1988) studied the water repellency of Dutch plaggen soils in a large area to the northwest and northeast of Arnhem. He collected samples of more than 150 black and brown plaggen soils. All brown plaggen soil samples were wettable and nearly all black plaggen soil samples were slightly to extremely water repellent.

4.3 MATERIALS AND METHODS

Experimental Site

The variation in soil water content was studied in a black plaggen soil at the Heino experimental farm in the eastern part of the Netherlands (Fig. 4.1). The anthropogenic, humose, sandy, A-horizon there is approximately 70 cm thick. The regularly ploughed 25 cm thick topsoil has an organic matter content of 4.3%. The subsoil at depths of 25-70 cm contains 4.6-5.0% organic matter, while 4.0% was found for the top of the old podzol profile, starting at a depth of approximately 70 cm.

The soil has been used as arable land for decades and was cropped with maize during the study period. The maize had been planted in rows about 75 cm apart.

Soil Water Content and Dry Bulk Density Measurements

Volumetric water content was determined by sampling the soil at different depths using steel cylinders (100 cm^3), with a height and diameter of 5 cm. The cylinders were pressed vertically into the soil and emptied into plastic bags. The plastic bags were tightly sealed to minimize evaporation. The wet soil in the plastic bags was weighed, dried for several days at 65^0C, and weighed again to determine soil water content and dry bulk density.

During the growing season the soil was sampled 5 times between June 5 and September 18, 1989. Twenty five samples were taken at depths of 10-15, 25-30, and 40-50 cm, at close intervals along 150 cm transects, starting and ending in a maize row.

The crop of maize for silage was harvested in the last week of September 1989. The soil was then sampled again at depths of 10-15 and 25-30 cm on October 5, 1989, taking 100 samples at each depth, at 18.75 cm intervals along a 18 m transect, including 25 maize rows.

After the harvest the soil was sampled for moisture content and dry bulk density at three depths on October 12, 1989, at four depths on November 1, 1989, and at five depths on December 11, 18, and 28, 1989. At each depth, 75 samples were taken at 6 cm intervals along 450 cm transects.

Water Repellency Measurements

The degree of potential water repellency was measured using the water drop penetration time (WDPT) test (e.g. Krammes and DeBano, 1965; Watson and Letey, 1970; Dekker and Ritsema, 1994b). Twenty five samples were taken at close intervals, at depths of 0-5, 10-15, 20-25, 30-35, 40-45, 50-55, 60-65, and 70-75 cm. The samples were dried at 65°C for several days. After drying, the samples were kept at a constant temperature of 20°C and a relative air humidity of 50%, for at least two days, to allow the samples to equilibrate with the ambient air humidity. Three drops of distilled water from a standard medicine dropper were placed on the smoothed surface of the samples, and the time to penetrate into the soil was recorded. In general, a soil is considered water repellent if the WDPT exceeds 5 s (e.g. Bond and Harris, 1964; DeBano, 1981; Dekker and Ritsema, 1994b).

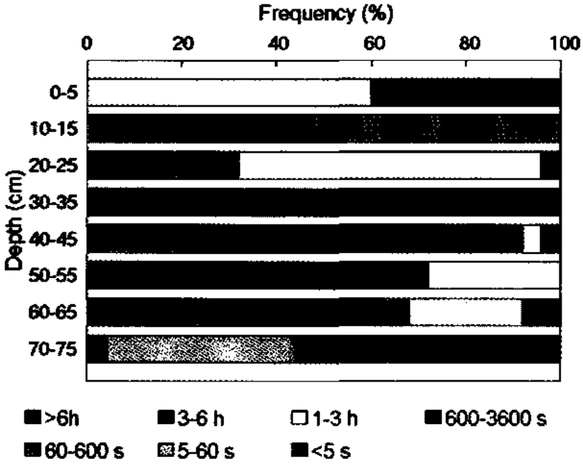


Fig. 4.2 *Relative frequency of the degree of potential water repellency of samples (n = 25) at eight depths in the black plaggen soil at Heino.*

Wetting Rate Measurements

Resistance to wetting was determined by measuring the wetting of samples after they had been dried at 65°C. Samples were taken at depths of 10-15, 20-25, 30-35, and 50-55 cm. These samples, within their steel cylinders (100 cm^3), with a height and diameter of 5 cm, were subjected to a constant pressure head of -2.5 cm water from below the bottom of the sample (Fig. 8.2, Chapter 8). The experimental set-up was designed in such a way that water content increments of 0.2 vol% were recorded automatically over a period of one week (Dekker and Ritsema, 1996c).

4.4 RESULTS

Degree of Water Repellency

The black plaggen soil studied was grey and water repellent during dry spells, and in this condition the soil could only absorb water with difficulty. Figure 4.2 shows the degree of potential water repellency, expressed as WDPT, of dried samples taken at eight depths. All samples from the A-horizon (taken at depths between 0 and 65 cm) exhibited strong to extreme water repellency. Water drops often remained on their surfaces for hours, especially on those sampled at depths between 30 and 65 cm. Of the samples taken at depths of 70-75 cm some were slightly water repellent and others wettable.

Table 4.1 *Soil water content and dry bulk density per depth (n = 25) for five trenches.*

	Soil water content			Dry bulk density			
Depth (cm)	Mean (vol%)	SD (vol%)	CV (%)	Mean (g/cm³)	SD (g/cm³)	CV (%)	*r*
				June 5, 1989			
10-15	23.3	4.1	17.6	1.39	0.07	5.0	+0.40
25-30	20.8	2.4	11.5	1.37	0.05	3.6	+0.59
40-45	16.7	0.8	4.8	1.35	0.02	1.5	+0.09
				June 26, 1989			
10-15	10.3	1.1	10.7	1.40	0.07	5.0	+0.73
25-30	12.8	2.1	16.4	1.43	0.05	3.5	+0.66
40-45	12.6	1.0	7.9	1.37	0.02	1.5	+0.16
				July 3, 1989			
10-15	19.7	5.1	25.9	1.44	0.10	6.9	+0.49
25-30	17.6	3.6	4.9	1.49	0.05	3.4	+0.09
40-45	13.1	1.5	11.5	1.35	0.03	2.2	+0.29
				July 24, 1989			
10-15	18.5	5.1	27.6	1.48	0.06	4.1	+0.19
25-30	13.6	2.3	16.9	1.52	0.04	2.6	+0.52
40-45	10.1	0.5	5.0	1.40	0.04	2.9	+0.54
				September 18, 1989			
10-15	17.7	4.0	22.6	1.46	0.09	6.2	+0.09
25-30	12.6	4.1	32.5	1.46	0.03	2.1	-0.28
40-45	10.5	2.8	26.7	1.40	0.03	2.1	+0.65

Here, SD denotes standard deviation, CV denotes coefficient of variation, and *r* is the correlation coefficient for the relationship between dry bulk density and volumetric soil water content.

Spatial Variability of Soil Water Content and Wetting Patterns

Soil water content varied for all depths on all sampling days in the trenches dug during the growing period of the maize (Table 4.1). The June 26 trench was the driest, with mean soil water contents between 10.3 and 12.8 vol%. The June 5 trench was the wettest, with mean water contents between 16.7 and 23.3 vol%.

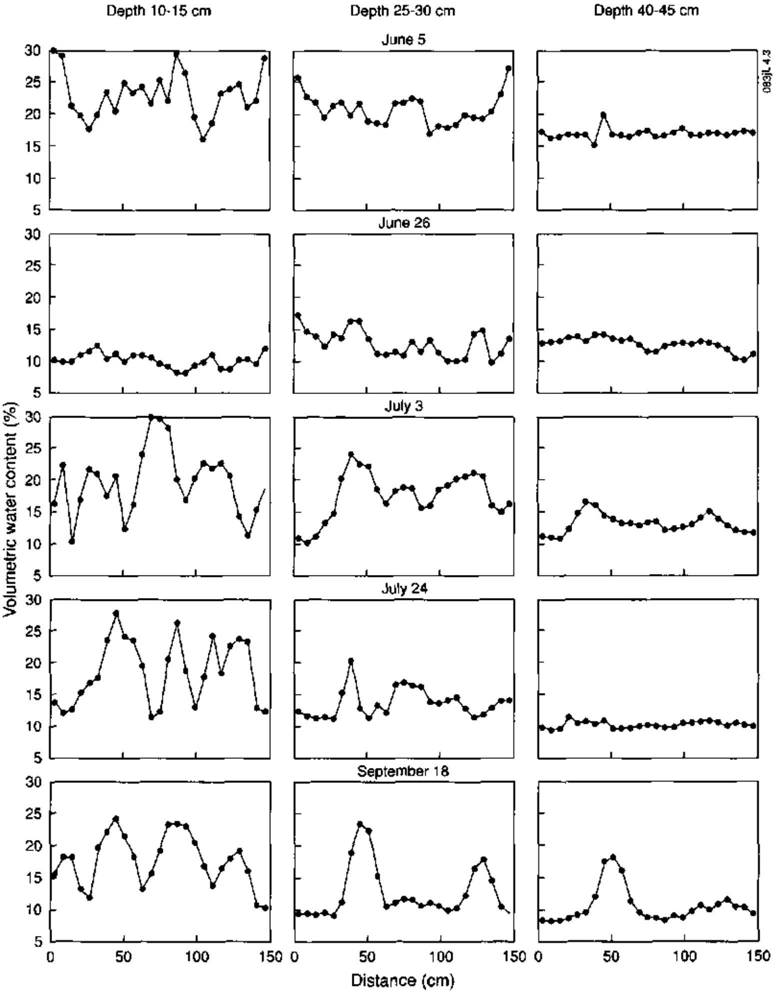


Fig. 4.3 *Volumetric soil water content at three depths over a distance of 150 cm (including 3 maize rows) on five sampling days during the growing season of 1989.*

The variations in soil water content of the samples taken at close intervals at three depths in the five trenches are shown in Figure 4.3. Huge differences, with water contents varying between 10 and 30 vol%, occurred at depths of 10-15 cm in the July 3 and July 24 trenches. Wetting patterns were present (the peaks in the diagrams) at several depths and on several sampling days (Fig. 4.3). Small differences in soil water content occurred for example at depths of 40-45 cm in the June 26 and July 24 trenches.

Fig. 4.4 *Soil moisture patterns (dark areas) in the water repellent black plaggen soil at Heino on September 26, 1989.*

On September 26, 1989, when maize crop had just been harvested, distinct moisture patterns were found in the black plaggen soil (Fig. 4.4). Due to interception and stemflow, water was funnelled towards the roots, and thus concentrated in the maize rows. But distinctive wetting patterns were also formed between the maize rows, caused by rain water dripping to the ground from overhanging leaves. Microtopographical depressions further concentrated the water that dripped down. The difference in elevation between the top of the row and the bottom of the interrow was about 7 cm. Figure 4.4 shows clearly wetter soil areas near the roots in the maize row and halfway between the maize rows. The transport of water took place mainly through these wetter portions. Side and downwards movement in the wet soil portion was restricted because of the actual water repellency of the dry sand. As a consequence, the difference in soil water content was considerable.

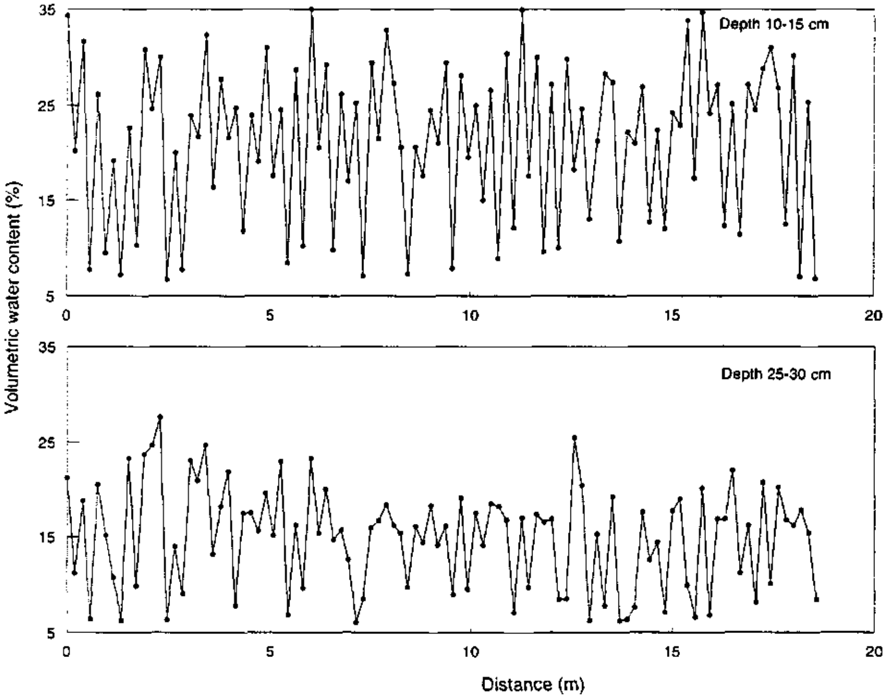


Fig. 4.5 *Variation in soil water content at two depths over a distance of 18 m on October 5, 1989.*

Figure 4.5 shows the great variability of the soil water content for samples taken at depths of 10-15 and 25-30 cm on October 5, 1989, after the maize had been harvested. High soil water contents were found halfway between the maize rows (interrows) and under the maize rows. Low soil water contents were present in the dry, actually water repellent soil pockets or zones between the rows and interrows.

During the three months after the harvest no tillage took place. We sampled the stubbly, black plaggen soil five times. Samples were taken in trenches at several depths at 6 cm intervals over a distance of 450 cm. The mean, standard deviation, and coefficient of variation of the soil water content of the 75 samples per depth are summarized in Table 4.2. On October 12, the topsoil was wet at depths of 10-15 cm, with a mean water content of 20.6 vol%, whereas the subsoil was still dry, with a mean value of 8.5 vol% at depths of 40-45 cm. The deeper subsoil (not sampled) was also dry and water repellent at that time. Afterwards, the soil wetted gradually, but the deeper subsoil was still dry below about 50 cm on November 1 and below about 65 cm on December 11. During the period of December 11 to 28, the entire thick A-horizon and the top of the podzol profile at depths of 70-75 cm became wetted.

Table 4.2 *Soil water content and dry bulk density per depth (n = 75) for five trenches.*

	Soil water content			Dry bulk density			
Depth (cm)	**Mean (vol%)**	**SD (vol%)**	**CV (%)**	**Mean (g/cm^3)**	**SD (g/cm^3)**	**CV (%)**	***r***
				October 12, 1989			
10-15	20.6	3.3	16.0	1.44	0.06	4.2	+0.49
25-30	14.8	4.8	32.4	1.38	0.05	3.6	+0.40
40-45	8.5	2.3	27.1	1.34	0.03	2.2	+0.20
				November 1, 1989			
10-15	24.3	3.2	13.2	1.47	0.05	3.4	+0.45
25-30	17.9	4.0	22.3	1.42	0.05	3.5	+0.27
40-45	14.6	3.8	26.0	1.37	0.03	2.2	+0.38
55-60	9.9	2.0	20.2	1.27	0.03	2.4	+0.41
				December 11, 1989			
10-15	19.8	1.5	7.6	1.44	0.06	4.2	+0.69
25-30	17.3	1.8	10.4	1.42	0.05	3.5	+0.60
40-45	16.5	2.0	12.1	1.36	0.02	1.5	+0.22
55-60	15.1	3.2	21.2	1.28	0.03	2.3	+0.51
70-75	9.7	2.1	21.6	1.27	0.04	3.1	+0.04
				December 18, 1989			
10-15	25.9	2.2	8.5	1.46	0.05	3.4	+0.45
25-30	22.7	2.8	12.4	1.42	0.05	3.5	+0.50
40-45	21.9	1.7	7.8	1.36	0.03	2.2	-0.10
55-60	21.8	3.0	13.8	1.30	0.03	2.3	+0.31
70-75	16.5	4.6	27.9	1.27	0.03	2.4	+0.21
				December 28, 1989			
10-15	23.4	1.7	7.3	1.44	0.05	3.5	+0.77
25-30	20.3	2.1	10.3	1.39	0.06	4.3	+0.64
40-45	20.2	1.5	7.4	1.37	0.03	2.2	+0.02
55-60	22.5	1.4	6.2	1.30	0.03	2.3	-0.20
70-75	18.9	1.3	6.9	1.31	0.04	3.1	-0.26

Here, SD denotes standard deviation, CV denotes coefficient of variation, and *r* is the correlation coefficient for the relationship between bulk density and volumetric soil water content.

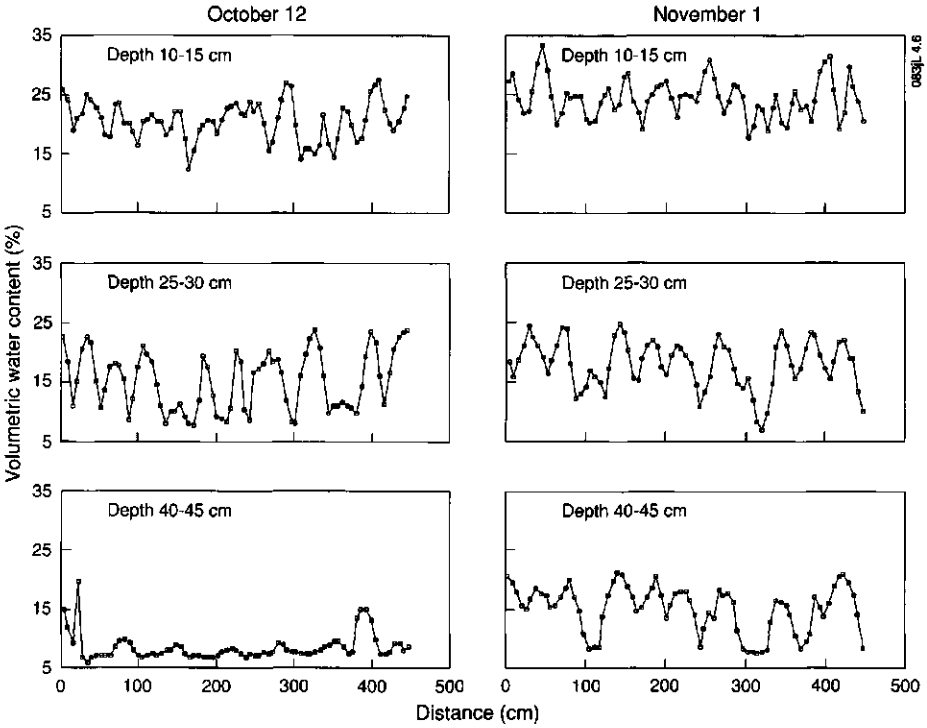


Fig. 4.6 *Soil moisture variability at three depths over a distance of 450 cm on October 12 and November 1, 1989.*

The spatial variation in the soil water content for three depths, measured on October 12 and November 1, are shown in Figure 4.6. Irregular wetting patterns with differences of 5-10 vol% in soil water content over short distances occurred in the two upper layers sampled on October 12 and in all three layers sampled on November 1. Figure 4.6 shows that the irregular wetting front had just reached the 40-45 cm layer in two places (the peaks in the diagram) on October 12, and that the wetting front had passed this depth in several places before November 1.

Figure 4.7 shows three contour plots with the water distribution in the soil on three sampling days, obtained with the help of the statistical computer program Genstat 5, release 2. On October 12, irregular wetting patterns occurred from the surface down to a depth of 30-35 cm, while very dry sand with a soil water content of 4-8 vol% was locally present at depths of 30-45 cm. Rain events between

October 12 and November 1, with a total amount of 37 mm, caused not only an increase in the water content of the surface layer, but also a slight wetting of the soil at depths of 40-50 cm. Between November 1 and December 11, precipitation amounted to 18.1 mm, which led to a deeper wetting front. However, rather wider soil moisture patterns were found and the spatial variability of the soil water content was obviously lower on December 11 than on the two previous sampling dates (Fig. 4.7).

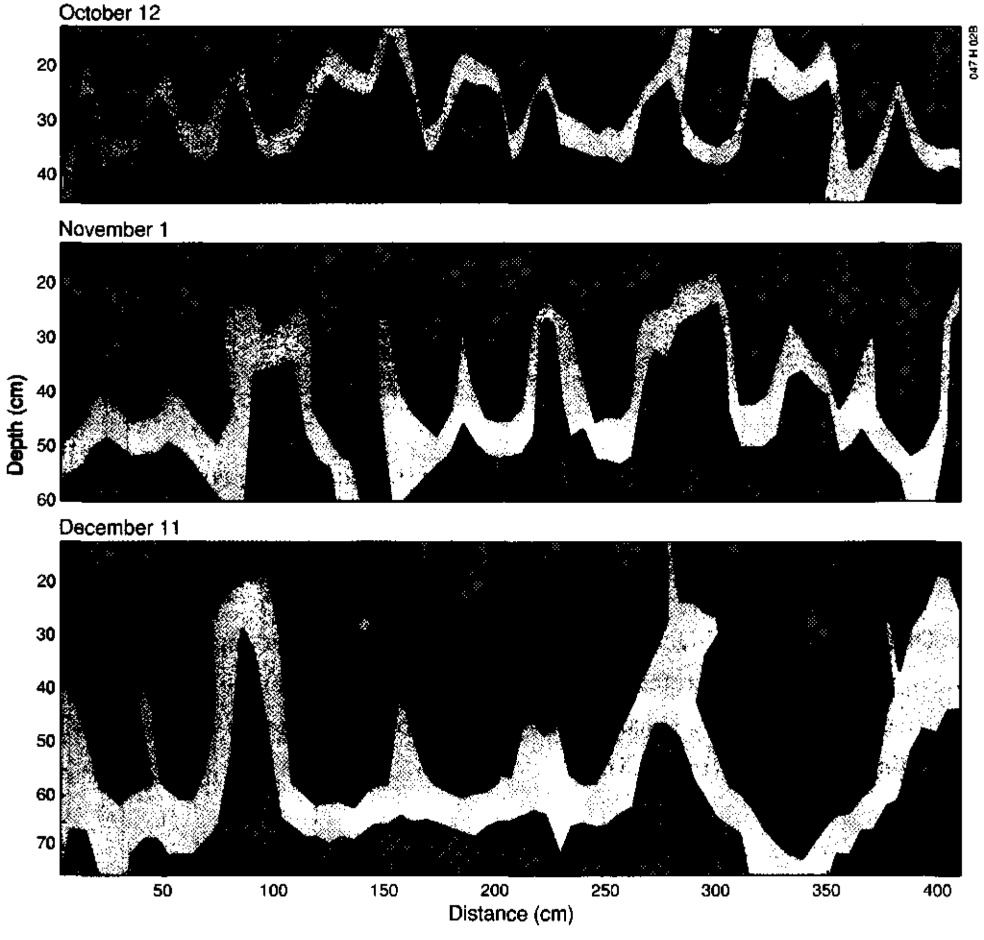


Fig. 4.7 *Contour plots showing the spatial distribution of the volumetric soil water content on October 12, November 1, and December 11, 1989.*

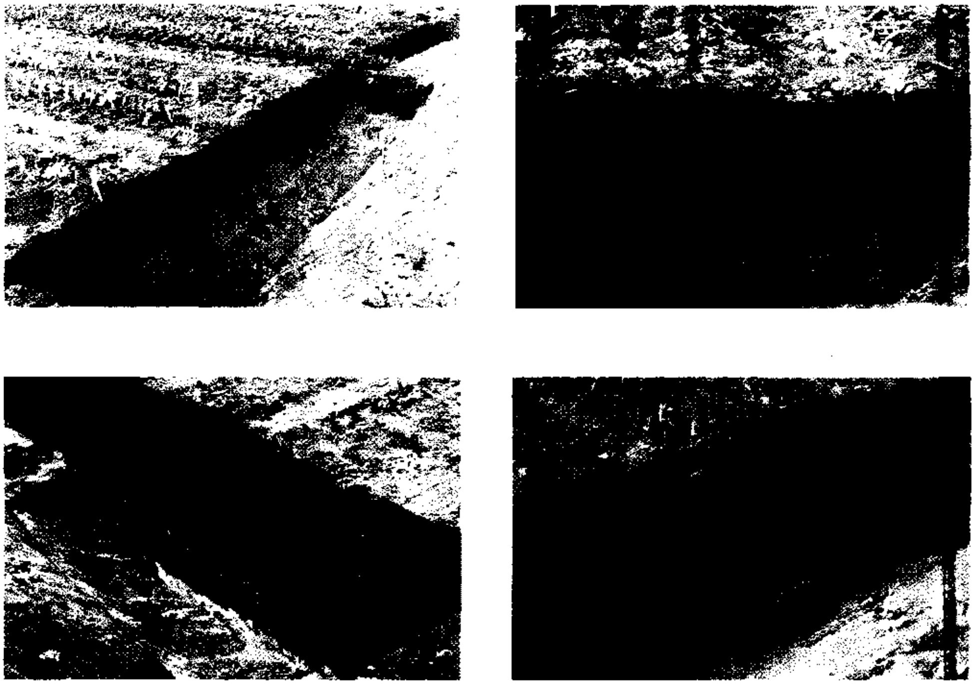


Fig. 4.8 *Sequence of soil moisture patterns in the black plaggen soil at Heino. The (black) irregular wetting patterns become wider and deeper during the rainy autumn of 1989.*

That water in this black plaggen soil unlike other water repellent soil did not move rapidly through preferential flow paths with gravity to the subsoil, shows the distribution of moisture (black parts) in the photographs made during the various sampling campaigns (Fig. 4.8).

Resistance to Wetting

In an effort to explain the flow patterns described in the previous section, laboratory measurements were made of the wetting capacities of different layers of the Heino site. Figure 4.9 shows great differences between topsoil and subsoil samples regarding the increase in water content versus time. Water uptake during one week by the samples from depths of 30-35 and 50-55 cm led to increases in the soil water content of only 0.5 and 1.6 vol%, respectively. By contrast, the increases in water content for the samples from depths of 10-15 and 20-25 cm were 24.1 and 23.5 vol%, respectively, over the same period of time. However, water uptake by both samples was slow during the first 20 hours, with increases in water content of only 1.8 and 1.2 vol%, respectively. From that time on, wetting was very rapid in both samples, followed by a decrease in the water uptake after two days, as the samples reached their equilibrium. This means that it is easier for the water to flow in lateral direction than downward in the water repellent dry subsoil.

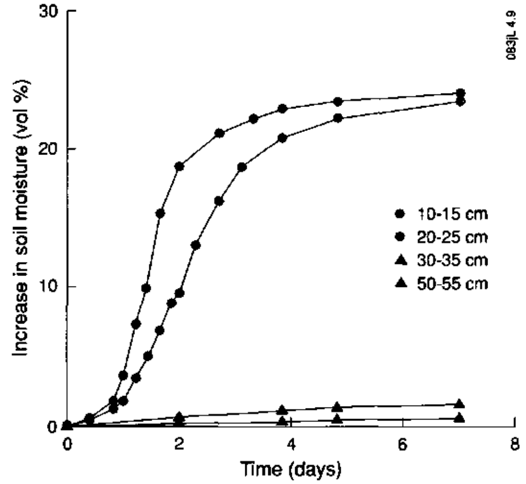


Fig. 4.9 *Increase in soil water content versus time of dried soil samples from the Heino site, placed at a constant pressure head of -2.5 cm water below the bottom of the sample.*

Dry Bulk Density and Soil Water Content

Besides the effect of the water repellency of the various layers on the observed wetting patterns, the relationship between dry bulk density and soil water content was investigated as well. Tables 4.1 and 4.2 summarize some statistics of the dry bulk density measurements. Mean dry bulk density values of 1.39-1.48 g.cm^{-3} were measured at depths of 10-15 cm, 1.37-1.52 $g.cm^{-3}$ at 25-30 cm, 1.27-1.40 $g.cm^{-3}$ at 40-45 cm, and 1.27-1.31 $g.cm^{-3}$ at 55-75 cm. The variation in the two upper (plow) layers was relatively high, with SDs of between 0.03 and 0.10 $g.cm^{-3}$ and CVs of between 2.1 and 6.9%. The variation in dry bulk density in the deeper layers was less, with SDs of between 0.02 and 0.04 $g.cm^{-3}$ and CVs of between 1.5 and 3.1%.

Tables 4.1 and 4.2 also list correlation coefficients between dry bulk density and soil water content. A negative relationship was found in 4 layers, with a correlation coefficient (r) between -0.10 and -0.28, while the relationship in the other 33 layers was positive, with r values ranging between +0.02 and +0.77. In general, no clear relationship could be found between dry bulk density and soil water content. It can be concluded that the variability of the soil water content in this particular soil was not clearly related to differences in dry bulk density. Stemflow, leaf drip, microtopography and water repellency were the main factors responsible for the formation of the irregular moisture patterns in this black plaggen soil.

4.5 CONCLUSIONS

In the black plaggen soil studied, stemflow and microtopography were found to play an important role in the occurrence of irregular wetting patterns. Wetter areas were established within the rows of the maize field, due to stemflow, and halfway between the rows, due to leaf drip and microtopographical depressions. The spatial variability of the soil water content was often found to be high. However, the irregular wetting patterns did not develop into distinct preferential flow paths. During the rainy autumn period, the wetting patterns extended, though not only in the vertical but also in the horizontal direction. It seems plausible that this can be attributed to the dry subsoil, which inhibits further downward movement of the infiltrating wetting front due to its extreme water repellent character (Fig. 4.2) and its low wetting rate (Fig. 4.9). Thus, when dry, the subsoil impedes and resists the deeper movement of water, and as a consequence the less water repellent parts in the topsoil between the wet zones are wetted first. After continuing rainfall, wetting patterns extend in all directions, but are most pronounced in the lateral direction, and thus become less irregular in time, as is illustrated by the photos in Fig. 4.8.

CHAPTER 5

WETTING PATTERNS IN A WATER REPELLENT SILT LOAM SOIL

Adapted version of "Fingerlike wetting patterns in two water-repellent loam soils" by Louis W. Dekker and Coen J. Ritsema, published in the Journal of Environmental Quality 24: 324-333, 1995.

5 WETTING PATTERNS IN A WATER REPELLENT SILT LOAM SOIL

Abstract

In soils with fingered flow, surface-applied solutes can reach the groundwater more rapidly than in the case of a homogeneous wetting. So far, fingered flow has been thought to be restricted to fine over coarse-textured soils and homogeneous sandy soils. The present study was undertaken to demonstrate the occurrence of fingerlike wetting patterns in a silt loam soil, and to investigate the influence of dry bulk density and water repellency on the observed soil moisture patterns. Fingerlike patterns were photographed and soil water contents determined by intensive soil core sampling. Dry bulk density was not a main factor in inducing wet fingerlike patterns and high water content variability. The persistence of potential water repellency was measured on soil samples using the water drop penetration time (WDPT) test. Spatial variability of potential water repellency and, accordingly, soil water contents were high. The actual water repellency was measured on field-moist samples to obtain critical soil water content values. The soil is wettable above and water repellent below these values.

5.1 INTRODUCTION

The phenomenon of fingered flow during infiltration into soils has attracted increasing interest since the work of Miller and Gardner (1962). They first documented that fingering can occur in a fine over coarse-textured profile. In laboratory infiltration experiments, they observed that as the water passed through the initially dry lower sand, "it characteristically wets up in only a few places with the rest of the sand remaining dry". The movement of water through the coarse sand was then restricted to the water-filled channels. In recent decades, there have been numerous laboratory studies specifically designed to examine wetting front instability for layered soils (e.g. Hill and Parlange, 1972; Diment and Watson, 1985; Baker and Hillel, 1990). The early laboratory experiments of Miller and Gardner (1962) and Hill and Parlange (1972) also served as a stimulus for theoretical analysis of the fingering phenomenon (Raats, 1973; Parlange and Hill, 1976).

Although observing fingering in the field using traditional field measurement techniques is extremely difficult, the use of dyes in infiltration water actually showed that fingering does occur in field soils (Glass et al., 1988). Van Ommen et al. (1988), and Hendrickx et al. (1993) observed fingers in sandy soils using a visualization technique with iodide as a tracer. Ritsema et al. (1993) demonstrated evidence of fingers in a water repellent sandy soil, by intensive soil core sampling, without using dye-staining techniques. Dekker and Ritsema (1994a) and Ritsema and Dekker (1994a) showed the occurrence of fingers by intensive sampling in vertical cross-sections of bare, homogeneous, wettable dune and beach sands.

Also in structured soils, water may not move in a homogeneous front through the soil. Lawes et al. (1882) found that a considerable part of the water added to soil profiles moves immediately through open channels and interacts only slightly with the water in the soil itself. Hursh and Hoover (1941) and Gaiser (1952) stated that the decomposition of roots, and their subsequent channelling by microorganisms and small insects create relatively large continuous openings that serve as hydraulic pathways for the rapid movement of water. Bodman and Colman (1943), however, found that when water was added to dry soils a distinct wetting front developed and that the maximum soil water content reached was approximately field capacity. It is apparent that among hydrologists, soil physicists, and soil scientists the findings of Bodman and Colman (1943) are the concepts generally held. For a long time, the rapid drainage reported by Lawes et al. (1882) has been completely ignored. Only in recent decades have soil scientists rediscovered these findings. Scientific publications that show such movement through structured soils include those by Elrick and French (1966), Ritchie et al. (1972), Ehlers (1975), Quisenberry and Phillips (1976), Bouma and Dekker (1978), Bouma et al. (1981), Beven and Germann (1982), Dekker and Bouma (1984), Edwards et al. (1988), and Roth et al. (1991). These reports all show that partial displacement of soil water occurs in structured soils when much of the water from rainfall or irrigation flows through macropores. Macropores may consist of interaggregate pore space, shrinkage cracks and fissures, root channels, or faunal tunnels; mechanically-induced fissures cut by the tine of the mole plough may also be important in promoting a fast flow response (Robinson and Beven, 1983). The macropores need not be very large to induce preferential flow. According to Scotter (1978) the minimum channel diameter for preferential flow is approximately 0.2 mm and the minimum crack width approximately 0.1 mm.

So far cracks and biopores (macropores) have generally been assumed to be the operational preferential flow paths in loam and clay soils. Measurements of soil water content within short distances, which can easily be obtained, as shown by Dekker and Jungerius (1990), Ritsema and Dekker (1994a,b) and by Dekker and Ritsema (1994a,b), have, we know, never been performed in such soils. The objectives of this study are (i) to show evidence of the occurrence of flow through the matrix (meso and micropores) of a silt loam soil in the Netherlands, and (ii) to investigate the influence of dry bulk density and water repellency on the observed moisture patterns.

5.2 MATERIALS AND METHODS

Experimental Site and Soil

In the Netherlands, many grass-covered loam and clay soils are difficult to wet after a prolonged dry period, due to the water repellent character of the topsoil. A site was selected on a permanent well-managed pasture, located at Yerseke Moer in the southwestern part of the Netherlands. Normal farming practices of grazing cattle and growing grass for fodder were continued during this investigation. The soil is classified as a mesic Typic Fluvaquent according to the U.S. Soil Taxonomy and as Eutric Fluvisol (FAO, 1988), and their parent material consists of non-calcareous, medium to fine-textured, illitic marine sediment.

The Yerseke Moer site has a silt loam (20% clay), humose, moderately fine, subangular blocky Ah horizon, from the 0- to 18-cm depth with a decreasing organic matter content from 15% at the top to 6% at the bottom. The subsoil from the 18- to 82-cm depth consists of a silt loam (22% clay) with moderately medium to fine prismatic and fine subangular blocky elements. The deeper subsoil up to 120 cm is a silty clay loam (28% clay), with a medium weak prismatic structure.

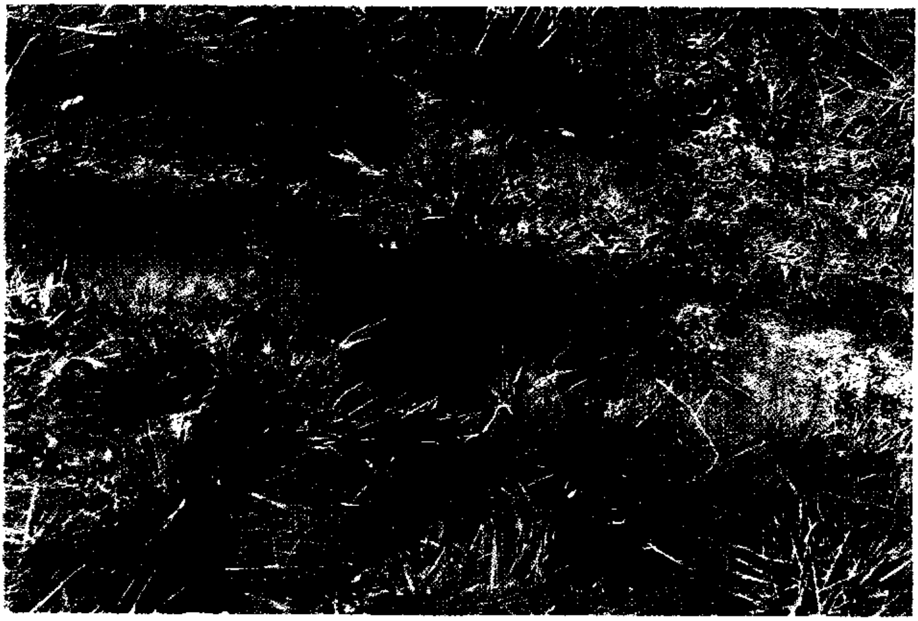


Fig. 5.1 *A wet thin distribution layer and fingerlike moisture pattern in a silt loam of the Yerseke Moer site on 24 November 1992.*

Fig. 5.2 *Dry soil areas still exist in the silt loam soil on 22 March 1993 after a long, wet winter period. The depth of the excavation is 20 cm.*

Soil Sampling

To determine volumetric water contents, the soil was sampled at different depths using steel cylinders (100 cm^3), with a height and diameter of 5 cm. At each depth 25 or 50 samples were taken at close spacings over a distance of 137 or 275 cm, respectively. The wet soil was weighed, dried for several days at 65°C, and weighed again to determine soil water content and dry bulk density. The soil was sampled six times (25 Mar. and 30 Dec. 1991, 21 Apr. and 21 Oct. 1992, and 15 Jan. and 23 Feb. 1993) to a maximum of 60 to 65 cm deep.

Persistence of Water Repellency

The persistence of potential water repellency was measured using the water drop penetration time (WDPT) test (Chapter 2).

The test was conducted on all dried samples taken for measurement of soil moisture content, with the exception of the 25 Mar. 1991 samples. All samples taken from the 0- to 5-cm depth were split up in an upper and a lower part.

After removing the samples from the oven, they were kept under controlled conditions, at a constant temperature of 20°C and a relative air humidity of 50%. The WDPT tests were deferred for at least 2 d to allow the samples to equilibrate with the ambient air humidity. We measured the WDPT of the samples up to at least 3600 s.

Using the WDPT-test on dried samples, gives the persistence of *potential* water repellency (Chapter 2). In the field, some of these samples were dry, but others were moist or wet. Therefore, we also checked the *actual* water repellency of all field-moist samples taken on 21 Oct. 1992, 15 Jan. 1993 and 23 Feb. 1993. Because the soil moisture content of these samples was also measured, *critical soil water contents* could be assessed for the distinct layers. The soil samples are water repellent below and wettable above these values. The distinction between *potential* and *actual* water repellency and the assessment of the *critical soil water content* are introduced and highlighted by Dekker and Ritsema (1994b), and are also reported in Chapter 2.

Table 5.1 *Volumetric soil water content and dry bulk density per depth for the six trenches. Minimum, mean, maximum, standard deviation (SD), and the correlation coefficient (r) for the relationship between bulk density and volumetric water content are presented.*

	Soil water content				Dry bulk density				
Depth	**Min.**	**Max.**	**Mean**	**SD**	**Min.**	**Max.**	**Mean**	**SD**	***r***
cm	vol%				g.cm^{-3}				
					25 March 1991 (n = 25)				
0- 5	26.3	42.0	35.9	3.7	0.44	0.88	0.65	0.11	+0.04
5-10	24.1	40.0	33.6	4.9	0.95	1.16	1.05	0.05	+0.30
15-20	14.9	35.6	29.3	6.6	0.97	1.25	1.11	0.08	+0.24
20-25	13.7	30.6	24.7	5.6	0.96	1.21	1.10	0.06	-0.10
30-35	13.1	27.9	23.4	5.0	0.95	1.20	1.12	0.06	+0.21
40-45	15.6	30.6	23.7	4.8	1.10	1.38	1.26	0.08	+0.28
50-55	20.5	35.2	28.6	4.7	1.26	1.48	1.38	0.05	+0.63
					30 December 1991 (n = 50)				
0- 5	24.7	55.4	43.8	7.7	0.64	1.07	0.87	0.10	+0.43
10-15	13.3	44.9	30.4	9.3	0.81	1.22	1.07	0.07	+0.24
20-25	12.3	41.6	27.4	7.8	0.94	1.25	1.13	0.06	+0.23
					21 April 1992 (n = 50)				
0- 2.5	11.9	45.3	27.8	9.7	0.27	0.96	0.52	0.15	+0.63
2.5- 5	14.7	41.9	30.7	8.4	0.65	1.17	0.93	0.12	-0.04
0- 5	13.5	43.6	29.3	8.8	0.57	1.04	0.75	0.11	+0.39
					21 October 1992 (n = 50)				
0- 5	16.7	48.0	29.1	8.8	0.62	1.08	0.85	0.11	-0.18
10-15	15.3	38.2	23.1	6.2	0.88	1.21	1.10	0.06	+0.03
20-25	14.0	37.8	23.7	6.2	0.90	1.33	1.17	0.10	+0.19
30-35	16.7	34.7	24.7	5.4	1.24	1.42	1.35	0.04	-0.06
40-45	18.4	37.5	27.4	5.3	1.30	1.52	1.40	0.06	+0.26
					15 January 1993 (n = 50)				
0- 5	40.0	63.5	52.8	6.2	0.51	1.14	0.73	0.14	+0.50
10-15	13.7	46.1	31.3	10.1	0.94	1.18	1.03	0.05	-0.31
20-25	11.8	38.7	25.3	8.4	0.88	1.17	1.07	0.06	+0.30
30-35	11.0	45.4	25.1	8.3	1.01	1.25	1.16	0.06	+0.20
40-45	15.6	36.9	26.7	6.8	1.14	1.34	1.27	0.05	-0.24
					23 February 1993 **(n = 25)**				
0- 5	22.2	59.3	44.6	9.5	0.25	0.96	0.63	0.17	+0.23
10-15	13.8	38.0	25.9	8.8	0.93	1.21	1.08	0.06	-0.67
20-25	12.2	38.0	22.4	7.6	0.93	1.21	1.12	0.06	+0.01
30-35	17.4	33.9	25.3	4.7	1.14	1.35	1.25	0.05	+0.20
40-45	27.0	35.0	30.4	2.2	1.40	1.51	1.44	0.03	-0.14
50-55	33.8	40.1	37.3	1.4	1.30	1.56	1.47	0.06	+0.31
60-65	35.9	45.7	41.0	2.3	1.37	1.51	1.43	0.04	+0.22

5.3 RESULTS

Soil Moisture Variability

Fingerlike wetting patterns were visible in the silt loam topsoil of the Yerseke Moer site (Fig. 5.1), where dry soil areas can always be found, even after large amounts of rain during the winter period (Fig. 5.2). The variation in soil water content is large in all layers of the trenches sampled (Table 5.1). An extreme example of soil water content variation was observed in the top layer at the 0- to 5-cm depth in the 23 Feb. 1993 trench. The lowest volumetric water content in this layer was 22.2% and the highest 59.3%, resulting in a difference of 37.1%. The standard deviation of the soil moisture content varied in the layers of all the trenches between 1.4 and 10.1%.

Figure 5.3 shows the volumetric soil water content of samples at five depths of the 21 Oct. and 15 Jan. trenches. The variation in water content is large in all layers sampled. The finger width in the 21 Oct. trench varied between 10 and 50 cm. As a result of the autumn and winter rains, the fingers widened to between 70 and 100 cm, as shown by the 15 Jan. 1993 trench.

Dry Bulk Density

The mean dry bulk density at the 0- to 5-cm depth varies between 0.63 and 0.87 g cm^{-3}, with SDs of between 0.10 and 0.17 g.cm^{-3} (Table 5.1). The samples taken at the 0- to 5-cm depth on 21 Apr. 1992 were cut into two 2.5-cm parts. The upper part is less dense, with a mean bulk density of 0.52 g.cm^{-3}, while the lower part is denser with a mean value of 0.93 g.cm^{-3}. The mean dry bulk densities between the 5- and 35-cm depth slightly increase with depth and show mean values of between 1.05 and 1.35 g.cm^{-3}. The SD values vary between 0.04 and 0.10 g.cm^{-3}. Deeper in the profile, between the 40- and 65-cm depth, the dry bulk density is even larger with mean values between 1.26 and 1.47 g.cm^{-3}. The SD varies between 0.03 and 0.08 g.cm^{-3}.

Dry Bulk Density and Soil Water Content

The results of the measurements do not confirm the negative relationship often assumed between dry bulk density and volumetric water content. The correlation

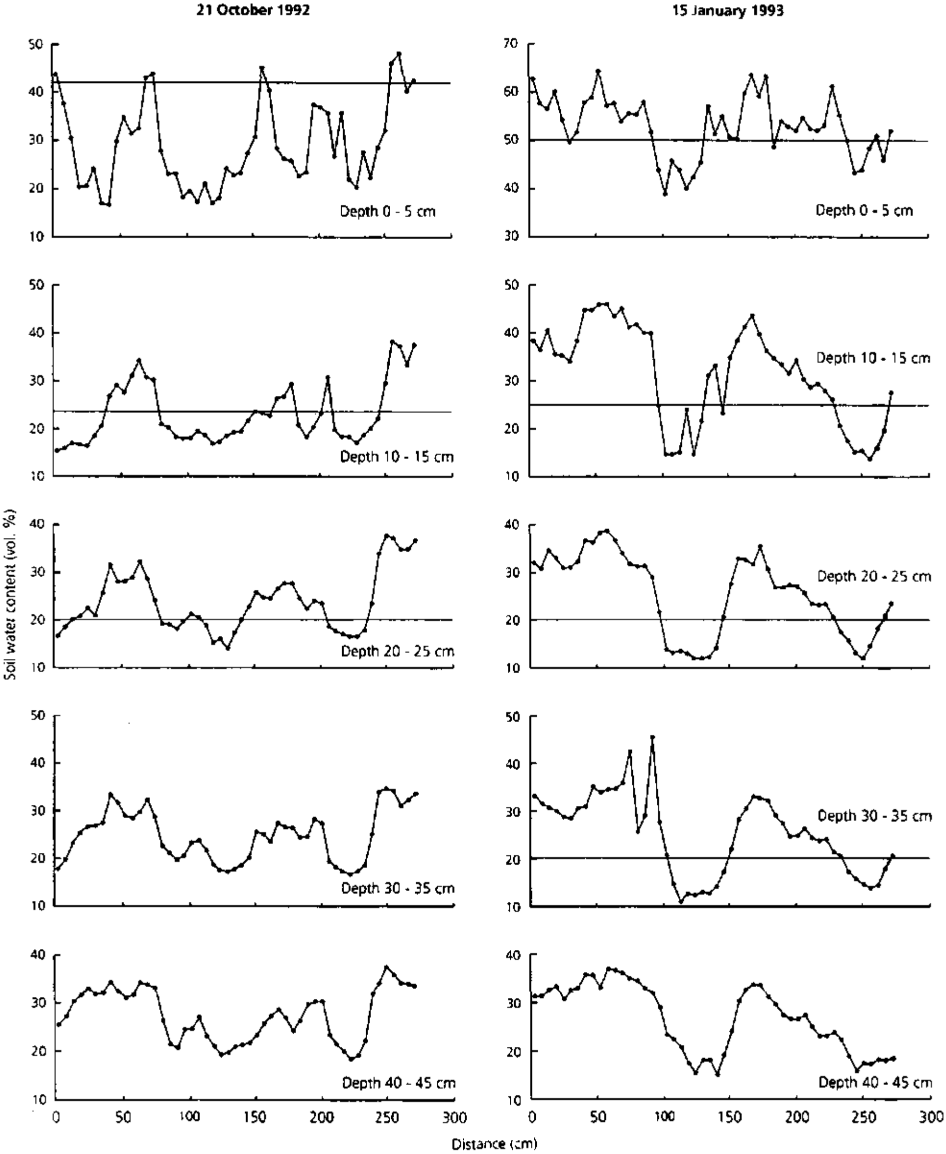


Fig. 5.3 *Volumetric water contents of samples in 275-cm transections in the silt loam soil on 21 October 1992 and on 15 January 1993. The horizontal lines in the diagrams indicate the critical soil water content value, below which the soil is water repellent.*

coefficient for the relationship between dry bulk density and volumetric water content is in most cases positive and in some negative, with *r* values of between 0.01 and 0.67 (Table 5.1).

In general it can be stated that in the soil studied, variability in soil water content is not clearly related to differences in dry bulk density. Therefore, we conclude that dry bulk density is not the regulating factor that induces the wet fingerlike patterns in the soil studied. Thus, there must be another factor responsible for the formation of these vertical soil moisture patterns.

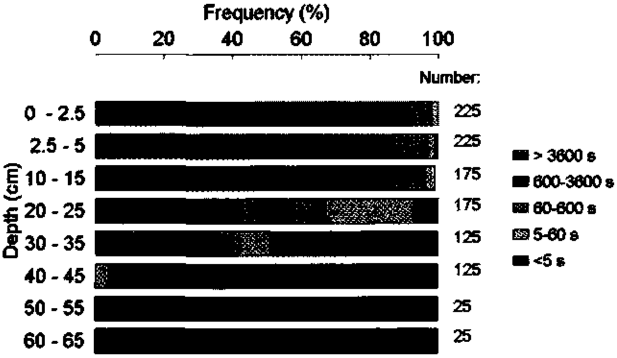


Fig. 5.4 *Relative frequencies of the WDPT test of samples at different depths in the Yerseke Moer silt loam soil. For each depth the persistence of potential water repellency was measured on a minimum of 25 and a maximum of 225 samples.*

Potential Water Repellency and Soil Water Content

The persistence or stability of potential water repellency, expressed by the WDPT, influences the wetting of the soil. Nearly all samples taken up to 15-cm depth are strongly to extremely water repellent, and the persistence of water repellency decreases with increasing depth (Fig. 5.4). However, even at the 30- to 35-cm depth, 30% of the samples show severe to extreme water repellency.

In Figure 5.5, locations of dry soil areas with low soil water content partly correspond with extremely water repellent soil parts and, on the other hand, wet fingerlike patterns are found in areas with low persistence.

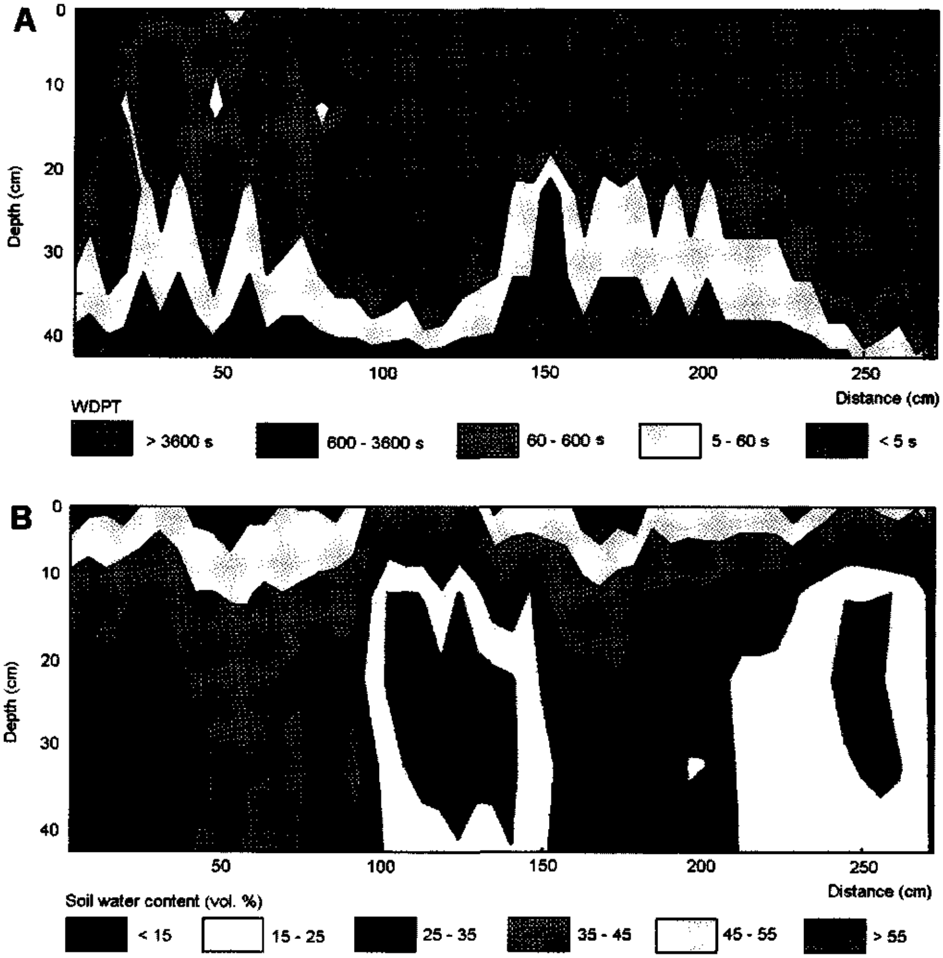


Fig. 5.5 *Contour plots showing the (A) potential water repellency and (B) volumetric soil water content in the silt loam on 15 January 1993.*

Actual Water Repellency and Soil Water Content

According to Dekker and Ritsema (1994b), water repellency appears to be a time-dependent property of the soil, because resistance to wetting of a water repellent soil will decrease over time. This is confirmed by the measurements of the actual water repellency using the WDPT test on samples of the silt loam. Figure 5.6 shows two cross-sections with the distribution of actually wettable and actually water repellent soil parts. In the 21 Oct. 1992 trench, a considerable part of the topsoil is water repellent and only small wettable channels occur. After a total amount of 246 mm rain, the channels or fingers widened and the wettable soil parts enlarged, as shown by the 15 Jan. 1993 trench. The patterns, especially the drier parts of the silt loam, are clearly related to the occurrence of the actually water repellent soil areas (Fig. 5.6). Because both actual water repellency and soil water contents were measured, critical soil water contents for different depths of the silt loam could beassessed. The critical soil water content at the 10- to 15-cm depth is about 24% and at 20- to 25- and 30- to 35-cm depths 20%. These values are indicated in Fig. 5.3. All samples above the lines were actually wettable and below actually water repellent. The critical soil water content at the 0- to 5-cm depth is about 40%.

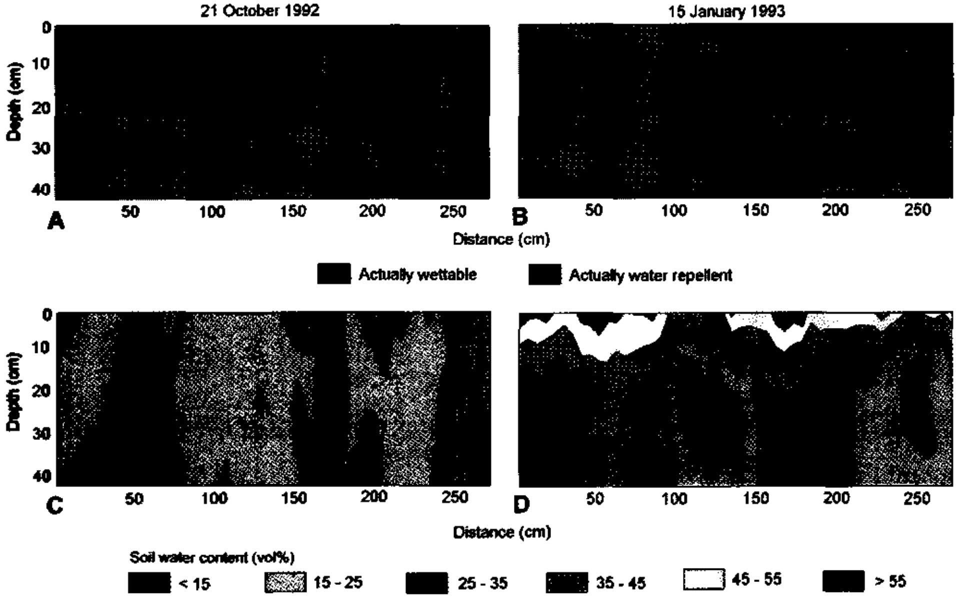


Fig. 5.6 *Contour plots (A, B) showing the actually water repellent and actually wettable zones in the silt loam and the (C, D) volumetric soil water content on 21 October 1992 and 15 January 1993.*

However, this value is difficult to assess in this layer, because the upper part of the soil samples was often wet, whereas the bottom part was still dry and actually water repellent. The ratio wettable and water repellent soil is time-dependent. Figure 5.7

shows the percentages of the actually water repellent soil samples between the 0- and 50-cm depth for three trenches. As might be expected, the percentages of actually water repellent samples decrease deeper in the profiles and the percentages differ at different times. The percentages correspond with soil volumes excluded from direct water and solute transport.

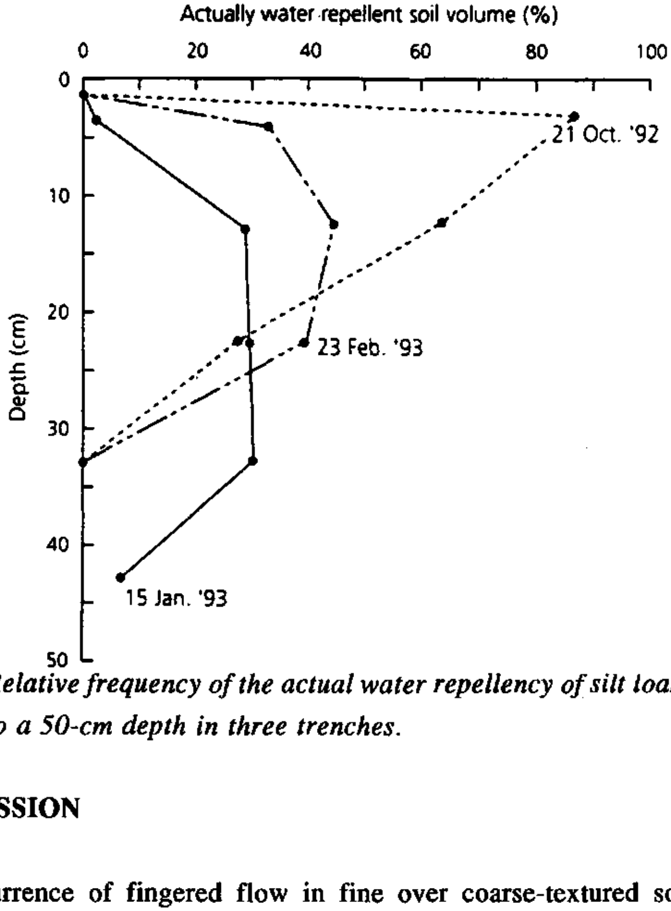


Fig. 5.7 *Relative frequency of the actual water repellency of silt loam samples up to a 50-cm depth in three trenches.*

5.4 DISCUSSION

The occurrence of fingered flow in fine over coarse-textured soils has been known since the laboratory studies of Miller and Gardner (1962), whereas Glass et al. (1988) have shown fingering to occur in layered field soils. Van Ommen et al. (1988) and Ritsema et al. (1993) have shown that fingering occurs in water repellent sandy soils, whereas Ritsema and Dekker (1994a) and Dekker and Ritsema (1994a) highlighted the occurrence of fingers in homogeneous, wettable dune and beach sands. This study shows evidence of the occurrence of fingerlike flow patterns in a water repellent silt loam soil. Wet fingerlike patterns have also been detected by Dekker and Ritsema (1996c) in peaty clay and clayey peat soils (see also Chapter 7). In a study of the wetting of heavy (> 60% clay) basin clay soils with a slightly water repellent topsoil, Dekker and Ritsema (1996d) also found wet fingerlike patterns (see also Chapter 6).

The occurrence of fingerlike wetting patterns seriously accelerates the transport of water and surface-applied solutes, particularly sorbing and degrading solutes such as pesticides toward the saturated zone, and consequently increases the risk of contaminating groundwater reservoirs. Knowledge of spatial patterns in soil water content in the unsaturated zone is essential in field-scale modeling of water and solute transport. When fingered flow occurs, a certain volume of the soil, varying in space and time, does not participate in the transport of water and solutes. Therefore, information is needed about the finger dimensions and their spatial and temporal behavior (Ritsema and Dekker, 1994b). From a management point of view it is essential to know where and when preferential flow may be expected in field situations and to what extent it may accelerate water and solute transport, to develop consistent strategies to minimize environmental risk to groundwater and surface waters. Therefore, further research is required to define more precisely sites where fingerlike wetting patterns and fingered flow should be expected based on climate and soil conditions.

5.5 CONCLUSIONS

- In a loam soil in the Netherlands with grass cover and a water repellent topsoil, wet fingerlike patterns and dry soil areas persisted during long periods, due to the actual wettability and actual water repellency of these soil parts, respectively.

- Water repellency is a time-dependent property of the soil. Its dynamic behavior is demonstrated by varying percentages of actually water repellent soil at different times.

- Fingerlike wetting patterns were found at places with a relatively low persistence of potential water repellency.

- The measurements in this study do not confirm a frequently assumed negative relationship between dry bulk density and volumetric water content. Positive as well as negative correlations were found.

- In this fine-textured soil, fingerlike patterns were much wider than fingers observed in sandy soils. The wet patterns in the loam soil of Yerseke Moer sometimes had diameters of up to 70 to 100 cm.

- Preferential flow through the wet fingerlike patterns shortens the travel time of surface-applied solutes and reduces the adsorbing capacity of the soil, and -in the case of toxic substances- increases the risk of groundwater contamination.

CHAPTER 6

PREFERENTIAL FLOW PATHS IN A WATER REPELLENT CLAY SOIL

Adapted version of "Preferential flow paths in a water repellent clay soil with grass cover" by Louis W. Dekker and Coen J. Ritsema, published in Water Resources Research 32: 1239-1249, 1996.

6 PREFERENTIAL FLOW PATHS IN A WATER REPELLENT CLAY SOIL

Abstract

Grass-covered heavy basin clay soils in the Netherlands appeared to be water repellent. Water repellency in the top layers of these soils occurred mainly as a coating on the aggregates. The variation in soil moisture content over short distances was studied by sampling the soil 10 times during the period August 31, 1993, to December 22, 1994. Each time, 35 samples (100 cm^3) were taken in close order over a distance of 195 cm at depths of 0-5, 10-15, 20-25, and 30-35 cm. Differences between minimum and maximum soil moisture contents were high in all layers sampled, occasionally as much as 28 vol%. When the clay soil is dry, a major proportion of the water from precipitation or sprinkler irrigation may flow rapidly through shrinkage cracks to the subsoil, bypassing the matrix of the clay peds. However, preferential flow is not limited to macropore flow: irregular wetting patterns are also formed through the small pores of the matrix. The relationship between dry bulk density and volumetric water content was found to be positive when the clay soil was relatively dry and negative when it was relatively wet.

6.1 INTRODUCTION

More than a century ago, Schumacher (1864) and Lawes et al. (1882) indicated the rapid flow of water through macropores in soils. For a long time these findings were completely ignored, but in recent decades numerous researchers have rediscovered them. Their publications show that in many soils a major proportion of the water from precipitation and irrigation flows preferentially through macropores toward the subsoil, thus bypassing the matrix of the topsoil (e.g. Elrick and French, 1966; Ritchie et al., 1972; Quisenberry and Phillips, 1976; Bouma and Dekker, 1978; Bronswijk, 1988; Brusseau and Rao, 1990; Dekker and Ritsema, 1995). Macropores may consist of interaggregate pore space, shrinkage cracks and fissures, root channels or faunal tunnels, and fissures cut by the tine of the mole plough (Ehlers, 1975; Beven and Germann, 1982; Robinson and Beven, 1983; Meek et al., 1989; Edwards et al., 1990). The macropores need not be very large to induce preferential flow. Scotter (1978) stated that the minimum channel diameter for preferential flow is approximately 0.2 mm and the minimum crack width approximately 0.1 mm.

Surface-applied solutes can reach the saturated zone more rapidly in soils with preferential flow paths than in those with homogeneous wetting, increasing the risk of contaminating groundwater reservoirs (e.g. Thomas and Phillips, 1979; Dekker and Bouma, 1984; Germann et al., 1984; White, 1985; Roth et al., 1991; Quisenberry et al., 1993; Ritsema and Dekker, 1995; Bronswijk et al., 1995). In drained agricultural areas, preferential flow may lead to a loss of nutrients and an increased contamination risk of surface waters. From a management point of view it is essential to know where and when preferential flow may be expected in field situations in order to develop consistent strategies to minimize environmental risks to groundwater and surface water.

So far, cracks and biopores (macropores) have generally been assumed to be the operational preferential flow paths in clay soils. Also water repellency has serious consequences for soil wetting and for transport of water and solutes through soils (DeBano, 1969; Ritsema and Dekker, 1995). In Germany, Australia, New Zealand and the United States the phenomenon of water repellency has been observed primarily on sandy soils and was found to be caused by organic coating on the sand grains (Albert and Köhn, 1926; Van 't Woudt, 1959; Bond, 1969; Roberts and Carbon, 1972; Ma'shum et al., 1989). According to Ma'shum et al. (1989), water repellency in sandy soils is determined by the amount of hydrophobic organic matter coating the sand particles and the specific surface area of the sands. They found that for larger surface areas, such those as in sandy loams or loams, very large quantities of waxes would be required to create severe water repellency, while the limited surface area of coarse sands would be readily covered by waxes. However, Bond (1969) and McGhie and Posner (1980) reported that in special circumstances water repellency occurs in loams in western Australia, which contain more than 20% clay. Giovannini et al. (1983) studied a water repellent surface layer of a clay soil with 40% clay in Italy. They found that the natural hydrophobic covering of the aggregates increased their stability but restricted water infiltration into the aggregates. Dekker and Ritsema (1995) showed fingerlike wetting patterns in water repellent aggregated loam soils in the Netherlands.

Land use may influence the degree of water repellency as was shown by Dekker and Jungerius (1990) and Bisdom et al. (1993). They found that sandy soils under grassland are much more susceptible to water repellency than sandy soils under arable land.

Measurements of differences in soil water content over short distances, as implemented for several soils by Ritsema and Dekker (1994a,b; 1996a) and Dekker and Ritsema (1994a,b; 1995; 1996b), have never been performed in clay soils.

The objectives of the present study were, (1) to investigate the water repellency of heavy basin clay soils in the Netherlands, depending on their land use, (2) to measure short distance variations in soil water content in a water repellent heavy clay soil with grass cover, (3) to determine the relationship between dry bulk density and soil moisture content.

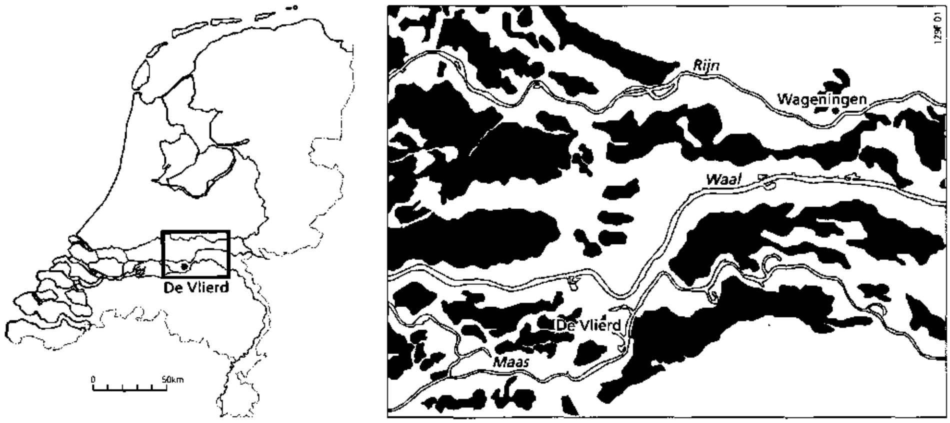


Fig. 6.1 *Schematic map showing the distribution of water repellent basin clay soils in the Netherlands (shaded areas) and the location of the study site.*

6.2 MATERIALS AND METHODS

Sites and Soil

The experimental field is located at the experiment station De Vlierd, in the alluvial heavy clay soils in the central part of the Netherlands (Fig. 6.1). The field has been in use as pasture land for decades, and grass was last resown in 1986. Normal farming practices of grazing cattle and growing grass for fodder were continued during the investigation.

The soil is a very fine clayey, mixed illitic-montmorillonitic, mesic, Typic Fluvaquent (De Bakker, 1979). The clay content (particles < 2 µm) ranges from 55 to 60%. Soil structure consists of moderately developed, medium-sized prismatic peds composed of fine subangular and angular blocky peds. The effective root zone is restricted to a depth of approximately 20 cm. The soil is tile-drained at a depth of about 1 m, with 10-m spacings.

Earlier experiments showed that the soil exhibits distinct swelling and shrinkage and extensive preferential flow through structural voids such as shrinkage cracks (Bouma and Dekker, 1978; Bouma et al., 1981; Dekker and Bouma, 1984; Bronswijk, 1988).

Soil moisture measurements were conducted at the experimental field during the period August 31, 1993 to December 22, 1994. The degree of water repellency was measured on samples from De Vlierd and on samples taken in heavy clay soils outside De Vlierd.

Climate and Weather Conditions

In the Netherlands mean monthly temperatures vary between 1.7°C in January and 17°C in July. Long-term annual precipitation averages 765 mm per year, and potential evaporation 690 mm. From September to mid-April there is a precipitation surplus, and from mid-April to September there is a precipitation deficit. Precipitation was measured daily at the experimental station. Daily potential evaporation rates were derived from a nearby meteorological station. Figure 6.2 shows the precipitation surplus and the evaporation surplus for 10-day periods in 1993 and 1994. By way of comparison, the 30-year (1960-1990) long-term averages are also given. The diagrams show that the second and third 10-day periods of July 1993 were relatively wet, and that the period from June 11 to August 20, 1994 was relatively dry. The diagrams also show that individual peaks of precipitation surplus were much higher than the long-term means.

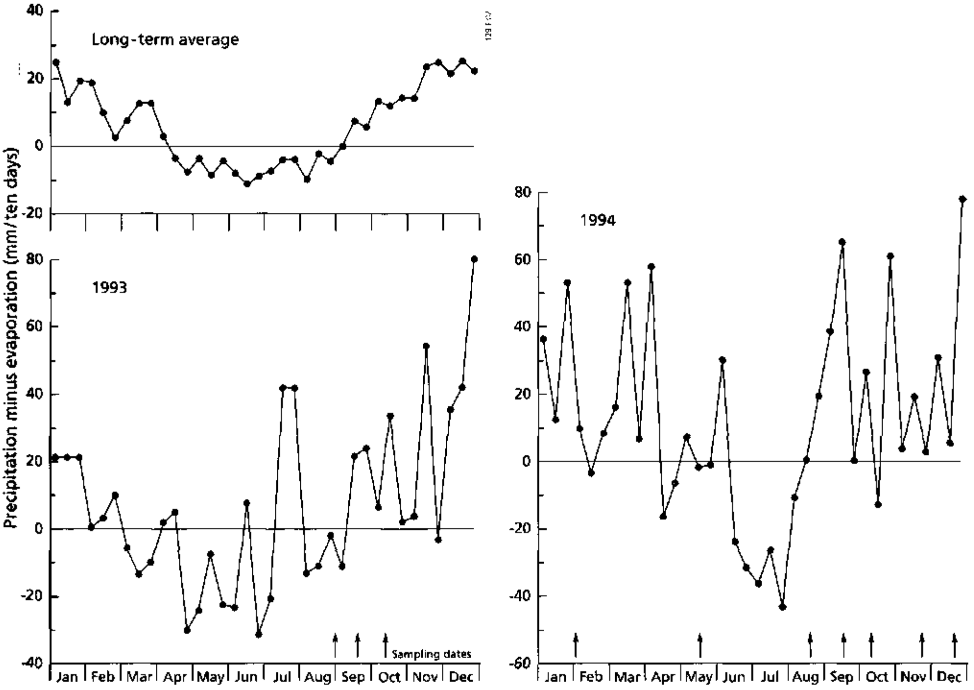


Fig. 6.2 *Precipitation surplus and precipitation deficit for 10-day periods in 1993 and 1994. For comparison the long-term 10-day averages are given. The arrows indicate the sampling dates.*

Soil Moisture Sampling

Between August 31, 1993 and December 22, 1994, 10 trenches were dug at De Vlierd site to sample the heavy clay soil. The sampling dates are indicated in Figure 6.2. Samples were taken at depths of 0-5, 10-15, 20-25, and 30-35 cm, using steel cylinders (100 cm^3) with a height and diameter of 5 cm. At each depth, 35 samples were taken at close spacings over a distance of 195 cm, yielding 140 samples per trench. The wet soil of each sample was weighed, dried for several days at 65^{0}C, and weighed again to determine soil water content and dry bulk density.

Table 6.1 shows values of precipitation, potential evaporation, and precipitation surplus or deficit for the periods between the 10 sampling days. All of these periods showed a precipitation surplus, with the exception of the period May 16 to August

Table 6.2 *Soil water content and dry bulk density at four depths (n = 35) for all the trenches.*

	Soil water content			Dry bulk density			
Depth cm	Mean vol%	s.d. vol%	CV %	Mean g/cm³	s.d. g/cm³	CV %	*r*
				Aug. 31, 1993			
0-5	29.8	2.4	7.9	1.05	0.11	10.5	+0.53
10-15	30.6	1.8	5.7	1.15	0.12	10.7	+0.05
20-25	31.5	2.2	7.0	1.01	0.11	10.6	+0.15
30-35	36.8	3.5	9.5	1.17	0.12	10.1	-0.03
				Sept. 17, 1993			
0-5	45.1	3.9	8.7	1.03	0.10	9.6	+0.04
10-15	32.1	1.6	5.1	1.18	0.07	6.2	+0.48
20-25	33.2	2.9	8.6	0.99	0.09	8.6	+0.36
30-35	43.0	2.4	5.6	1.14	0.09	7.8	-0.45
				Oct. 11, 1993			
0-5	47.1	8.1	17.2	1.02	0.10	10.2	-0.33
10-15	38.5	3.4	8.8	1.17	0.06	5.4	+0.06
20-25	36.2	3.8	10.5	1.05	0.08	7.3	+0.50
30-35	42.9	2.8	6.5	1.09	0.12	10.7	-0.07
				Feb. 1, 1994			
0-5	57.7	3.7	6.4	0.94	0.08	8.9	-0.40
10-15	44.9	2.5	5.6	1.08	0.07	6.5	-0.26
20-25	46.6	3.2	6.9	1.00	0.09	9.3	-0.13
30-35	47.6	2.6	5.4	1.17	0.10	8.6	-0.71
				May 16, 1994			
0-5	44.9	6.2	13.9	0.98	0.11	12.1	-0.35
10-15	37.8	3.4	9.0	1.20	0.08	6.6	-0.26
20-25	37.0	4.2	11.4	1.05	0.10	9.9	-0.09
30-35	42.8	2.6	6.0	1.18	0.06	5.5	-0.15
				Aug. 16, 1994			
0-5	22.4	3.8	16.7	1.09	0.14	13.3	+0.53
10-15	26.3	3.1	11.9	1.13	0.17	15.1	+0.92
20-25	28.3	2.3	8.0	1.13	0.10	9.1	+0.56
30-35	30.0	2.6	8.6	1.19	0.08	7.1	+0.77
				Sept. 14, 1994			
0-5	43.3	3.2	7.5	1.04	0.08	7.9	+0.02
10-15	35.8	3.4	9.5	1.21	0.09	7.6	+0.22
20-25	33.8	4.0	11.7	1.03	0.11	11.1	+0.57
30-35	42.6	2.5	5.8	1.05	0.08	8.0	+0.07
				Oct. 6, 1994			
0-5	46.9	2.7	5.7	1.01	0.10	10.3	+0.09
10-15	41.0	3.0	7.4	1.17	0.06	5.0	-0.20
20-25	40.9	4.0	9.8	1.05	0.08	7.2	+0.12
30-35	47.3	4.0	8.8	1.15	0.12	10.7	-0.70
				Nov. 22, 1994			
0-5	51.9	3.2	6.2	1.00	0.10	10.2	+0.01
10-15	45.0	2.0	4.4	1.12	0.08	7.1	-0.37
20-25	46.4	2.5	5.4	0.98	0.10	9.7	+0.03
30-35	45.9	2.6	5.6	1.25	0.07	5.5	-0.85
				Dec. 22, 1994			
0-5	53.0	3.4	6.4	0.93	0.08	8.3	-0.24
10-15	46.8	2.2	4.3	1.19	0.06	5.4	-0.40
20-25	46.8	2.9	6.2	1.04	0.07	6.5	-0.08
30-35	47.9	2.9	6.0	1.11	0.11	10.3	-0.29

Here, *r* is the correlation coefficient for the relationship between bulk density and soil water content.

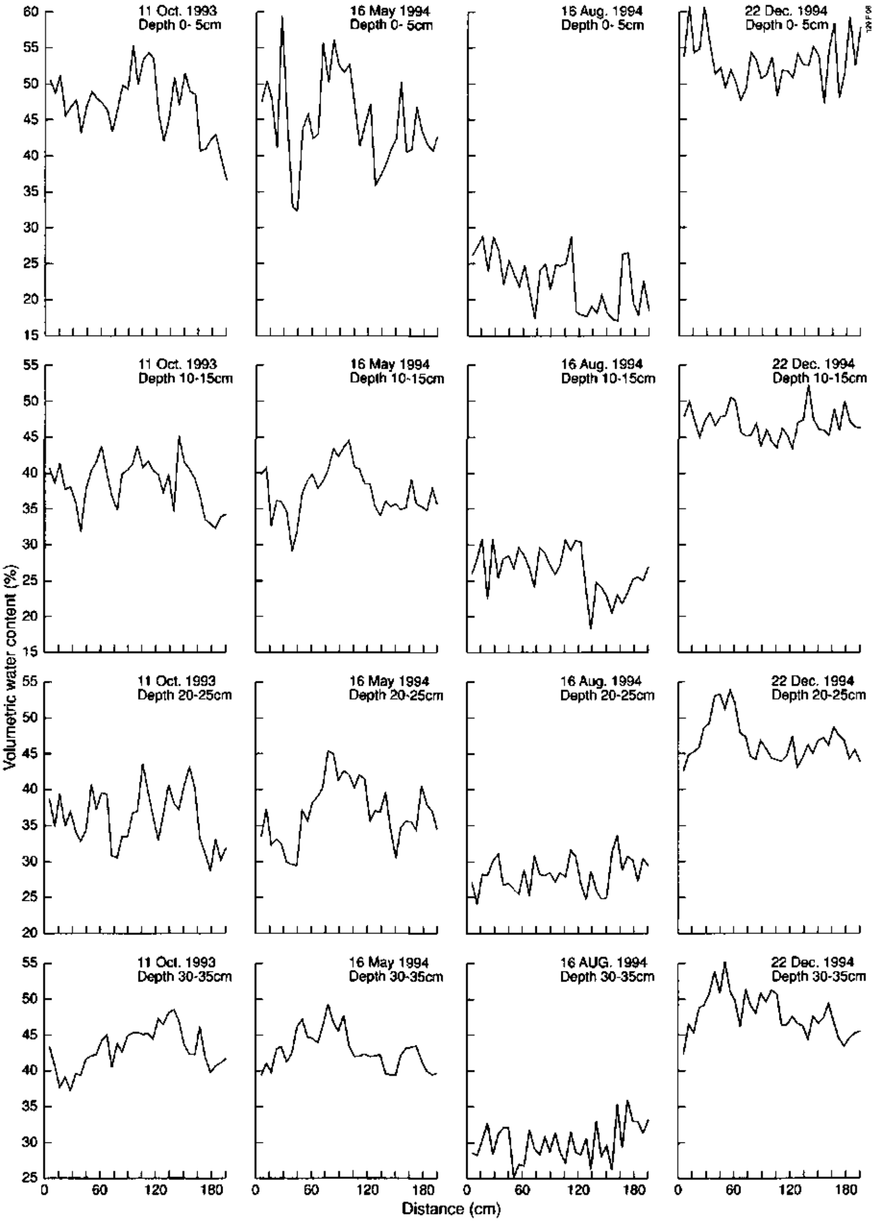


Fig. 6.5 *Water content in the clay soil at four depths over a distance of 195 cm on 4 sampling days.*

May 16, 1994, and October 11, 1993, with values of 6.2% and 8.1%, respectively. On the other sampling days the s.d. at this depth varied between 2.4 and 3.9%. On the 10 sampling days, s.d. varied between 1.6 and 3.4% at a depth of 10-15 cm, between 2.2 and 4.2% at a depth of 20-25 cm, and between 2.4 and 4.0% at a depth of 30-35 cm. The coefficient of variation (CV) of the soil water content at the four depths in the 10 trenches varied between 4.3 and 17.2% (Table 6.2).

The variations in soil moisture content of samples taken over short distances at four depths from four trenches are shown in Figure 6.5. Large differences, with volumetric water contents between 32 and 60%, occurred at a depth of 0-5 cm in the May 16, 1994, trench. Small wet patterns were present (the peaks in the diagram). Wider moisture patterns occurred in this trench at depths of 10-15 and 20-25 cm. Differences in soil water content of 5 to 15% were often found over short distances in all soil layers of the 10 trenches.

Moisture Patterns

Figure 6.6 shows the spatial distribution of the volumetric soil water content in the 10 trenches sampled. The soil profile on August 31, 1993, was relatively dry, and moisture patterns appeared to be vertically oriented. After 43 mm of precipitation had fallen (Table 6.1) the soil moisture content of the surface layer and of the layer between 25 and 35 cm of the September 17, 1993, trench increased from 25-35% to 35-55%. However, at depths between 10 and 25 cm a large part of the clay soil remained relatively dry, with soil water contents between 30 and 35% and occasionally less than 30%. After an additional 52 mm of precipitation, vertically directed wetting patterns were formed, as shown in the diagram of the October 11, 1993, trench (Fig. 6.6). The diameter of these wetting patterns exceeded the width of individual cracks, indicating that the surrounding matrix was participating in the vertically directed flow as well. From October 11, 1993, to the following sampling date, February 1, 1994, a total amount of 389 mm of precipitation was recorded. The clay soil clearly became wetter, with moisture contents of 50% to more than 55% in the surface layer, and moisture contents of 40-55% at depths between 10 and 35 cm. After February 1, 1994, the soil dried out to a large extent, as can be seen in the May 16 and August 16 trenches. With increasing rainfall, irregular wetting of the soil started again, often with the occurrence of similar wetting patterns as found in the October 11, 1993, trench.

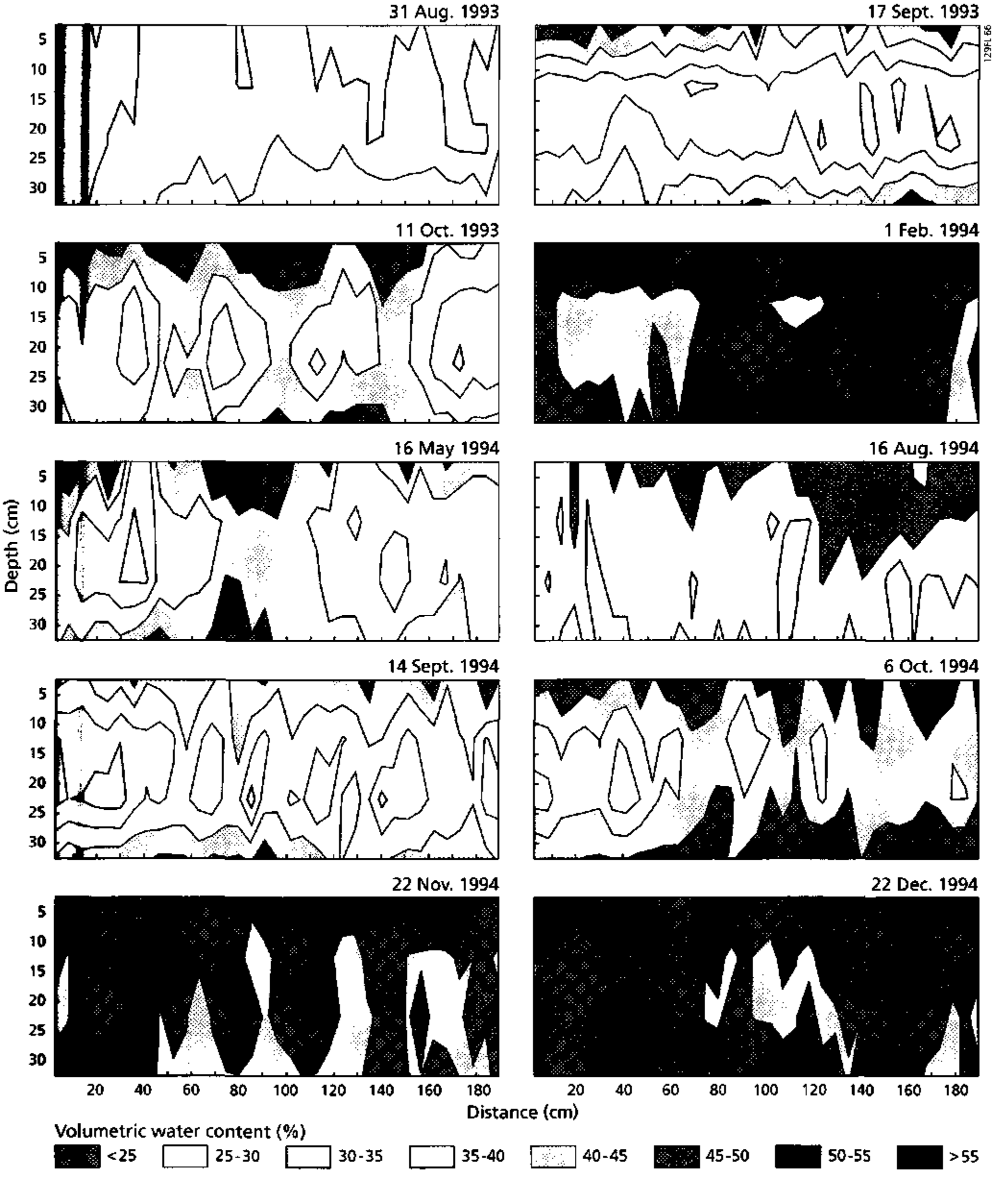


Fig 6.6 *Contour plots showing the spatial distribution of volumetric water content for all the trenches.*

Dry Bulk Density and Soil Moisture Content

The mean dry bulk density of the surface layer at a depth of 0-5 cm varied between 0.93 and 1.09 g/cm^3, as is shown in Table 6.2. In the three deeper layers the mean value varied between 0.98 and 1.25 g/cm^3. The standard deviation of the dry bulk density in the layers sampled fluctuated between 0.06 and 0.17 g/cm^3 and the coefficient of variation ranged from 5.4 to 15.1%.

The relationship between dry bulk density and volumetric water content of the 35 samples taken at four depths in the 10 trenches also is given in Table 6.2. The relationship was found to be positive in 20 layers, with a correlation coefficient (r) between +0.01 and +0.92, and negative in the other 20 layers, with r values ranging between -0.03 and -0.85. A negative relationship was found for all layers sampled in the February 1, May 16, and December 22, 1994, trenches and a positive relationship for those of the August 16 and September 14, 1994, trenches (Table 6.2).

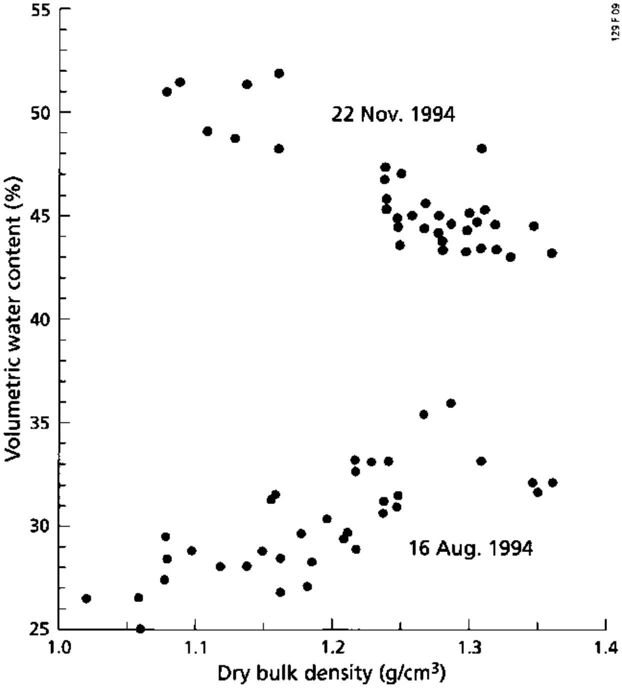


Fig. 6.7 *Relationship between dry bulk density and volumetric water content of samples (n = 35) at 30-35 cm depth on August 16 and November 22, 1994.*

Figure 6.7 shows the relationship for the samples from a depth of 30-35 cm from the August 16 and November 22, 1994, trenches, which showed a positive (r equals +0.77) and a negative (r equals -0.85) relationship, respectively. The soil in the August trench was rather dry, with volumetric water contents between 24 and 37%, whereas those from the November trench were rather wet, with water contents between 43 and 53%. This implies that under dry conditions water can be found mainly in places with a relatively high bulk density (i.e., in the smaller pores). Under wet conditions water can be found in places with low bulk densities (i.e., in the larger pores).

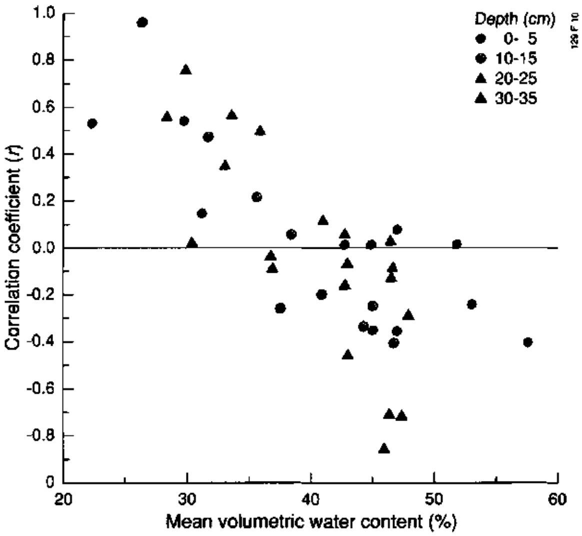


Fig. 6.8 *Relationship between the average volumetric water content and the correlation coefficient of bulk density versus water content of samples per depth for all trenches.*

Figure 6.8 shows the relationship between the mean water contents of each layer sampled and the related correlation coefficient between the dry bulk density and the soil water content. It was found that layers with a mean water content below 36% showed a positive correlation coefficient, whereas layers with a mean water content above 36% generally showed negative coefficients. This indicates that when the soil is rather dry, samples with a high bulk density contain more water than those with a low density. By contrast, when the soil is rather wet, samples with a low dry bulk density contain more water.

6.4 DISCUSSION AND CONCLUSIONS

Occurrence of Water Repellent Clay Soils

Although water repellency is a common phenomenon in surface soil horizons that frequently dry out, it is generally not recognized (Dekker, 1988; Dekker and Jungerius, 1990; Wallis and Horne, 1992). Over the last decades, numerous investigations of water and solute transport have been performed on the clay of this study (Bouma and Dekker, 1978; Bouma et al.,1978; Hoogmoed and Bouma, 1980; Bouma and De Laat, 1981; Bouma et al., 1981; Dekker et al., 1981a, b; Dekker and Bouma, 1984; Bronswijk, 1988; Bouma, 1990; Bronswijk et al., 1995). Notwithstanding the overwhelming amount of research on this particular clay soil, this study is the first to indicate the presence of water repellency and its role in forming preferential flow paths.

The present study indicates that large areas of riverine clay soils with grass cover in the central part of the Netherlands are water repellent. Soils may become water repellent as a result of decay of organic matter compounds and the production of organic substances, such as humic and fulvic acids (Bisdom et al., 1993). In structured soils, like the clay soil studied, roots are often found in the interaggregate pore network, and therefore water repellent substances are found upon the faces of aggregates and/or larger structural elements. Within aggregates and larger structural elements where no roots occur, water repellency is generally absent. When this clay soil is used as arable land, the topsoil was found to be wettable in most cases, and only slighty water repellent in some cases (see Fig. 6.3b). Slightly water repellent topsoils were only found in young arable fields, those that were used as pasture until recently. The disappearance of water repellency in arable soils is probably partly the result of the oxidation of water repellent organic matter and partly the result of the destruction of clay aggregates by cultivation of the arable land.

Water Uptake During Sprinkler Irrigation

In previous studies at the De Vlierd experiment station, for example, those by Bouma et al. (1981) and Dekker and Bouma (1984), preferential flow was measured by using undisturbed cores taken from the topsoil and sampled in cylinders with a length and diameter of 20 cm. The cores were placed on a perforated disk on top of a funnel, under a standard sprinkler irrigation in the field, and the outflow at the bottom of the cores was measured. The mass of the soil-filled cylinders was determined before and after sprinkling, and the oven-dried mass was measured at the end, thus allowing calculation of moisture contents and soil moisture increase. Results, reported by Bouma et al. (1978, 1981) and Dekker and Bouma (1984), showed that preferential flow increases and water uptake decreases at higher moisture contents of the clay soil. On the other hand, Dekker and Ritsema (1996e) found little water uptake and large amounts of preferential flow for this soil at low moisture contents. They collected and described all data of previous studies which made use of sprinkler irrigation on clay cores taken from the topsoil of the De Vlierd experiment station. Of these cores, 78 received approximately 25 mm water at a rate of 16 mm/h. Figure 6.9 shows the relationship between the initial moisture content of the clay cores and the increase in water content. The water uptake is low

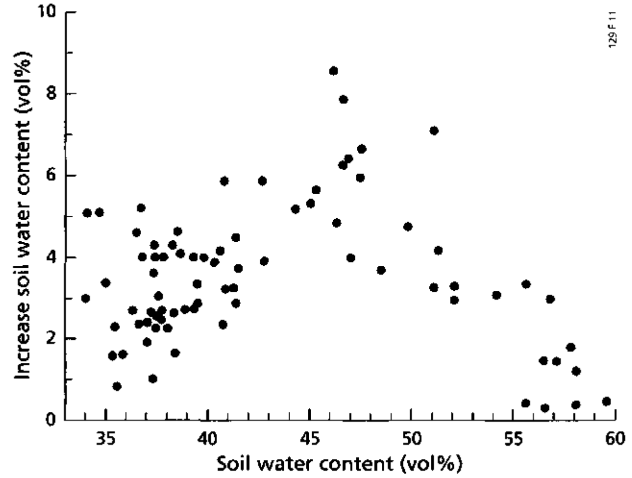


Fig. 6.9 *Relationship between the initial moisture content of clay columns and the increase in moisture content after about 25 mm of sprinkler irrigation.*

in the soil moisture range 34-42% and moderate in the range 42-52%, and it decreases between 52 and 60%. We assume that the walls of many of the aggregates and prisms of the clay cores with a moisture content below 42% were initially actually water repellent, thus causing an accelerating water flow through the interaggregate pore networks of the soil. The increase in volumetric water content after irrigation ranged from 1 to 5%, corresponding with 2 to 10 mm of the water applied, while the rest of the 25 mm was lost by preferential flow. An optimal (but still bad) result of wetting was found when the soil moisture content ranged between 42 and 52%. At these moisture contents, the outsides of prisms and aggregates were most likely not actually water repellent, allowing the peds to absorb 7 to 17 mm of the water applied. In agreement with the results of Bouma et al. (1978, 1981) and Dekker and Bouma (1984), preferential flow was found to increase and water uptake to decrease at higher moisture contents. However, the negative relationship between initial soil moisture content and water uptake for this clay topsoil was only valid for initial volumetric water contents exceeding 45%, as can be seen in Figure 6.9.

Preferential Flow and Preferred Pathways

When the clay soil we studied is dry, the exteriors of the prisms and aggregates are actually water repellent. Under these conditions rain and water from sprinkler irrigation flows through structural cracks between the prisms and aggregates. A methylene blue dye tracer applied on August 16, 1994 showed that water could flow through structural cracks between 10-15 cm wide prisms. Water was sprinkled on a 0.5-m by 1.0-m plot at a rate of 10 mm/h for 3 hours. Blue colored bands, mainly 4 to 12 mm wide, were found on the outside of the prisms down to a depth of more than 80 cm. Figure 6.10 shows a prism at a depth of 2 to 17 cm with blue "fingers". Water does not spread in a film over its water repellent faces, because the attraction between the water molecules (cohesion) exceeds the adhesive forces of the clay surfaces.

The flow of water along cracks in this clay soil was also studied after sprinkling with a methylene blue solution in the dry summer of 1976 by Bouma and Dekker (1978). They found vertical blue bands 3 to 8 mm wide on the ped faces, and they detected more and deeper bands for higher sprinkler intensity and larger applications. The total surface area of the bands was asumed to be an important

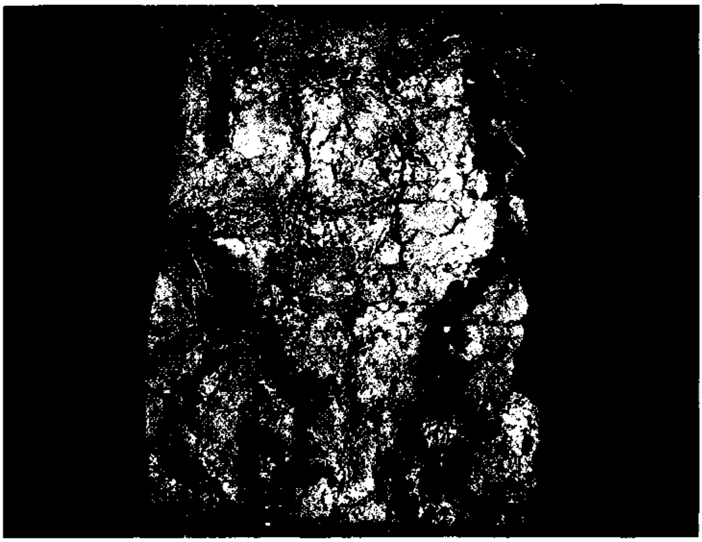


Fig. 6.10 *Methylene blue bands on the wall of a dry clay prism, showing the preferential flow paths of water during sprinkler irrigation.*

characteristic, as it defines the area which is available for lateral infiltration into the peds. The dye studies clearly showed that only a tiny fraction (1 to 2%) of the larger type of pores took part in the downward transport process. Deep penetration of water in the cracks was primarily due to the small contact area (Bouma and Dekker, 1978; Hoogmoed and Bouma, 1980). However, Bouma and his coworkers did not indicate the reason for the small contact area, surely because at that time they were not familiar with the water repellent character of the crack walls.

The present study is the first to show the formation of irregular wetting patterns through the small pores in the matrix of a clay soil. These preferred pathways are thought to form at places with cracks which receive relatively large amounts of water, due to the occurrence of distribution flow. Hence, the surrounding small pores in the matrix can be wetted as well, resulting in irregular wetting patterns. This contrasts with cracks receiving relatively small amounts of water, where wetting of the water repellent crack walls takes much more time, preventing the formation of these wetting patterns.

CHAPTER 7

MOISTURE VARIABILITY IN PEATY CLAY AND CLAYEY PEAT SOILS

Adapted version of "Variation in water content and wetting patterns in Dutch water repellent peaty clay and clayey peat soils" by Louis W. Dekker and Coen J. Ritsema, published in Catena 28: 89-105, 1996.

7 MOISTURE VARIABILITY IN PEATY CLAY AND CLAYEY PEAT SOILS

Abstract

The variation in water content of grass-covered peaty clay and clayey peat soils was studied at six sites in the Netherlands. The topsoils were water repellent during dry spells. When the topsoils were dry, they could only absorb water with difficulty, which is illustrated by wetting rate measurements. Precipitation could flow rapidly through shrinkage cracks towards the subsoil, bypassing the matrix of the peat. However, the measurements revealed that preferential flow was not limited to macropore flow: irregular, fingerlike wetting patterns were also formed in the soil matrix. Due to these typical wetting patterns, soil water content varied over short distances at all sites at all sampling dates.

7.1 INTRODUCTION

Over the last decades several researchers have indicated that in many soils, a major proportion of the water from precipitation and irrigation flows through macropores towards the subsoil, thus bypassing the matrix of the topsoil (e.g. Bouma and Dekker, 1978). Macropores may consist of interaggregate space, shrinkage cracks and fissures, root channels or faunal tunnels (Beven and Germann, 1982; Meek et al., 1989; Edwards et al., 1990). The macropores need not be very large to induce preferential flow. Scotter (1978) stated that the minimum channel diameter for preferential flow is approximately 0.2 mm and the minimum crack width approximately 0.1 mm.

Another cause of preferential flow may be the presence of soil water repellency. In the Netherlands, for example, many grass-covered clayey peat and peaty clay soils are susceptible to drought and difficult to wet after a prolonged dry period. When dry, these soils are water repellent. Their distribution has been recorded by soil surveyors at our institute on several soil maps at different scales. Figure 7.1 shows the distribution of water repellent peaty clay and clayey peat soils in the Netherlands. The total area of these soils amounts to 120,000 hectare, representing approximately 3.5% of the country.

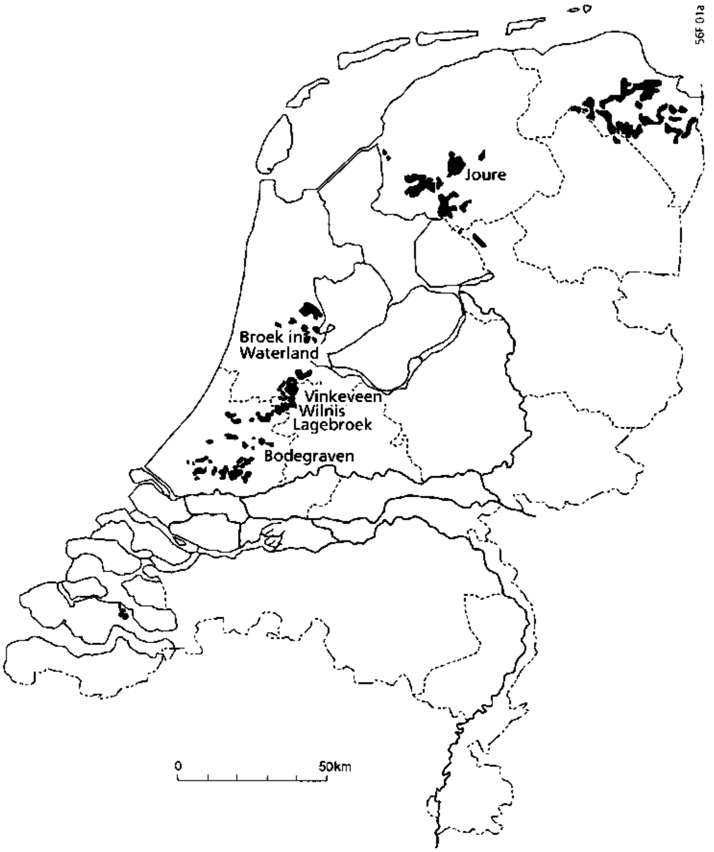


Fig. 7.1 *Schematic map showing the sites studied and the distribution of water repellent and difficult-to-wet peat soils in the Netherlands.*

So far, cracks (macropores) have generally been assumed to be the operational preferential flow paths in peaty clay and clayey peat soils. The consequences of water repellency for soil wetting and for the transport of water and solutes through these soils have not been studied before. Measurements of differences in soil water content over short distances, as implemented for several soils by Ritsema and Dekker (1994a, b, 1995) and Dekker and Ritsema (1994a, b, 1995, 1996b, d), have never been performed in peat soils.

Therefore, the objectives of this study were to indicate the variability of soil water content over short distances in water repellent peaty clay and clayey peat soils, and to relate the observed irregular wetting patterns to the process of preferential flow.

7.2 MATERIALS AND METHODS

Experimental Sites and Soils

Six sites with poorly wettable peaty clay and clayey peat topsoils were selected for a study of the variation in water content at different times. All sites were permanent, well-managed, pastures and located in different parts of the Netherlands (Fig. 7.1). Normal farming practices of grazing cattle and growing grass for fodder were continued during the investigation. Soils at the Bodegraven and Lagebroek sites consisted of peaty clay (with organic matter contents between 20 and 35%) down to a depth of more than 1 m. Peat soils with a clayey peat topsoil (with organic matter contents between 40 and 70%) were found at the Wilnis, Vinkeveen, Broek in Waterland, and Joure sites. All soils studied were classified as mesic Typic Medihemist according to Soil Taxonomy and as Histosol in the FAO system (De Bakker, 1979).

Soil Water Content Measurements

Volumetric water content was determined by sampling the soils studied at different depths using steel cylinders (100 cm^3), with a height and diameter of 5 cm. At each depth, 25 samples were taken at close intervals along a 137 cm transect. The wet soil was weighed, dried for several days at 65°C, and weighed again to calculate soil water content and dry bulk density.

Soil sampling took place between 13 September 1990 and 11 October 1991 at the Lagebroek, Bodegraven, Vinkeveen and Wilnis sites, and between 19 September 1991 and 22 May 1992 at the Broek in Waterland and Joure sites. The last two sites were additionally sampled on 24 and 26 October 1995, respectively; 50 samples were taken at each depth over a 275 cm transect. Table 7.1 shows the sampling depths and sampling dates for all sites studied.

exhibited extreme water repellency after being dried at 25°C, and the same was found after a further drying at 65°C. The Broek in Waterland samples taken at depths of 20-25 cm were also equally divided over the WDPT classes for both temperatures. However, 15 of the 17 Joure samples taken at depths of 20-25 cm, which were severely water repellent after drying at 25°C, exhibited extreme repellency after drying at 65°C. This indicates that a temperature of 65°C may

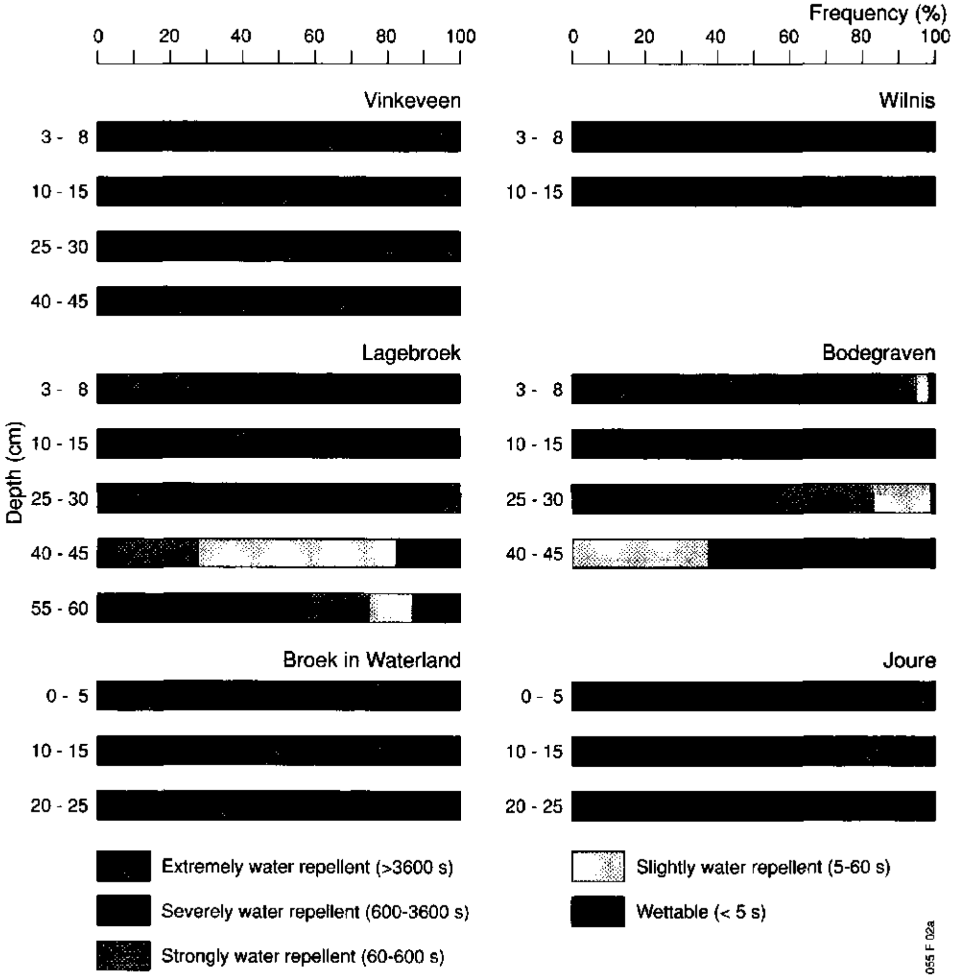


Fig. 7.2 *Relative frequency of the degree of potential water repellency of samples (n = 50) from the topsoils of the six sites studied.*

increase the severity of water repellency, which is why drying at 25°C is to be preferred for future measurements of potential water repellency of peat soils.

Table 7.2 *Frequency of the degree of potential water repellency of samples (n = 50) dried at 25°C and at 65°C.*

Depth (cm)	Water content after drying at 25°C (vol%)	WDPT 25°C		WDPT 65°C	
		600-3600s	>3600s	600-3600s	>3600s
		Broek in Waterland			
0- 5	2.1-5.4	-	50	-	50
10-15	2.1-5.1	-	50	-	50
20-25	1.4-4.1	12	38	12	38
		Joure			
0- 5	3.5-6.7	-	50	-	50
10-15	3.5-7.0	-	50	-	50
20-25	2.2-4.0	17	33	2	48

Actual Water Repellency

The soils were only water repellent when relatively dry, while they were wettable when moist or wet. For instance, all field-moist samples taken at depths of 0-5 cm and 10-15 cm at the Broek in Waterland site were water repellent on 24 Oct. 1995 (Fig. 7.3). The volumetric soil water content varied between 18.4 and 33.7% at depths of 0-5 cm, and between 21.2 and 33.6% at depths of 10-15 cm. This means that water repellency only disappeared at a water content which was certainly higher than 33.7%. At depths of 20-25 cm, 42 samples (84%) were water repellent, whereas 8 samples (16%) were wettable. The water content of the water repellent samples varied between 21.8 and 38.4%, while that of the wettable ones ranged from 38.8 to 47.8%. This indicates that the critical soil water content above which water repellency disappears is around 38.5% for this layer.

At the Joure site, all samples at depths of 10-15 cm were water repellent on 26 Oct. 1995 (Fig. 7.3). Their water content varied between 26.6 and 37.2%, indicating that the critical soil water content was higher than 37.2%. At depths of 20-25 cm all samples were wettable, with water contents ranging from 51.3 to 71.7%. These samples were dried gradually in the laboratory and their weights and WDPT were measured regularly, until WDPT exceeded 5 s. The measurements revealed that the soil became water repellent around a volumetric water content of 38%. The water content of the water repellent samples at depths of 0-5 cm varied between 26.2 and 38.2%, whereas that of the wettable samples ranged from 34.6 to 44.6%. Thus, the critical soil water content must be somewhere in the range 34.6-38.2%. The critical soil water content of the surface layer (0-5 cm) was difficult to determine, because sometimes the upper cms were found to be wet, whereas the lower cms were dry.

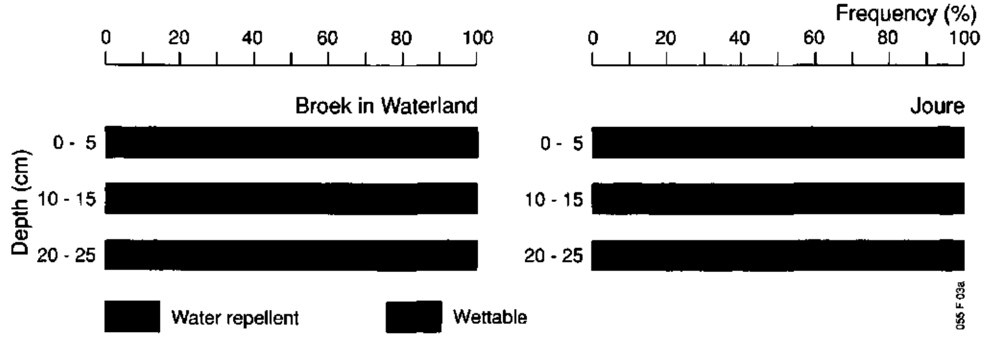


Fig. 7.3 *Percentage of actually water repellent soil samples (n=50) at three depths at the Broek in Waterland and Joure sites, on 24 and 26 October 1995, respectively.*

Generally speaking, it can be stated that the critical soil water content for the Broek in Waterland and Joure sites was somewhere between 34 and 38.5%, which contrasts with the critical soil water contents of less than 5% found for sandy soils by Dekker and Ritsema (1994b).

Resistance to wetting

Large differences in wettability exist between wettable and water repellent peat soils. Wetting is fast in wettable peat, whereas in actually water repellent peat wetting may be a very slow process. Figure 7.4 shows that the increase in water content versus time in field-moist samples originating from two sites differed greatly. The water uptake during one week by the actually water repellent peat samples, with initial water contents between 25.1% and 31.1%, led to an increase in the soil water content of only 1.4-3.6%. By contrast, the increase in the water content of the wettable sample from Joure, which had an initial water content of

41.1%, was 23.2% over the same period of time. The wetting of the other wettable sample was also very fast, but the water uptake decreased after one day, as the sample reached its equilibrium.

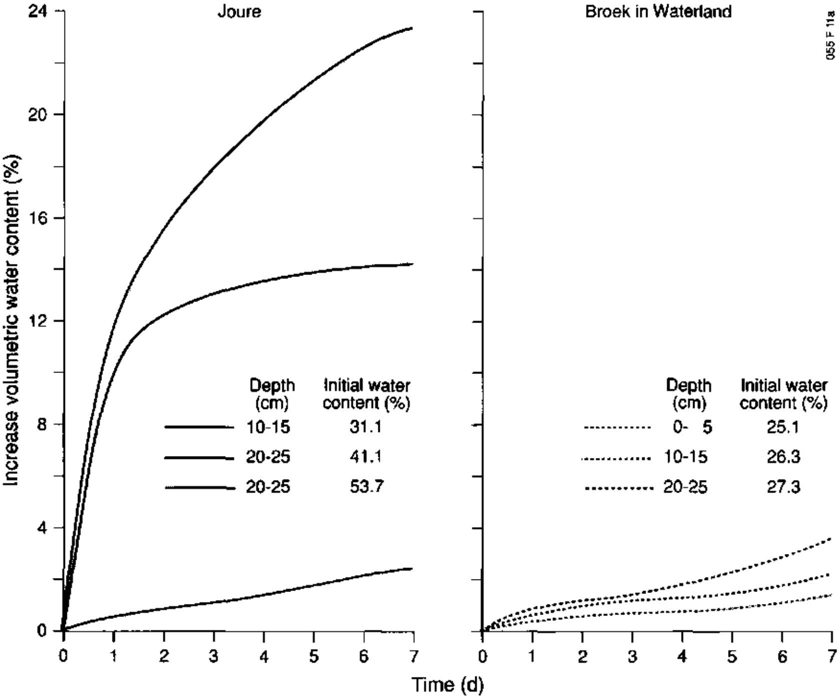


Fig. 7.4 *Increase in volumetric soil water content versus time of field-moist soil samples placed at a constant pressure head of -2.5 cm water below the bottom of the sample.*

Spatial Variability in Soil Water Content and Wetting Patterns

Soil water content varied at all depths, at all sites, and on all sampling dates, and irregular wetting patterns were often found, as is described below for each of the six sites.

Lagebroek site

Figure 7.5 shows the range of volumetric soil water content at five depths of the peaty clay soil at the Lagebroek site on six days. The difference between minimum and maximum values for soil water content within the layers sampled was at least 5 vol% and occasionally even 20 vol%. In the two weeks preceding the first sampling date, on 18 Sept. 1990, total precipitation amounted to 27 mm. Between this sampling date and the next one, on 2 Oct. 1990, precipitation amounted to 71 mm. As can be seen in Figure 7.5, there was only a small increase in water content in the two upper layers at depths of 3-8 cm and 10-15 cm. This increase corresponded to only about 10 mm of the 71 mm precipitation. The water content of the soil profile also hardly increased as a result of the 65 mm of rain which fell between 2 Oct. and 5 Nov. 1990, but the 83 mm of precipitation between 5 and 30 Nov. 1990 resulted in a slight wetting of the topsoil at depths of 3-8 cm and 10-15 cm, and of the subsoil at depths of 55-60 cm. The subsequent winter rains hereafter, between 30 Nov. 1990 and 27 Feb. 1991, with a total amount of 115 mm, scarcely induced a further wetting of the peaty clay profile. On 27 Feb. 1991, the soil profile still exhibited small open cracks at depths between 20 cm and more than 65 cm, whereas no cracks were visible in the topsoil at the time.

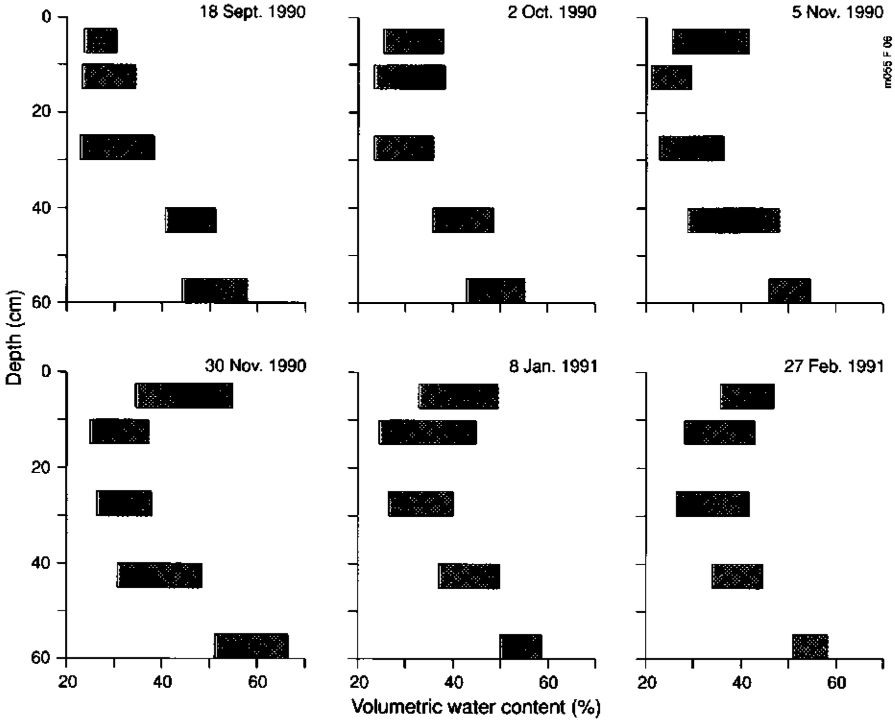


Fig. 7.5 *Range of volumetric soil water content (n = 25) at five depths on six sampling dates at the Lagebroek site.*

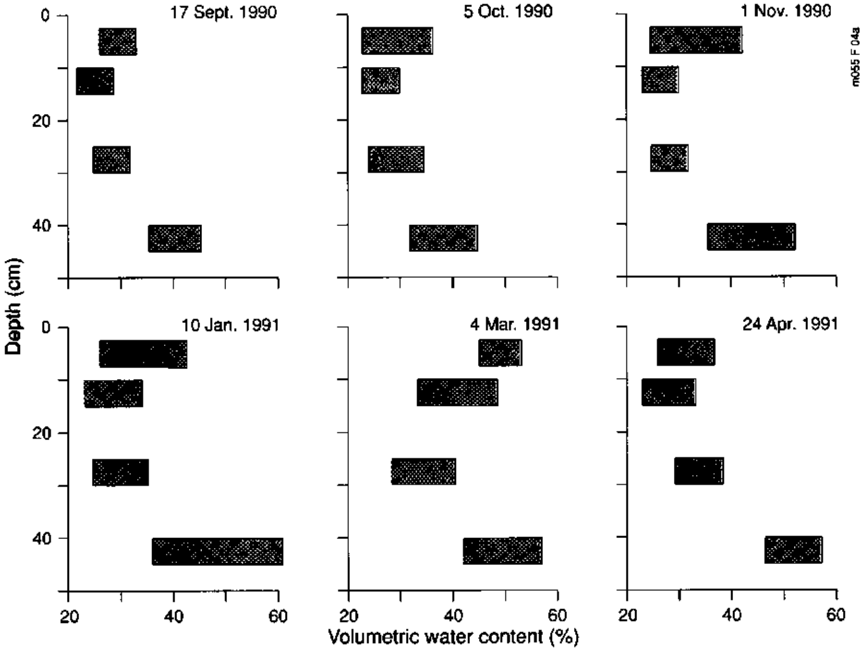


Fig. 7.6 *Range of volumetric soil water content (n = 25) at four depths on six sampling dates at the Bodegraven site.*

Bodegraven site

A more or less similar wetting process was found in the peaty clay soil at the Bodegraven site (Fig. 7.6). Total rainfalls of 79 mm between 17 Sept. and 5 Oct., and of 47 mm between 5 Oct. and 1 Nov. 1990, only slightly influenced the water content of the soil profile. Soil water contents at depths of 10-15 cm and 25-30 cm were almost the same on the three sampling days, although the average soil water content and its variation at depths of 3-8 cm and 40-45 cm increased slightly. The 213 mm of precipitation between 1 Nov. 1990 and 10 Jan. 1991 also had only minor influence on the water content of the soil profile. Between 17 Sept. 1990 and 4 Mar. 1991, the groundwater table rose from 1.3 m to 0.5 m below the soil surface. This rise evidently influenced the wetting of the soil at depths of 40-45 cm. The 52 mm of rainfall between 10 Jan. and 4 Mar. 1991 caused a significant increase in water content at depths of 3-8 cm and 10-15 cm. The topsoil dried considerably between

4 Mar. and 24 Apr. 1991, due to an evaporation surplus of 66 mm, whereas the subsoil remained rather wet in this period. Between 24 and 30 Apr. 1991, precipitation amounted to 39 mm, and this caused an irregular wetting pattern in the dry topsoil, as is shown in Figure 7.7.

Fig. 7.7 *Uneven wetting patterns (dark areas) in the peaty clay soil at the Bodegraven site on 30 April 1991.*

Vinkeveen site

Average soil water contents at the Vinkeveen site increased gradually between 14 Sept. 1990 and 4 Mar. 1991 (Fig. 7.8). During this period, 358 mm of precipitation was recorded. Highly variable water contents were found in September and October 1990; variations of 15 vol% or even 30 vol% were measured within short distances. The lowest variability in water content was found on 4 Mar. 1991, when the soil profile was rather wet. The surface layer of the soil dried between 21 Mar. and 17 Apr. 1991. Rain showers with a total amount of 22 mm in the week preceding 25 Apr. 1991 again caused an irregular wetting of the peat profile; for example, the soil water content at depths of 3-8 cm varied between 42 and 58 vol% on this day (Fig. 7.8).

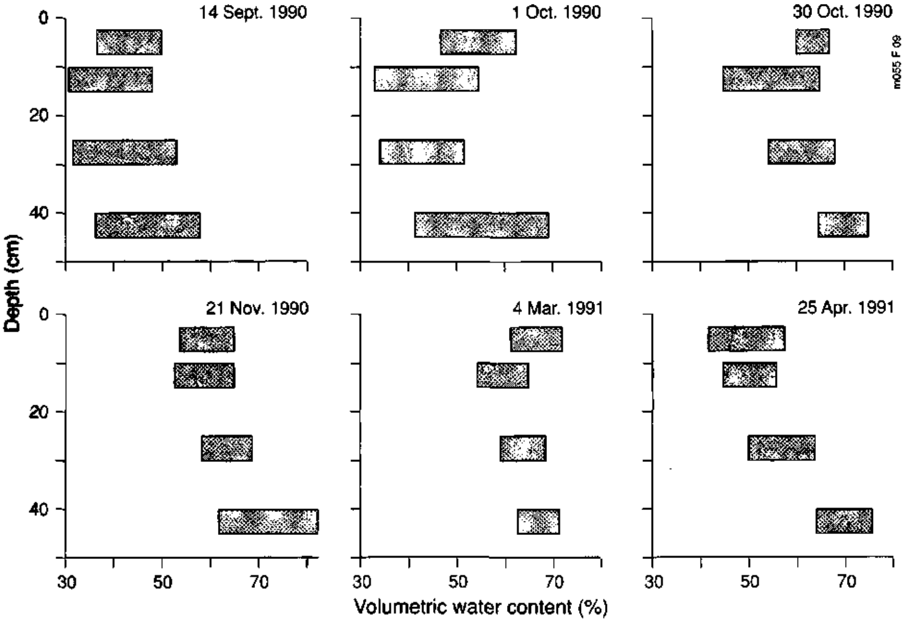


Fig. 7.8 *Range of volumetric soil water content (n = 25) at four depths on six sampling dates at the Vinkeveen site.*

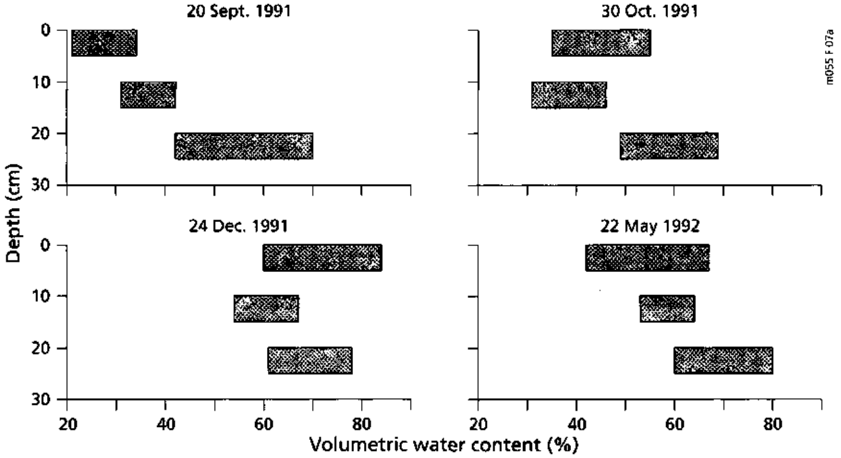


Fig. 7.9 *Range of volumetric soil water content (n = 25) at depths of 0-5, 10-15, and 20-25 cm, on four sampling dates at the Joure site.*

Joure site

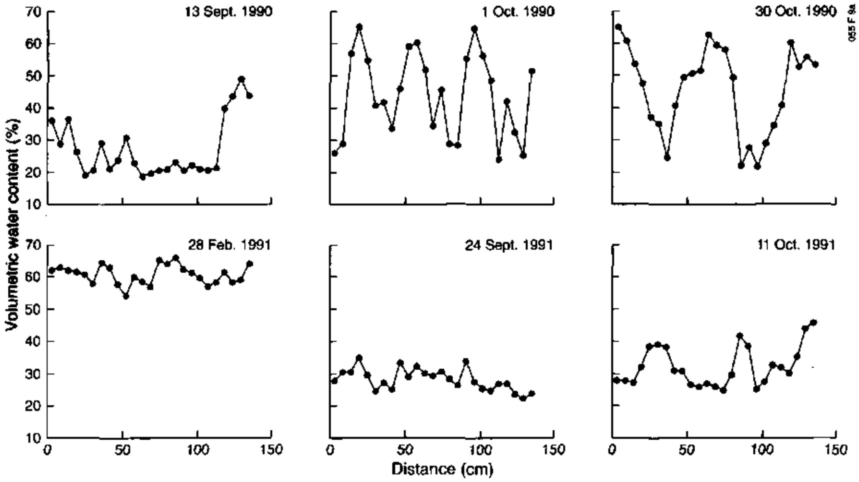
Due to an evaporation surplus of 170 mm in the period 1 July to 20 Sept. 1991, the clayey peat topsoil of the Joure site became relatively dry (Fig. 7.9). On 20 Sept., the soil water content varied between 21 and 34 vol% at depths of 0-5 cm, between 31 and 43 vol% at depths of 10-15 cm, and between 42 and 70 vol% at depths of 20-25 cm. In the period between this sampling and the next one on 30 Oct. 1991, 78 mm of precipitation was recorded. This caused an increase in the water content of the surface layer of between 35 and 55 vol%, whereas the water content of the two deeper layers hardly changed. An increased water content for all three soil layers was induced by 116 mm of precipitation between 30 Oct. and 24 Dec. 1991. However, differences in water content of between 10 and 20 vol% still occurred. In the period between 24 Dec. 1991 and 13 May 1992 a total amount of 256 mm precipitation was recorded, while the total potential evaporation amounted to 133 mm. A dry period started on 13 May, no rain being recorded until 22 May 1992. On that date water content of the surface layer varied between 42 and 69 vol%, and that at depths of 20-25 cm between 60 and 80 vol%.

Fig. 7.10 *View of a vertical cross-section of the clayey peat topsoil at the Wilnis research site on 1 Oct. 1990, after a rain event (dark areas are wet, light areas are dry).*

Wilnis site

Figure 7.10 shows the very uneven wetting of the extremely water repellent clayey peat topsoil of the Wilnis site on 1 Oct. 1990. The dark areas were actually wettable, whereas the light area was actually water repellent. Water drops remained on the surface of this dry peat material for hours, as was checked in the field.

A Depth 3-8cm



B Depth 10-15cm

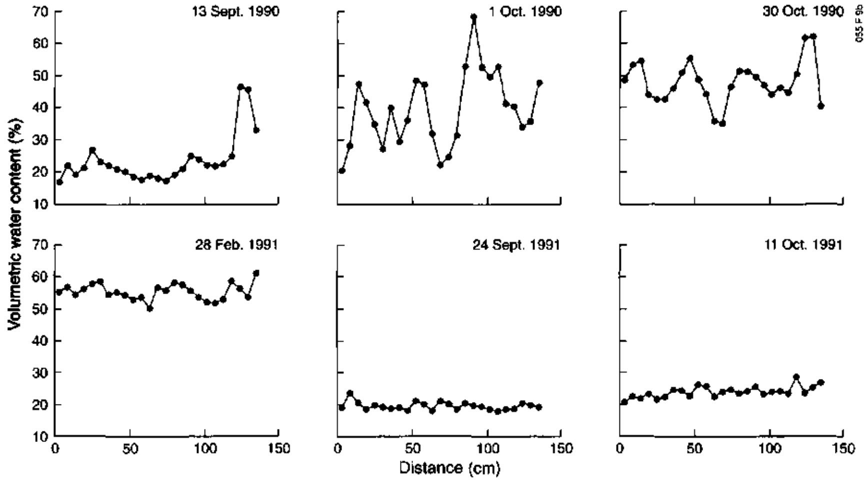


Fig. 7.11 *Volumetric soil water content (A) at depths of 3-8 cm and (B) at depths of 10-15 cm in the clayey peat topsoil of the Wilnis site on six sampling days.*

The upper part of Figure 7.11 shows the variation in soil water content at depths of 3-8 cm on six days. Soil water content fluctuated between 20 and 50 vol% on 13 Sept. 1990. Fingerlike wetting patterns, the peaks in the diagram, occurred at this depth on 1 Oct. 1990. Cumulative precipitation since 13 Sept. amounted to 68 mm on 1 Oct. 1990. Rather wider wetting patterns were found at this depth on 30 Oct., after another 55 mm of rainfall. The total amount of 228 mm of precipitation between 30 Oct. 1990 and 28 Feb. 1991, in combination with a rise in the groundwater table to 15 cm below the soil surface, caused a nearly complete wetting of the surface layer, with a soil water content of about 60 vol% on 28 Feb. 1991. After a dry summer period, the soil water content decreased to approximately 30 vol%, as is indicated by the 24 Sept. 1991 sampling. Rain events between 24 Sept. and 11 Oct. 1991 with a total amount of 63 mm, once again caused the soil water content to fluctuate between 28 and 48 vol% at depths of 3-8 cm. As can be seen in the lower part of Figure 7.11, these rain events hardly increased the water content at depths of 10-15 cm. Large fluctuations in water content at depths of 10-15 cm occurred on 1 Oct. 1990 (see also Fig. 7.10) and on 30 Oct. 1990 (Fig. 7.11).

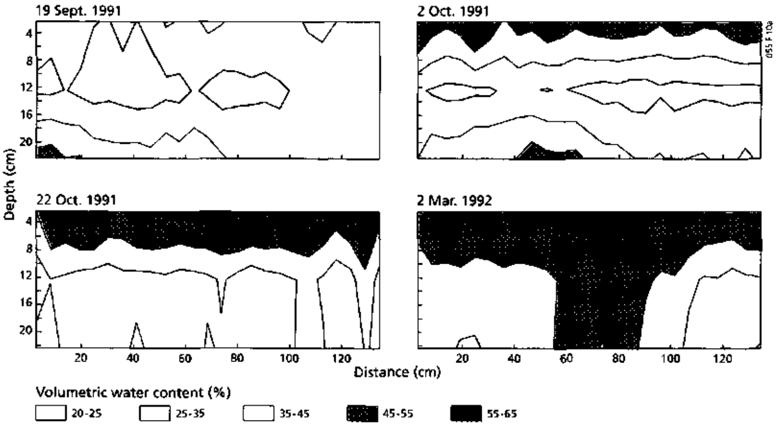


Fig. 7.12 *Cross-sections showing the spatial distribution of the volumetric soil water content in the clayey peat soil of the Broek in Waterland site on 19 Sept., 2 and 22 Oct. 1991, and on 2 Mar. 1992.*

Broek in Waterland site

Figure 7.12 shows four contour plots with the soil water distribution of the water repellent clayey peat topsoil at the Broek in Waterland site on four sampling days, obtained using the statistical computer program Genstat 5, release 2. In the period from 1 Aug. to 19 Sept. 1991, the topsoil at this site became rather dry and actually water repellent, as the critical soil moisture content was around 34%. This was due to the high potential evaporation of 125 mm in this period. A large part of the topsoil dried to a soil water content of between 20 and 35 vol%. Between this sampling date and the next, on 2 Oct. 1991, precipitation amounted to 61 mm. Only the surface layer was wetted due to this precipitation. The 46 mm of precipitation recorded between 2 and 22 Oct. 1991, led to the formation of small wetting patterns at depths of 10 to 25 cm, although a major part of the peat at this depth was still rather dry and actually water repellent. In the period between this sampling date and that on 2 Mar. 1992, rainfall amounted to 256 mm. As is shown in Figure 7.12, the centre of the fingerlike wetting pattern in the cross-section of 2 Mar. 1992 has a soil water content of 45 to 55 vol%, whereas actually water repellent soil parts still occurred at the same depth, with water contents between 25 and 35 vol%. It can be seen from Figure 7.12, and for the Wilnis site from Figure 7.11, that the fingerlike wetting patterns have widths between 15 and 40 cm, which means that these flow paths are presumably not related to positions with cracks or biopores. It is more likely that such wetting patterns form within the soil matrix, as has previously been found for two water repellent loam soils (Dekker and Ritsema, 1995) and for a water repellent clay soil (Dekker and Ritsema, 1996d). Based upon these observations, it might therefore be concluded that water transport through peat soils is not solely restricted to macropore flow, but that fingerlike wetting paths in the soil matrix are of importance too.

7.4 CONCLUDING REMARKS

Preferential flow in peat soils may occur through cracks or biopores, but as was shown in our study, irregular, fingerlike preferential flow paths through the matrix are also formed in peaty clay and clayey peat soils. These preferred pathways are thought to form at places with cracks which receive relatively large amounts of

8 DRYING TEMPERATURE AND POTENTIAL WATER REPELLENCY

Abstract

Soil water repellency is often recognized in surface layers of soils that frequently dry out. The degree of water repellency of a soil can be measured by using the water drop penetration time (WDPT) test on field-moist or on dried samples, referred as actual and potential water repellency, respectively. A soil layer is actually water repellent below and actually wettable above its critical soil water content. Findings of the present study indicated that the degree of potential water repellency might change with different drying temperatures. For 4 out of 7 sandy soil sites in the Netherlands, potential water repellency was greater after drying at 65^{0}C relative to 25^{0}C, whereas it decreased for 2 others, and remained unchanged for one. The most reliable estimate of water repellency was obtained from undried samples collected during dry periods. Wetting rate measurements illustrated that increasing water repellency as a result of high drying temperatures led to decreasing water absorption by samples. Micromorphological investigations indicated that high drying temperatures resulted in an increase in the formation of organic carbon coatings responsible for soil water repellency.

8.1 INTRODUCTION

Water repellency of surface layers is often recognized in soils that frequently dry out and are not cultivated. When dry, they resist or retard water infiltration into the soil matrix (Debano, 1981; Wallis and Horne, 1992). Water repellent soils can be found in many parts of the world under a variety of climatic conditions, and may occupy large areas (DeBano, 1981; Blackwell, 1993; Ritsema and Dekker, 1995, 1996; Doerr et al., 1996). Blackwell (1993) stated that water repellency affects about 5 million hectares of agricultural land in sandy districts of Western Australia, South Australia and Victoria. Water repellent soils are also widespread in the Netherlands and occur in sand, loam, clay and peat areas (Chapter 2, 5, 6, 7). Water repellency of soils in the USA has been described by numerous researchers (e.g. Jamison, 1946; Krammes and DeBano, 1965; DeBano, 1981; McNabb et al., 1989).

in the eastern part of the country (Fig. 8.1). The dune sands of Ouddorp, Schoorl,

Table 8.1 *Mean dry bulk densities, organic matter contents, pH, and soil water contents, at several depths at the four dune sand sites.*

Depth	**Bulk density**	**Org. matter**	**pH**	**Soil water content**		
(cm)	**(g.cm^{-3})**	**(w%)**		**Minimum (vol%)**	**Mean (vol%)**	**Maximum (vol%)**
			Ouddorp, November 28, 1995			
0-5	**0.90**	**8.9**	**5.4**	**18.6**	**30.5**	**38.3**
9-14	**1.42**	**1.3**	**4.6**	**1.9**	**6.2**	**14.3**
19-24	**1.42**	**1.2**	**4.6**	**1.5**	**4.6**	**11.4**
30-35	**1.49**	**0.6**	**4.7**	**0.7**	**4.4**	**10.0**
42-47	**1.49**	**0.5**	**4.8**	**1.0**	**3.4**	**7.9**
55-60	**1.48**	**0.4**	**4.8**	**1.0**	**3.8**	**9.0**
69-74	**1.47**	**0.6**	**4.7**	**3.9**	**7.4**	**9.6**
			Westduinen, August 16, 1996			
0-5	**0.88**	**2.1**	**3.4**	**4.9**	**11.1**	**23.7**
7-12	**1.49**	**0.6**	**3.5**	**1.1**	**3.1**	**6.1**
14-19	**1.54**	**0.5**	**3.6**	**0.9**	**2.8**	**10.6**
21-26	**1.53**	**0.3**	**3.7**	**1.0**	**4.0**	**7.2**
28-33	**1.53**	**0.3**	**3.9**	**2.3**	**5.4**	**7.4**
35-40	**1.54**	**0.2**	**4.0**	**3.9**	**6.0**	**8.3**
			Schoorl, November 4, 1996			
0-2.5	**0.61**	**12.4**	**3.6**	**17.3**	**37.3**	**71.7**
2.5-5	**1.38**	**0.6**	**3.9**	**7.3**	**14.7**	**41.5**
7-12	**1.51**	**0.5**	**3.9**	**4.4**	**7.0**	**10.7**
14-19	**1.49**	**0.3**	**3.8**	**1.4**	**4.8**	**10.9**
21-26	**1.53**	**0.4**	**4.1**	**1.0**	**2.7**	**6.8**
28-33	**1.53**	**0.2**	**4.1**	**0.7**	**1.9**	**6.6**
35-40	**1.58**	**0.3**	**3.9**	**0.6**	**1.3**	**4.6**
			Zwanenwater, October 30, 1996			
0-5	**0.28**	**40.4**	**3.7**	**22.8**	**34.1**	**43.7**
7-12	**1.21**	**0.8**	**3.8**	**2.8**	**10.8**	**22.6**
14-19	**1.46**	**0.8**	**4.0**	**1.2**	**4.1**	**9.0**
21-26	**1.48**	**0.7**	**4.1**	**1.0**	**4.3**	**9.1**
28-33	**1.48**	**0.6**	**4.0**	**2.2**	**6.3**	**10.6**
35-40	**1.48**	**0.6**	**4.2**	**4.7**	**7.9**	**12.6**

Westduinen, and Zwanenwater are classified as mesic Typic Psammaquent; the soils of the experimental farms Heino and Cranendonck as mesic Plaggept; and the soil of the experimental farm Vredepeel as mesic Typic Haplaquod (De Bakker, 1979).

The Ouddorp site is grass-covered, is in use as pasture, and has not been tilled for at least several decades. The other three dune sands are situated in nature reserves. The Westduinen site is covered with grey hair grass and mosses, the Zwanenwater site with a grass vegetation and the Schoorl site is occupied by Pinus Sylvestris. The soils of the Cranendonck and Vredepeel sites are used as arable land and the soil of the Heino site is grass-covered and in use as pasture.

At each site, samples were taken at several depths to determine the organic matter content and the pH of the soil profiles (Table 8.1 and Table 8.2). The organic matter content was measured by drying the sample for 1 day at 105^{0}C and igniting the dried sample for 4 h at 650^{0}C. The weight difference between the dried and ignited samples was taken as the organic matter content. pH was measured by using standard pH electrodes which were placed in a solution obtained by adding water in a ratio of 1 : 2.5 (soil : water).

The soils were sampled at different depths using steel cylinders (100 cm^3), each with a diameter and height of 5 cm. An exception was made for the uppermost layers of the Schoorl and Heino sites, where 50 cm^3 cylinders, with a height of 2.5 cm, were used. The cylinders were pressed vertically into the soil, emptied in plastic bags and used again. The field-moist soil in the plastic bags was weighed, and soil water content and dry bulk density of the samples were calculated after drying at 65^{0}C. At the Cranendonck site, twenty five samples were taken at close intervals (cylinders nearly touching one another) in a transect, at depths of 0-5, 20-25, 30-35, and 50-55 cm. At the other six sites, soil blocks were sampled. The sampling dates and depths of layers sampled are indicated in Table 8.1 and Table 8.2. At the Ouddorp site a large soil block was sampled and a total of 1680 samples were collected; 240 samples were taken at seven depths, in a regular grid with 40 by 6 samples. At the Westduinen, Schoorl, Zwanenwater, Heino and Vredepeel sites, smaller soil blocks were sampled and in these cases 75 samples were taken at each depth, in a grid with 15 by 5 samples. In addition, a transect was sampled at the Heino site on August 10, 1995, during a period of dry weather 25 samples were taken in close order at 12 depths (Table 8.3).

Table 8.2 *Mean dry bulk densities, organic matter contents, pH, and soil water contents, at several depths at the Heino, Cranendonck, and Vredepeel sites.*

Depth (cm)	**Bulk density** (g.cm^{-3})	**Org. matter** (w%)	**pH**	**Soil water content** Minimum (vol%)	Mean (vol%)	Maximum (vol%)
Heino, February 7, 1997						
0-2.5	1.50	8.5	5.6	35.0	41.4	51.3
2.5-5	1.47	6.9	5.9	33.1	36.9	39.8
7-12	1.44	5.2	5.1	32.2	35.3	39.7
14-19	1.37	5.8	5.2	32.7	37.7	44.0
21-26	1.36	5.7	5.3	28.5	33.7	44.6
28-33	1.42	5.0	4.9	24.0	30.3	36.8
35-40	1.35	5.2	4.4	18.5	21.2	25.3
45-50	1.30	5.5	4.2	19.7	21.6	22.6
55-60	1.28	5.2	4.3	16.9	19.4	20.2
Cranendonck, February 26, 1997						
0-5	1.34	2.5	5.6	20.2	25.0	29.6
20-25	1.46	2.3	5.8	18.6	21.0	25.1
30-35	1.51	2.1	5.4	18.8	19.2	22.8
50-55	1.65	1.7	5.3	18.8	22.9	25.3
Vredepeel, November 4, 1996						
0-5	1.16	6.8	5.8	16.4	23.3	33.4
7-12	1.32	6.9	5.9	19.2	22.6	26.6
14-19	1.43	6.7	5.7	20.0	23.5	30.8
21-26	1.40	5.8	5.7	15.4	18.6	26.1
28-33	1.45	4.9	5.6	7.2	12.8	19.5
35-40	1.52	0.5	6.0	6.3	7.2	9.2

Water Repellency Measurements

The actual water repellency was measured using the WDPT test on the field-moist samples. Measurements were performed immediately after assessment of the wet weights. The samples were divided into two groups: wettable (< 5 s) and water repellent (>5 s). The actual water repellency of the samples from the Ouddorp site was measured for up to more than 6 hours. The samples from 0-5 cm depth at the Ouddorp and Westduinen sites were split up into two 2.5 cm parts.

After the assessment of the actual water repellency the samples were dried in an oven at 25°C for one week. After equilibration in the laboratory for two days, at a temperature of 20°C and at 50% air humidity, samples were used to determine the degree of potential water repellency using the WDPT test. The samples from the four dune sand sites were further dried at 65°C for three days and the potential water repellency was measured again after equilibration with the ambient air humidity of the conditioned laboratory. The effect of temperatures in the range of 25°C to 125°C on water repellency was investigated in the same way for samples from Cranendonk, Vredepeel and Heino.

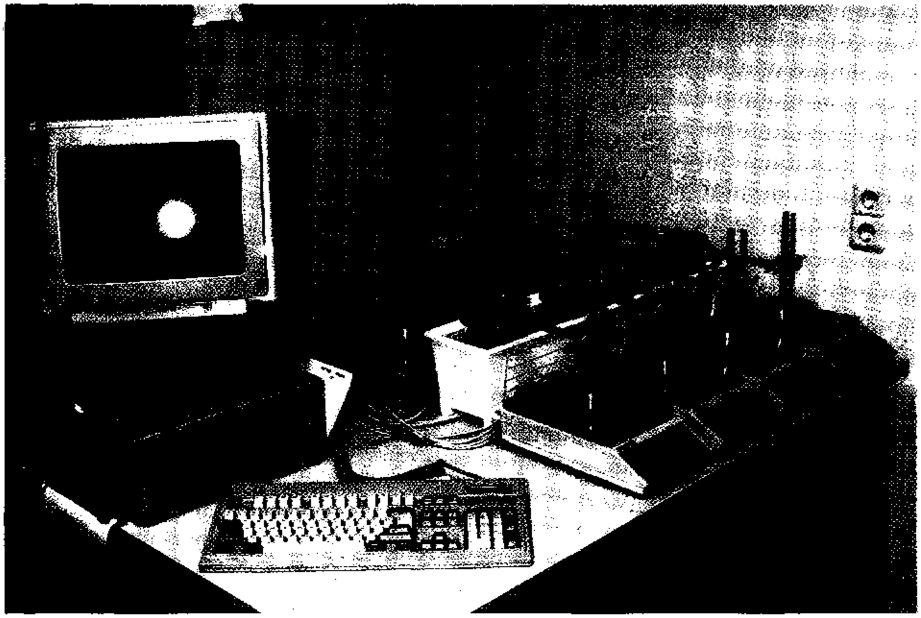


Fig. 8.2 *Measurement of the wetting rate of eight soil samples, placed on ceramic filters and subjected to a pressure head of -2.5 cm water at the bottom of the samples. During the measurements the water level in the basin is kept constant. The water uptake of the samples is recorded by the balances and stored by the computer.*

Wetting Rate Measurements

Resistance to wetting was determined by measuring the wetting of samples after they had been dried at different temperatures. Samples were taken at depths of 0-2.5

cm at Schoorl, 0-5 cm at Zwanenwater, 7-12 cm at Heino, and 20-25 cm at the Cranendonck site. After drying, the samples were kept at a constant temperature of 20^{0}C and a relative air humidity of 50%, for at least two days, to allow the samples to equilibrate with the ambient air humidity. In the same laboratory these samples, within their steel cylinders of 50 or 100 cm^3, were subjected to a constant pressure head of -2.5 cm water applied at the bottom of the sample (Fig. 8.2). The experimental set-up was designed in such a way that water content increments of 0.2 vol% were recorded automatically over a period of one week.

Micromorphological Analysis

A Cambridge Stereoscan (Energy dispersive X-ray analysis) 240 electron microscope, equiped with an system for determining chemical elements was used for dry chemical analysis of coatings on selected sand grains of samples at different drying temperatures. The acceleration voltage was 10 KV. Micrographs were made at magnifications of 240 to 310 times.

Statistical Analysis

The effect of drying temperature on the WDPT was tested using a regression model for ordinal response variables (MacCullagh and Nelder, 1989). This model was used because WDPT was measured in ordered categories and not on an interval scale. The regressions were carried out separately for the seven sites with temperature and depth as predictor variables and the significance of temperature was tested.

8.3 RESULTS

Organic Matter Content and pH

The organic matter contents and pH values of the four dune sand profiles are shown in Table 8.1. Organic matter contents of 8.9 to 40.4 w% were found in the thatch layer of the Ouddorp and Zwanenwater sites and in the uppermost layer, including some litter, of the Schoorl site. Grey sand at depths of 9-24 cm at the Ouddorp, and at depths of 7-26 cm at the Zwanenwater site, contained 0.7 to 1.3 w% organic matter, whereas the yellow sand, deeper in both profiles and from 7 cm downwards at the Westduinen and Schoorl sites, contained only 0.2 to 0.6 w%.

Higher organic matter contents go hand in hand with lower dry bulk density values; values ranging from 0.28-0.90 g.cm^{-3} were found for those surface layers rich in organic matter, whereas values ranging from 1.21-1.58 g.cm^{-3} were established for the layers with 1.3 w% organic matter and less (Table 8.1).

Very low pH values, ranging from 3.4 to 4.2, were assessed for the three dune sand profiles in the nature reserves. Relatively higher pH values were measured for the cultivated pasture at Ouddorp, ranging from 4.6 to 4.8 for depths of 9-74 cm, to 5.4 for the 0-5 cm thatch layer.

Dry bulk density, organic matter, and pH values for the Heino, Cranendonck and Vredepeel sites are summarized in Table 8.2. There were relatively high organic matter contents of around 5 w% throughout the approximately 70 cm thick anthropogenic A-horizon at the Heino site. The organic matter content of the anthropogenic A-horizon at the Cranendonck site is evidently lower and decreases from 2.5 w% at depths of 0-5 cm to 1.7 w% at depths of 50-55 cm. High organic matter contents of around 6.8 w% were measured for the topsoil of the Vredepeel site, whereas the yellow sand of the subsoil at depths of 35-40 cm contained only 0.5 w%. Low pH values, in the range of 4.2 to 4.9, were established at depths of 28-60 cm at the Heino site, whereas in all other cases pH values ranged between 5.1 and 6.0 (Table 8.2).

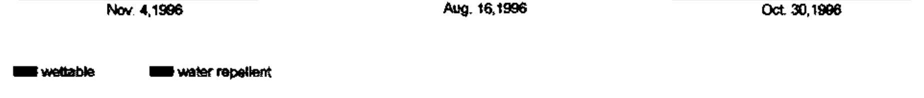


Fig. 8.3 *Percentages of actually wettable and actually water repellent soil samples ($n = 75$) at several depths at the Schoorl, Westduinen and Zwanenwater sites on their respective sampling dates.*

Soil Water Content and Actual Water Repellency

Soil water contents of the layers sampled at the Ouddorp, Westduinen, Schoorl and Zwanenwater sites ranged between 1.3 and 37.3 vol% (Table 8.1). Some of the samples, with relatively low water contents, taken at depths of 2.5-60 cm at Ouddorp, at depths of 21-40 cm at Schoorl, at depths of 0-26 cm at Westduinen, and at depths of 14-26 at the Zwanenwater site, were determined as actually water repellent, whereas all or nearly all samples from the other depths were actually wettable. Figure 8.3 shows the relative frequencies of actually wettable and actually water repellent samples from three of the four dune sand sites.

The soil profiles of the Vredepeel, Heino and Cranendonck sites were moist to wet, with soil water contents ranging from 6.3 to 51.3 vol% and with mean contents ranging from 7.2 to 41.4 vol% (Table 8.2). All field-moist samples were assessed as actually wettable, with WDPT values below 5 s.

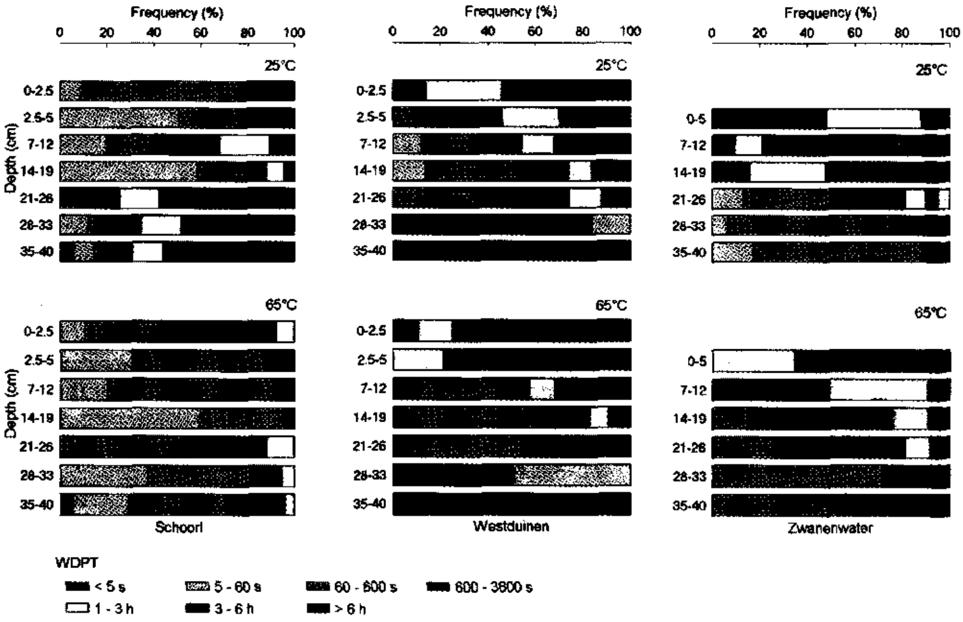


Fig. 8.4 *Relative frequency of the degree of potential water repellency of samples (n = 75) at several depths in three dune sands, measured after drying at 25°C and 65°C.*

Potential Water Repellency and Drying Temperature

The potential water repellency values measured on the dune sand samples from Schoorl, Westduinen, and Zwanenwater at 25⁰C and at 65⁰C are shown in Figure 8.4. For the Schoorl and Zwanenwater samples potential water repellency at a drying temperature of 65⁰C was lower than or the same as that at 25⁰C, except for the 0-2.5 cm layer at Schoorl and the 0-5 cm layer at Zwanenwater. In contrast to this, repellency at 65⁰C was significantly higher for these surface layers and for the 0-12 cm layers at the Westduinen site.

Potential water repellency values of samples taken at depths of 9-60 cm at the Ouddorp site after drying at 25⁰C were comparable to those derived after further drying at 65⁰C (Fig. 8.5). Figure 8.5 also shows the actual water repellency of the field-moist samples from Ouddorp (1920 in all), indicating that soil water repellency was restricted to the 2.5 to 60 cm zone at the moment of sampling.

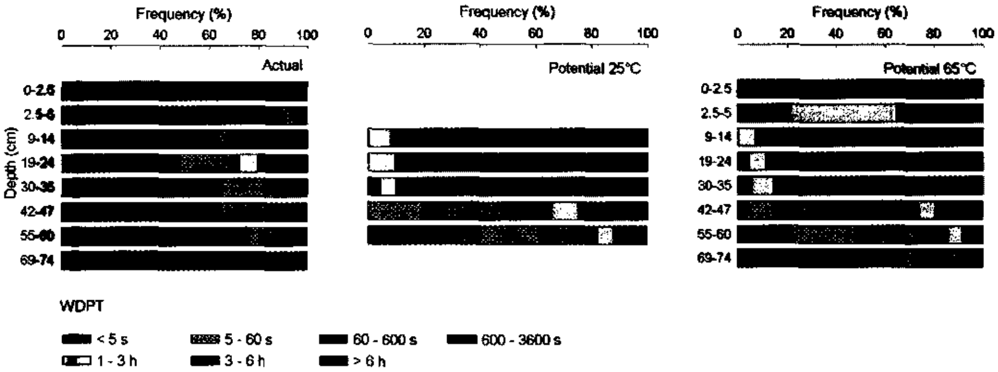


Fig. 8.5 *Relative frequency of the degree of actual and potential (25⁰C and 65⁰C) water repellency of samples (n = 240), at several depths in the dune sand at Ouddorp, sampled on November 28, 1995.*

The left diagram at the top of Figure 8.6 shows that all actually wettable field-moist samples from depths of 9-47 cm at the Ouddorp site became slightly to extremely water repellent after drying at 25⁰C. The left diagram at the bottom of Figure 8.6 shows, however, that the potential water repellency of the actually water repellent samples was significantly more extreme after drying at 25⁰C. Drying at 65⁰C hardly changed the severity of repellency of the samples in both groups, as can be concluded from a comparison of the diagrams on the right-hand side with those on the left-hand side. This will be further discussed later.

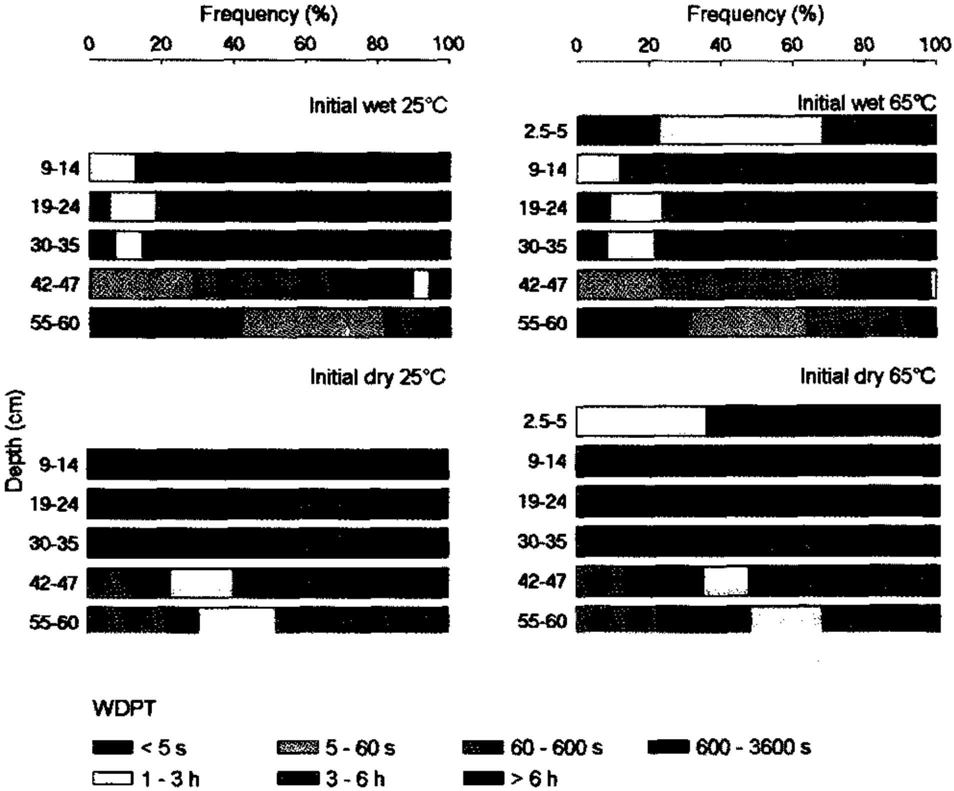


Fig. 8.6 *Relative frequency of the degree of potential water repellency of initially wet (actually wettable) and dry (actually water repellent) dune sand samples from Ouddorp, after drying at 25⁰C and 65⁰C.*

The actually water repellent dune sand samples from the Westduinen, Schoorl, and Zwanenwater sites also exhibited significantly more extreme water repellency than the actually wettable ones after drying at 25⁰C, as can be seen by comparing the lower and upper left-hand diagrams in Figure 8.7. A remarkable feature is the significant decrease in water repellency after further drying at 65⁰C for the actually wettable as well as the actually repellent samples from the Schoorl and Zwanenwater sites. At the same time, however, there was a significant increase in repellency of the actually wettable as well as the actually repellent samples from depths of 0-12 cm at the Westduinen site.

Potential Water Repellency and Drying Temperature

The potential water repellency values measured on the dune sand samples from Schoorl, Westduinen, and Zwanenwater at 25°C and at 65°C are shown in Figure 8.4. For the Schoorl and Zwanenwater samples potential water repellency at a drying temperature of 65°C was lower than or the same as that at 25°C, except for the 0-2.5 cm layer at Schoorl and the 0-5 cm layer at Zwanenwater. In contrast to this, repellency at 65°C was significantly higher for these surface layers and for the 0-12 cm layers at the Westduinen site.

Potential water repellency values of samples taken at depths of 9-60 cm at the Ouddorp site after drying at 25°C were comparable to those derived after further drying at 65°C (Fig. 8.5). Figure 8.5 also shows the actual water repellency of the field-moist samples from Ouddorp (1920 in all), indicating that soil water repellency was restricted to the 2.5 to 60 cm zone at the moment of sampling.

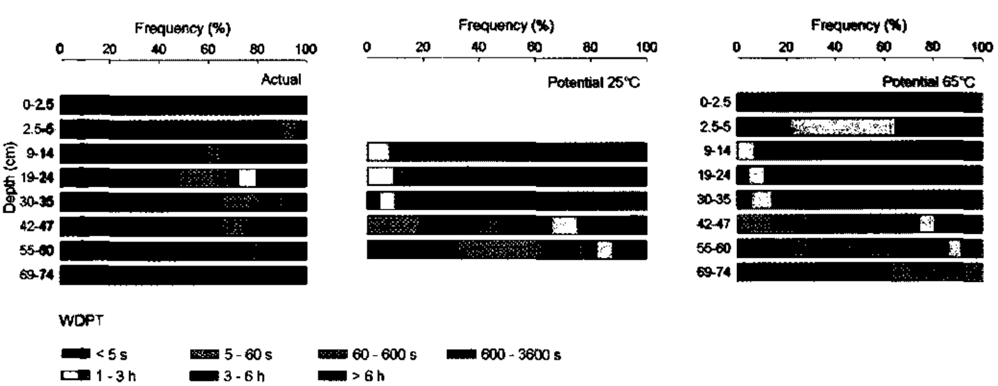


Fig. 8.5 *Relative frequency of the degree of actual and potential (25°C and 65°C) water repellency of samples (n = 240), at several depths in the dune sand at Ouddorp, sampled on November 28, 1995.*

The left diagram at the top of Figure 8.6 shows that all actually wettable field-moist samples from depths of 9-47 cm at the Ouddorp site became slightly to extremely water repellent after drying at 25°C. The left diagram at the bottom of Figure 8.6 shows, however, that the potential water repellency of the actually water repellent samples was significantly more extreme after drying at 25°C. Drying at 65°C hardly changed the severity of repellency of the samples in both groups, as can be concluded from a comparison of the diagrams on the right-hand side with those on the left-hand side. This will be further discussed later.

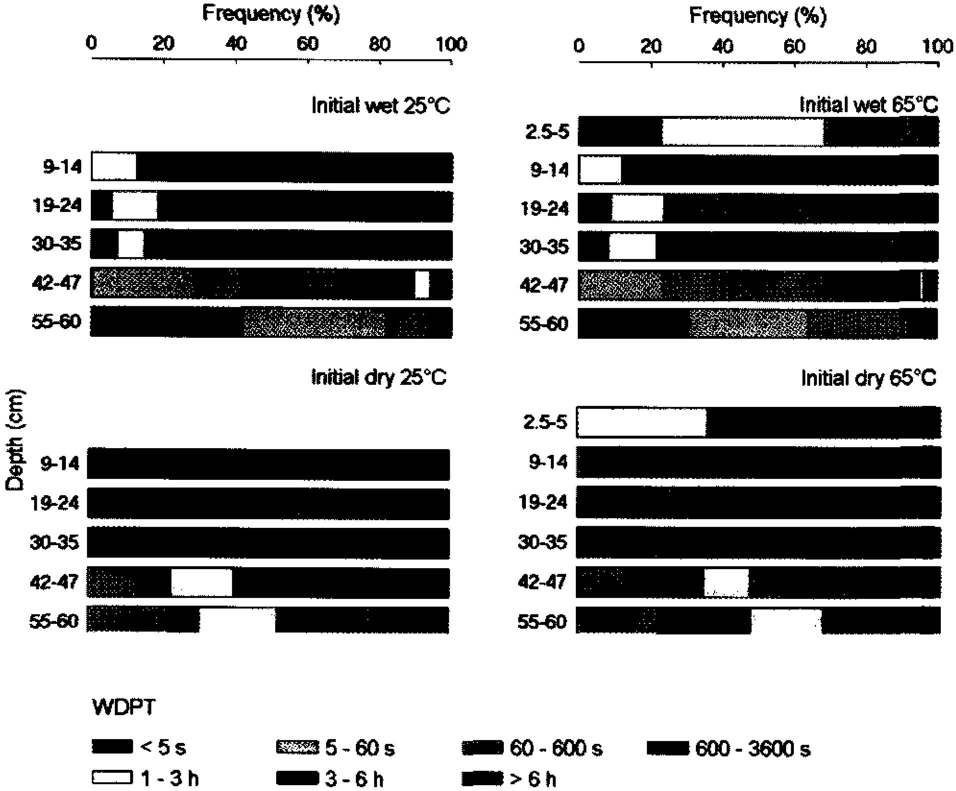


Fig. 8.6 *Relative frequency of the degree of potential water repellency of initially wet (actually wettable) and dry (actually water repellent) dune sand samples from Ouddorp, after drying at 25°C and 65°C.*

The actually water repellent dune sand samples from the Westduinen, Schoorl, and Zwanenwater sites also exhibited significantly more extreme water repellency than the actually wettable ones after drying at 25°C, as can be seen by comparing the lower and upper left-hand diagrams in Figure 8.7. A remarkable feature is the significant decrease in water repellency after further drying at 65°C for the actually wettable as well as the actually repellent samples from the Schoorl and Zwanenwater sites. At the same time, however, there was a significant increase in repellency of the actually wettable as well as the actually repellent samples from depths of 0-12 cm at the Westduinen site.

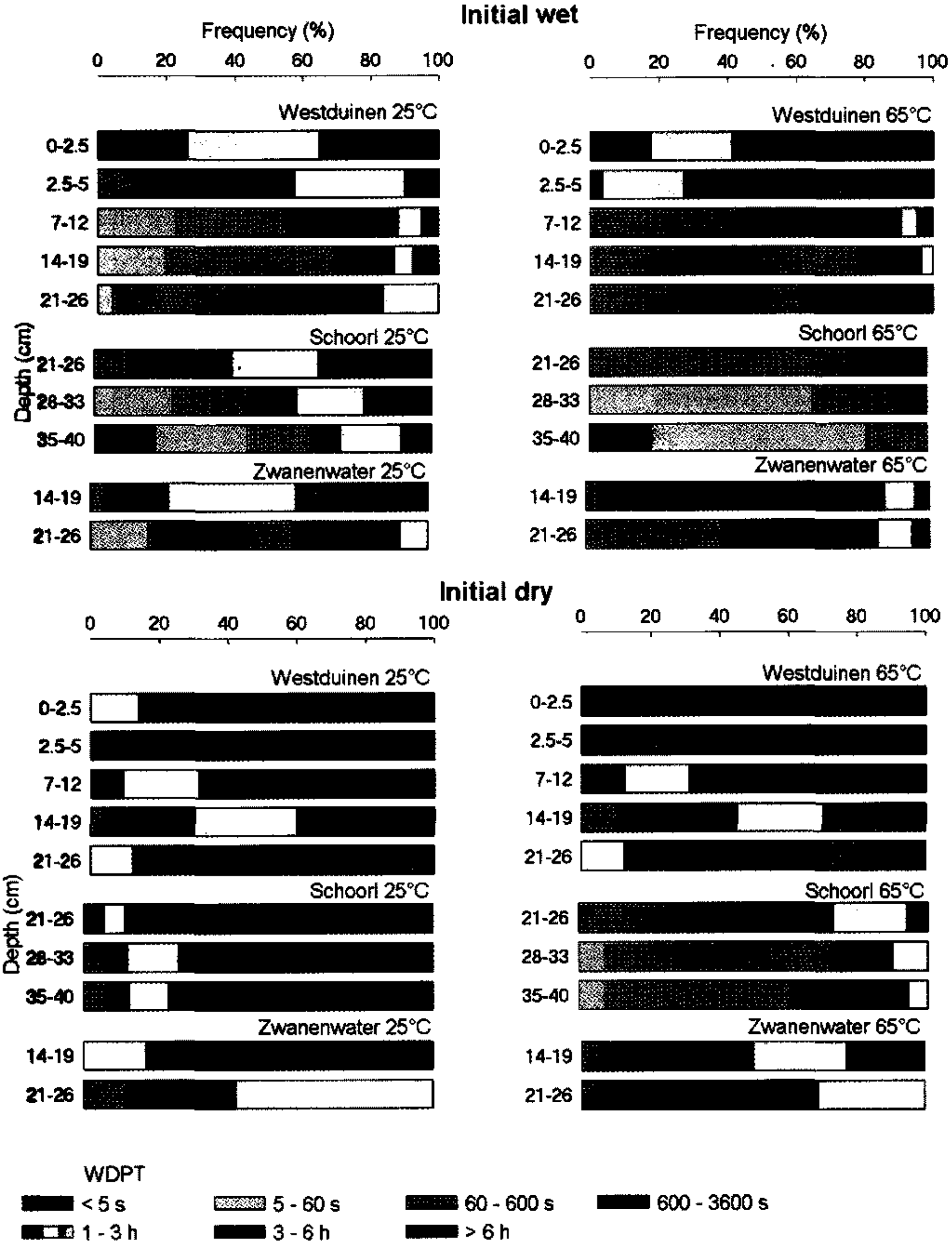


Fig. 8.7 *Relative frequency of the degree of potential water repellency of initially wet (actually wettable) and dry (actually repellent) samples at several depths in three dune sands, after drying at 25°C and 65°C.*

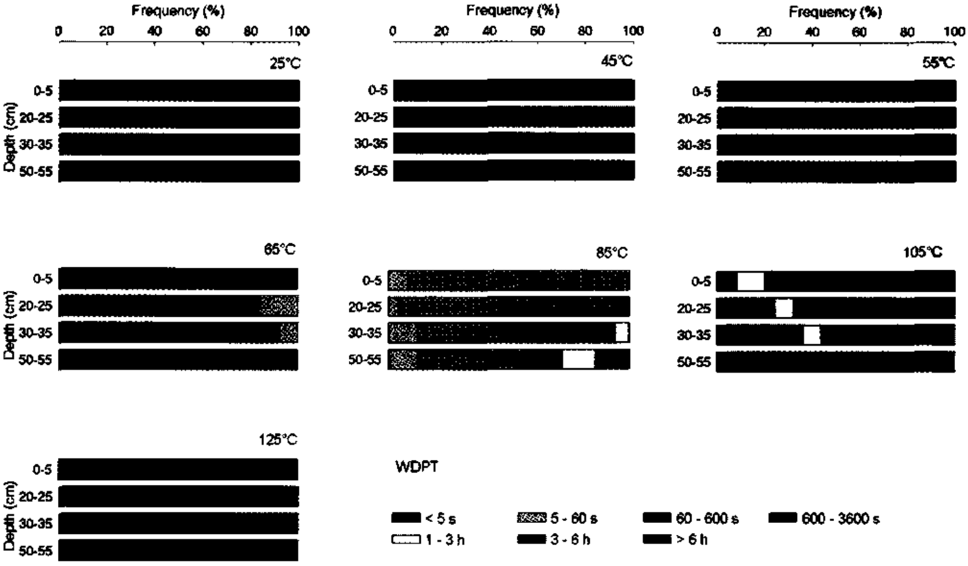


Fig. 8.8 *Relative frequency of the degree of potential water repellency of samples (n = 25) from four depths at Cranendonck, measured seven times after drying at increasing temperatures.*

Samples obtained from the Cranendonck site were actually wettable at the time of sampling. All samples remained wettable after drying at 25°C, 45°C and 55°C (Fig. 8.8). Some samples exhibited slight water repellency after drying at 65°C, while most samples showed strong repellency after further drying at 85°C. Drying at 125°C induced extreme repellency, with water drops remaining on the surfaces of all 100 samples for more than six hours. A significant increase in water repellency was found between the drying temperatures 65°C and 85°C, between 85°C and 105°C, and between 105°C and 125°C.

The samples from the Vredepeel site were also actually wettable during the sampling. Some of the samples from the upper layers in particular became slightly repellent after drying at 25°C and 45°C (Fig. 8.9). Further drying at 65°C induced slight to extreme water repellency for samples taken at depths of 0-33 cm. Extreme water repellency, with WDPT values exceeding 6 h, was caused for all samples by a drying temperature of 85°C. However, the wettable samples from the subsoil at

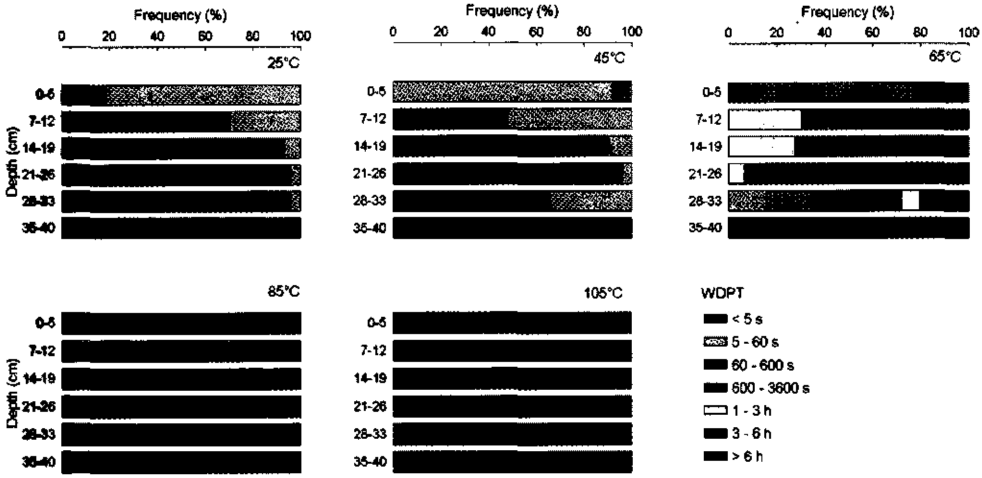


Fig. 8.9 *Relative frequency of the degree of potential water repellency of samples (n = 75) from six depths at Vredepeel, measured five times after drying at increasing temperatures.*

depths of 35-40 cm did not react to the higher drying temperatures and remained wettable. The increase in water repellency of samples from depths of 0-33 cm was significant after drying at 65°C compared to 45°C, and after drying at 85°C compared to 65°C.

Figure 8.10 shows the influence of drying temperatures on the potential water repellency of samples from the Heino site. Repellency clearly increased at higher temperatures. Variability in severity was highest after drying at 65°C, whereas after drying at 85°C all samples were extremely water repellent, with WDPT values exceeding 6 h. Significant increases in water repellency were found between measurements of samples from depths of 0-60 cm, after drying at 55°C in comparison with 45°C, after drying at 65°C in comparison with 55°C, and after drying at 85°C compared to 65°C.

Micromorphological Findings

Figure 8.11 shows 2 micrographs of sand grains from samples taken at the Vredepeel site. Figure 8.11A shows an example of a scarcely coated sand grain obtained from a sample taken at a depth of 14-19 cm, dried at 25°C, and exhibiting

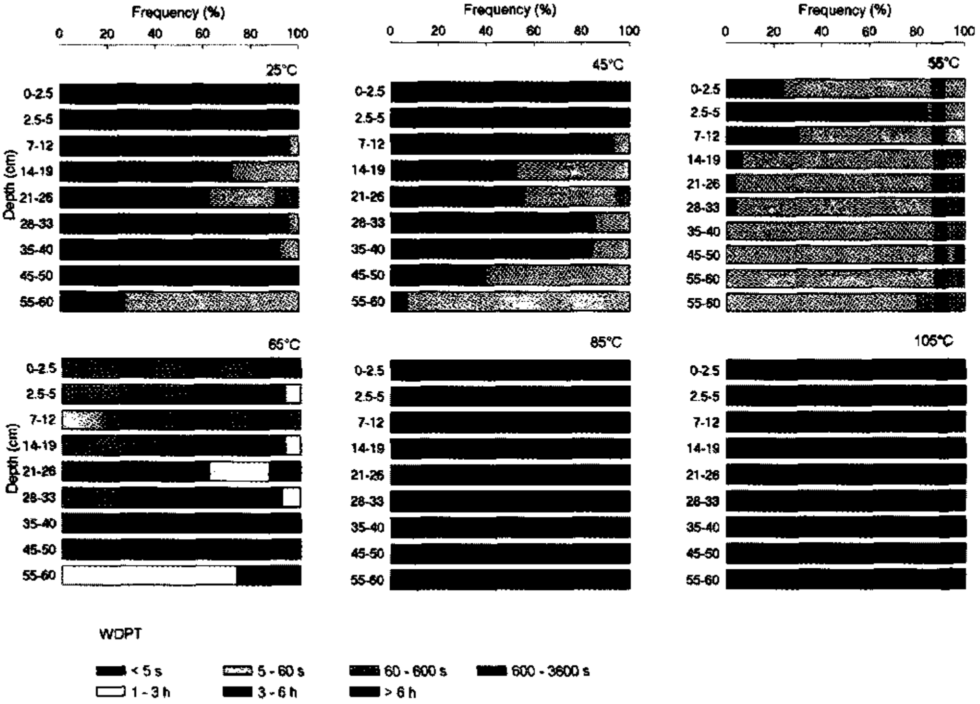


Fig. 8.10 *Relative frequency of the degree of potential water repellency of samples (n = 75) from nine depths at Heino, measured six times after drying at increasing temperatures.*

no water repellency (WDPT < 5 s). Electron-microscope analysis of the particles in the coating revealed a low carbon (C) and a high silicon (Si) peak. Drying of the same sample at 85°C induced more extended coatings on the sand grains (Fig. 8.11B). In this case, the electron microscope indicated a high C and a low Si peak. The WDPT of this sample exceeded 6 h. When the sample was mixed with water and dried again at 25°C, WDPT still exceeded 6 h, and an extensive carbon coating was still present. A sample from the wettable subsoil at depths of 35-40 cm also exhibited a fragmentary coating, predominantly consisting of silicon. Heating of the sample at 105°C produced identical images of the sand grains, and the electron microscope displayed similar Si peaks. Comparable results were obtained with samples from the Cranendonk site. Up till now, no micromorphological results are available to explain the decrease in water repellency at higher temperatures for the Schoorl and Zwanenwater dune sand samples.

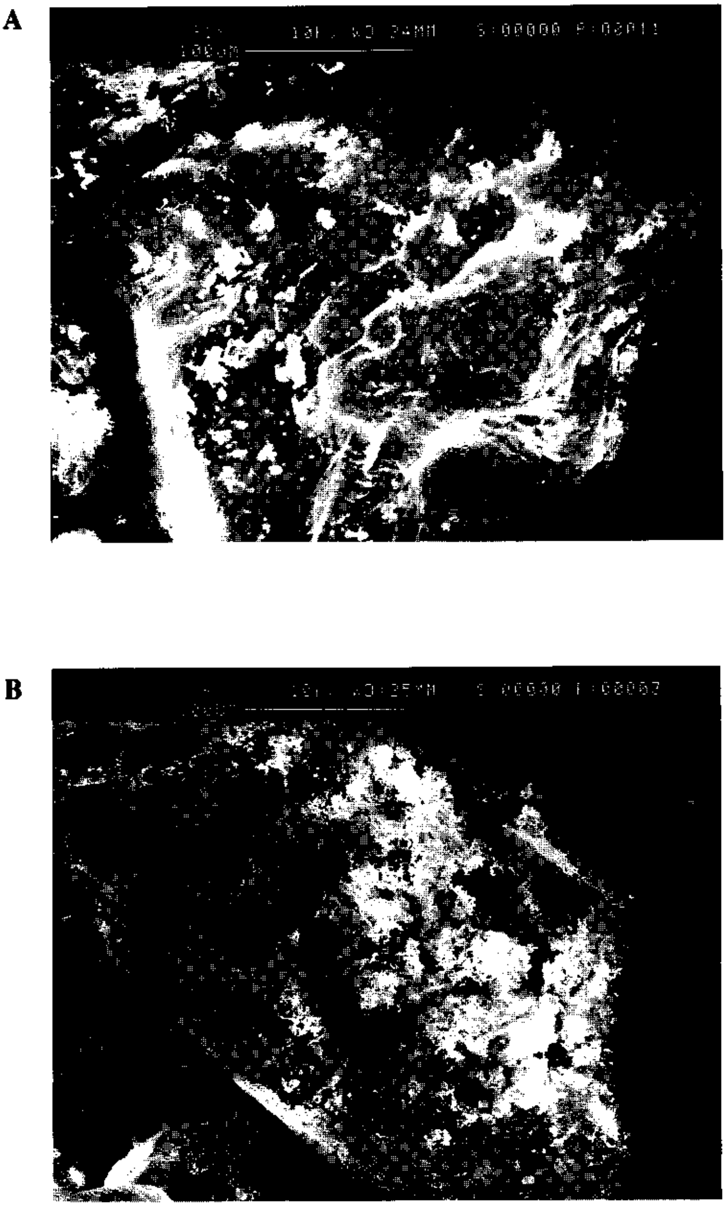


Fig. 8.11 *Enlargements of coated sand grains from the water repellent topsoil of Vredepeel, (A) dried at 25 °C and (B) dried at 85 °C.*

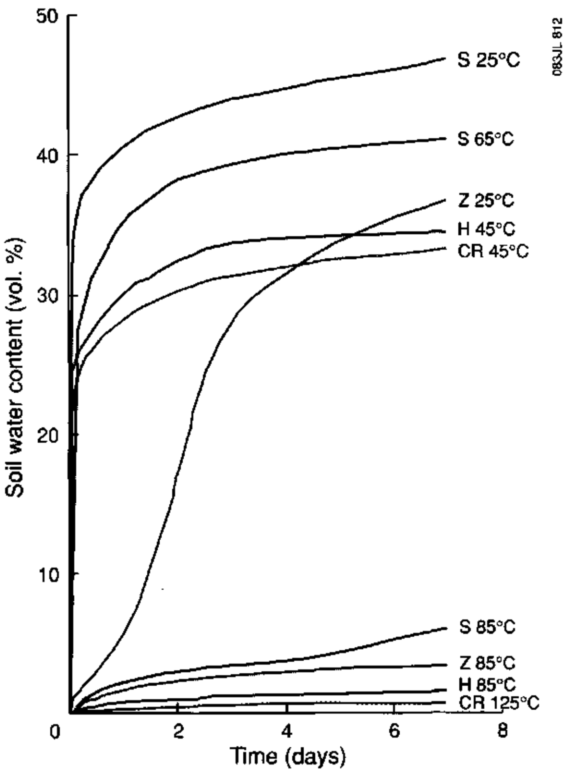


Fig. 8.12 Volumetric water content versus time of sand samples, dried at different temperatures, and placed at a constant pressure head of -2.5 cm water applied at the bottom of the sample; samples from Schoorl 0-2.5 cm (S), Zwanenwater 0-5 cm (Z), Heino 7-12 cm (H), and Cranendonck 20-25 cm (CR).

Drying Temperature and Resistance to Wetting

Laboratory measurements were made of the wetting capacities of samples from layers showing an increase in water repellency upon drying. Figure 8.12 shows great differences between samples dried at temperatures below and above 85^{0}C regarding the increase in water content versus time. When the samples collected at different depths from the topsoils of the Schoorl, Zwanenwater and Heino sites, and dried at 85^{0}C were allowed to take up water for one week, this led to increases in the soil water content of 6.0, 3.4 and 1.5 vol%, respectively. By contrast, the water content of the samples taken from the same soil layers, but dried at temperatures ranging from 25°C to 65°C, increased by between 34.4 and 46.6 vol% over the same period of time. A large difference in the degree of wetting was also found for two samples from a depth of 20-25 cm at the Cranendonck site. The water uptake of the sample dried at 125°C was only 0.6 vol%, whereas the increase in water content of the sample dried at 45°C was 33.2 vol%. Water uptake is lower in samples dried at higher temperatures due to the increased water repellency.

Similar measurements on Ouddorp samples indicated negligible water uptake even after drying at 25°C, because of their extreme water repellency (Ritsema and Dekker, 1996).

8.4 DISCUSSION AND CONCLUSIONS

Water Repellency Measurements

Many techniques for measuring soil water repellency have been developed, among which the WDPT test and the MED or alcohol percentage test are the most common methods used (Watson and Letey, 1970; King, 1981; Wallis and Horne, 1992; Chapter 2). The MED test measures the molarity of drops of ethanol solutions that infiltrate within 5 s (e.g. Watson and Letey, 1970; Richardson 1984) or within 10 s (e.g King, 1981; Wallis et al., 1993). The more water repellent the soil, the higher the molarity of ethanol needed to penetrate the soil. Richardson (1984), Crockford et al. (1991), and Dekker and Ritsema (1994b) expressed the degree of water repellency, simply, as the lowest alcohol percentage of the solution that penetrates the soil in 5 s or less.

The air temperature at the time of testing should be between 18 to 23°C, because the surface tension of the water and liquids changes as a function of temperature (Richardson, 1984). For instance, King (1981) showed that water repellency decreased markedly with increasing air temperatures in the range 0-45°C. Also the relative air humidity affects the water repellency measurements; higher values are obtained with increasing humidity (e.g. Wallis and Horne, 1992; Hendrickx et al., 1993). Therefore, we performed the measurements under laboratory conditions with a constant air temperature of 20°C and a relative humidity of 50%, and tests were deferred for at least 2 days to obtain samples in equilibrium with the ambient air temperature and humidity.

Influence Drying Temperature and Initial Soil Moisture Content

Until recently, workers engaged in soil water repellency research were not aware of the influence of drying temperature on the severity of soil water repellency. For instance, King (1981) recommended to measure soil water repellency on samples air-dried at 20°C or oven-dried at 105°C. Numerous researchers assessed water repellency on air-dried soil samples (e.g. Jungerius and De Jong, 1989; Barrett and Slaymaker, 1989; Wallis et al., 1993; Harper and Gilkes (1994) and Doerr et al. (1996), whereas others dried the samples at 105°C (e.g. Ma'shum and Farmer, 1985; Ma'shum et al., 1988; Roper 1994; Michelsen and Franco, 1996). But also intermediate drying temperatures have been used, for example Karnok et al. (1993) dried the soil samples at 30-35°C, Giovannini et al. (1987) at 40°C, Bisdom et al. (1993) at 60°C, and Ritsema et al. (1997) at 65°C.

Recently, it has become evident that the temperature during drying may affect the severity of soil water repellency. Michelsen and Franco (1994) measured MED values of sandy samples after air-drying and after drying at temperatures of 70°C and 105°C. They found that the MED values increased with temperature and they concluded that drying at 105°C induces the maximum soil water repellency. Therefore, they decided and recommended to use the MED values obtained after drying the soil at 105°C. Michelsen and Franco (1996) found similar results with high MED values for soil dried at 105°C and lower ones for samples dried at 70°C and air-dried. Roper (1994) found that soils dried at 40°C in comparison with drying at 105°C resulted in lower MED values. However, she stated that it was not clear whether the lower MED values at 40°C resulted from poor drying or whether the MED values after drying at 105°C were artificially high due to melting and redistribution of waxes on the sand grain surfaces.

Carter et al. (1994) found that the MED values varied with the moisture status of the soil at the time of sampling and with the temperature used for drying. They established that the 40°C drying temperature was underestimating MED values for the naturally wetted soils. There was a shift of about two MED units between a wet soil and a dry soil, and therefore they recommended that, if possible, dry soils should be taken from the field and the soils should be dried at 105°C for 48 hours prior to measuring the MED value. Also Moore et al. (1997) stated that the MED test is sensitive to drying temperature and the initial moisture content of the soil, and therefore they advised to dry the samples at 105^{0}C for at least 24 hours prior to the measurement of MED.

In most previous studies of the present authors soil samples were dried in an oven at a temperature of 60-65^{0}C during at least three days before measuring the potential water repellency with the alcohol percentage and/or WDPT test (e.g. Dekker and Jungerius, 1990; Chapter 2 and Chapter 5). This temperature was chosen because of practical reasons: drying at lower temperatures should last longer, and drying at higher temperatures should melt the plastic bags, in which the samples were collected. However, for some peat soils (Chapter 7) studied by Dekker and Ritsema (1996c) lower WDPT values were obtained for samples dried at 25^{0}C compared to those dried at 65^{0}C, and they concluded that drying at 25^{0}C is to be preferred for future measurements of peat soils. For another study on water repellent dune sand soil, no differences in measured WDPT values were found for samples dried at 25, 45, and 65^{0}C (Ritsema et al., 1997).

The present study using sand samples collected at seven sites, provides evidence that the sensitivity of WDPT to drying temperature and initial soil water content differs from soil to soil.

Dune Sand Sites

Samples from the 4 dune sand sites were partly wettable and partly water repellent at the time of sampling (Figs. 8.3 and 8.5). All wettable samples from depths of 9-47 cm at the Ouddorp site became repellent after drying at 25^{0}C and no significant change in WDPT was found after further drying at 65^{0}C (Fig. 8.6). A significant increase in WDPT was established for the water repellent field-moist samples from depths of 9-60 cm after drying at 25^{0}C. Also the WDPT of these samples did not change significantly after further drying at 65^{0}C.

The initial wet and wettable field-moist samples had significant lower WDPT's after drying at 25^{0}C and 65^{0}C compared to the initial dry and water repellent field-moist samples (Fig. 8.6). We consider these differences to be caused by spatial heterogeneity due to the existence of permanent preferential flow paths, which in time become less water repellent as a consequence of leaching of hydrophobic substances to the subsoil (Ritsema et al., 1997).

Also all wettable field-moist samples from depths of 0-26 cm at Westduinen became water repellent after drying at 25°C (Fig. 8.7). However, compared to the water repellent field-moist samples the WDPT was significantly lower. After drying at 65°C the WDPT of samples from depths of 0-12 cm increased significantly, whereas no significant change was found for samples from depths of 14-26 cm. A significant increase in WDPT after drying at 65°C was also found for samples (rich in organic matter) from depth of 0-5 cm at Zwanenwater and depth of 0-2.5 cm at Schoorl (Fig. 8.4). We suppose that the difference in sensitivity to drying temperature may be related to differences in content and character of the organic matter.

Remarkably, a significant decrease in WDPT was found for initial wet as well as dry dune sand samples (with low organic matter content) from depths of 21-40 cm at Schoorl and depths of 7-19 cm at Zwanenwater, after drying at 65°C. Most probably, the decrease in water repellency is due to cracking of less solid hydrophobic coatings on the grains of these sands, in comparison to more firm coatings on the grains of the Ouddorp sand. However, further micromorphological research is needed to confirm this hypothesis.

Heino, Vredepeel and Cranendonck Sites

The sandy topsoils of the Cranendonck, Vredepeel, and Heino sites were found actually water repellent during dry periods, as was often assessed with WDPT and alcohol percentage measurements by the author visiting the fields. For example, the soil samples taken on August 10, 1995 at the Heino site, at depths of 0-40 cm, were all actually water repellent, and 24-88% of the soil at depths of 45-70 cm (Table 8.3). The soil water contents at depths of 0-40 cm varied between 3.3 and 10.3 vol%. The water content of the actually water repellent samples at depths of 45-70 cm ranged between 6.8 and 12.5 vol%, whereas the water content of the actually wettable samples at these depths ranged between 10.0 and 15.7 vol%. This means that the 'critical soil water content', below which the soil in the field is actually water repellent (Dekker and Ritsema, 1994b; Chapter 2), will be around 11 vol% at depths of 45-70 cm. Notably, most wet samples from this site were still wettable after they had been dried at 25°C and 45°C to much lower water contents (Fig. 8.10). Similar results were established at the Vredepeel site. In an ongoing study we have found that the critical soil water content for the humose topsoil of the Vrede-

Table 8.3 *Mean soil water contents (n = 25), range of water contents of actually water repellent and actually wettable samples, percentages of actually water repellent soil, and range of WDPT values after drying at 65^{0}C. Samples taken at 12 depths at the Heino site on August 10, 1995.*

Depth (cm)	**Mean (vol%)**	**Actually repellent (vol%)**	**Actually wettable (vol%)**	**Actually repellent soil (%)**	**WDPT 65°C**
0-2.5	6.8	3.3 - 9.7	---	100	600s - 6h
2.5-5	6.9	5.2 - 9.0	---	100	1 - 6h
7-12	6.8	5.5 - 9.0	---	100	1 - >6h
14-19	7.3	5.3 - 10.3	---	100	3 - >6h
21-26	7.1	5.6 - 9.6	---	100	3 - >6h
28-33	6.5	5.2 - 7.9	---	100	3 - >6h
35-40	6.8	5.2 - 8.4	---	100	3 - >6h
45-50	8.5	6.8 - 9.5	10.4 - 11.2	88	3 - >6h
55-60	11.5	8.6 - 11.2	10.0 - 14.3	24	>6h
60-65	12.6	9.4 - 11.9	10.4 - 15.1	28	3 - >6h
65-70	13.2	10.1 - 12.5	10.9 - 15.7	24	3 - >6h
70-75	11.5	---	7.7 - 15.7	0	3 - >6h

peel site is around 5.8 vol%, based on WDPT measurements on field-moist samples. However, most wet samples from this site were still wettable after drying in the laboratory at 45^{0}C (Fig. 8.9). Remarkably, most samples from the Cranendonck site were still wettable after drying at 65°C (Fig. 8.8). The process of drying in the field appears to affect water repellency in a different way compared to drying in a fan oven. This is probably related to the enforced drying in the oven which takes place much faster compared to common field conditions. Moleculair conformational changes in the organic substances responsible for the water repellency might be the result. As a consequence, drying at 25-65^{0}C in a fan oven can underestimate the occurrence and severity of water repellency compared to what happens in the field. On the other hand overestimations may be expected after drying at higher temperatures. For example we found for all samples from the humose sandy topsoils of the Vredepeel and Heino sites extreme water repellency, with WDPT's exceeding

6 h, after drying at temperatures above 85^{0}C. These values were never encoutered in the field. Therefore, it should be recommended for further studies to measure the severity of water repellency on field-moist samples and, preferably, to collect them during dry periods.

CHAPTER 9

INFLUENCE SAMPLE SPACING AND VOLUME ON DETECTING PREFERENTIAL FLOW PATHS

Adapted version of "Influence of sampling strategy on detecting preferential flow paths in water-repellent sand" by Coen J. Ritsema and Louis W. Dekker, published in Journal of Hydrology 177: 33-45, 1996.

9 INFLUENCE SAMPLE SPACING AND VOLUME ON DETECTING PREFERENTIAL FLOW PATHS

Abstract

Rapid response tensiometers or TDR (time domain reflectometry) probes in soil profiles, or early arrival of solutes in groundwater or drainwater after a rain event, provide direct evidence of preferential flow in soils. However, little information about the amount and magnitude of preferential flow paths is obtained by such measurement methods. Here, two intensively sampled vertical trenches illustrate the effect of sample spacing and the effect of sample volume on the detection of preferential flow paths. In a water repellent sandy soil, a sample spacing of up to 22 cm over a distance of several metres is just sufficient to collect information about preferential flow paths. Using larger sample spacings, the water content distributions apparently became more horizontally stratified. Increasing the sample volume by pooling pairs of adjacent 100 cm^3 soil samples over a distance of several metres, still allowed the detection of preferential flow paths. Preferential flow paths were no longer observed for larger volumes. Enlarging the sample volume reduces the calculated standard deviation and coefficient of variation. As preferential flow paths may vary in space and time, so the optimal number of samples to detect these paths in vertical trenches may vary, indicating that sampling strategies need to be flexible in design.

9.1 INTRODUCTION

Knowledge of the movement of water and solutes through the unsaturated zone of field soils is essential to make reliable predictions of pollution risks to groundwater and/or nutrient losses from agricultural soils. So far, most models simulating water and solute transport through the unsaturated zone assume homogeneous infiltration and a subsequent downward movement of the wetting front parallel to the soil surface. This type of flow, i.e. stable flow, however, is uncommon in field soils (Gee et al., 1991; Jury and Flühler, 1992). This may be caused by a variety of mechanisms, which in general are related to specific soil properties or soil characteristics. First, preferential flow of water and solutes may occur in well-structured clay and/or peat soils owing to the presence of shrinkage cracks and/or biopores (Bouma and Dekker, 1978, 1983; Dekker, 1982, 1983a, b; Beven and Germann, 1982). Second, preferential flow may occur also in non-structured sandy soils owing to the development of unstable wetting fronts (Raats, 1973; Philip, 1975b; Parlange and Hill, 1976). Perturbations in an initially flat wetting front may grow to fingers when: (1) the hydraulic conductivity increases with depth, as encountered in soils with a fine over a coarse sandy layer (Hillel and Baker, 1988; Baker and Hillel, 1990), or a dense over a loosely packed sandy layer (Dekker and Hendrickx, 1992; Ritsema and Dekker, 1994a); (2) the soil is hydrophobic (Ritsema et al., 1993; Ritsema and Dekker, 1994b); (3) air entrapment takes place during an infiltration event (Glass et al., 1990).

Numerous studies have reported the occurrence of preferential flow in a variety of soil types. In most studies, the occurrence of preferential flow was inferred from observations using rapidly responding tensiometers or TDR (time domain reflectometry) probes, or from the early arrival of solutes in groundwater, drainwater or surface waters after a rain event. Further, use of dyes may indicate the occurrence of preferential flow paths, as shown by Van Ommen et al. (1988) and Hendrickx et al. (1988). Notwithstanding that such observations provide direct evidence of the occurrence of preferential flow, no information is obtained about the amount, dimensions and water content distributions of preferential flow paths. An appropriate method to obtain such information is to sample a vertical trench using numerous small cylinders a short distance apart at several depths in the soil profile (Dekker and Ritsema, 1994a, b). These samples are used for the determination of soil water content and for the generation of contour plots to visualize possible preferential flow paths. Depending on the amount and dimensions of the preferential flow paths, it might be expected that a certain minimal sample spacing is needed to detect these paths. Further, it might be expected that sample volume may affect the detection of preferential flow paths in vertical trenches. The objective of this study is to illustrate and discuss the effects of varying sample spacings and volumes on the detection of preferential flow paths in vertical trenches. The importance of a well-designed sampling scheme to detect preferential flow paths in other soil types is also discussed.

9.2 MATERIALS AND METHODS

Soil

The experimental site is located at Ouddorp, the Netherlands. The soil is classified as a mesic Typic Psammaquent (De Bakker, 1979), and consists of a humic topsoil of 5 cm thickness, an intermediate layer up to 9 cm depth, and noncalcareous dune sand below. The soil is potentially water repellent up to a depth of 45 cm (Ritsema et al., 1993; Dekker and Ritsema, 1994b). Ritsema and Dekker (1994b) presented extensive information on the occurrence and dynamics of fingered flow in this particular soil. In total, they sampled ten vertical trenches in a 1 year cycle. It appeared that fingers were present in this soil almost throughout the year, and that the amount and dimensions of these fingers may vary depending on the sequence of weather conditions. A few fingers, of approximately 10 cm width, were found just after a dry summer and significantly broader ones (20-25 cm) were present in the autumn, during the wet season. In this study, results from two of the ten trenches were selected, i.e. the July 12 and the October 11 trench, to investigate the influence of sample spacing and sample volume on generated soil water content contour plots.

Study Method

In total, 500 samples were collected per trench. Each trench was approximately 5.5 m long, and five layers per trench were sampled, i.e. in the ranges 5-10, 15-20, 25-30, 35-40 and 45-50 cm below soil surface. Each layer was sampled by taking 100 small cylinders in close proximity to one another. The cylinders, each 100 cm^3 in volume, were 5 cm in diameter and 5 cm high. The horizontal distance between two adjacent samples was 0.5 cm, making the distance between the two cylinder centres 5.5 cm. All samples were used for the determination of soil water content, whereafter contour plots were made using the statistical computer program Genstat.

In general, soil sampling strategies used in research in soil science and hydrology vary enormously depending on the topic studied and on the scale of observation. Here, two commonly used sampling strategies were examined, one with regular (horizontally directed) sample spacings between adjacent soil samples, and the other in which adjacent soil samples are pooled (in the horizontal direction). The latter

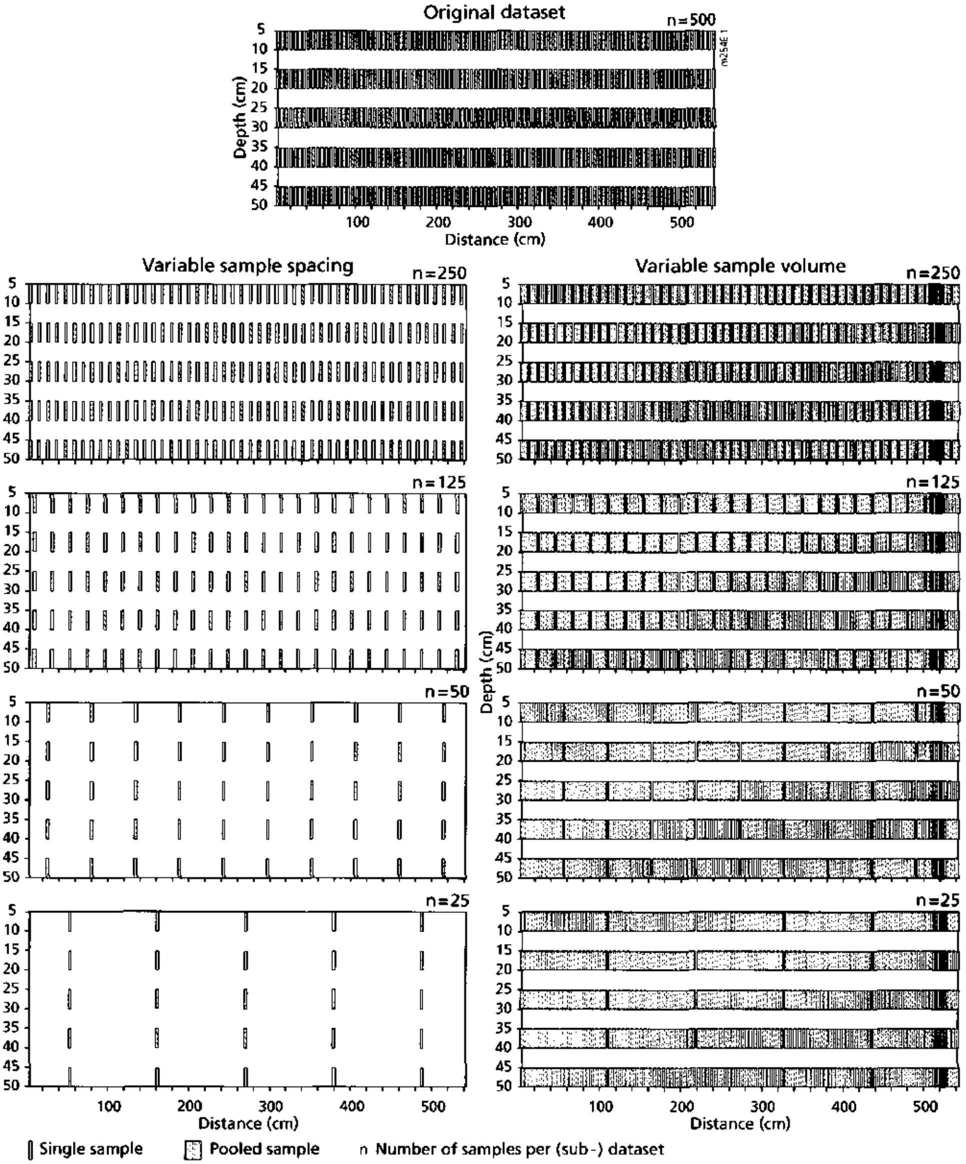


Fig. 9.1 *System used for creating sub-datasets to evaluate effects of sample spacing (left-hand side) and sample volume (right-hand side) on spatial distribution of volumetric water content for the July 12 and October 11 trenches in the water repellent sandy soil of Ouddorp, the Netherlands.*

method is popular among researchers involved in studies on pesticide transport and/or behaviour of heavy metals. The main reason is that, by sample pooling, laboratory costs for chemical analysis remain within acceptable limits. Pooling of adjacent soil samples directly results in a proportional increase in sample volume.

To study the effect of variable sample spacing on the detection of preferential flow paths in the two selected trenches, sub-datasets were created from the original data-sets, each of which contained 500 data; the sub-datasets contained 250, 125, 50 and 25 data, resembling sample spacings (defined as the distance from cylinder centre to cylinder centre of two adjacent soil samples) of 11, 22, 55 and 110 cm, respectively. The sub-datasets were created according to the scheme shown on the left-hand side of Fig. 9.1. For each of these sub-datasets, spatial distribution of soil water content was visualized by generating contour plots.

To study the effect of sample volume, sub-datasets containing 250, 125, 50 and 25 data were also created by pooling two, four, ten and 20 adjacent soil samples, following the scheme presented on the right-hand side of Fig. 9.1. For each of these sub-datasets, a contour plot was again made.

9.3 RESULTS

Effect of Sample Spacing

On the left-hand side of Fig. 9.1, only four examples illustrate the effect of variable sample spacing on the presence of preferential flow paths. Actually, if 125 samples from the original 500 are used, a total of four different graphs can be generated depending om whether the first, second, third or fourth sample in the vertical trench is used as starting point in creating the sub-dataset. If 50 samples are used, ten different graphs can be constructed and, when only 25 samples are used, a total of 20 contour plots can be made.

Here, for each defined sampling strategy with specified sample spacing, only one example of the water content distribution in the vertical transect is shown on the left-hand side of Fig. 9.2 for the July 12 trench. An increase in sample spacing resulted in the resolution in the graphs declining. This process was most marked for relatively large sample spacings, such as 55 and 110 cm. The basically vertical flow paths in the original transect, shown at the top of Fig. 9.2, changed to an approxi-

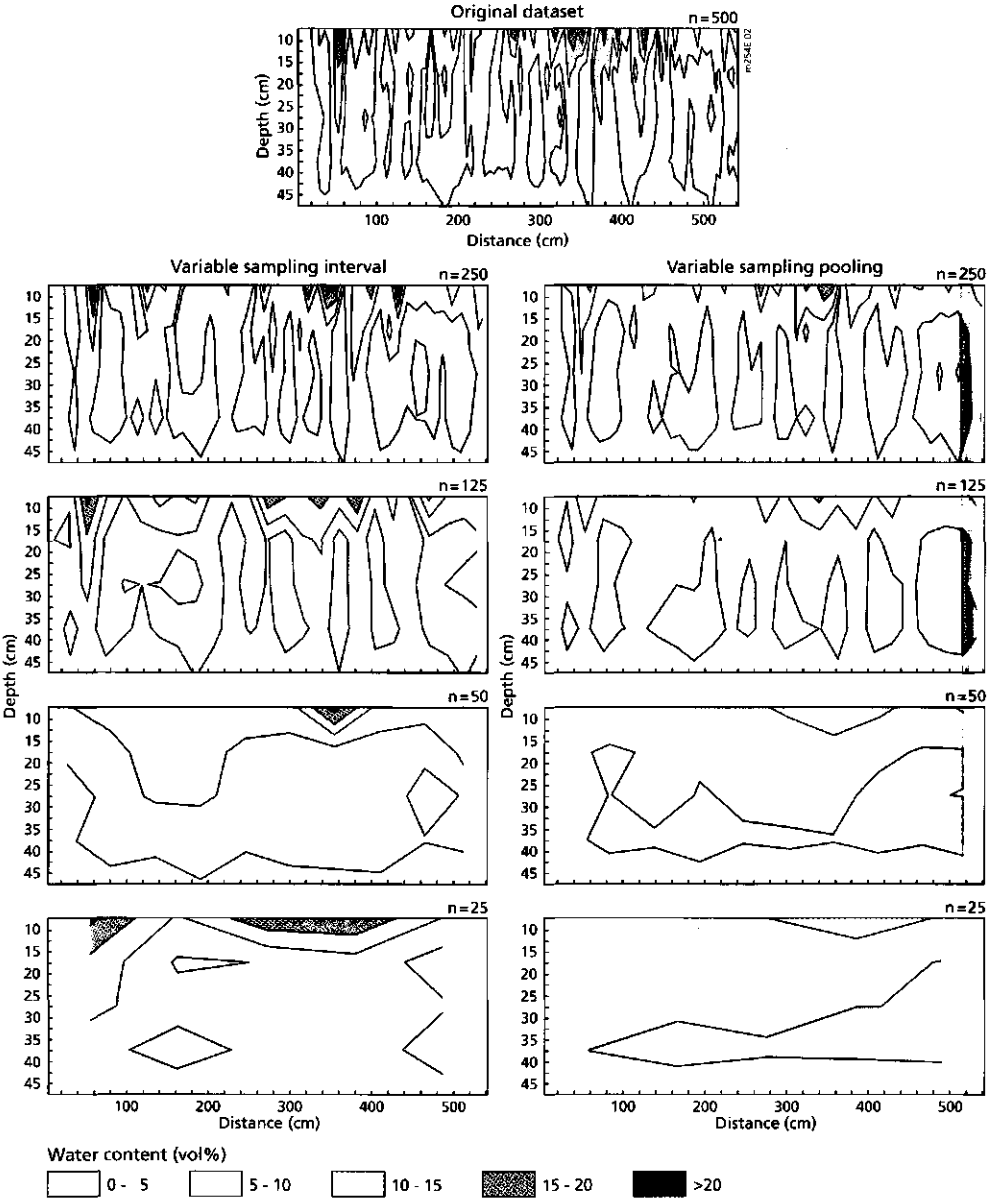


Fig. 9.2 *Contour plots showing the effects of using variable sample spacings (left-hand side) and sample volumes (right-hand side) on volumetric water content distributions in the July 12 trench.*

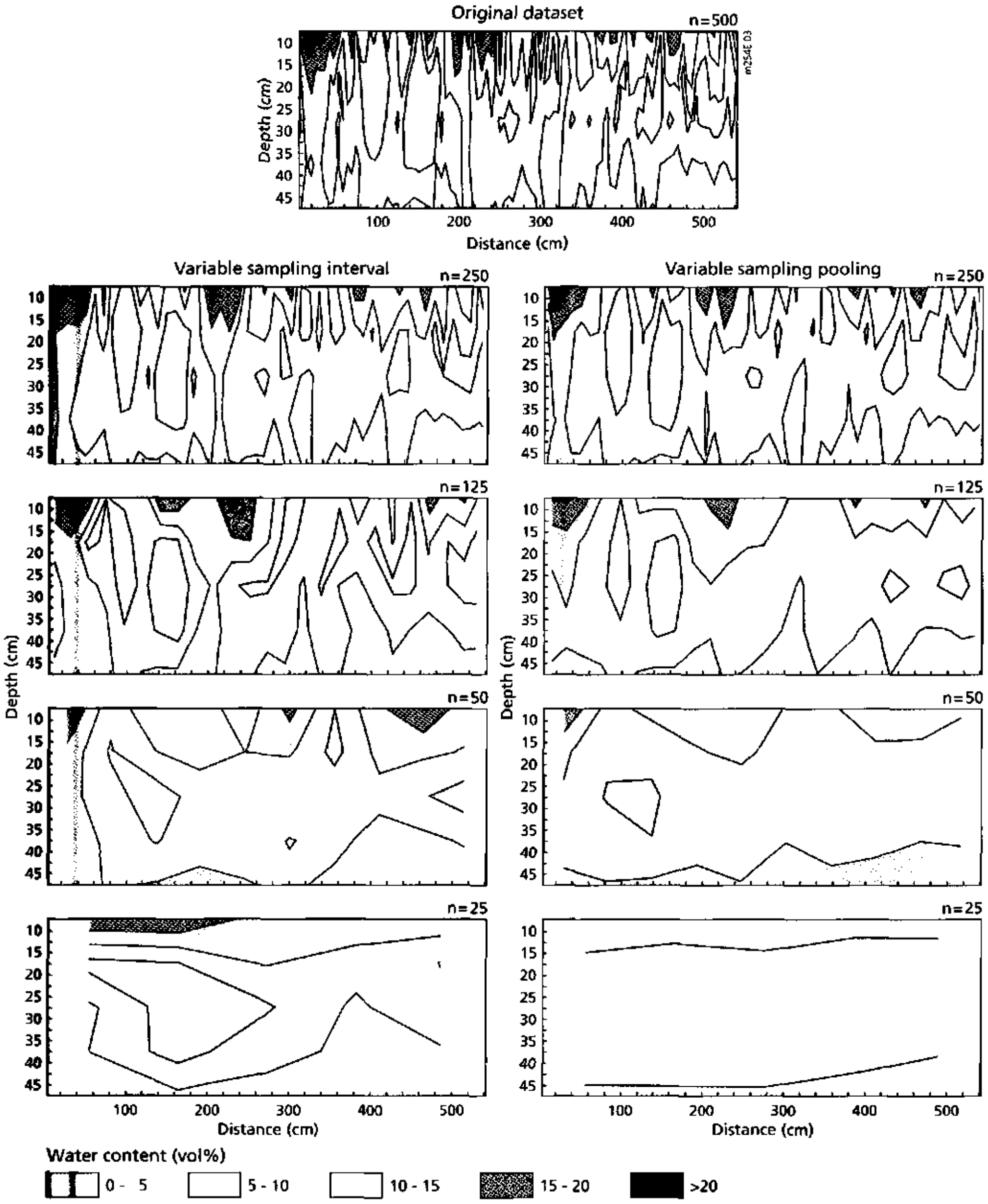


Fig. 9.3 *Contour plots showing the effects of using variable sample spacings (left-hand side) and sample volumes (right-hand side) on volumetric water content distributions in the October 11 trench.*

mately horizontal water distribution when the sample spacing increased to around 55 cm and higher (see left-hand side of Fig. 9.2, top vs. bottom graphs). This means that, when such a sampling strategy is applied, no preferential flow paths may be detected. This is equally valid for the October 11 trench shown on the left-hand side of Fig. 9.3. However, it seems that the resolution in water contents in these graphs was slightly better than for the July trench. The fingers in the October trench, which was sampled during the wet season may have been wider. However, for both cases the vertical fingers virtually disappeared when the sample spacing exceeded 22 cm.

Hence, when a trench is sampled, the starting point within the trench may have a serious effect on the water distributions obtained. This is illustrated in Fig. 9.4, showing four water content distributions for the October 11 trench, all based upon using a sample spacing of 22 cm, i.e. using 25 samples per layer instead of 100. Fig. 9.4 shows clearly that different graphs were obtained, depending on the starting point within the original transect. Sometimes preferential flow paths are detected, depending on whether or not the selected samples coincide with the wet fingers.

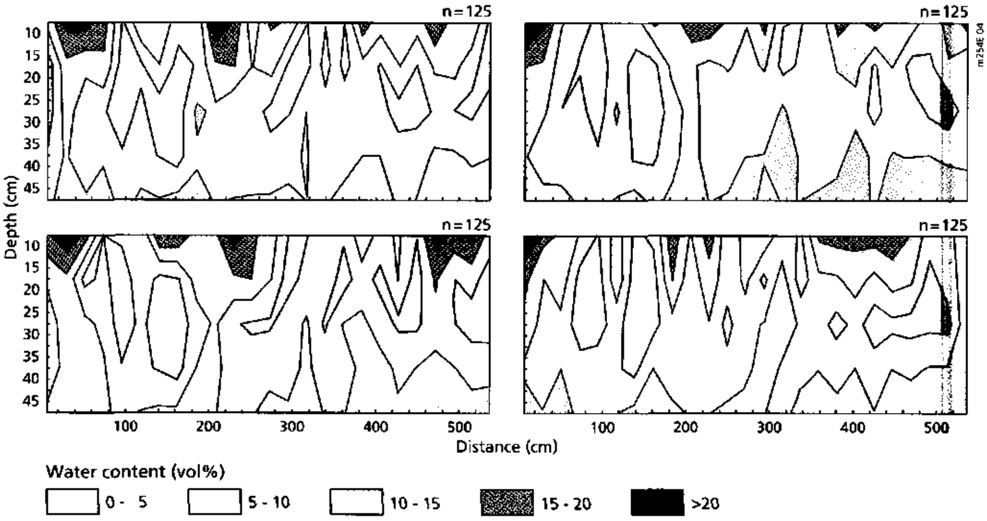


Fig. 9.4 *Contour plots showing the spatial distribution of volumetric soil water content for four sub-datasets of the October 11 trench using a sample spacing of 22 cm.*

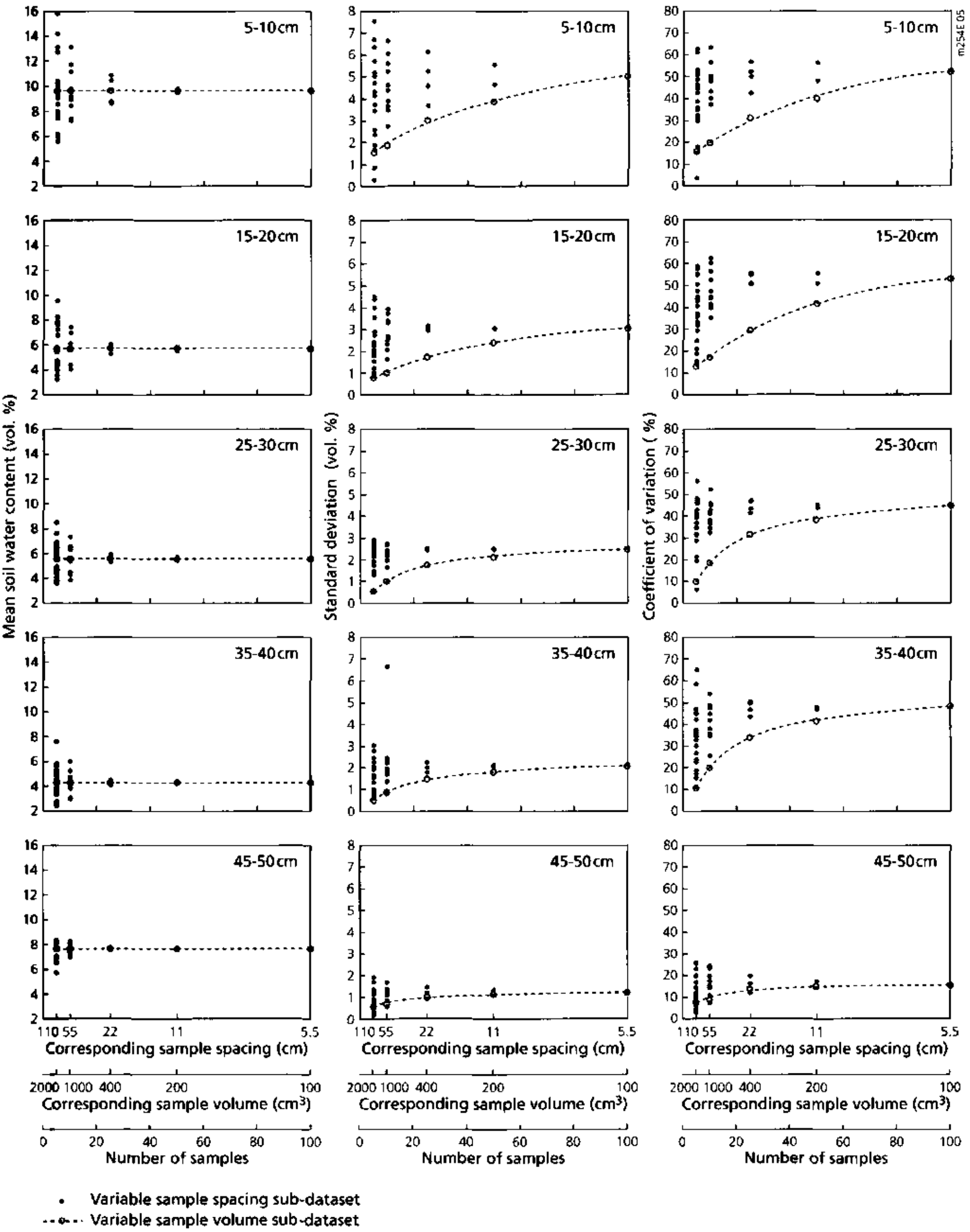


Fig. 9.5 *Mean soil water contents, standard deviations and coefficients of variation vs. the amount of data per depth of sub-datasets used in evaluating effects of sample spacing and sample volume on soil water distributions obtained for the July 12 trench.*

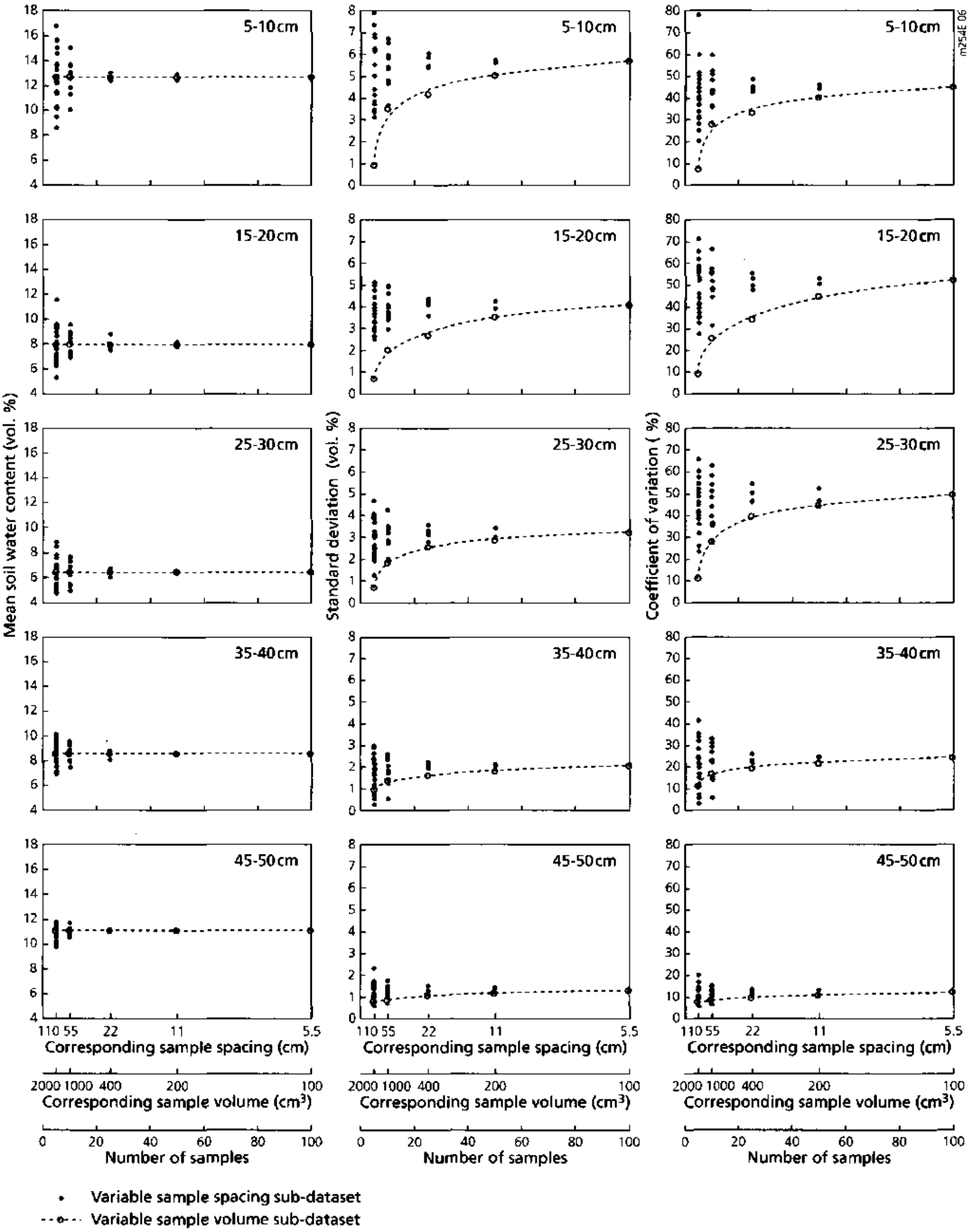


Fig. 9.6 *Mean soil water contents, standard deviations and coefficients of variation vs. the amount of data per depth of sub-datasets used in evaluating effects of sample spacing and sample volume on soil water distributions obtained for the October 11 trench.*

Each selected sub-dataset is characterized by its own statistical distribution. In Figs. 9.5 and 9.6, mean soil water content, standard deviation, and coefficient of variation are shown for each of the sub-datasets distinguished at each depth belonging to the July and October trench plotted against the number of samples per depth, and the applied sample spacing. Going from the right-hand side to the left-hand side on the x-axis, the number of samples per depth decreases, i.e. the corresponding sample spacings increase from 5.5 cm up to 110 cm. Hence, by using large sample spacings, mean soil water contents, standard deviations, and coefficients of variation may differ significantly from values belonging to the original, complete, trenches. This means that when large sample spacings are used, the probability detecting preferential flow paths decreases; this is also shown by the water content distributions in Figs. 9.2 and 9.3.

Effect of Sample Volume

Soil water distributions recorded will depend on the sample volume used. On the right-hand side of Fig. 9.2, the spatial distributions of soil water content within the July trench are shown using different sample volumes obtained by pooling samples according to the scheme pictured on the right-hand side of Fig. 9.1. Here, as was found by using larger sample spacings, resolution in soil water content distributions declined rapidly when larger samples were used. Fig. 9.2 shows that maximally 200 cm^3 samples, i.e. two adjacent samples pooled, may be used to maintain the fingered flow pattern in this particular trench. Use of 400 cm^3 or larger samples resulted in a significant loss of information and in more horizontally stratified soil water content distributions (see Fig. 9.2). This particular trend was also found for the October 11 trench shown in Fig. 9.3.

Sample volume affected the statistical distribution of the sub-datasets obtained. In Figs. 9.5 and 9.6, the mean soil water contents of individual sub-datasets are similar to those of the original transect. This is logical, as the sample volumes used were based upon pooling all individual 100 cm^3 samples. However, sample volume affected the values of standard deviations and coefficients of variation (Figs. 9.5 and 9.6); as the samples increase in volume, so the standard deviation and coefficient of variation decrease considerably. The decline in standard deviation and coefficient of variation with increasing sample volume was more pronounced than in the case that sampling spacings were increased. This indicates that by using larger sample volumes, the mean soil water content values obtained remained similar, but the standard deviations and coefficients of variation changed significantly. Larger sample volumes, obtained by pooling individual samples, suppress information about extreme values (high and low ones) and lead to less resolution in the soil water content distributions, as indicated in Figs. 9.2 and 9.3.

9.4 DISCUSSION

In this study, only two typical sampling strategies have been used to illustrate the effect of varying sampling methods on obtained water content distributions. In reality, sampling strategies vary enormously. Unfortunately, effort is seldom put into selecting an optimum sampling strategy. As the sampling strategy may have a major impact on the results obtained, it is essential that development and selection of optimum sampling schemes receive the attention they deserve. This is needed from a fundamental soil science and hydrology point of view to obtain accurate information on the topic under investigation, and from an efficiency point of view to obtain as much reliable information as possible with a minimum of effort. Depending on the topic studied, the scale of observation etc., optimum sampling strategies may differ in structure and character.

The two examples shown in this study indicate that a minimum sample spacing needs to be used to detect the preferential flow paths. However, the presence of such fingers is time-dependent, as shown by Ritsema and Dekker (1994b). In the experimental field, no fingers were found at the end of the winter (April) as the soil was more or less uniformly wetted then, and similarly in June during a prolonged dry period. This means that at such times, significantly fewer samples are needed to characterize the soil water status. In completely homogeneously wetted or dried soil, only one sample per depth would be needed to obtain reliable information about the actual soil water content. This indicates that sampling strategies need to be flexible and adaptable depending on the sequence of weather conditions: relatively few samples are needed in prolonged dry or wet periods and significantly more during changeable weather.

Further, the examples shown in this study deal with water content distributions in one particular soil, i.e. in a water repellent sandy soil. As water content distributions differ among different soil types, it is clear that sampling strategies need to be fine tuned, depending not only on the weather conditions but also on soil type. It is, for instance, known that fingered flow patterns also occur in loam, clay and peat soils (Dekker and Ritsema, 1995, 1996b; see also Chapter 5, 6, 7). As finger diameters are dependent on soil texture (Selker et al., 1991), with small fingers (of a few centimetres) in coarse sandy soils and wide ones (up to 1 m) in finer material, it is clear that optimized sampling schemes may differ from soil to soil. Therefore, more emphasis should be placed on designing appropriate sampling strategies for various soil types.

Finally, it can be stated that, at this moment, a general lack of knowledge exists about how water actually moves through unsaturated field soils. Several workers have indicated that good field data on this particular topic are needed urgently (Beven, 1989; Vauclin, 1989; Philip, 1991; Thomas, 1992; Jury and Flühler, 1992). Recent studies on various soil types (Dekker and Ritsema, 1995, 1996b; Ritsema and Dekker, 1995; Ritsema et al., 1996), demonstrated that much of how water moves through soils is determined locally. Therefore, actual flow patterns should be studied in greater detail when vertical transects are sampled than when samples are collected randomly over entire fields. It is suggested, therefore, that this particular sampling approach be used more frequently in future research dealing with unsaturated zone hydrology.

9.5 CONCLUSIONS

To optimize sampling strategies focusing on water content distribution in soils, general knowledge about actual flow patterns is needed. In this study, for two intensively sampled trenches in a water repellent sandy soil, selection of an appropriate sampling strategy has been shown to be essential to obtain realistic information about the presence of preferential flow paths. When samples are taken at regular intervals over a distance of a few metres, the spacing between two adjacent soil samples should not exceed 20-25 cm, if preferential flow paths are to be detected. If 200 cm^3 samples are used, by pooling adjacent soil samples, information about preferential flow paths is maintained. When larger soil samples are used, detection of preferential flow paths becomes unlikely. Sample volume seriously affects statistical properties such as standard deviation and coefficient of variation, although reliable information about mean soil water contents is maintained even when using large samples. In general, sampling strategies should be developed on the basis of the actual or expected flow patterns in soils. As these flow patterns may vary according to season and soil type, more effort should be made to unravel these flow systems and to define more appropriate soil sampling strategies.

CHAPTER 10

SUMMARY AND CONCLUSIONS

10 SUMMARY AND CONCLUSIONS

Water Repellency and Water Flow

Water repellency is an important, often neglected property of many soils, which has its greatest effect in relatively dry soils. It has serious consequences for the wetting of the soil. Infiltration rates into water repellent soils can be considerably lower than those into wettable soils. During rain events after prolonged dry periods, water repellency of the topsoil may cause surface runoff, especially in sloping areas. Thus, water repellency tends to increase runoff and erosion and decrease the volume of water absorbed by the soil. With increasing rainfall, water infiltration proceeds and finally starts to break through the water repellent layer by creating irregular wetting patterns. Water and solutes often flow in these soils through preferential flow paths, the so-called "tongues" or "fingers". This phenomenon shortens solute travel time and increases the risk of groundwater contamination by surface-applied agrichemicals.

The degree of soil water repellency can be quickly measured on samples, using the alcohol percentage test. The persistence or stability of water repellency can be measured using the water drop penetration time (WDPT) test, especially when these measurements are extended to several hours. Measurements of water repellency on dried soil samples give information about the occurrence, depth, distribution, variability, degree and persistence of water repellency, allowing comparisons between soils.

Objectives

The objectives of the research reported in the present thesis were (i) to investigate the occurrence of water repellency in major soils of the Netherlands; (ii) to identify a standard technique for the measurement of water repellency; and (iii) to study the influence of landuse and vegetation type on water repellency for major Dutch soils and to determine its effect on wetting patterns, soil moisture variabilty, and water flow.

Actual Water Repellency and Critical Soil Water Content

Chapter 2 of this thesis introduces and highlights a distinction between "potential" and "actual" water repellency and the assessment of the "critical soil water content". The persistence and degree of *potential* water repellency of dried samples were examined for 10 trenches in a dune sand with grass cover. The spatial variability of water repellency and, therefore, of soil wetting was extremely high. However, water repellency is a time-dependent physical property of the soil, because resistance to wetting of a water repellent soil will decrease over time. This increasing wettability makes static measurements of water repellency inadequate. *Actual* water repellency was therefore measured using the WDPT test on field-moist samples. The percentage of the actually water repellent samples indicates the soil fraction excluded from direct solute and water flow. Because we also measured the water content of the samples, we could assess *critical soil water contents* for the different depths of the intensively sampled trenches. The soil is wettable above and water repellent below these values. The critical soil water content varied between 4.8 vol% at 5-10 cm and 1.8 vol% at depths of 45-50 cm in this sandy soil.

In the dune sand, the decrease in the degree of potential water repellency with depth was closely related to reduced amounts of organic matter. On the other hand, there was no significant relationship between the organic matter content and the persistence of potential water repellency.

Influence Type of Vegetation

Chapter 3 deals with the influence of the type of vegetation upon the severity of water repellency and the thickness of the water repellent sand layer in the dune area along the Dutch coast. Samples were taken at 865 sites, distributed throughout the dune sand area, including the North Sea Islands. The samples were taken at depths of 0-5, 5-10, 10-20, 20-30, 30-40, and 40-50 cm. The vegetation at the sites consisted of marram grass, buckthorn, grey hair grass, pine, oak, other grasses, and heather. The 5190 samples were dried at the laboratory at an oven temperature of 65°C, after which the severity of water repellency was measured using the WDPT test. 30-40% of the samples with a sparse vegetation of marram grass were slightly to strongly water repellent, whereas the other samples were wettable. The samples taken at depths of 0-5 cm at the sites with a different vegetation were all strongly to severely water repellent. At all of these sites water repellency decreased with depth. The decrease was most evident at the grey hair grass sites. Differences in water repellency among the other sites were insignificant. The large variabilitity over short distances in the water repellency and moisture content of the soil in the dune-sand area was demonstrated by intensive sampling of soil blocks at the Ouddorp, Westduinen, Schoorl, and Zwanenwater sites.

Stemflow, Microtopography and Water Repellency

Chapter 4 deals with man-made, raised sandy soils in the Netherlands, which are classified as "brown" or "black" plaggen soils. When dry, the brown soils are wettable, but the black soils are water repellent. In the course of one growing season, transects were sampled in a maize-cropped black plaggen soil at the Heino experimental farm. Stemflow and microtopography were found to play an important role in the development of irregular wetting patterns in this water repellent sandy soil during rain events after a dry period. Wetter areas were established within the rows of the maize field, due to stemflow, as well as halfway between the rows, due to leaf drip and microtopographical depressions. The spatial variability of the water content of the soil was often found to be high. However, the irregular wetting patterns did not develop into distinct preferential flow paths. During the rainy autumn period, the wetting patterns extended further downwards, though not only in the vertical but also in the horizontal direction. It seems plausible that this can be attributed to the dry subsoil, which inhibits further downward movement of the infiltrating wetting front due to its extremely water repellent character and its low wetting rate. Thus, when dry, the subsoil impedes and resists the deeper movement of water, and, as a consequence, the less water repellent parts in the topsoil between the wet zones are wetted first. After continuing rainfall, wetting patterns extend in all directions, but extensions are most pronounced in the lateral direction, making the patterns less irregular over time.

Fingerlike Wetting Patterns

Chapter 5 demonstrates the occurrence of fingerlike wetting patterns in a silt loam soil at Yerseke Moer, in the southwestern part of the country. Trenches dug in this loam showed that dry soil areas can always be found, even after large amounts of rainfall during the winter period. The variation in soil water content was large in all layers of the trenches sampled. An extreme example was measured in the surface layer at a depth of 0-5 cm on February 23, 1993, with water contents ranging between 22 and 59 vol%.

Locations of dry soil areas with low water content partly corresponded with extremely water repellent soil parts, while on the other hand, wet fingerlike patterns were found in areas with low persistence. The dynamic behavior of water repellency in this silt loam soil is demonstrated by varying percentages of actually water repellent soil at different times. The critical soil water content at a depth of 10-15 cm is about 24 vol%; that at 20-35 cm 20 vol%.

Influence of Landuse

Chapter 6 shows that grass-covered heavy basin clay soils in the Netherlands are water repellent when they are dry. Water repellency in the top layers of these soils was mainly due to a coating on the aggregates. The variation in moisture content over short distances was studied by sampling the soil 10 times during the period August 31, 1993, to December 22, 1994. Differences between minimum and maximum moisture contents were high in all layers sampled, occasionally as much as 28 vol%.

When the clay soil is dry, a major proportion of the water from precipitation or sprinkler irrigation may flow rapidly through shrinkage cracks to the subsoil, bypassing the matrix of the clay peds. However, preferential flow is not limited to macropore flow: irregular wetting patterns are also formed through the small pores of the matrix. These preferred pathways are thought to form at places with cracks which receive relatively large amounts of water, due to rainwater moving over the surface and through the surface layer towards slightly lower places, the so-called "distribution flow". Hence, the surrounding small pores in the matrix can be wetted as well, resulting in irregular wetting patterns.

Notwithstanding the overwhelming amount of research on this particular clay soil, this study is the first to indicate the presence of water repellency and its role in forming preferential flow paths. The study found that large areas of riverine clay soils with grass cover in the central part of the Netherlands are water repellent. In structured soils, like the clay soil studied, roots are often found in the interaggregate pore network, so water repellent substances are found on the faces of aggregates and/or larger structural elements. Within aggregates and larger structural elements, where no roots occur, water repellency is generally absent. When this clay soil was used as arable land (for maize), the topsoil was often found to be wettable, and only slightly water repellent in some cases. The disappearance of water repellency in arable soils is probably partly the result of the oxidation of water repellent organic matter and partly the result of the destruction of clay aggregates by the cultivation measures used on the land.

Wetting Rate of Peat Samples

Chapter 7 describes the variation in water content of grass-covered peaty clay and clayey peat soils at six sites. The topsoils were water repellent during dry spells. When the topsoils were dry, they could only absorb water with difficulty, which is illustrated by wetting-rate measurements. The water uptake over one week by the water repellent peat samples, with initial water contents between 25 and 31 vol%, led to an increase in the water content of only 1.5-3.5 vol%. By contrast, the increase in the water content of a wettable sample, which had an initial water content of 41 vol%, was 23 vol% over the same period of time.

Preferential flow in peat soils may occur through cracks or biopores, bypassing the matrix of the peat, but as is shown in Chapter 7, irregular, fingerlike preferential flow paths are also formed in the matrix. Due to these typical wetting patterns, the water content of the soil varied over short distances at all sites and on all sampling dates.

Effect of Drying Temperature

The degree of water repellency of a soil under field conditions may be strongly influenced by seasonal weather conditions, so measurements are often made using dried soil samples. However, the severity of water repellency measured on dried samples may be influenced by the heating temperature during drying. Therefore, the study described in Chapter 8 was performed to determine the effects of the drying temperature on the severity of the potential water repellency of sand samples taken at several depths on seven locations. Findings of this study indicated that the degree of potential water repellency changes with different drying temperatures. For 4 of the 7 sandy soil sites, potential water repellency was greater after drying at 65°C than at 25°C, whereas it decreased for 2 other sites, and remained unchanged for one. Wetting- rate measurements illustrated that increasing water repellency as a result of high drying temperatures led to decreasing water absorption by samples. Micromorpho-logical investigations indicated that high drying temperatures resulted in an increase in the organic carbon coatings responsible for soil water repellency.

The humose sandy topsoils of the Heino and Vredepeel sites are actually water repellent during dry spells. The critical water content for the Heino topsoil was found to be around 11 vol% and that for the Vredepeel topsoil around 5.8 vol%. Notably, most wet samples taken from both sites were still wettable after they had been dried at 45°C to much lower water contents. This means that the process of drying in the field appears to affect water repellency in a different way compared to drying in a fan oven. This is probably related to the enforced drying in the oven which takes place much faster than under common field conditions, which may result in molecular conformational changes in the organic substances responsible for the water repellency. As a consequence, drying at 25-65°C in a fan oven may underestimate the occurrence and severity of water repellency compared to what happens in the field. On the other hand, overestimations may be expected after drying at higher temperatures. For example, we found extreme water repellency on all samples from the humose sandy topsoils of the Vredepeel and Heino sites, with WDPT's exceeding 6 h, after drying at temperatures above 85°C. These values were never encoutered in the field. Therefore, it is recommended for further studies to measure the severity of water repellency on field-moist samples, which should preferably be collected during dry periods.

Sample Spacing and Sample Volume

In general, soil sampling strategies used in soil science and hydrology research vary enormously, depending on the topic studied and on the scale of observation. To optimize sampling strategies for water content distributions in soils, general knowledge about actual flow patterns is needed. The study described in Chapter 9, covering two intensively sampled trenches in a water repellent sandy soil, showed the selection of an appropriate sampling strategy to be essential for obtaining realistic information about the presence of preferential flow paths. Two commonly used sampling strategies were examined, one with regular (horizontally directed) spacings between adjacent soil samples of 100 cm^3, and one in which adjacent soil samples were pooled to different volumes (in the horizontal direction).

When soil samples are taken at regular intervals over a distance of a few metres, the spacing between two adjacent samples should not exceed 20-25 cm, if preferential flow paths are to be detected in this soil. Using larger sample spacings resulted in the water content distributions apparently becoming more horizontally stratified.

When the sample volume was increased to 200 cm^3 by pooling adjacent soil samples, information about preferential flow paths was maintained. When larger soil samples were used, detection of preferential flow paths became unlikely. Sample volume seriously affects statistical properties such as standard deviation and coefficient of variation, although reliable information about mean water contents is maintained even when using large soil samples.

In general, sampling strategies should be developed on the basis of actual or expected flow patterns in soils. As these flow patterns may vary according to season and soil type, more effort should be made to unravel these flow systems and to define more appropriate soil sampling strategies.

Major Conclusions

To conclude, the major research findings of this thesis are:

1) Most agricultural soils in the Netherlands are water repellent after a dry period.

2) Use as pasture increases, while use as arable land decreases the degree of soil water repellency.

3) It is recommended to measure the severity of water repellent soils with the water drop penetration time (WDPT) test on field-moist samples during a dry spell.

4) Sprinkler irrigation of agricultural soils is most efficient and effective when the water content of the topsoil is still above the critical level, as defined in this study.

5) Soil water repellency may lead to the development of unstable wetting fronts and preferential flow paths, which have wide-ranging significance for rapid transport of surface-applied solutes, such as agrichemicals, to ground water and surface water.

6) Soil moisture variability is large at short distances in water repellent soils, due to the occurrence of dry soil bodies and wet fingerlike patterns.

7) Vegetated sandy topsoils in nature reserves are strongly to extremely water repellent during dry spells, resulting in unexpectedly high surface runoff and erosion in undulating areas.

CHAPTER 11

SAMENVATTING EN CONCLUSIES

Invloed van waterafstotendheid op de variabiliteit van het vochtgehalte in Nederlandse gronden

11 SAMENVATTING EN CONCLUSIES

Waterafstotendheid en Stroming van Water

Waterafstotendheid is een belangrijke, vaak niet onderkende eigenschap van humushoudende bovengronden. Het voorkomen van moeilijk bevochtigbare veenbovengronden is in Nederland weliswaar al meer dan een halve eeuw bekend, maar bij onze zand- en kleibovengronden is waterafstotenheid pas recentelijk vastgesteld. Vooral na uitdroging heeft waterafstotendheid belangrijke gevolgen voor de bevochtiging en verdeling van het regenwater in deze gronden. Water infiltreert aanzienlijk slechter in gronden, die waterafstotend zijn na droging, dan in droge gronden waarbij deze eigenschap ontbreekt. De waterafstotende bovengronden kunnen tijdens regenbuien na langdurig droge perioden zowel oppervlakkige afstroming als bodemerosie veroorzaken, en bovendien de opname van water in de wortelzone sterk beperken. Met toenemende regenval zal het water de grond wel dieper indringen, maar hierbij onregelmatige vochtpatronen creëren, die kunnen uitgroeien tot preferente stroombanen. Water en opgeloste stoffen kunnen zich in deze gronden dan verplaatsen via deze stroombanen, die ook wel "tongen", maar meestal "vingers" worden genoemd. Het fenomeen van voorkeursbanen versnelt de stroming van water naar de ondergrond en het grondwater, en verkort daarmee de reistijd van opgeloste stoffen door de onverzadigde bovengrond. Het risico van verontreiniging van het grondwater neemt hierdoor drastisch toe.

De mate van waterafstotendheid van de grond kan gemakkelijk en snel worden vastgesteld met de alcoholpercentagetest. De stabiliteit van de waterafstotendheid kan goed worden gemeten met de waterdruppeltest (WDPT test), vooral wanneer de metingen enkele uren worden voortgezet. Meten van de waterafstotendheid aan grondmonsters geeft de mogelijkheid om de verbreiding van waterafstotende gronden na te gaan. Bovendien om de dikte van de waterafstotende lagen te bepalen, alsmede om de variabiliteit in mate en in stabiliteit van de waterafstotendheid in diverse gronden vast te stellen. Hierdoor kunnen deze gronden ook met elkaar worden vergeleken.

Doelstellingen

De doelstellingen van het onderzoek beschreven in dit proefschrift waren (i) het nagaan van het optreden van waterafstotendheid in de belangrijkste Nederlandse gronden; (ii) het vaststellen van een standaardtechniek voor de meting van waterafstotendheid in gronden; en (iii) het bestuderen van de invloed van het bodemgebruik en het type vegetatie op de mate van waterafstotendenheid voor de belangrijkste Nederlandse gronden en het effect ervan vast te stellen op bevochtigingspatronen, op de variabiliteit van het bodemvochtgehalte en op de stroming van het water in de grond.

Actuele Waterafstotendheid en het Kritische Bodemvochtgehalte

In hoofdstuk 2 van dit proefschrift is een onderscheid gemaakt tussen "potentiële" en "actuele" waterafstotendheid, en is bovendien het "kritische bodemvochtgehalte" geïntroduceerd en toegelicht. Met de alcoholpercentagetest en de waterdruppeltest werden de mate en stabiliteit van de *potentiële* waterafstotendheid gemeten bij duinzandmonsters, nadat deze in een oven waren gedroogd. In totaal werden 10 keer 500 monsters van 100 cm^3 genomen uit 50 cm diepe sleuven, gegraven over een lengte van 5 m in een duinzandgrond, die in gebruik was als grasland. De ruimtelijke variabiliteit van de waterafstotendheid en daarmee van de bevochtigbaarheid van de grond was extreem.

Waterafstotendheid is echter een tijdsafhankelijke fysische eigenschap van de grond, omdat de weerstand tegen bevochtiging in de loop van de tijd afneemt. Toename van de bevochtigbaarheid daardoor maakt dat statische metingen van de waterafstotendheid niet toereikend zijn. Daarom werd ook de *actuele* waterafstotendheid van de veldvochtige monsters gemeten met de waterdruppeltest. Het percentage van de actueel waterafstotende monsters geeft hierbij de fractie van de grond aan die, op het moment van de bemonstering, van directe stroming van water en opgeloste stoffen is uitgesloten. Omdat we ook de bodemvochtgehalten van de monsters maten, konden we *het kritische bodemvochtgehalte* voor verschillende diepten in deze duinzandgrond vaststellen. Het zand is bevochtigbaar boven en waterafstotend beneden deze waarde. Het kritische bodemvochtgehalte liep hierbij uiteen van 4,8 vol.% op 5-10 cm diepte tot 1,8 vol.% op 45-50 cm.

In de bestudeerde duinzandgrond werd een significant verband vastgesteld tussen de mate van potentiële waterafstotendheid gemeten met de alcoholpercentagetest en de diepte waarop de monsters waren genomen. Dit als gevolg van een sterke afname van het organischestofgehalte met de diepte en daarmee een lager benodigd alcoholpercentage. In tegenstelling hiermee werd geen significant verband gevonden tussen het organischestofgehalte en de stabiliteit van de potentiële waterafstotendheid gemeten met de waterdruppeltest. Dit omdat bij zandmonsters uit de ondergrond met minder dan 1% organische stof vaak nog een extreme waterafstotendheid met WDPT's van meer dan 5 uur werd gemeten.

Invloed Type Vegetatie

In hoofdstuk 3 wordt de invloed van de vegetatie op de mate van waterafstotendheid en op de dikte van de waterafstotende zandlaag in het duingebied langs de Nederlandse kust besproken. Verspreid over het duingebied, inclusief de Waddeneilanden, werden op 865 plekken zandmonsters verzameld. De monsters werden genomen uit de lagen 0-5, 5-10, 10-20, 20-30, 30-40 en 40-50 cm diepte. De vegetatie op de plekken bestond uit helmgras, duindoorn, buntgras en mos, den, eik, gras en heide. De 5190 monsters zijn in het laboratorium gedroogd bij 65 °C, waarna de mate van waterafstotendheid werd bepaald met de waterdruppeltest. Van de monsters genomen op dieptes van 0-50 cm in de duinstrook vlak langs het strand met een schaarse begroeiing van helmgras, waren er 30-40% zwak tot matig waterafstotend, terwijl de resterende monsters goed bevochtigbaar en dus niet waterafstotend waren. De monsters genomen op 0-5 cm diepte op de plekken met een andere vegetatie waren allemaal matig tot extreem waterafstotend. Op al deze plekken nam de mate van waterafstotendheid met de diepte van de bemonsterde lagen af. Deze afname was het sterkst bij het buntgras. Tussen de overige plekken werd in de mate en diepte van de waterafstotendheid geen significant verschil vastgesteld. Met behulp van vier intensief bemonsterde blokken in Ouddorp, Westduinen, Schoorl en Zwanenwater werd de sterke variabiliteit op korte afstand van zowel de waterafstotendheid als het vochtgehalte van de duinzandgronden aangetoond.

Invloed Gewas en Microreliëf op Vochtpatronen

In hoofdstuk 4 wordt aangegeven dat er een verschil bestaat in de bevochtigbaarheid van enkeerdgronden, kunstmatig opgehoogde gronden, die vroeger bekend stondenals essen en enken. De bruine, iets kleirijkere enkeerdgronden zijn namelijk goed bevochtigbaar als ze droog zijn. Droge zwarte enkeergronden, daarentegen, zijn matig tot soms zelfs extreem waterafstotend.

Gedurende één groeiseizoen werden op de proefboerderij Heino, vlakbij Zwolle, transecten bemonsterd in een zwarte enkeerdgrond met maïsgewas. Tijdens regenbuien na droge perioden bleek dat de stroming van water via de bladeren en stengels, alsmede het microreliëf van het bodemoppervlak, een belangrijke rol speelden bij de verdeling van het regenwater in de grond. Rondom de hoofdstengels van het gewas en op lagere plekken verzamelde het water zich en vond een diepere bevochtiging van de waterafstotende dikke bovengrond plaats. De ruimtelijke variabiliteit van het bodemvochtgehalte was daardoor zeer groot. De onregelmatige vochtpatronen groeiden echter niet uit tot duidelijk verticaal gerichte preferente stroombanen. Gedurende de regenrijke herfst breidden de vochtpatronen zich weliswaar uit, maar meer in horizontale dan in verticale richting. Het lijkt aannemelijk dat dit het gevolg was van de droge ondergrond, die door zijn extreem waterafstotende karakter en geringe bevochtigingssnelheid verdere neerwaartse beweging van het infiltrerende bevochtigingsfront afremde. Na voortgaande regenval breidden de vochtpatronen zich in alle richtingen uit, maar vooral in laterale richting, waardoor het vochtfront uiteindelijk min of meer homogeen en regelmatig werd.

Vingervormige Vochtpatronen

Hoofdstuk 5 demonstreert het voorkomen van vochtpatronen in een extreem waterafstotende zavelgrond in Yerseke Moer in Zeeland. Door het graven van sleuven werd ook vastgesteld dat altijd wel droge zavelgedeelten in deze grond voorkomen, zelfs na grote hoeveelheden neerslag in herfst en winter. Het vochtgehalte van de grond varieerde steeds sterk in alle lagen van de bemonsterde transecten. Op 23 februari 1993 werden bijvoorbeeld in de oppervlaktelaag van 0-5 cm diepte vochtgehalten gemeten die uiteenliepen van 22-59 vol.%.

De zavelgedeelten met geringe vochtgehalten waren hoofdzakelijk extreem waterafstotend. Anderzijds werden natte vingervormige patronen gevonden op plekken met een geringe waterafstotendheid. Het dynamische gedrag van de waterafstotendheid in deze zavelgrond werd gedemonstreerd door de variërende percentages van actuele waterafstotendheid op verschillende tijden. Het kritische bodemvochtgehalte van deze zavelgrond was op 10-15 cm diepte ongeveer 24 vol.% en op 20-35 cm 20 vol.%.

Invloed Bodemgebruik

In hoofdstuk 6 wordt aangetoond dat zware komkleigronden waterafstotend zijn bij gebruik als grasland. De waterafstotendheid in de bovengrond van deze kleigronden wordt voornamelijk veroorzaakt door een coating op de kleiaggregaten. De variatie in vochtgehalte op korte afstand werd bestudeerd in een komkleigrasland van proefboerderij "De Vlierd", bij Zaltbommel. Hiertoe werd de kleigrond tien keer intensief bemonsterd in de periode van 31 augustus 1993 tot 22 december 1994. De verschillen in bodemvochtgehalte waren in alle bemonsterde lagen steeds zeer groot en het verschil tussen het minimum- en maximumvochtgehalte was soms zelfs 28 vol.%.

Als de kleigrond droog is, kan een groot deel van het regen- en beregeningswater door de krimpscheuren naar de ondergrond stromen. Preferente stroming is echter niet beperkt tot stroming door de macroporiën: ook worden onregelmatige vochtpatronen gevormd in de matrix van de kleigrond. Deze ontstaan op plekken waar scheuren relatief veel water ontvangen. Dit als gevolg van stroming van regenwater over het bodemoppervlak en door de oppervlaktelaag naar iets lagere plekken door de zogenoemde "distributiestroming".

Ondanks dat er in de loop van de tijd veel bodemfysisch onderzoek aan deze zware komkleigrond werd gedaan, is dit de eerste studie die wijst op de eigenschap van waterafstotendheid van deze komkleigrond en op de bijdrage ervan aan de preferente stroming door scheuren en de vorming van vochtpatronen in de matrix.

Deze studie toonde tevens aan dat komkleigrasland in een groot gebied van Midden-Nederland waterafstotendheidsverschijnselen vertoont. In de komkleigrond worden graswortels veelvuldig aangetroffen in het poriënnetwerk tussen de aggregaten, waardoor waterafstotende stoffen worden gevormd op de structuurvlakken ervan. In de aggregaten dringen daarentegen weinig wortels door en is de vorming van waterafstotende stoffen gering.

Wanneer de kleigrond als bouwland wordt gebruikt (teelt van maïs), blijkt de bovengrond meestal goed bevochtigbaar te zijn. Het verdwijnen van de waterafstotendheid komt vermoedelijk deels door oxidatie van waterafstotende organische stof in de bouwvoor en deels door het openbreken van de (inwendig niet-waterafstotende) kleiaggregaten bij de grondbewerkingen.

Moeilijk Bevochtigbare Veengronden

In hoofdstuk 7 komen de bevochtiging en de variatie in vochtgehalte bij venige klei- en kleiige veengronden aan bod. De bovengronden waren in droge perioden steeds waterafstotend. Ze nemen dan zeer moeilijk water op, zoals is geïllustreerd met metingen van de snelheid waarmee de veenmonsters water opnemen in het laboratorium, het bepalen van de zogenoemde "wetting rate". De toename in vochtgehalte van waterafstotende veenmonsters met initiële vochtgehalten van 25-31 vol.% bedroeg na een week slechts 1,5-3,5 vol.%. In tegenstelling hiermee bedroeg gedurende dezelfde periode de toename van het vochtgehalte 23 vol.% bij een goed bevochtigbaar veenmonster, met een initieel vochtgehalte van 41 vol.%.

Net als bij de komkleigronden vindt in veengronden preferente stroming plaats via krimpscheuren en vingervormige stroompatronen in de matrix van de grond. Als gevolg van de aanwezigheid van de vochtpatronen varieerde het vochtgehalte in deze gronden op korte afstand aanzienlijk in alle bemonsterde lagen van de plekken op alle bemonsteringsdagen.

Invloed Temperatuur Tijdens Drogen

Onder veldomstandigheden kan de mate van waterafstotendheid sterk worden beïnvloed door de weersomstandigheden in de verschillende jaargetijden. Daarom worden de metingen vaak verricht op monsters die gedroogd zijn. De resultaten van deze metingen kunnen echter beïnvloed worden door de hoogte van de temperatuur tijdens het drogen, zoals in hoofdstuk 7 voor een aantal veenmonsters is aangetoond. Daarom is het effect bestudeerd van de temperatuur tijdens het drogen op de mate van potentiële waterafstotendheid van zandmonsters die op diverse diepten op zeven lokaties waren genomen (hoofdstuk 8). Bij vier van deze lokaties werd het zand meer waterafstotend na drogen bij 65 °C in vergelijking met 25 °C, terwijl het daarentegen minder waterafstotend werd bij twee andere en overanderd bleef voor de monsters van één lokatie. Metingen van de bevochtigingssnelheid illustreerden dat de toegenomen waterafstotendheid als gevolg van hogere droogtemperaturen ook leidde tot afname van de absorptie van water door de monsters. Micromorfologische onderzoekingen toonden aan dat hoge temperaturen bij het drogen resulteerden in een toename op de zandkorrels van de organische coating, die de mate van waterafstotendheid beïnvloedt.

De humeuze bovengronden van de lokaties Heino en Vredepeel zijn tijdens droge perioden actueel waterafstotend. Het kritische bodemvochtgehalte voor de bovengrond van Heino werd vastgesteld op 11 vol.% en voor die van Vredepeel op 5,8 vol.%. Het is opmerkelijk dat natte monsters van beide locaties niet waterafstotend werden nadat ze waren gedroogd bij 45 °C tot veel geringer vochtgehalten dan het kritische bodemvochtgehalte. Blijkbaar gebeuren er tijdens het (langzame) drogingsproces in het veld andere dingen met de organische substanties die waterafstotendheid kunnen veroorzaken dan tijdens het (snelle) drogen in een oven. Drogen bij 25-65 °C in een oven met een ventilator kan dan ook tot gevolg hebben dat de aanwezigheid en de mate van waterafstotendheid worden onderschat in vergelijking met hetgeen in het veld gebeurd.

Aan de andere kant kan de waterafstotendheid ook toenemen na het drogen bij nog hogere temperaturen, doordat dan de vetten en wassen aan de loop gaan. Zo stelden we bijvoorbeeld een extreme waterafstotendheid vast met WDPT's van meer dan 6 uur na droging bij temperaturen van 85 °C en hoger voor alle monsters van de humeuze zandige bovengronden van de locaties Vredepeel en Heino. Deze waarden zijn in het veld nooit gemeten. Daarom verdient het aanbeveling om voor verdere studies de mate van waterafstotendheid direct te meten aan monsters uit het veld, die het beste in droge perioden genomen kunnen worden.

Monsterafstand en Monstervolume

Voor grondbemonsteringen worden in de bodemkunde en hydrologie uiteenlopende strategieën gehanteerd, afhankelijk van het te bestuderen onderwerp en de schaal waarop de waarnemingen gedaan worden. Om bemonsteringsstrategieën voor vochtverdelingen in gronden te optimaliseren is kennis betreffende de actuele stroompatronen nodig. In hoofdstuk 9 worden twee intensief bemonsterde transecten in een waterafstotende zandgrond behandeld. Aangetoond wordt, dat de keuze van een geschikte bemonsteringsstrategie van essentieel belang is om realistische informatie te verkrijgen met betrekking tot de aanwezige stroombanen. Hiertoe werden twee veelvuldig gebruikte bemonsteringsstrategieën onderzocht, de ene met vaste (horizontale) afstanden tussen naast elkaar genomen monsters, en de andere waarbij monsters met verschillende grootte werden vergeleken. Als preferente stroombanen in deze zandgrond moeten worden vastgelegd, dient de afstand tussen de 100 cm^3 monsters niet groter te zijn dan 20-25 cm, als ze met een vaste interval worden genomen over een afstand van enkele meters.

Informatie over preferente stroombanen bleef gehandhaafd als bij het samenvoegen van naastliggende grondmonsters het monstervolume werd vergroot tot 200 cm^3. Bij het samenvoegen tot grotere volumes werd het vastleggen van preferente stroombanen onwaarschijnlijker.

Het monstervolume beïnvloedde duidelijk de statistische grootheden standaardafwijking en variatiecoëfficiënt. Het gemiddelde bodemvochtgehalte bleef echter betrouwbaar, zelfs als zeer grote monsters werden gebruikt.

Bemonsteringsstrategieën dienen te worden ontwikkeld op basis van actuele en verwachte stroompatronen in gronden. Daar deze kunnen variëren per seizoen en bodemtype, zal meer aandacht en energie moeten worden besteed aan het traceren van deze stroompatronen en aan het definiëren van betere grondbemonsteringsstrategieën.

Belangrijkste Conclusies

De belangrijkste conclusies van het onderzoek beschreven in dit proefschrift zijn:

1) De meeste landbouwgronden in Nederland vertonen na een droge periode verschijnselen van waterafstotendheid.

2) Gebruik als grasland versterkt de waterafstotendheid, terwijl door gebruik als bouwland de waterafstotendheid afneemt.

3) Het vaststellen van de mate van waterafstotendheid met de waterdruppeltest kan het beste worden gedaan aan veldvochtige grondmonsters tijdens een droge periode.

4) Beregening van landbouwgronden is effectief als het vochtgehalte van de bovengrond nog boven het kritische bodemvochtgehalte ligt, zoals in deze studie gedefinieerd.

5) Onstabiele vochtfronten en preferente stroombanen in waterafstotende gronden kunnen een versneld transport van aan het oppervlak toegediende landbouwchemicaliën naar het grondwater en oppervlaktewater tot gevolg hebben.

6) In waterafstotende gronden is de variabiliteit van het vochtgehalte op korte afstand vaak aanzienlijk door de aanwezigheid van droge grond naast natte grond in preferente banen.

7) Begroeide zandbovengronden in natuurgebieden zijn in droge perioden matig tot extreem waterafstotend, waardoor in hellende gebieden sterke oppervlakkige afstroming en erosie kan plaatsvinden.

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CURRICULUM VITAE

Louis (Ludovicus) W. (Willibrordus) Dekker was born in Obdam, a small village in the northwestern part of the Netherlands, on June 2, 1939. He was the ninth son and the twelfth of the thirteen children of Petrus Dekker and Antje Wester. In September 1951, he started secondary school (MULO) in Alkmaar graduating in June 1954. He attended the State Horticultural College (Rijkstuinbouwschool) in Hoorn from October 1954 to April 1956, and graduated with first class honours.

On November 1, 1956, when he was seventeen, he was employed as the "youngest soil surveyor ever" at the Netherlands Soil Survey Institute, and participated in the preparation of soil maps, soil survey interpretations and land evaluations, as well as in studies concerning the genesis of holocene sand, clay, and peat soils in the northwestern part of the country. Numerous publications testify to his interest in the historical, archaeological and geological aspects of the soil areas he studied. His knowledge of these aspects resulted in his first international paper, entitled "The value of soil survey for archaeology", published in the journal Geoderma in 1973. During the period 1970 to 1974 he investigated the influence of the physical properties of soils on the development of roots and the yields of roses and carnations grown on silty loam soils in glasshouses in the Heerhugowaard polder.

From 1975 to 1983 he worked at the department of Applied Soil Physics under the supervision of Dr. J. Bouma, and was involved in the development of laboratory and field methods for measuring the vertical and horizontal, saturated as well as unsaturated, hydraulic conductivity of soil layers and soil horizons. He also investigated the loss of water and fertilizers in heavy basin clay soils during sprinkler irrigation, resulting from bypass flow through cracks in these shrinking and swelling soils. From 1978 to 1980 he was a member of the Dutch-Rumanian research team engaged in training courses and the transfer of knowledge in applied soil physics. He was a member of the Dutch-German research team comparing soil survey, classification, and land evaluation systems within the Border Area Project, from 1980 to 1983.

He worked as a Soil Physicist at the Department of Soil Physics and Hydrology of the Netherlands Soil Survey Institute from 1983 to 1989. Since the merger between this institute and three other institutes in 1989 he has been employed at the Department of Soil Physical Transport Phenomena of the Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO). His main research fields are water repellency, preferential flow, solute transport in soils, environmental protection, soil wetting, and spatial and temporal variability in soil water contents.

From 1993 to 1994, he participated in a joint project with Prof. Dr. J.M.H. Hendrickx of the University of Socorro (USA) and Prof. Dr. T.S. Steenhuis of Cornell University (USA), entitled "Preferential water and solute transport in homogeneous water repellent soils". From 1996 to 1998, he was involved in a joint project entitled "Simulation of far reaching fingered flow" with Prof. Dr. T.S. Steenhuis of Cornell University and Prof. Dr. J.L. Nieber of the University of Minnesota (USA).

He has been co-organizer of two International Symposia: *"Fingered flow in unsaturated soil: from nature to model"* and *"Soil water repellency: origins, assessment, occurrence, modeling and amelioration"*. The former was held in Wageningen on April 20, 1994, while the second is to be held there on September 2-4, 1998. He gave or contributed to more than 70 presentations at International Conferences, Symposia, Workshops, and Seminars, held all over the world.

He has coauthored over 50 refereed publications, which have appeared in Water Resources Research (6), Geoderma (10), Soil Science Society America Journal (5), Journal Hydrology (9), Catena (3), Agricultural Water Management (4), Soil Science (3), Plant and Soil (2), Journal Environmental Quality (3), Soil & Tillage Research (2), Zeitschrift für Vegetationstechnik im Landschafts- und Sportstättenbau (2), Australian Journal Soil Research, Earth Surface Processes and Landforms, Journal of Contaminant Hydrology, and Hydrology and Earth System Sciences. He was sole or joint author of more than 95 articles and reports in the Dutch language, including papers in the Dutch journals Cultuurtechnisch Tijdschrift (12), H_2O (5), Boor en Spade (5), Stromingen (4), Bedrijfsontwikkeling (4), Boerderij/Veehouderij (3), Landbouwkundig Tijdschrift (2), De Buffer (2), Grondboor en Hamer (2), Westfrieslands Oud en Nieuw (2), Archeologisch Nieuws (2), Vakblad voor de Bloemisterij, Boer en Tuinder, Groen, Duin, Waddenbulletin, and Zeeuws Landschap.