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Recurring fingered flow pathways in a water repellent sandy field soil

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Abstract

Field evidence of finger formation and reformation during successive rain events over an eight months' observation period from June 1994 until January 1995 is presented. Fingered flow pathways were monitored in a no-tilled, grass-covered water repellent sandy field soil using an automated, stand-alone TDR device. Within a 2 m long and 0.7 m deep transect, 98 three-wire probes were installed horizontally at depths of 4, 12, 20, 30, 40, 55, and 70 cm. The horizontal distance between two adjacent probes was 15 cm. Finger formation occurred during distinct rainy periods and was most pronounced under heavy rainfall with initially wet topsoil conditions. The percentage of water infiltrated and transported preferentially through the fingers to the deep subsoil varied between 0 and 80%, depending on the wetting history of the soil and the rainfall characteristics.

Introduction

Preferential flow can occur in structured and in homogeneous soils. In structured soils, rapid transport of water and solutes may be caused by the presence of shrinkage cracks and/or biopores. In non-structured, homogeneous soils, water and solutes may move preferentially due to the development of unstable wetting fronts; the latter often occurs in water repellent soils. In the past, various studies have investigated water repellent soils in general, and aspects of water transport through these soils in particular.

Several studies in various soil types have shown that water repellency occurs in sand (Hendrickx *et al.*, 1993, Ritsema *et al.*, 1993), loam (McGhie and Posner, 1980; Dekker and Ritsema, 1995), clay (Dekker and Ritsema, 1996a), and peat soils (Dekker and Ritsema, 1996b). In addition, Ma'Shum *et al.* (1988), Bisdom *et al.* (1993) and Capriel *et al.* (1995) have linked water repellency with decaying organic material and the presence of fungi and/or algae. Other studies have evaluated the effect of water repellency on water flow and transport and suggested that water repellency might promote runoff generation (Burch *et al.*, 1989), lateral flow through surface layers (Ritsema and Dekker, 1995), irregular wetting of the soil (Jamison, 1945; DeBano, 1971) and the development of preferential flow paths (Ritsema and Dekker, 1994; Ritsema and Dekker, 1996a).

The effect of water moving preferentially through water repellent soils has been simulated by Van Dam *et al.* (1990), De Rooij (1995) and Ritsema *et al.* (1997b); downward transport of solutes in water repellent soils proved to be much faster than in comparable, wettable soils. Ritsema *et al.* (1996) predicted finger width in various water repellent field soils by applying laboratory derived equations. These predictions agreed well with field observations.

So far, the process of finger growth and persistence during successive rain events does not appear to have been studied in water repellent field soils. Therefore, the present study focused on measuring finger formation and finger recurrence in a water repellent sandy field soil, using a highly sophisticated stand-alone TDR device. The study aimed at i) presenting evidence of recurring fingered flow pathways during successive rain events, and ii) illustrating the effect of the wetting history of the soil and rain characteristics on the development of fingers and on the extent of drainage to the deep subsoil.

Materials and Methods

SITE

The experiment took place near Ouddorp, in the southwestern part of the Netherlands, on a mesic Typic Psammaquent soil (De Bakker, 1979), comprising a 9 cm

humic surface layer on top of fine dune sand. The organic matter content of the topsoil was 20 w.%, while that of the subsoil was lower than 0.5 w.%. The clay content of the soil was less than 3%. The WDPT test (Dekker and Ritsema, 1994) indicated that the soil exhibited extreme water repellency to a depth of around 50 cm. The highest degree of water repellency was found around the layer interface at a depth of 9 cm. Water repellency disappears above a certain 'critical' soil moisture content (Dekker and Ritsema, 1994). Ritsema *et al.* (1997a) showed that this critical (volumetric) soil moisture content decreased from 25% for the 0 to 5 cm layer to 1.7% at depths of 47–52 cm. Below this depth, the soil was classified as wettable even when dry. The site was grass-covered, and had not been tilled for several decades.

SOIL WATER CONTENT MEASUREMENTS USING TIME DOMAIN REFLECTOMETRY (TDR)

Experimental Set-up

To measure volumetric soil water contents in time at different positions in the profile, an automated measuring system based upon TDR was constructed (Topp *et al.*, 1980, Whalley, 1993). TDR is an extremely suitable method for automated measurements at remote sites (Baker and Allmaras, 1990, Heimovaara and Bouten, 1990, Van den Elsen *et al.*, 1995). The volumetric water content measurements were made automatically at 98 different positions using the commercially available TRASE model 6050X1 TDR device. The standard three-rod probes were installed horizontally in the wall of a pit in 7 rows of 14 probes each, covering an area 2 m wide and 0.7 m deep. The probes were placed 15 cm apart in the horizontal direction (centre-to-centre distance) at depths of 4, 12, 20, 30, 40, 55 and 70 cm.

The probes were connected to 7 multiplexer cards with 16 channels each (Fig. 1). Every 3 hours, the TDR device started a measurement series automatically, and the measurement of volumetric water content for each probe was stored, together with time and date information. One measurement cycle along the 98 probes took around 20 min. Up to 20,000 separate measurements could be stored in this way, equivalent to a data set covering 25 days. The measurements were retrieved from the TDR device once every three weeks using a laptop PC, after which the data were processed in the office.

TDR Probe Accuracy and Measuring Volume

Before the system was installed in the field, numerous volumetric water content measurements with the TDR device were compared with gravimetric measurements taken at the same spot in the profile to test the integrity of the TDR system across the entire water content range. Near each TDR measurement point, three 100 cm³ samples were taken to determine the average volumetric water content by weighing and drying. These comparisons showed

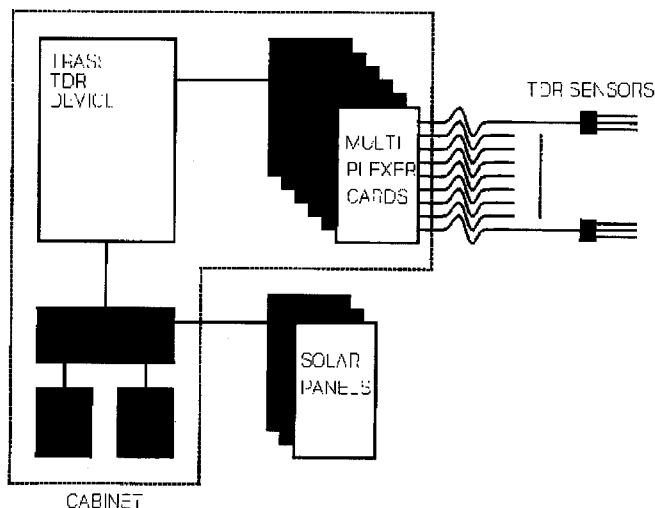


Fig. 1. Schematic set-up of the stand-alone TDR measurement device used to monitor soil water content changes in water repellent soil near Ouddorp, the Netherlands.

that the standard calibration curve of the device was accurate enough for application in the subsoil at Ouddorp, i.e. in the layers below a depth of 10 cm. The TDR measurements showed an average water content deviation of 0.7 vol.% from the gravimetrically obtained determinations. For the 0 to 10 cm layer, consisting of a mixture of organic matter, grass roots and sand, a separate calibration curve had to be determined in the laboratory because the standard calibration curve generated water content readings some 6 vol.% larger than the gravimetric determinations. The calibration curve thus adapted was used to recalculate the recorded water content values for the 14 TDR probes installed at a depth of 4 cm. The standard calibration curve of the TRASE device was used for the other 84 probes.

Standard commercially available buriable three-wire probes were used. The 3 mm diameter rods had a length of 20 cm, while the wires were placed 2.5 cm apart. From this geometry, the volume that holds 95% of the electrical energy, i.e. the approximate measuring volume, could be calculated, using the model introduced by Knight *et al.* (1994). The imaginary elliptical envelope around the horizontal rods of the sensors holding 95% of the radiated energy was about 7.2 cm in vertical diameter and 6.4 cm in horizontal diameter. This elliptical envelope covered an area of about 36 cm² so the measuring volume was about 720 cm³ per probe. In combination with the measuring grid used, which had horizontal distances of 15 cm and vertical distances of 8, 10 or 15 cm between adjacent probes, this guaranteed sufficient spatial resolution to detect any occurrence of fingered flow pathways (Ritsema and Dekker, 1996b).

Solar Power Supply

Since the system was placed in a remote area, it was powered by two 12 V, 50 Ah batteries in parallel. The

complete measuring system consumed about 1.4 Ah per 24-hour period. This battery capacity enabled the system to remain operational for at least four weeks without being recharged even during the winter period. The batteries were charged within three sunny days by a set of three Siemens 50 W solar panels, using a Siemens charging regulator. The power supply system caused no problems during the whole measuring period.

Data Processing

During the 8 months experimental period, almost 200,000 volumetric soil water content values were used to construct two-dimensional soil water content distributions for every 3 hour time-step, using the Genstat software package. In all, around 2,000 graphs were made, a selection of which are presented here.

PRECIPITATION, EVAPORATION AND GROUND WATER LEVEL

Precipitation was measured using an automatically recording tipping bucket system, with a resolution and accuracy of 1 mm. Daily evaporation estimates from a meteorological station nearby were converted to evapotranspiration rates using the appropriate crop factors. The ground water level was measured using a water level pressure sensor and a data logger with a measuring range of 1500 mm, resolution of 5 mm and accuracy of 10 mm. Evaporation and ground water level data were retrieved with a laptop PC every three weeks during the visits to the site.

Results

Values of precipitation, evapotranspiration, net infiltration and ground water level measured during the experiment are shown in Figures 2A, 2B, 2C and 2D, respectively. Most rainfall was recorded in the second half of the experimental period (Fig. 2A), the total rainfall registered being around 500 mm. Daily evapotranspiration ranged between 0 and 5 mm, with highest amounts in the summer, at the start of the experiment (Fig. 2B). Figure 2C shows that several major infiltration events occurred during the experiment, particularly between September 1994 and the end of January 1995. These events were accompanied by sharp rises in the ground water table (Fig. 2D), indicating rapid downward transport of water during such events.

Figure 3 shows examples of soil water contents measured by three TDR probes placed above each other at depths of 4, 30 and 70 cm. Data for a three week period in July 1994 were lost due to a computer breakdown. The probe at 4 cm (Fig. 3A) responded very quickly to rain events (see also Figs. 2A and 2C), and volumetric water contents varied from 3% to 30%. The probe at 30 cm showed a similar, but less pronounced, response to rain events (Fig. 3B). There was very little delay in wetting compared to the probe at 4 cm. Volumetric water contents

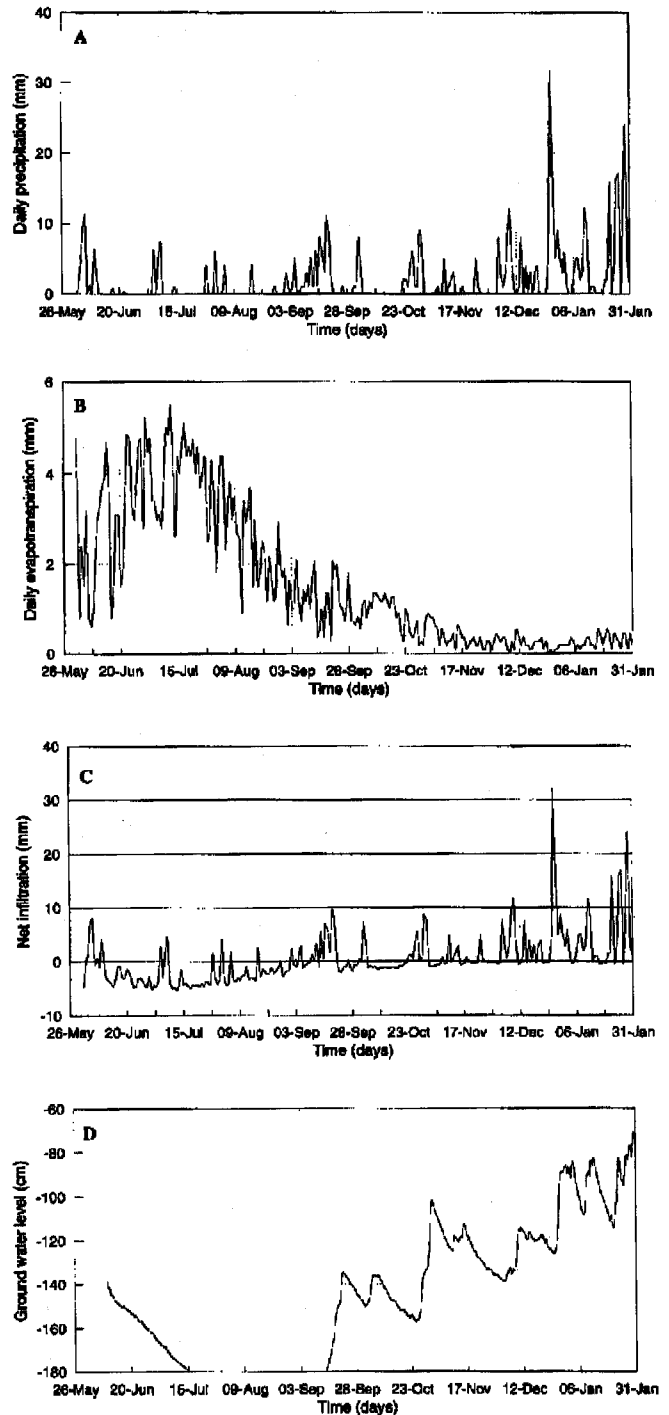


Fig. 2. Rainfall (A), evapotranspiration (B), net infiltration (C), and ground water level (D) measured at Ouddorp during the 8 months measurement campaign.

measured by the probe at 30 cm varied between 4% and 20%. Even at a depth of 70 cm, direct volumetric water content increments occurred during rain events (Fig. 3C), and the pattern showed a close resemblance to those observed by the other two probes. Water content

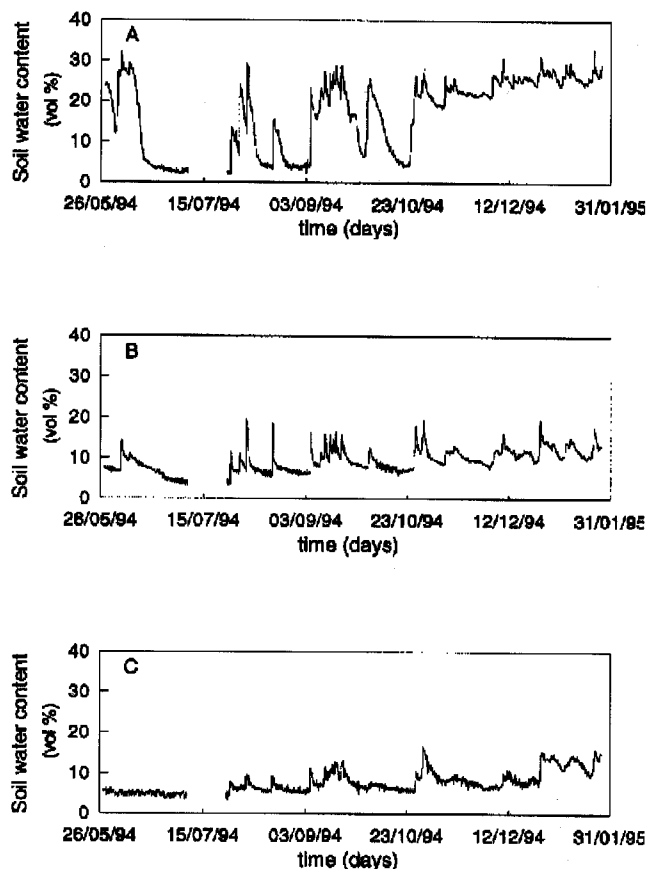


Fig. 3. Examples of soil water content values measured by three TDR probes arranged in a vertical line at depths of 4 (A), 30 (B) and 70 (C) cm.

variations at this depth were, however, less pronounced, and varied only from 4% and 15%.

To illustrate the process of finger formation and finger recurrence, a selection was made of the seven most pronounced rainy periods during the experimental period. (Table 1) The rainy periods selected occurred during the

Table 1. Rainfall duration and quantity, evapotranspiration, and net infiltration for the seven most distinct rainy periods during the period June 1994 until January 1995 at the Ouddorp experimental site.

Rainy period	Rainfall duration days	Rainfall amount mm	Evapotranspiration mm	Infiltration amount mm
1	11	36	23	13
2	10	47	11	36
3	10	34	3	31
4	8	40	3	37
5	10	81	2	79
6	8	39	2	37
7	8	57	3	54

months of June, September, October/November and December of 1994, and January of 1995. The duration of the rainy periods was between 8 and 11 days, and the total rainfall ranged from 34 to 81 mm per event. Subtraction of the evapotranspiration from the rainfall quantities yielded the amount of infiltrated water during the selected periods. Net infiltration varied between 13 and 79 mm (Table 1), with the most distinct events during the months of December and January. The cumulative rainfall, evapotranspiration, and net infiltration, and the course of the ground water level during the selected rainy periods are depicted in Figure 4. The ground water responded to each event, except for the period in June (missing data) (Fig. 4B).

For each rainy period, the soil water content distributions measured within the TDR-transect are shown just before, during (twice), and at the end or after cessation of the rainfall (Fig. 5). Soil water contents before the rain events (Fig. 5, left hand side) were generally below 10 vol.% for the water repellent subsoil, and up to 10–25 vol.% for the humic topsoil, although there were some differences. No fingered flow patterns were present before the start of the rain events, but these developed during all the rainy periods. The most distinct ones were monitored under conditions of heavy rainfall with initially slightly wetter soil (rainy periods 3, 5, 6, and 7). During rainy periods 1, 2 and 4, fingered flow patterns emerged as well, but with less evidence of protrusion of fingers to the deepest layers of the TDR transect. However, the ground water level rose during rain events 2 and 4 (Fig. 4), indicating downward transport to the ground water in both these cases.

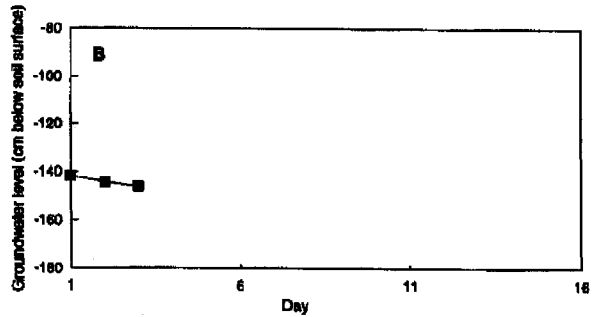
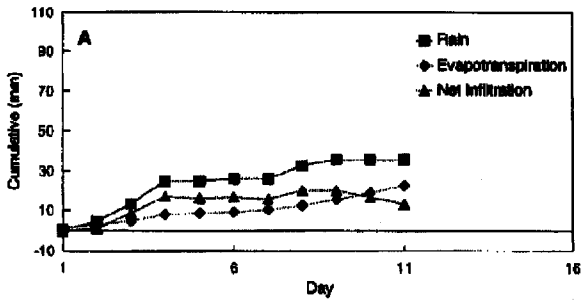
Based upon the arrangement of the TDR probes within the transect, the soil profile can be divided into seven layers, namely the 0–8, 8–16, 16–25, 25–35, 35–47.5, 47.5–62.5 and 62.5–77.5 cm layers. If the TDR probes are assumed to monitor soil water content changes for each of these layers, a total soil water balance can be made for the entire TDR transect. Table 2 shows the approximate water balance for the entire transect for each of the selected rainy periods. Net infiltration was derived by subtracting evapotranspiration from rainfall, and the change in soil water content in the transect down to a depth of 77.5 cm was determined using the individual TDR measurements. These two values were used to calculate deep drainage to the soil region below 77.5 cm. (Table 2) Deep drainage was most evident during the December and January rain events. Based upon the measured unsaturated hydraulic conductivity characteristic of the Ouddorp sand (Ritsema and Dekker, 1994), it might be concluded that mainly water flowing along the fingered flow pathways contributed to deep drainage. Unsaturated hydraulic conductivities at volumetric water contents of 5, 10, 15, 20 and 25% are 0.0002, 0.02, 0.2, 0.5, and 1.5 cm/day, respectively. This indicates, for instance, that the unsaturated hydraulic conductivity at a volumetric water content of

15% is a thousand times higher than that at a volumetric water content of 5%. The emerging fingered flow pathways in the TDR transect during the rainy periods 1 and 3 did not lead to considerable drainage below 77.5 cm. The percentage of the infiltrating water per rainy period which was transported preferentially through the fingers to the deep subsoil could also be derived, and ranged from 0 to 80%, depending on the wetting history of the soil and the

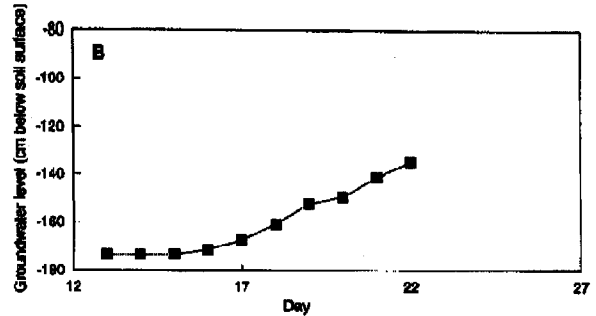
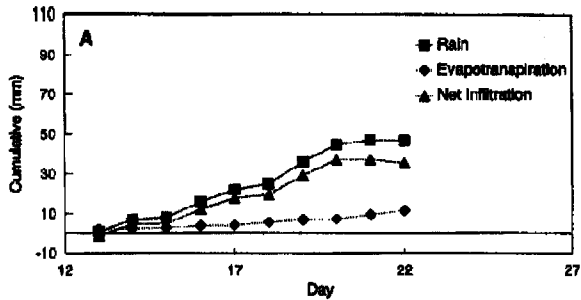
rainfall characteristics. The highest percentages occurred during the rainy periods in the winter (no. 5, 6, and 7).

The set-up of the TDR transect, with 98 probes in a fixed spatial grid, enabled 14 vertical soil columns to be distinguished within the transect, each with probes at seven depths. If the different TDR probes measure soil water contents for the same representative soil layers, i.e. the layers 0–8, 8–16, 16–25, 25–35, 35–47.5, 47.5–62.5 and

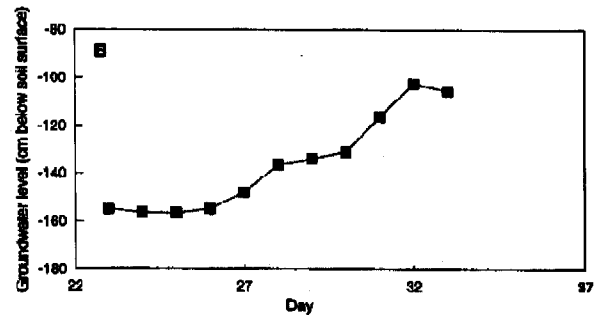
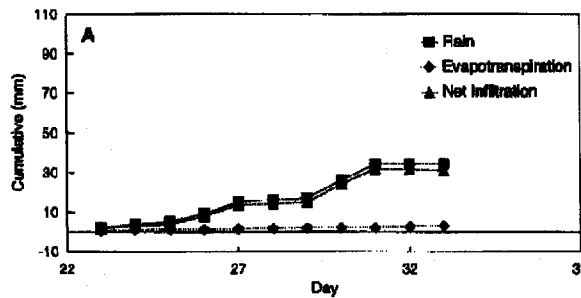
Rainy period 1: June 2 - 12, 1994



Rainy period 2: September 13 - 22, 1994



Rainy period 3: October 23 - November 2, 1994



Rainy period 4: December 3 - 12, 1994

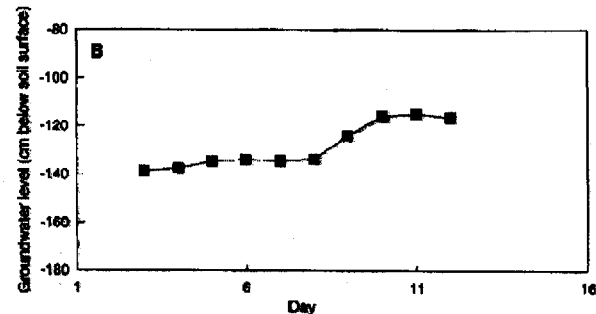
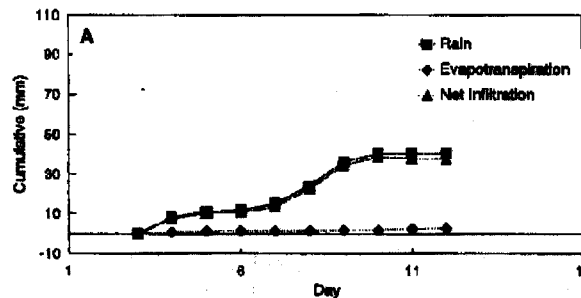
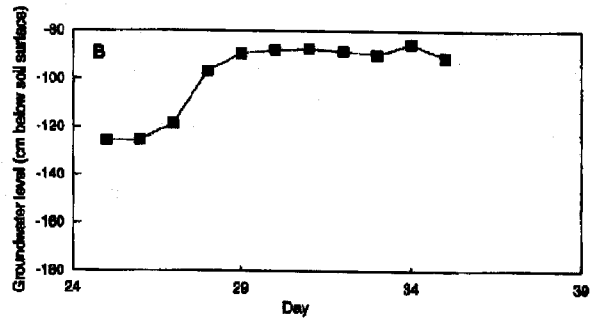
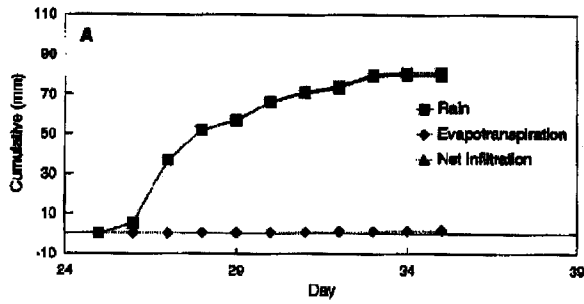
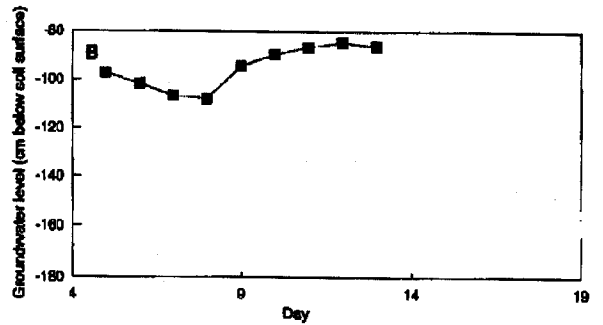
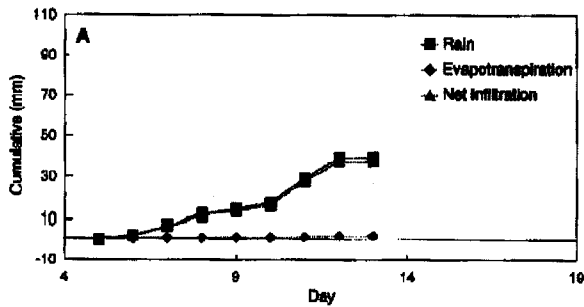


Fig. 4. (and over) Cumulative rainfall, evapotranspiration, and net infiltration (A), and the course of the ground water level (B) for the selected rainy periods.

Rainy period 5: December 25, 1994 - January 4, 1995



Rainy period 6: January 5 - 13, 1995



Rainy period 7: January 19 - 27, 1995

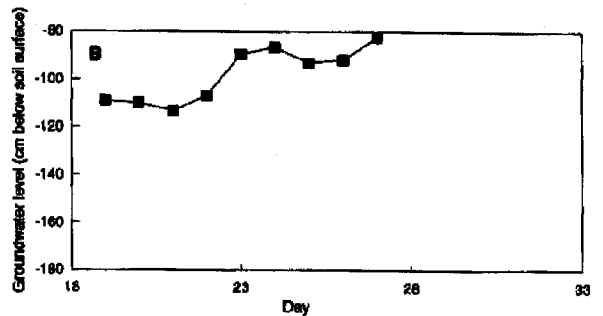
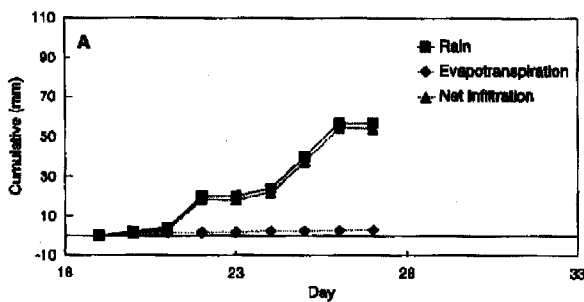


Fig. 4. (continued)

62.5–77.5 cm, the total water storage can be explored before and at the end of the rainy periods, as well as the changes per layer for each soil column. Figure 6 shows the total soil water content down to a depth of 77.5 cm for all 14 soil columns, just before the start of the rainy period

and at the end. The combined line-bar graphs in Fig. 6, show that some places within the TDR transect were initially wetter and were wetted to a greater extent during the rainy periods than others. The general trend seems to be that initially wetter places received more water than

Table 2. Estimated water balance for the 2 m long and 77.5 cm deep TDR transect for the selected rainy periods.

Rainy period	Net Infiltration amount mm	Water change in soil layer 0 to 77.5 cm mm	Deep drainage below 77.5 cm depth mm	Percentage of infiltrating water transported to depths below 77.5 cm %
1	13	13	0	0
2	35	21	14	40
3	31	31	0	0
4	37	20	17	46
5	79	16	63	80
6	37	11	26	70
7	54	24	30	56

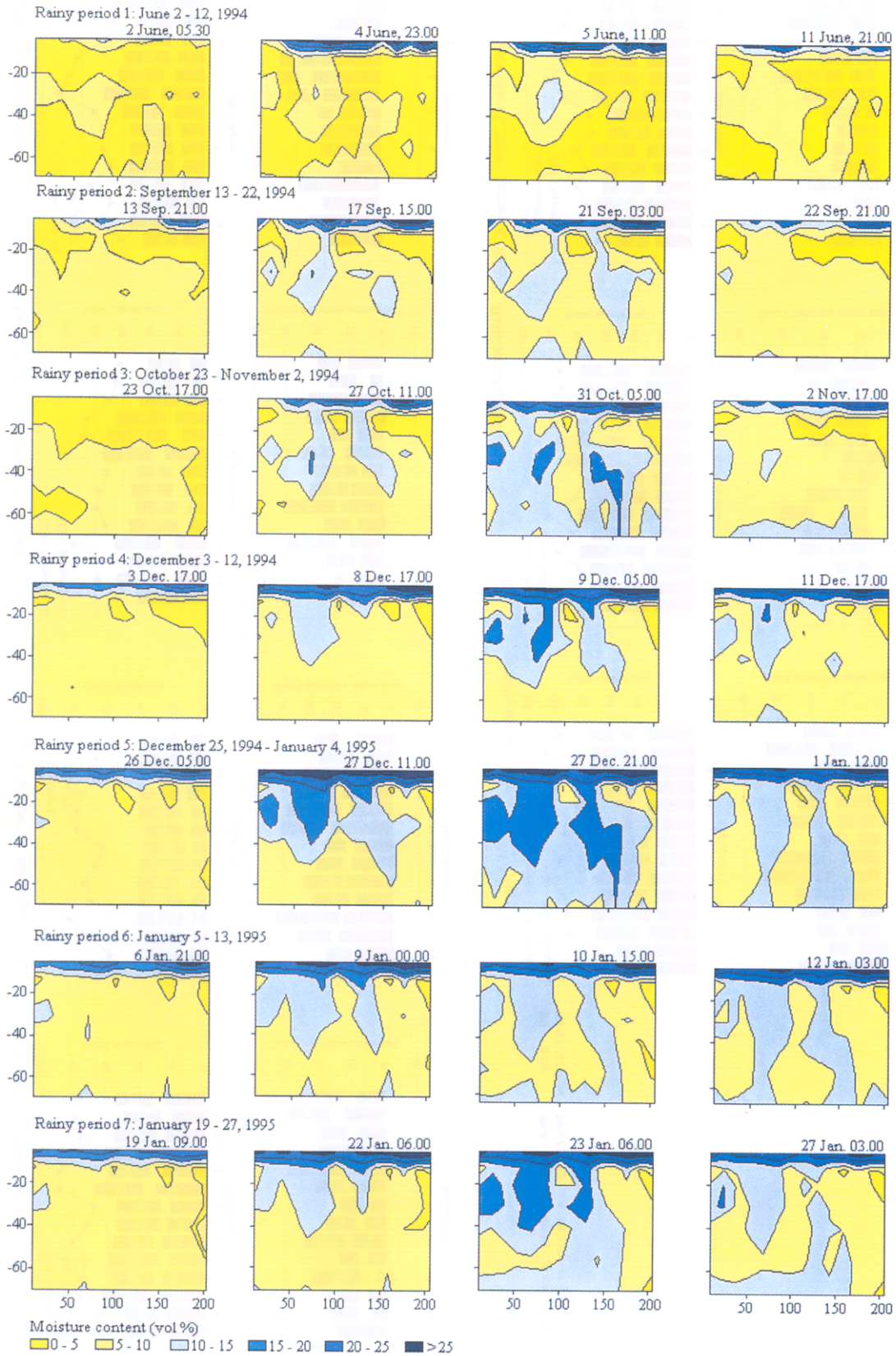


Fig. 5. Spatial distributions of soil water content in a vertical trench before, during and after the selected major rain periods. Horizontal and vertical scales in cm.

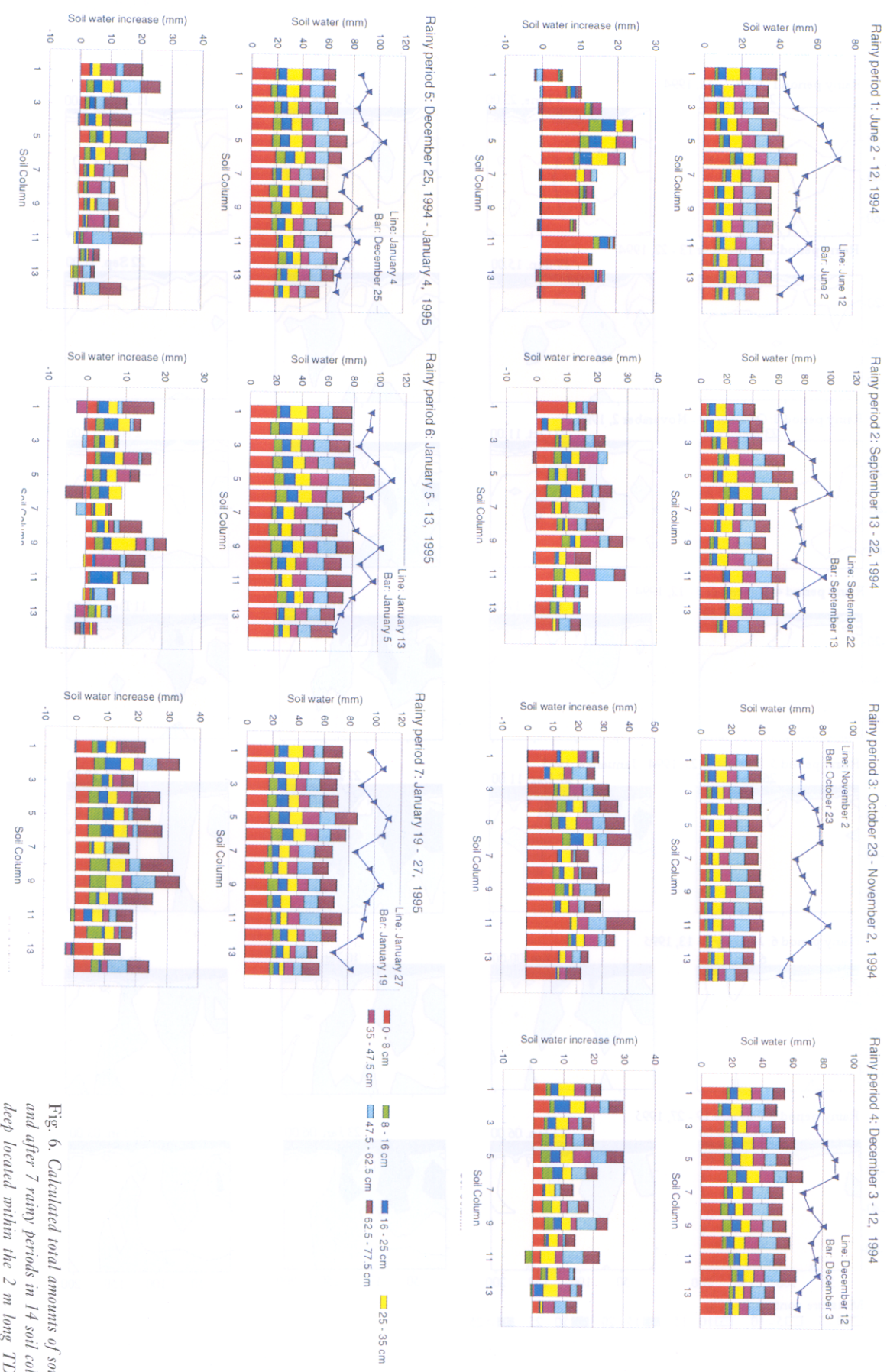


Fig. 6. Calculated total amounts of soil water before and after 7 rainy periods in 14 soil columns 77.5 cm deep located within the 2 m long TDR transect at Oudorp, and changes per layer.

deeper soil regions, even below a depth of 77.5 cm (Table 2). Despite the higher rainfall during December and January, the water content per layer showed a smaller increase during these events than during the other rainy periods. This can be attributed mainly to the initially higher soil water contents (of the humic topsoil) during the December and January rain events. Comparing the bar graphs in Fig. 6 with the wetting patterns in Fig. 5 suggests that below the humic topsoil, water was transported mainly through the fingers toward the deep subsoil.

Discussion

RESOLUTION OF MEASUREMENTS

Comparison of the two-dimensional soil water content distributions measured by the TDR device (Fig. 5) with those obtained via the intensive soil core sampling method (Ritsema and Dekker, 1994) revealed that the resolution was slightly poorer for the TDR transect. This is not unexpected, as the soil core sampling method uses 100 cm³ soil samples in a dense array to determine soil water contents. The TDR measurement set-up uses individual soil water content measurements which are representative of volumes of slightly more than 700 cm³ of soil. Despite the high quality measurements obtained in this study, resolution could be increased by using smaller TDR probes. Future studies of the dynamic behaviour of fingered flow processes would therefore benefit from using the smallest TDR probes available to maximize the resolution of the measurements. Using smaller probes would also allow the resolution of the measuring grid to be enhanced.

RECURRENCE OF FLOW FINGERS

This study indicates that fingers recur at the same locations during successive rain events. Ritsema *et al.* (1997b) showed that the water retention function of the Ouddorp sand is extremely hysteretic, characterized by a steep main wetting branch. This is typical for water repellent materials, and explains why vertical fingers can exist in dry soil (Nieber, 1996). The recurrence of fingers at the same locations can be attributed to the hysteretic, non-uniform water retention characteristic of the Ouddorp sand. After the cessation of rainfall, soil water contents decrease throughout the soil profile, within as well as outside the fingers. After a certain period of time, soil water content variations between former positions with and without fingers decrease, but differences do remain, due to their different wetting history. Even when the soil water content differences have become very small, water will still flow into the former pathways, as the water content in these places is slightly higher than in the immediate vicinity of the former fingers. Soil water contents even only slightly higher imply significantly larger unsaturated hydraulic conductivities, as illustrated by Ritsema and Dekker

(1994); thus, the flow of water is promoted through the wetter soil. This process of finger recurrence in soils might continue for an unlimited period of time, except that human influence might change the pattern drastically. The particular grass-covered experimental site used in the present study had not been tilled for several decades. If fields are used for the cultivation of crops, fingers might have stable spatial positions for one growing season only. In the following growing season, tillage treatments and seed bed preparation might cause fingers to occur at locations different from the year before. Therefore, persistent spatial finger patterns like those found in the present study might develop in, for instance, untilled agricultural fields, nature reserves and forests.

SOIL HETEROGENEITY

In waste land or extensively-used natural environments, the continuous recurrence of fingers at the same locations might lead to the inducement of heterogeneity in the physical and/or chemical properties of the soil. It is known for instance, that humic substances responsible for soil water repellency may leach through the vertical fingers to the subsoil (Ritsema and Dekker, 1996a). This may lead to a decrease in the extent of water repellency around the top end of the finger near the humic topsoil, and in an increase at the lower end of the finger deeper in the profile. In addition to such effects on the physical properties, continuously recurring fingered flow patterns might also induce heterogeneity in regard to soil chemical properties. For example, Ritsema and Dekker (1994) provided evidence of circular iron precipitates around the fingers at the boundary between dry and wet soil.

Conclusions

- The TDR measurement device used in the present study is a suitable instrument for detecting finger formation and finger recurrence in soils. The use of smaller TDR probes is recommended for future studies, to increase the measurement resolution.
- Finger formation depends on the wetting history of the soil and the rainfall characteristics. Fingers develop rapidly during severe rain storms, causing significant portions of the infiltrating water to be transported preferentially through the fingers to the deeper subsoil.
- Fingers recurred at the same sites during all rain events.

Acknowledgments

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References

- Baker, J.M. and Allmaras, R.R. (1990) System for automating and multiplexing soil moisture measurements by time-domain reflectometry. *Soil Sci. Soc. Am. J.* 54: 1–6.
- Bisdorn, E.B.A., Dekker, L.W. and Schoute, J.F.Th. (1993) Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. *Geoderma* 56: 105–118.
- Burch, G.J., Moore, I.D. and Burns, J. (1989) Soil hydrophobic effects on infiltration and catchment runoff. *Hydrol. Processes* 3: 211–222.
- Capriel, P., Beck, T., Borchert, H., Gronholz, J. and Zachmann, G. (1995) Hydrophobicity of the organic matter in arable soils. *Soil Biol. Biochem.* 27: 1453–1458.
- De Bakker, H. (1979) *Major soils and soil regions in the Netherlands*, Junk, The Hague, Netherlands, pp. 203.
- DeBano, L.F. (1971) The effect of hydrophobic substances on water movement in soil during infiltration. *Soil Sci. Soc. Am. Proc.* 35: 340–343.
- Dekker, L.W. and Ritsema, C.J. (1994) How water moves in water repellent sandy soil. 1. Potential and actual water repellency. *Wat. Resour. Res.* 30: 2507–2517.
- Dekker, L.W. and Ritsema, C.J. (1995) Fingerlike wetting patterns in two water repellent loam soils. *J. Environ. Qual.* 24: 324–333.
- Dekker, L.W. and Ritsema, C.J. (1996a) Preferential flow paths in a water repellent clay soil with grass cover. *Wat. Resour. Res.* 32: 1239–1249.
- Dekker, L.W. and Ritsema, C.J. (1996b) Variation in water content and wetting patterns in Dutch water repellent peaty clay and clayey peat soils. *Catena* 28: 89–105.
- De Rooij, G.H. (1995) A three-region analytical model of solute leaching in a soil with a water repellent top layer. *Wat. Resour. Res.* 31: 2701–2707.
- Heimovaara, T.J. and Bouten, W. (1990) A computer controlled 36-channel Time Domain Reflectometry system for monitoring soil water contents. *Wat. Resour. Res.* 26: 2311–2316.
- Hendrickx, J.M.H., Dekker, L.W. and Boersma, O.H. (1993) Unstable wetting fronts in water repellent field soils. *J. Environ. Qual.* 22: 109–118.
- Jamison, V.C. (1945) The penetration of irrigation and rainwater into sandy soils of central Florida. *Soil Sci. Soc. Am. Proc.* 10: 25–29.
- Knight, J.H., White, I. and Zegelin, S.J. (1994) Sampling volume of TDR probes used for water content monitoring. Proceedings of the symposium and workshop on *Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*. United States Department of Interior Bureau of Mines, Special Publication SP 19–94.
- Ma'shum, M., Tate, M.E., Jones, G.P. and Oades, J.M. (1988) Extraction and characterization of water repellent materials from Australian soils. *J. Soil Sci.* 39: 99–109.
- McGhie, D.A. and Posner, A.M. (1980) Water repellence of a heavy textured Western Australian soil. *Austr. J. Soil Res.* 18: 309–323.
- Nieber, J.L. (1996) Modeling finger development and persistence in initially dry porous media. *Geoderma* 70: 207–230.
- Ritsema, C.J., Dekker, L.W., Hendrickx, J.M.H. and Hamminga, W. (1993) Preferential flow mechanism in a water repellent sandy soil. *Wat. Resour. Res.* 29: 2183–2193.
- Ritsema, C.J. and Dekker, L.W. (1994) How water moves in a water repellent sandy soil. 2. Dynamics of fingered flow. *Wat. Resour. Res.* 30: 2519–2531.
- Ritsema, C.J. and Dekker, L.W. (1995) Distribution flow: a general process in the top layer of water repellent soils. *Wat. Resour. Res.* 31: 1187–1200.
- Ritsema, C.J. and Dekker, L.W. (1996a) Water repellency and its role in forming preferred flow paths in soils. *Austr. J. Soil Res.* 34: 475–487.
- Ritsema, C.J. and Dekker, L.W. (1996b) Influence of sampling strategy on detecting preferential flow paths in water repellent sand. *J. Hydrol.* 177: 33–45.
- Ritsema, C.J., Steenhuis, T.S., Parlange, J.-Y. and Dekker, L.W. (1996) Predicted and observed finger diameters in field soils. *Geoderma* 70: 185–196.
- Ritsema, C.J., Dekker, L.W. and Heijns, A.W.J. (1997a) Three-dimensional fingered flow patterns in a water repellent sandy field soil. *Soil Sci.* 162: 79–90.
- Ritsema, C.J., Dekker, L.W., Nieber, J.L. and Steenhuis, T.S. (1997b) Modeling and field evidence of finger formation and finger recurrence in a water repellent sandy soil. *Wat. Resour. Res.*, in press.
- Topp, G.C., Davis, J.L. and Annan, A.P. (1980) Electromagnetic determination of soil water content: Measurement in coaxial transmission lines. *Wat. Resour. Res.* 16: 579–582.
- Van Dam, J.C., Hendrickx, J.M.H., Ommen, H.V. van, Bannink, M.H., Genuchten, M.Th. van and Dekker, L.W. (1990) Water and solute movement in a coarse-textured water repellent field soil. *J. Hydrol.* 120: 359–379.
- Van den Elsen, H.G.M., Kokot, J., Skierucha, W. and Halbertsma, J.M. (1995) An automatic Time Domain Reflectometry device to measure and store soil moisture contents for stand-alone field use. *Agrophysics* 9: 235–241.
- Whalley, W.R. (1993) Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content. *J. Soil Sci.* 44: 1–9.