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Klaas Oostindie
Louis W. Dekker
Coen J. Ritsema

Alterra report 540, ISSN 1566-7197

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This study has been partly financed by Aquatrols, 5 North Olney Avenue, Phone: 800/257-7797, Fax: 856/751-3859, Cherry Hill, NJ 08003 U.S.A., and the Commission of the European Community under work programme FAIR (ref. 4027). The project does not necessarily reflect the Commission's views and in no way anticipates its future policy in this area.

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Report 540

ALTERRA, Green World Research, Wageningen, 2002

Abstract

Oostindie, K., Dekker, L.W. and C.J. Ritsema, 2002. *The effects of surfactant applications and irrigations on the wetting of a dune sand with grass cover.* Wageningen, Alterra, Report 540, 88 pp., 62 Figs; 29 References.

This study reports about amelioration trials to reduce water repellency in a dune sand with grass cover during the years 2000 and 2001. The experimental field was divided into four plots and three of them were treated in a different way. The first plot was used as a zero field, the second plot was treated with surfactant (Primer®604), the third plot was irrigated and the fourth plot was treated with surfactant and irrigated. The influence of these treatments on the wetting of the soil was studied by measuring the volumetric water content using the Time Domain Reflectometry (TDR) technique. At each plot the volumetric water content was measured at four depths (4, 10, 20 and 30 cm), and at these depths, up to a maximum of eight probes were installed into the soil, with a spacing of 10 cm. The measurement frequency differed from every three hours during the first project year to every hour in the second year. Furthermore, transects were sampled at each plot for the determination of the actual and potential water repellency. Irrigations took place during the periods April to September. The irrigation frequency differed from three weekly in the first year to weekly in the second year. Surfactant applications as well as irrigations lowered the persistence of actual water repellency in the surface layer (0-5 cm). The combination of irrigations and surfactant applications was most effective in beating the phenomenon, however a part of the soil at depths between 7 and 19 cm still exhibited water repellency during the first year. Primer applications resulted in higher mean soil water contents at 4 and 10 cm depth in the non-irrigated and irrigated plots, during the period July to November 2001.

Keywords: water repellency, Time Domain Reflectometry, TDR, critical soil water content, surfactant

ISSN 1566-7197

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ALTERRA is the amalgamation of the Institute for Forestry and Nature Research (IBN) and the Winand Staring Centre for Integrated Land, Soil and Water Research (SC). The merger took place on 1 January 2000.

Project 86151 [Report 540/KO/7-2002]

Contents

Summary

Dry soils are normally easily wetted by rainfall and irrigation. However, some soils resist wetting and are considered to be water repellent and to exhibit hydrophobic properties. The problem of soil water repellency has been recognized in sand, loam, clay and peat soils in various parts of the world and is common and most pronounced in sandy soils supporting turf or pasture grasses.

Water repellency is influenced by season and soil water content. In most cases, repellency is most severe during summer and decreases or disappears during the winter months. Water repellency may dramatically affect water and solute movement and has been shown to cause decreased infiltration of irrigation water and precipitaton, non-uniform wetting of soil profiles, and leaching due to preferential flow.

Soil wetting agents have been developed as a possible means for overcoming the problems caused by water repellent soils. Surfactants are well documented for the management of water repellency in thatch and surface layers in sandy soils and for the enhancement of soil hydration in managed turfgrass. The effectiveness of the surfactant Primer®604 for amelioration of soil water repellency was studied in a dune sand with grass cover near the village of Ouddorp, in the southwestern part of the Netherlands during the period April to November 1999 (Dekker et al., 2000b). Surfactant treatment significantly reduced soil water repellency in the surface layer of the plot when compared with the untreated control. As a consequence higher soil water contents were found for the surface layer of the treated plot. However, the surfactant did not improve the uneven moisture distribution in soil below the surface layer. Therefore, a further study was carried out in this experimental field in 2000 and 2001, by combining treatments with irrigations to prevent drying of the soil below the critical soil water contents, and hereby preventing the soil to become water repellent.

The experimental field was divided into four plots. The first plot was used as zero field, the second was treated with surfactant, the third was irrigated with water and the fourth plot was treated with surfactant and irrigated. In 2001 irrigation applications were increased compared to 2000.

Volumetric water contents were measured in time at 4, 10, 20, and 30 cm depth in all of the four different treated plots, using an automated measuring device based upon Time Domain Reflectometry (TDR) technique.

Soil samples were taken in vertical transects in the four plots to study the persistence and degree of the actual and potential water repellency in July 2000 and September 2001. The persistence of soil water repellency was measured with the water drop penetration time (WDPT) test, and the degree of soil water repellency with the alcohol percentage test.

Primer®604 applications as well as irrigations resulted in less persistence of the actual water repellency in the surface layer (0-5 cm) of the dune sand in 2000. The combination of irrigations and surfactant applications was most effective in beating the repellency, however a part of the soil at depths between 7 and 19 cm still exhibited extreme water repellency.

The degree of actual water repellency, measured with the alcohol percentage test, was in July 2000 significantly lower at depths of 0 to 2.5 cm in the non-irrigated, surfactant treated plot, and at depths of 0 to 26 cm in the irrigated, surfactant treated plot, when compared with the respective untreated plots. We note that according to the alcohol percentage test in the plots without surfactant applications the highest degree of actual water repellency occurred in the surface layer and decreased with depth, whereas according to the WDPT test the highest persistence existed at depths of 7 to 19 cm.

Surfactant applications resulted also in significantly less persistence and lower degree of water repellency after drying the soil samples in the temperature range from 30 to 85^0C, as was found for samples taken in July 2000. For the samples from September 2001 we found that surfactant applications lowered significantly the potential soil water repellency in the surface layer, and a combination with irrigation lowered the potential water repellency also significantly at depths of 7 to 19 cm.

The mean soil water content was slightly higher in the topsoil of the transect in the non-irrigated Primer treated plot, compared with the untreated plot on 27 July, 2000. A significant higher content was also detected in the surface layer (0-5 cm) of the transect in the treated irrigated plot, in comparison with the untreated irrigated plot on 21 July, 2000.

During the period July-September, 2000 large temporal differences in soil water content were detected at 4 cm depth in the irrigated plot with surfactant applications, and on the other hand slight differences were found in the other plots. It is also noteworthy that at 10 cm depth significantly higer mean soil water contents were found in the two plots with surfactant applications, in comparison with the untreated plots during the period 19 September to 31 December, 2000. Also between 1 July and 16 November, 2001 mean soil water contents at 4 and 10 cm depth in the non-irrigated plot with surfactant applications were often significantly higher, in comparison with the untreated plot.

During the period 1 May to 31 August, 2001 the soil water content at 4 cm depth in the non-irrigated untreated plot was regularly found below the transition zone of the critical soil water content, indicating actual soil water repellency. On the other hand, at this depth in the treated plot were indeed often water contents detected in the transition zone, but never below it. Between the irrigated plot without and the plot with Primer applications more or less similar differences were found.

Diagrams of the temporal wetting of the irrigated plots, measured just before the weekly irrigations during the period 18 July to 3 September, 2001, showed that a larger part of the soil profile wetted and that dry areas sooner disappeared in the Primer treated plot than in the untreated plot.

Numerous diagrams illustrate the better wetting of the soil profiles and the occurrence of less dry pockets in the Primer treated plots, due to rainfall and irrigations between 1 May and 17 September, 2001, when compared with the respective untreated plots.

1. Introduction

Dry soils are normally easily wetted by rainfall and irrigation. If the attractive forces are neutralized or absent, e.g. because of the presence of a hydrophobic coating on sand grains or aggregates, soils are said to resist wetting and are considered to be water repellent and to exhibit hydrophobic properties. A water repellent soil will be defined as one which does not wet spontaneously when a drop of water is placed upon the surface. Water repellency has been observed in sand, loam, clay, and peat soils all over the world (Wallis and Horne, 1992; Dekker and Ritsema, 2000; Jaramillo et al., 2000; Feng et al., 2002). However, the phenomenon is most pronounced in course textured soils and is common in sandy soils supporting turf or pasture grasses.

Although water repellent soil has several possible causes, numerous researchers agree that an organic coating on the soil particles causes the problem. This coating does not necessarily cover the soil particles completely nor is it always very thick. A thin and/or partial covering of the soil particles can render them water repellent (Bisdom et al., 1993). However, mineral particles need not be individually coated with hydrophobic material; intermixing of mineral soil particles with particulate organic matter, like remnants of roots, leaves, and stems, may also induce severe water repellency (Bisdom et al., 1993).

Water repellency is influenced by season and soil water content. In most cases, repellency decreases during the winter months and is most severe during summer. This seasonal variation may be due to soil moisture conditions. Long, hot, dry periods are helping to produce the formation of water repellent soils. Likewise, extremely wet weather can lessen or even eliminate water repellency for several weeks. There appears to be a critical soil water content for each water repellent soil layer, below which the soil is water repellent and above which the soil is wettable (Dekker and Ritsema, 1994).

Water repellency may dramatically affect water and solute movement at the field-scale, a process which has often been underestimated (Bauters et al., 2000). Water repellency and its spatial variability have been shown to cause decreased infiltration of irrigation water and precipitation, non-uniform wetting of soil profiles, increased runoff, and leaching due to preferential flow (Dekker et al., 2001a,b).

Soil wetting agents have been developed as a possible means for overcoming the problems caused by water repellent soils (Letey et al., 1962; Moore, 1981; Kostka et al., 1997; Kostka, 2000). Surfactants are well documented for the management of water repellency in thatch and surface layers in sandy soils and for the enhancement of soil hydration in managed turfgrass (Miller and Kostka, 1998; Karnok and Tucker, 2001).

Maintenance of turf quality and simultaneous optimization of irrigation and conservation of water are goals of turfgrass managers, especially under drought conditions. Water may be conserved by maximizing the effectiveness of irrigation and precipitation or by minimizing the losses of transpiration, evaporation, and leaching or drainage below the rootzone.

Dekker et al. (2000b) studied the effectiveness of the surfactant Primer®604 for amelioration and management of soil water repellency in a dune sand with grass cover near the village of Ouddorp, in the southwestern part of the Netherlands during the period 22 April to 23 November 1999. During that period the surfactant was applied twelve times at a rate of 1.85 ml per square m. Soil samples were taken at six depths in trenches in a treated and an untreated plot over a seven-month period. Surfactant treatment significantly reduced soil water repellency in the surface layer of the plot when compared with the untreated one. As a consequence an increase in the wetting rate and higher soil water contents were found for the surface layer of the treated plot. The critical soil water content, below which the soil is actually water repellent in the field, was lowered significantly by the application of Primer®604 for the surface layer at depths of 0-5 cm. This means that the soil in the Primer treated plot may dry to a lower water content than the surface layer of the untreated plot before water repellency is initiated. However, the surfactant did not improve the uneven moisture distribution in soil below the surface layer. Therefore, Dekker et al. (2000b) recommended a further study of this experimental field by combining treatments with irrigations to prevent drying of the soil below the critical soil water content, and thereby preventing the soil to become water repellent.

In the present study the same experimental field on the dune sand with grass cover near the village of Ouddorp has been used. Effects of Primer®604 applications and water irrigations on the wetting and severity of water repellency were studied during the summer periods of 2000 and 2001. Time Domain Reflectometry has been used for the measurement of volumetric soil water contents in the four different treated plots.

2. Materials and Methods

2.1. Field soil and Field setup

The experimental field is located on a dune sand near Ouddorp, in the south-western part of the Netherlands. The soil consists of fine sand with less than 3% clay to a depth of more than 3 m and is classified as Typic Psammaquent (Dekker, 1998). The site is a grass-covered pasture and has not been tilled for at least several decades. An organic matter content of 12.5 w% was established in the surface layer (0-2.5 cm) and of 9.5 w% in the second layer (2.5-5 cm). At depths of 7-9.5 cm an organic matter content was detected of 4.8 w% and at depths of 9.5-12 cm of 2.4 w%. It further decreased to 1.5 w% at depth of 14-16.5 cm and 1.1 w% at depths of 16.5-19 cm. Below this depth the organic matter content was found to be around 0.5 w%.

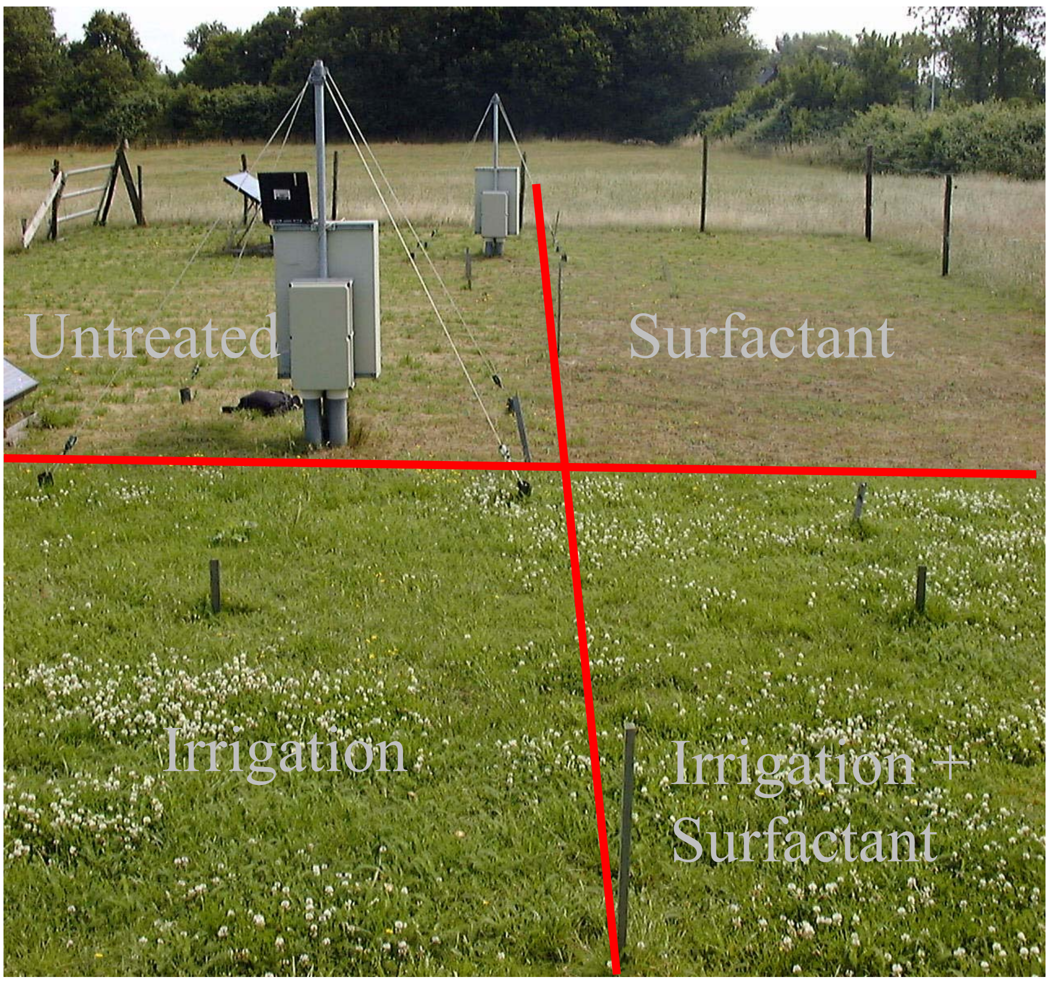

Figure 1 Experimental field setup.

The soil studied can be severely to extremely water repellent to a depth of more than 50 cm during dry periods (Dekker and Ritsema, 1994, Dekker et al., 2000a).

To study the effects of surfactant and water applications on the wetting of the soil, the experimental field was divided into four plots (Fig. 1). The first plot was used as zero field, the second was treated with surfactant, the third was irrigated with water and the fourth plot was treated with surfactant and irrigated.

2.2. Treatments and Irrigation

Treatments with the wetting agent Primer®604 (Aquatrols, Cherry Hill, New Jersey, U.S.A) were applied to a part of the experimental field (25 m by 5 m) at a rate of 1.85 ml/m^2 with a volume solution of 70 ml/m^2 with a Mesto Pico backpack-type sprayer. Dates of treatments are given in Table 1. The same area was also twelve times treated with Primer ®604 in 1999 (Dekker et. al., 2000b). An adjacent same area was not treated and was used for comparison.

In the summer periods of 2000 and 2001 a part of the treated area (5 m by 5 m) as well as a same part of the adjacent untreated area were used for water irrigations. Dates of these irrigations and amounts of water are stated in table 1.

Table 1 Dates of surfactant treatments and amounts of irrigation water in 2000 and 2001.

	2000			2001	
Date	Surfactant (?)	Irrigation (mm)	Date	Surfactant (?)	Irrigation (mm)
10 April	No	15	12 January	Yes	0
25 April	Yes	15	16 February	Yes	0
16 May	Yes	20	12 March	Yes	0
6 June	Yes	20	19 April	Yes	20
28 June	Yes	20	18 May	Yes	20
14 July	Yes	0	29 May	Yes	20
25 July	No	20	11 June	Yes	20
7 August	Yes	20	18 June	Yes	30
18 August	Yes	20	25 June	Yes	30
31 August	Yes	20	2 July	Yes	30
19 September	Yes	20	9 July	Yes	30
9 October	Yes	0	16 July	Yes	30
26 October	Yes	0	23 July	Yes	30
10 November	Yes	0	30 July	Yes	30
12 December	Yes	0	6 August	No	20
			13 August	No	20
			20 August	Yes	20
			27 August	No	20
			10 September	Yes	0
			16 October	Yes	0
			16 November	Yes	0
			18 December	Yes	0

The aim of irrigations in 2000 was to transport surfactant deeper into the soil profile, whereas in 2001 the intention of the irrigations was to keep the soil profile moist and the soil layers above their critical soil water contents.

2.3. Soil Water Content Measurements with Time Domain Reflectometry

Volumetric water contents were measured in time and at different positions in the profile in all of the four different treated plots, using an automated measuring device based upon Time Domain Reflectometry (TDR). This technique was introduced into soil science in 1980 (Topp et al., 1980) and has become widely accepted (e.g., Baker and Allmaras, 1990; Heimovaara and Bouten, 1990; Van den Elsen et al., 1995; Ritsema et. al., 1997). The volumetric water contents were measured automatically by two stations, each equipped with a TRASE 6050 X1 TDR device. Each device measured water contents at 31 different positions in the surfactant treated plot and at 30 positions in the untreated plot.

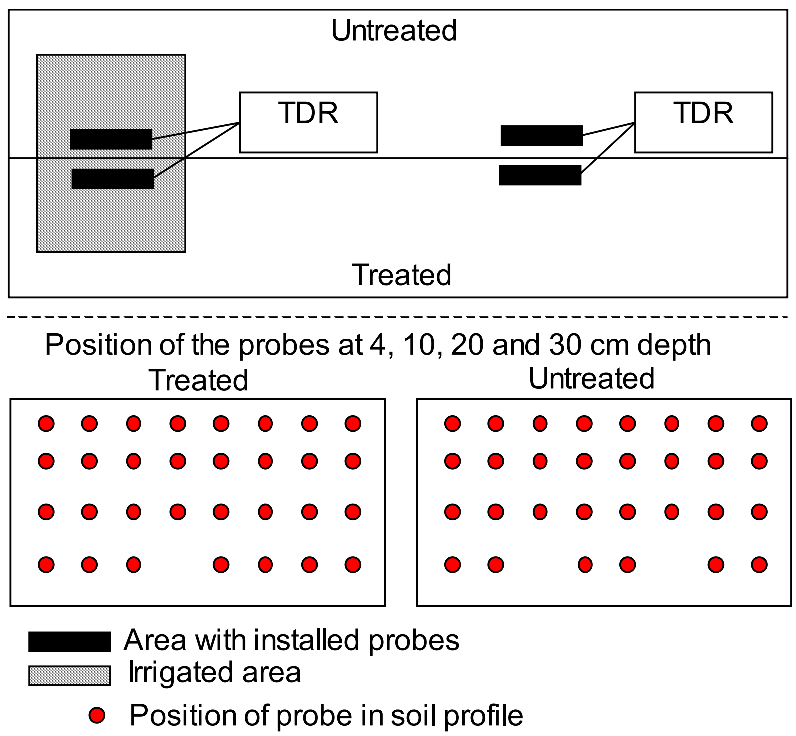

Figure 2 Layout of the experimental field.

One station was installed in the untreated and treated plots without irrigation and the other station in the untreated and treated plots with irrigation (Fig. 2). The standard three-rods probes were placed horizontally into the walls of a pit. Figure 2 also shows the installation scheme of the probes in a treated and untreated plot. The probes were installed at depths of 4, 10, 20, and 30 cm with a horizontal spacing of 10 cm. Some probes at 30 cm depth were not installed due to the maximum capacity of the multiplexer cards. The stations started at least every three hours automatically to perform a measurement cycle. During the summer of 2001 this frequency was set to every hour. Date, time, and values of the measured soil water contents were stored in the memory of the TDR units. Regularly, these data have been retrieved from the units with a laptop computer and further processed at the office. Each TDR unit was powered by two parallel 12 V batteries, charged by solar panels.

2.4. Calibration of TDR Measurements

The TDR device has been calibrated in the laboratory to obtain more accurate measurements for this specific soil. Soil samples for calibration have been taken in the untreated and treated plot at depths of 0-8, 8-15, and 15-30 cm. So, in total six calibration procedures have been performed (3 depths, 2 plots). The procedure consisted of several steps. First of all, two litre (2000 cm^3) of the soil samples were oven-dried at 105^oC. Then a container with a content of 475 cm^3 was filled with dry soil, in the continuance of slight compression. A TDR probe was pressed into the soil in the middle of the container and the apparent dielectric constant (K_a value) was measured three times and subsequently averaged. This resulted in the first

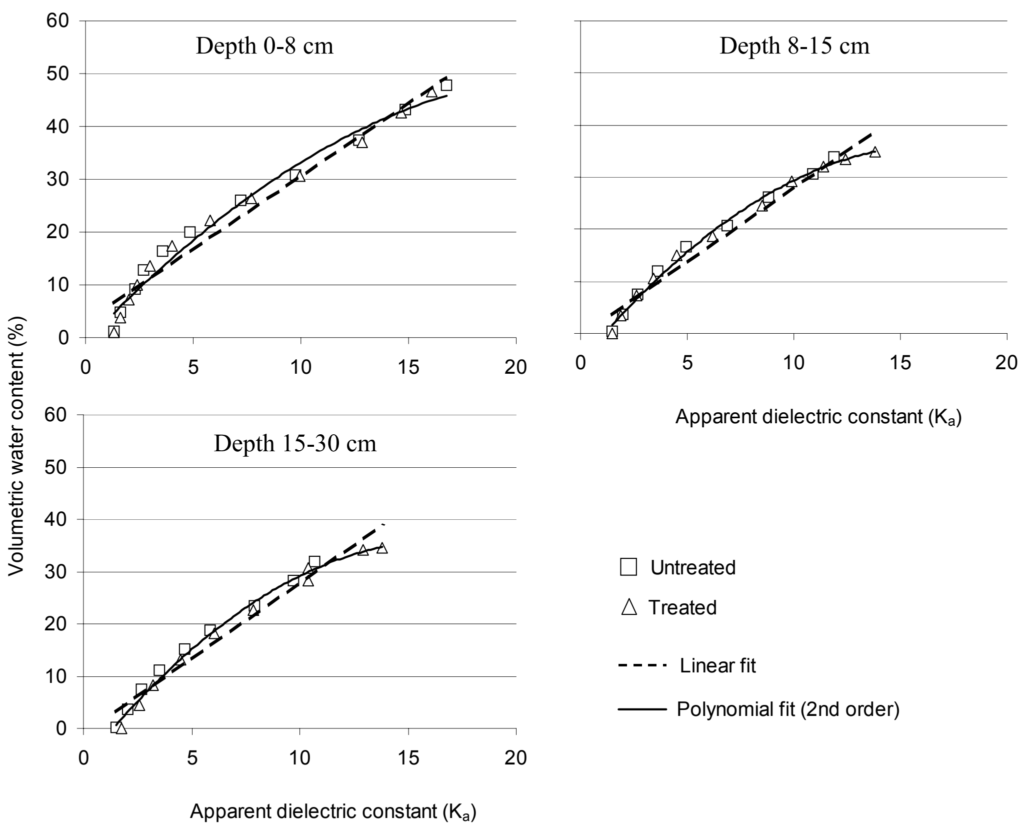

Figure 3 Calibration lines at three depths for combined data series of the treated and untreated plot, fitted by a linear and a 2nd order polynomial method.

calibration value for a volumetric water content of 0%. Then the soil in the container was put back to the rest of the soil. An estimation was made for the amount of water to saturate the 2 litre of soil. This amount of water was added to the soil in 10 equal steps. During each step, a tenth of the total amount was added to the soil with a plant sprayer and thoroughly mixed by hand. The container was filled with the wetted soil, compressed slightly, and weighed on a balance. Then the TDR probe was placed into the soil to measure the K_a value three times and an avaraged value was calculated. A small sub sample was taken with a spoon from the wetted soil in the container and weighed. This sample was dried at 105°C and weighed again. The water content as a mass ratio of this sub sample can be calculated with:

$$w=(m_w - m_d) / m_d$$

where w is the water content as a mass ratio ($kg.kg^{-1}$), m_w is mass of the wet soil (kg) and m_d is the mass of the dry soil (kg). Subsequently, the dry mass of the soil in the container can be calculated with:

$$m_{d,con} = m_{w,con} / (w + 1)$$

where $m_{d,con}$ is the dry mass of the soil in the container (kg) and $m_{w,con}$ is the mass of the wet soil in the container (kg). The volumetric water content (Θ) can be calculated with:

$$\Theta = (m_{w,con} - m_{d,con}) / V_{con}$$

in which Vcon is the volume of the container (m^3). The soil in the container was put back to the rest of the soil. This step was repeated till the soil was saturated. In this way, measured K_a values and calculated volumetric water contents were obtained at a regular scale from completely dry to saturation.

The data series from three depths of the treated and untreated plot show the same trend, as can be seen in Figure 3. Therefore these series were combined per depth and thereafter fitted by a linear and by a 2nd order polynomial method according to the following formulas:

$$\Theta = a.K_a + b \qquad \text{(linear)} \qquad \text{and}$$

$$\Theta = a.\ K_a^2 + b.\ K_a + c: \qquad \text{(polynomial)}$$

where Θ is the volumetric water content (%), K_a is the dielectric constant and a, b, and c are regression constants. The coefficients of these functions and the squared multiple correlation index (R^2) for the three depths are given in Table 2. The polynomial method of approach shows in general a better fit at the beginning and at the end of the curves, which is also substantiated by higher multiple correlation coefficients. Therefore, these equations were used to compute the volumetric water contents from the measured dielectric constant.

Table 2 Calculated linear and polynomial regression coefficients per depth.

Depth	Linear			Polynomial			
(cm)	a	b	r^2	a	b	c	r^2
0-8	2.77	2.94	0.97	0.09	4.32	-0.88	0.98
8-15	2.86	-0.46	0.97	0.15	4.93	-5.40	0.99
15-30	2.91	-1.09	0.96	0.15	5.14	-6.72	0.99

2.5. Precipitation and Ground Water Level

Precipitation at the experimental field has been recorded with a rain gauge, provided with a tipping bucket system. The accurancy of this device is 0.2 mm. Date and time of each 0.2 mm precipitation was stored in the memory and retrieved monthly.

Measurements with the rain gauge started in April 2000. From then until the end of the year 760 mm water had been collected. A total of 1041 mm precipitation was measured from January to the end of December 2001. Total water irrigations in 2000 and 2001 amounted to 190 mm and 370 mm, respectively. Figure 4 shows the distribution of amounts of precipitation and irrigation for both years.

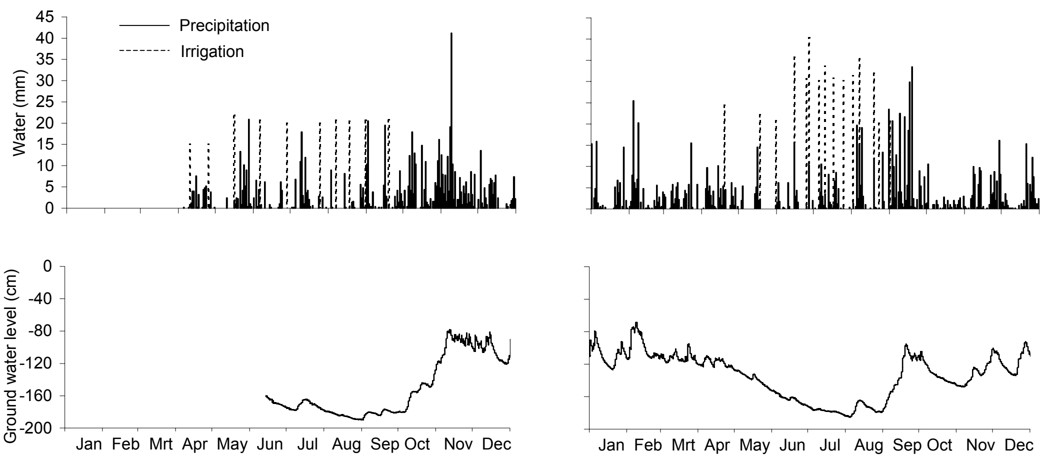

Figure 4 Amounts of precipitation and irrigation and course of the ground water level in 2000 and 2001.

The ground water level has been measured with an automated logger, equipped with a water level pressure sensor. Measurements were recorded in the memory of the logger. Once a month the memory of the logger was downloaded with a labtop computer.

The ground water levels ranged from 70 cm below the surface in the winter periods to 190 cm in the summer periods (Fig. 4). Water applications and precipitation during the summer periods did not clearly influence the fluctuations of the ground water level.

2.6. Soil Sampling

On 21 and 27 July 2000 soil samples were taken at ten depths in vertical transects in the four plots of the experimental field to study the persistence and degree of the actual and potential water repellency. The soil was sampled at depths of 0-2.5, 2.5-5, 7-9.5, 9.5-12, 14-16.5, 16.5-19, 21-26, 28-33, 35-40, and 42-47 cm, using steel cylinders with a diameter of 5 cm. At each depth 15 samples were taken in close order over a distance of about 80 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 and the persistence and degree of actual water repellency were measured. All samples had been oven-dried and weighed to calculate the soil water content.

The soil in the four plots was also sampled for soil water content and repellency measurements on 28 September 2001. In these four transects 25 samples were taken at six depths (0-2.5, 2.5-5, 7-9.5, 9.5-12, 14-16.5, and 16.5-19 cm) over a horizontal distance of around 140 cm.

2.7. Water Drop Penetration Time (WDPT) Test

The persistence or stability of water repellency of the soil samples was examined using the water drop penetration time (WDPT) test. Three drops of distilled water from a standard medicine dropper were placed on the smoothed surface of a soil sample, and the time that elapses before the drops were absorbed was determined. We measured the water repellency of the soil samples under controlled conditions at a constant temperature of 20^0C and a relative air humidity of 50%. In general, a soil is considered to be water repellent if the WDPT exceeds 5 s (Dekker, 1998). We applied an index allowing a quantitative definition of the persistence of soil water repellency as described by Dekker and Jungerius (1990). In the present study seven classes of repellency were distinguished, based upon the time needed for the water drops to penetrate into the soil: class 0, wettable, non-water repellent (infiltration within 5 s); class 1, slightly water repellent (5 to 60 s); class 2, strongly water repellent (60 to 600 s); class 3, severely water repellent (600 s to 1 h); and extremely water repellent (more than 1 h), further subdivided into class 4, 1 to 3 h; class 5, 3 to 6 h; and class 6, >6 h.

We measured the water repellency of the field-moist samples, the so-called "actual soil water repellency", and of the samples after drying in an oven, the so-called "potential soil water repellency" (Dekker and Ritsema, 1994). Measurements of the actual water repellency on the field-moist samples were performed immediately after assessment of the wet weights. The persistence of potential water repellency of samples taken in the two irrigated plots on 21 July 2000 were measured after drying at 30^0C and after further drying at 65^0C, 75^0C, 85^0C, and 105^0C. These measurements were performed to study the effect of drying temperature on the severity of soil water repellency, as was also studied for several other soils in the Netherlands by Dekker et al. (1998). The WDPT tests were deferred for at least 2 days to obtain samples in equilibrium with the ambient air humidity (Doerr et al., 2002).

Actual water repellency and potential water repellency (after drying at 30^0C) were also determined on the 600 soil samples taken in the four plots on 28 September 2001.

2.8. Alcohol Percentage Test

Over the years many techniques have been developed to measure soil water repellency (King, 1981; DeBano, 2000). One of the simplest and most common methods of classifying water repellency is the (WDPT) test, as described before. Another common used method is the alcohol percentage test (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 infiltration occurs within 5 s. 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.

We measured the degree of water repellency of the samples taken in the transects on 21 and 27 July 2000 and on 28 September 2001, 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 30% of ethanol on a volume basis. Alcohol percentage tests were conducted on the field-moist samples taken in the 21 and 27 July transects and on the dried samples of the 28 September transects. The degree of potential water repellency of samples taken in the two irrigated plots on 21 July 2000 were measured after drying at 30^0C and after further drying at 65^0C, 75^0C, 85^0C, and 105^0C. These measurements were performed to study the effect of drying temperature on the degree of soil water repellency.

3. Results

3.1. Year 2000

3.1.1. Transect Sampling

3.1.1.1. Actual Soil Water Repellency on 21 and 27 July

All samples taken at depths of 0-2.5 and 2.5-5 cm in the irrigated plot with Primer®604 applications were wettable (WDPT < 5 s) on 21 July, 2000, whereas most samples in the irrigated untreated plot exhibited slight (WDPT 5-60 s) to severe (WDPT 600-3600 s) water repellency (see Fig. 5, lower diagrams). Slight to extreme (WDPT > 1 h) water repellency was found for 65-85% of the samples at depths of 7-26 cm in the irrigated plot without surfactant and for 10-80% at depths of 7-26 cm in the irrigated plot with surfactant applications. Thus, the combination of irrigation and surfactant resulted in a wettable surface layer and a larger part of wettable soil at depths of 7-26 cm, in comparison with the irrigated plot without surfactant.

The persistence of actual water repellency was significant lower at depths of 0-5 cm in the non-irrigated plot with surfactant on 27 July, 2000, in comparison with the plot without surfactant, although large variations in persistence occurred at these depths in both plots (see Fig. 5, upper diagrams).

To conclude, surfactant applications as well as irrigations lowered the persistence of actual water repellency in the surface layer (0-5 cm) of the dune sand with grass cover. The combination of irrigations and surfactant applications was most effective in beating the phenomenon, however a part of the soil at depths between 7 and 19 cm still exhibited extreme water repellency (Fig. 5).

Large differences in degree of actual soil water repellency were measured with the alcohol percentage test between the two irrigated plots on 21 July, 2000. For instance the surface layer in the Primer®640 treated plot was wettable (0% alcohol), whereas in the untreated plot 85% of the soil samples at 0-2.5 cm depth and 45% of the samples at 2.5-5 cm depth showed extreme water repellency with alcohol percentages of 27.5 and 30% (Fig. 6, lower diagrams). But also at depths between 7 and 26 cm the alcohol percentages were significantly higher in the untreated plot compared with the treated plot.

The alcohol percentages measured in the non-irrigated plot without and the the plot with surfactant treatment are only slightly different, with the exception of significantly lower percentages at 0-2.5 cm depth in the surfactant treated plot (Fig. 6, upper diagrams).

The diagrams of the plots without surfactant applications show the highest degree of water repellency in the surface layer and a decrease in degree with depth (Fig. 6). On the other hand, the highest persistence of actual water repellency was found at depths of 7 to 19 cm, as shown in the diagrams of Figure 5.

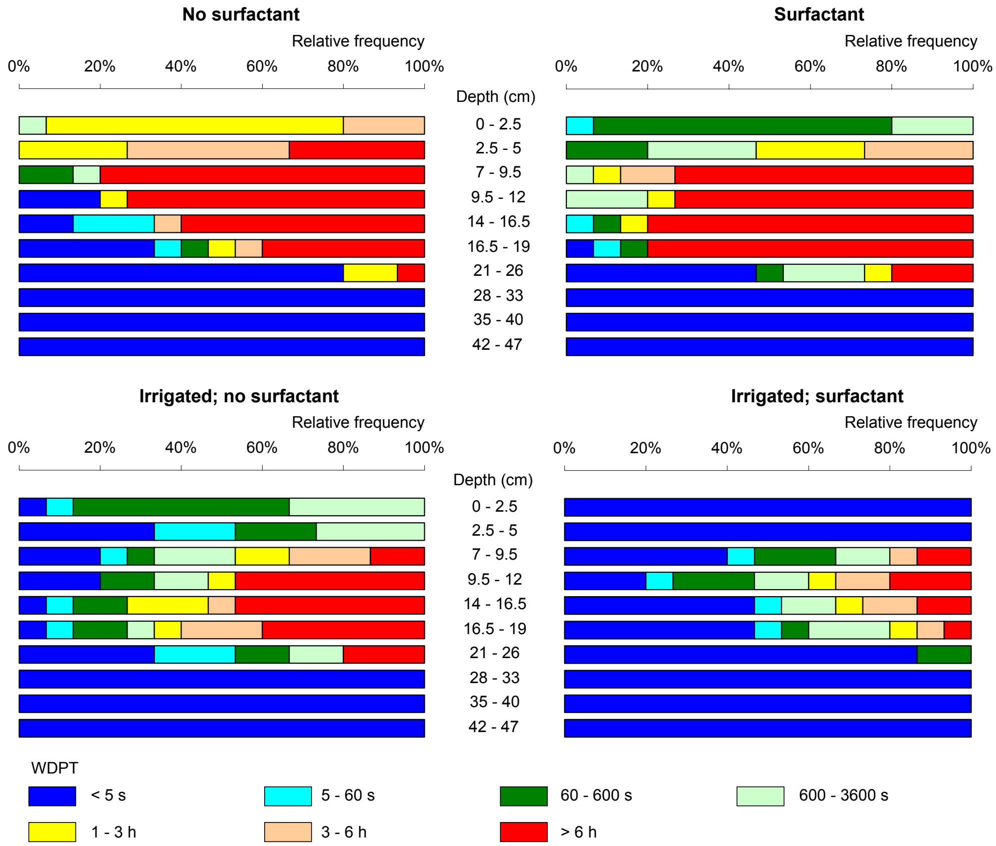

Figure 5 Relative frequency of the persistence of actual water repellency of field-moist samples taken at 10 depths in the non-irrigated untreated and treated plots on 27 July, and in the irrigated untreated and treated plots on 21 July, 2000 (n = 15).

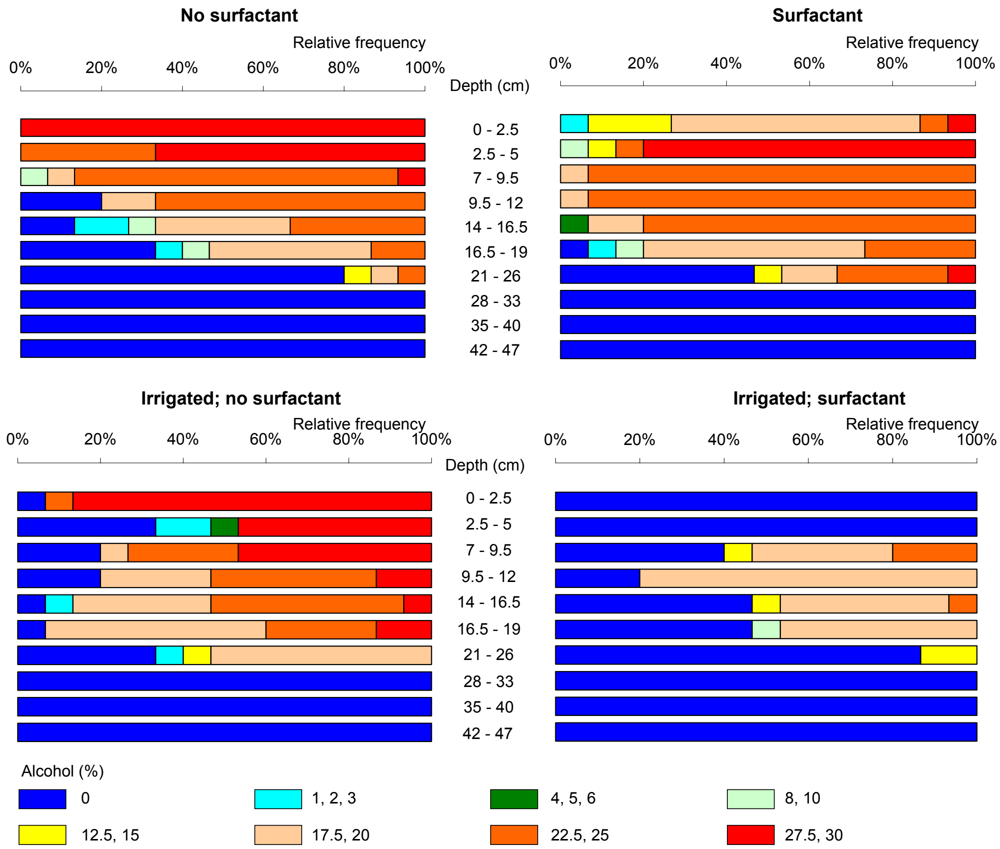

Figure 6 Relative frequency of the degree of actual water repellency of field-moist samples taken at 10 depths in the non-irrigated untreated and treated plots on 27 July, and in the irrigated untreated and treated plots on 21 July, 2000 (n = 15).

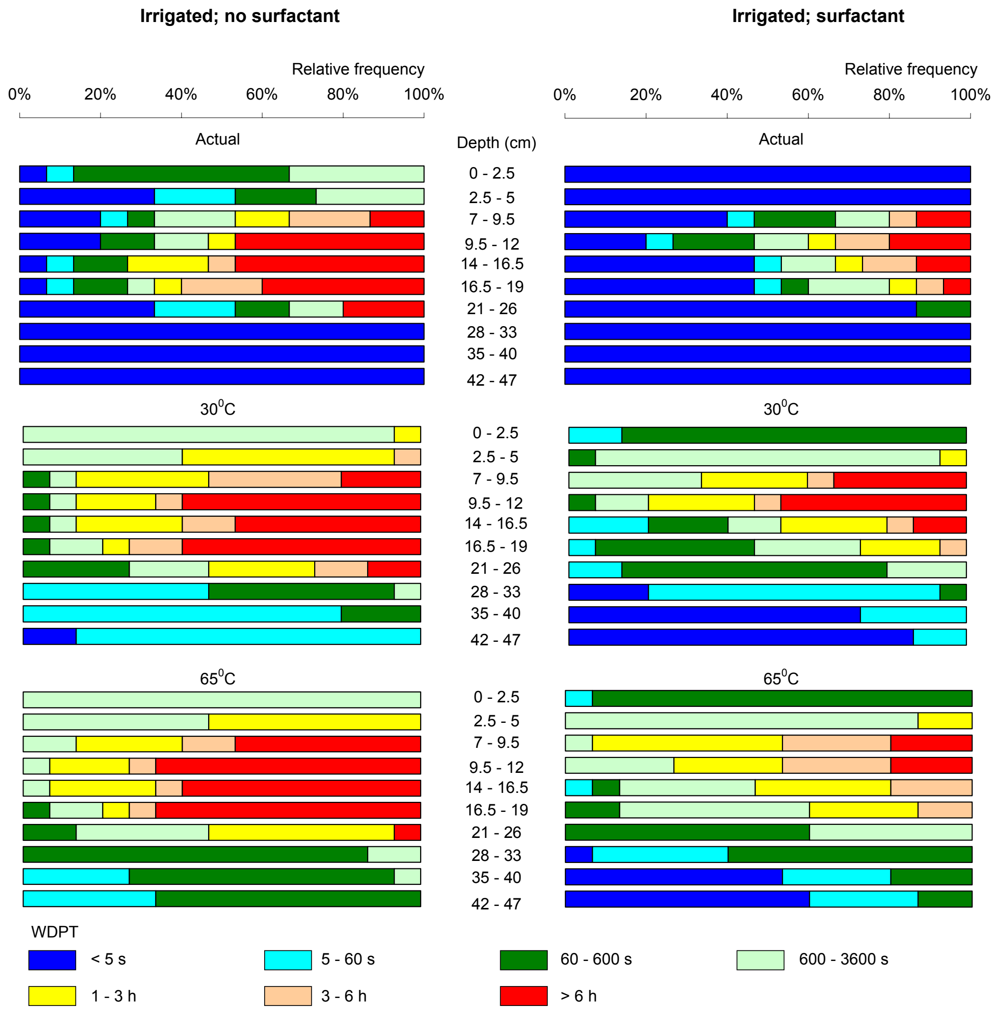

Figure 7 Relative frequency of the persistence of water repellency of soil samples taken at 10 depths in the irrigated untreated and treated plots after drying at increasing temperatures (n = 15).

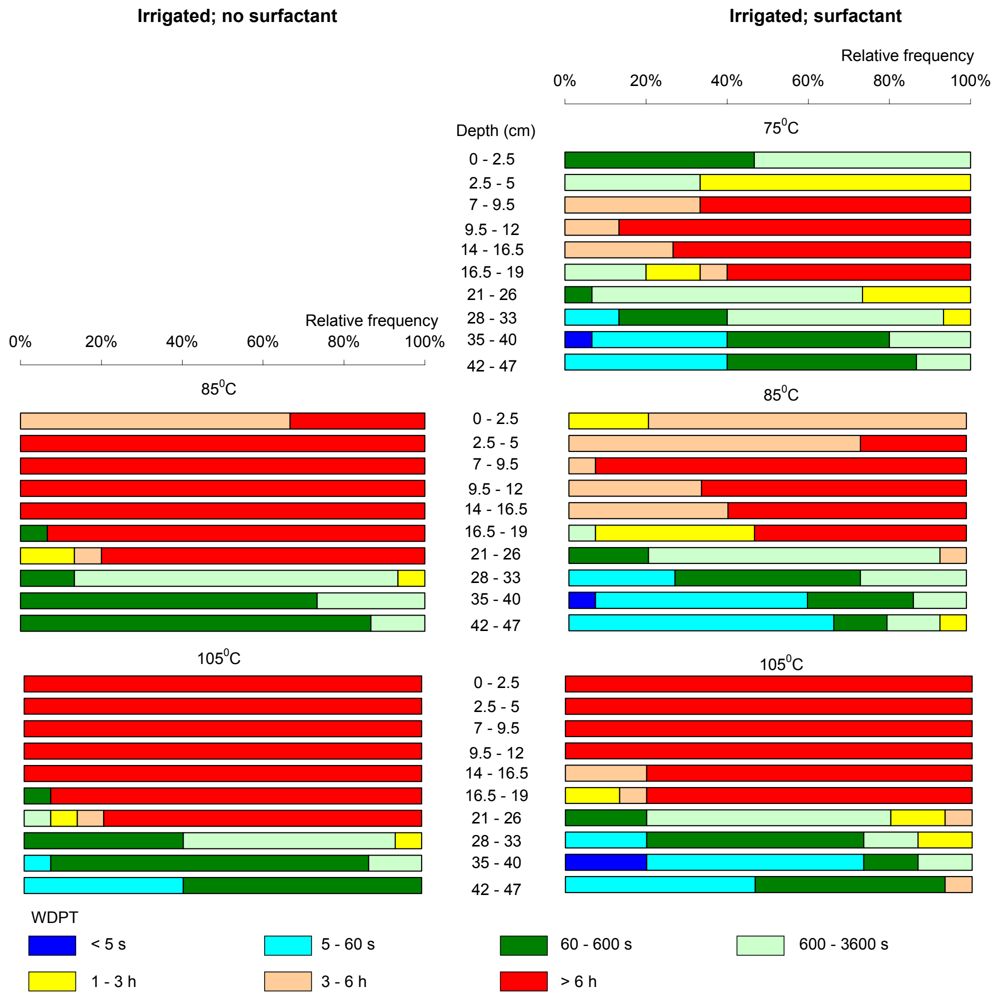

Figure 7 Continued.

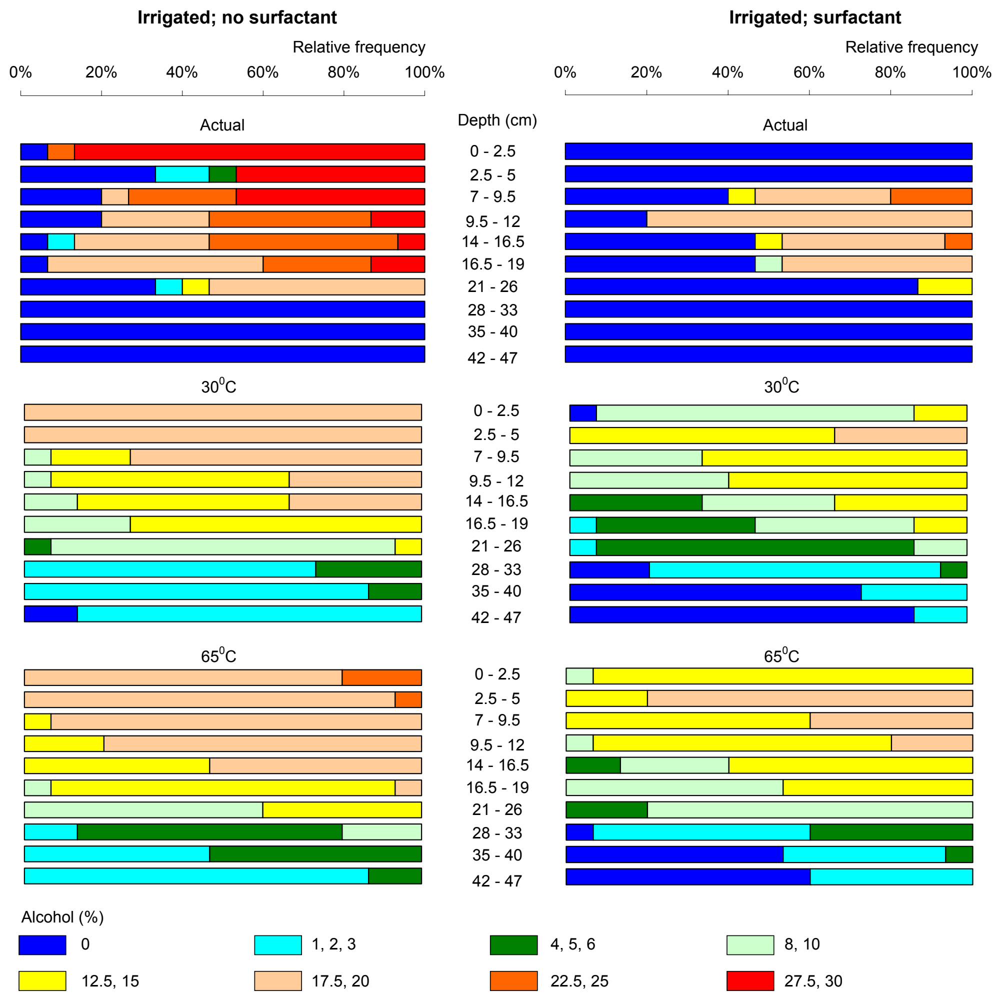

Figure 8 Relative frequency of the degree of water repellency of soil samples taken at 10 depths in the irrigated untreated and treated plots after drying at increasing temperatures (n = 15).

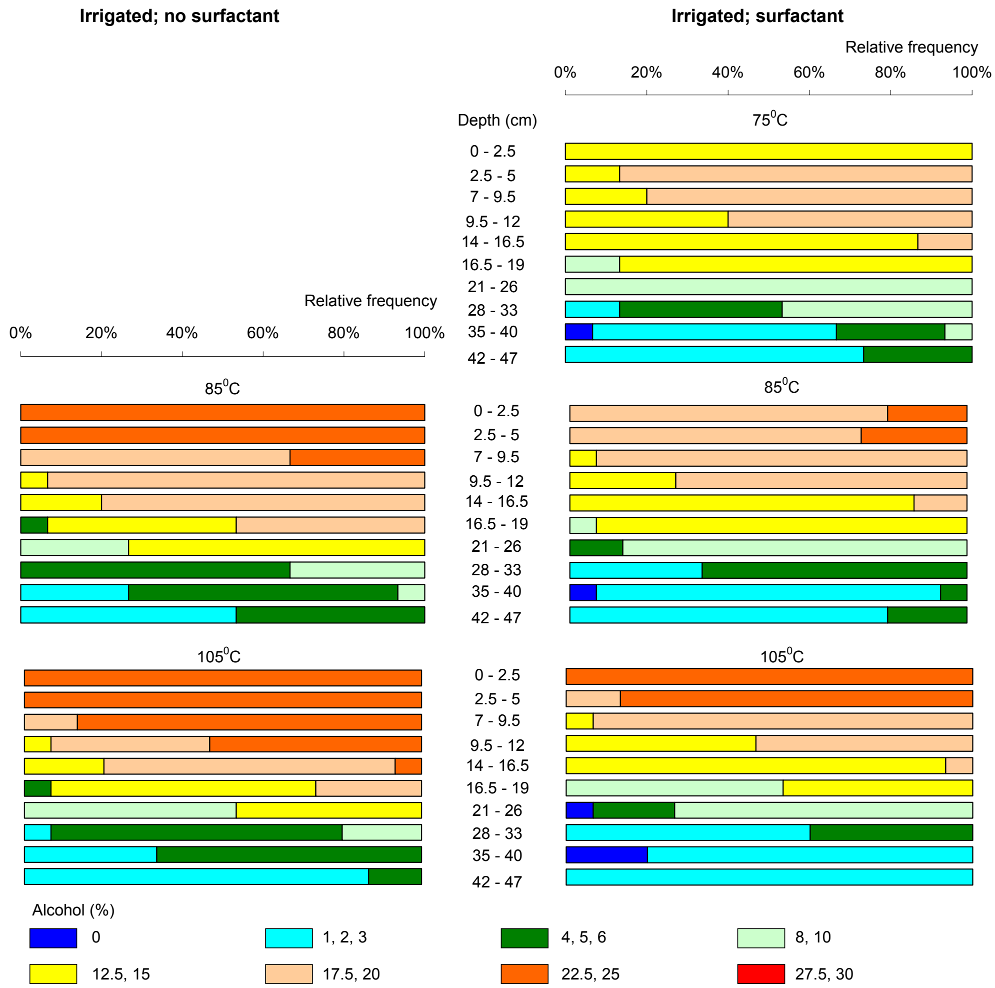

Figure 8 Continued.

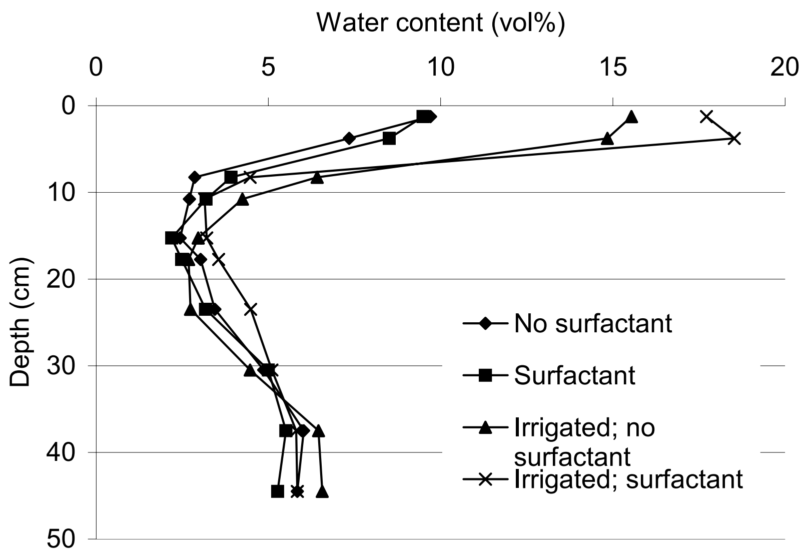

Figure 9 Mean water contents (n =15) in the soil profiles of the four transects to a depth of 47 cm on 21 and 27 July, 2000.

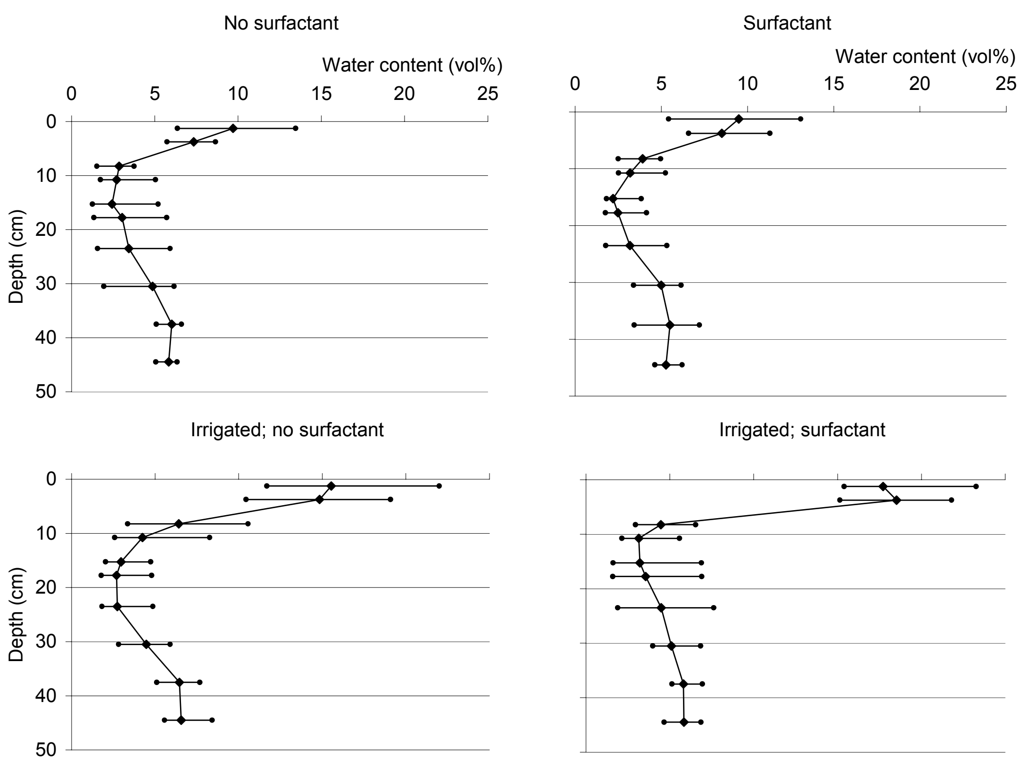

Figure 10 Minimum, mean, and maximum soil water contents (n = 15) to a depth of 47 cm in the four transects.

3.1.1.2. Effect of Drying Temperature on Potential Soil Water Repellency

The temperature during drying of the samples has an enormous influence on the potential soil water repellency, as is illustrated for the samples taken in the irrigated plot without and the irrigated plot with Primer®604 applications by the diagrams of Figure 7. All actually wettable samples at depths between 0 and 26 cm of both plots became water repellent after drying at 30^0C. A slight increase in repellency occurred after further drying of the samples at 65^0C. An enormous increase in persistence occurred after further drying of the samples at 85^0C. All samples of the surface layer (0-5 cm) became even extremely water repellent. Significantly less persistence of potential water repellency was found for samples in the plot with surfactant applications after drying at 30, 65, and 85^0C in comparison with the untreated plot. Drying at a temperature of 105^0C resulted in extreme water repellency for the samples from 0 to 19 cm in both plots.

To conclude, surfactant applications resulted in significantly less persistence of potential water repellency after drying the soil samples in the temperature range from 30 to 85^0C (Fig. 7). This means that regular surfactant applications will cause the soil to alter and become less water repellent.

Nearly all actually wettable samples of the irrigated plots taken between 0 and 26 cm depth became repellent after drying at 30^0C (Fig. 8). Remarkable is that on the other hand a decrease in degree of repellency occurred for the actually water repellent samples after drying at 30^0C. An increase in degree of repellency occurred in both plots after drying the samples at 65^0C. A further increase in degree was found after drying at 85^0C and 105^0C. Significantly lower values of the degree were detected for the samples from the Primer®604 treated plot at all (30, 65, 85, and 105^0C) drying temperatures, compared with those from the untreated plot.

We note that there always is a decrease with depth in degree of soil water repellency in the irrigated untreated plot after the several drying temperatures.

A comparison of Figures 7 and 8 shows that the persistence of potential water repellency, measured with the WDPT test after drying the samples at 30 and 65^0C, is the highest between 7 and 19 cm depth (Fig. 7), whereas the degree of potential water repellency in the untreated plot, measured with the alcohol percentage test, always is the highest in the surface layer (0-5 cm depth) and decreases with depth (Fig. 8).

3.1.1.3. Soil Water Contents in the Four Transects

The mean soil water content was slightly higher in the topsoil of the non-irrigated Primer®604 treated plot, compared with the untreated plot on 27 July, 2000 (Fig. 9). In particular the surface layer (0-5 cm depth) of the irrigated plots contained much more water than the one of the non-irrigated plots on 27 July, 2000. A significant higher content was detected in the plot with surfactant applications on its turn in comparison with the untreated plot (Fig. 9).

The variability in soil water was high in all four plots, especially in the surface layer of the irrigated plots, as is demonstrated by the minimum and maximum soil water contents in the diagrams of Figure 10.

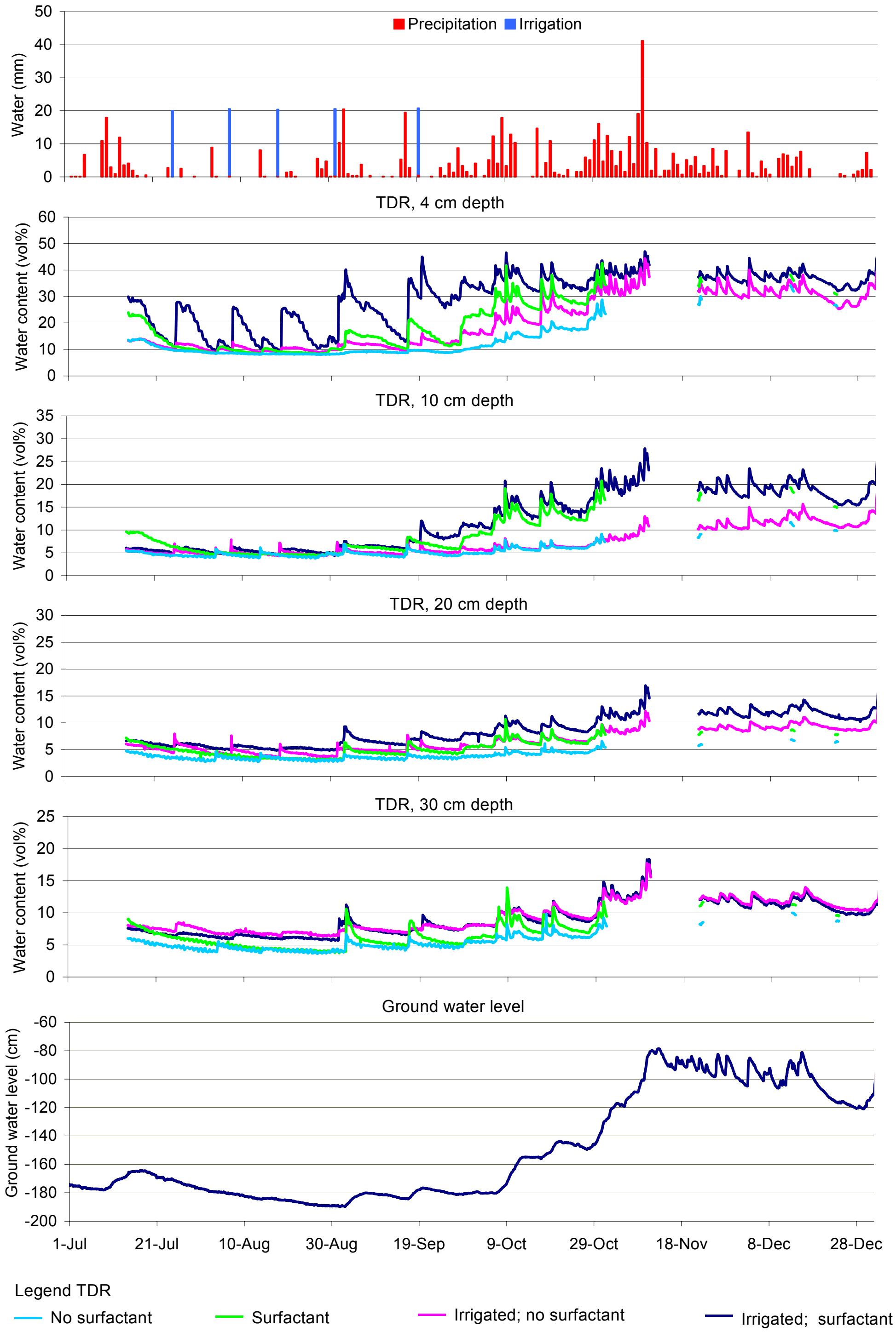

Figure 11 Mean soil water contents measured with the TDR probes at 4, 10, 20, and 30 cm depths in the four plots during the period July-December 2000. Also the amounts of precipitation and irrigation, and the course of the ground water level have been indicated.

3.1.2. TDR Measurements

The mean soil water contents measured with the TDR probes at 4, 10, 20, and 30 cm depth in the four plots during the period July-December, 2000 are shown in Figure 11. Due to irrigation during the period July-September large temporal differences in soil water content were detected at 4 cm depth in the irrigated plot with surfactant applications, and on the other hand, the irrigated plot without surfactant applications did hardly react on these irrigations. Only small effects of the few rain events during this period could be found for the other plots

It is remarkable that at 10 cm depth significantly higher mean soil water contents were found in the two plots with surfactant applications, in comparison with the two untreated plots during the period 19 September to 31 December, 2000 (Fig. 11), when rain events became more regular.

Soil water contents of the individual probes during the period 15 July to 31 August, 2000 are shown in Figures 12 and 13. Remarkable are the water content measurements in the untreated plot at 4 cm depth, with hardly any influence of the rain showers, whereas the probes in the surfactant treated plot slightly react (Fig. 12). One of the probes in the untreated plot at 10 cm depth (blue line in the diagram) evidently reacts on the rain showers and is supposed to present the location of a preferred pathway.

It is noteworthy that several probes at 4 cm depth in the irrigated plot with surfactant applications reacted immediately after the irrigation with an enormous increase in soil water content, whereas there was hardly any influence at 20 and 30 cm depth (Fig. 13).

A preferential flow path was obviously detected by probes above each other in the irrigated not treated plot at 4, 10, and 20 cm depth (Fig. 13).

The spatial and temporal variations in soil water content during the rainy period from 1 September to 31 October are depicted in the diagrams of Figures 14 and 15. It is obvious that several probes reacted on the rain showers, but at different depths in the four plots some probes showed continiously more or less the same low soil water contents, indicating dry pockets not influenced by precipitation and irrigations.

Contour plots of the soil moisture content in the four plots on 8 October, 2000 are shown in Figure 16. Surfactant applications resulted in a wetter surface layer in the non-irrigated plot, in comparison with the plot without Primer®604 applications. The surfactant treated plot and the irrigated plot show fingerlike wetting patterns with partly soil water contents above 18 vol%, whereas at the same depths dry soil areas occur with soil water contents of less than 3 vol%.

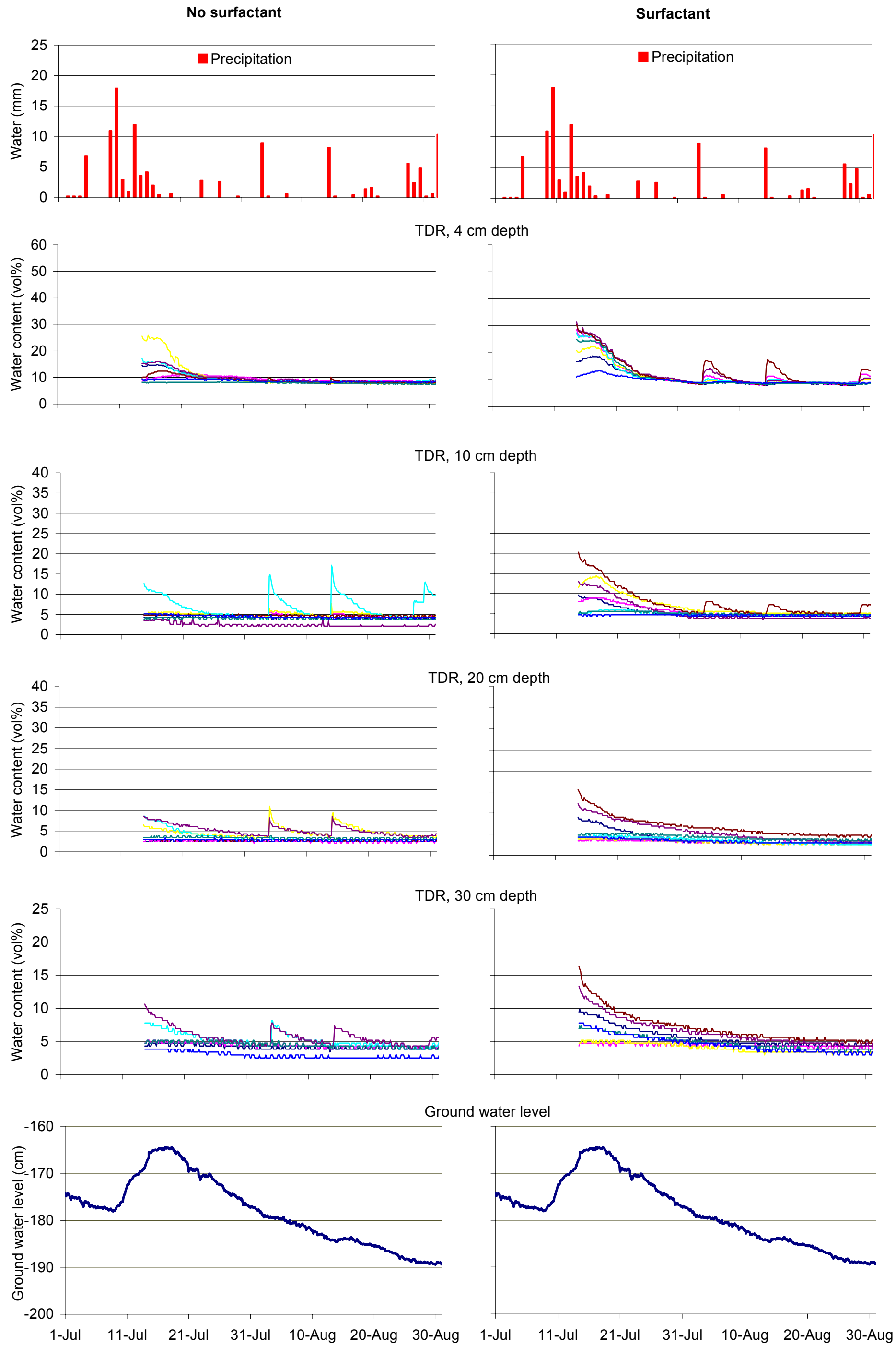

Figure 12 Soil water contents measured by the individual probes in the plot without and the plot with surfactant applications during the period 15 July to 31 August, 2000. Same colours at the four depths have been used for measurements with probes above each other. Also the amounts of precipitation, and the course of the ground water level have been indicated.

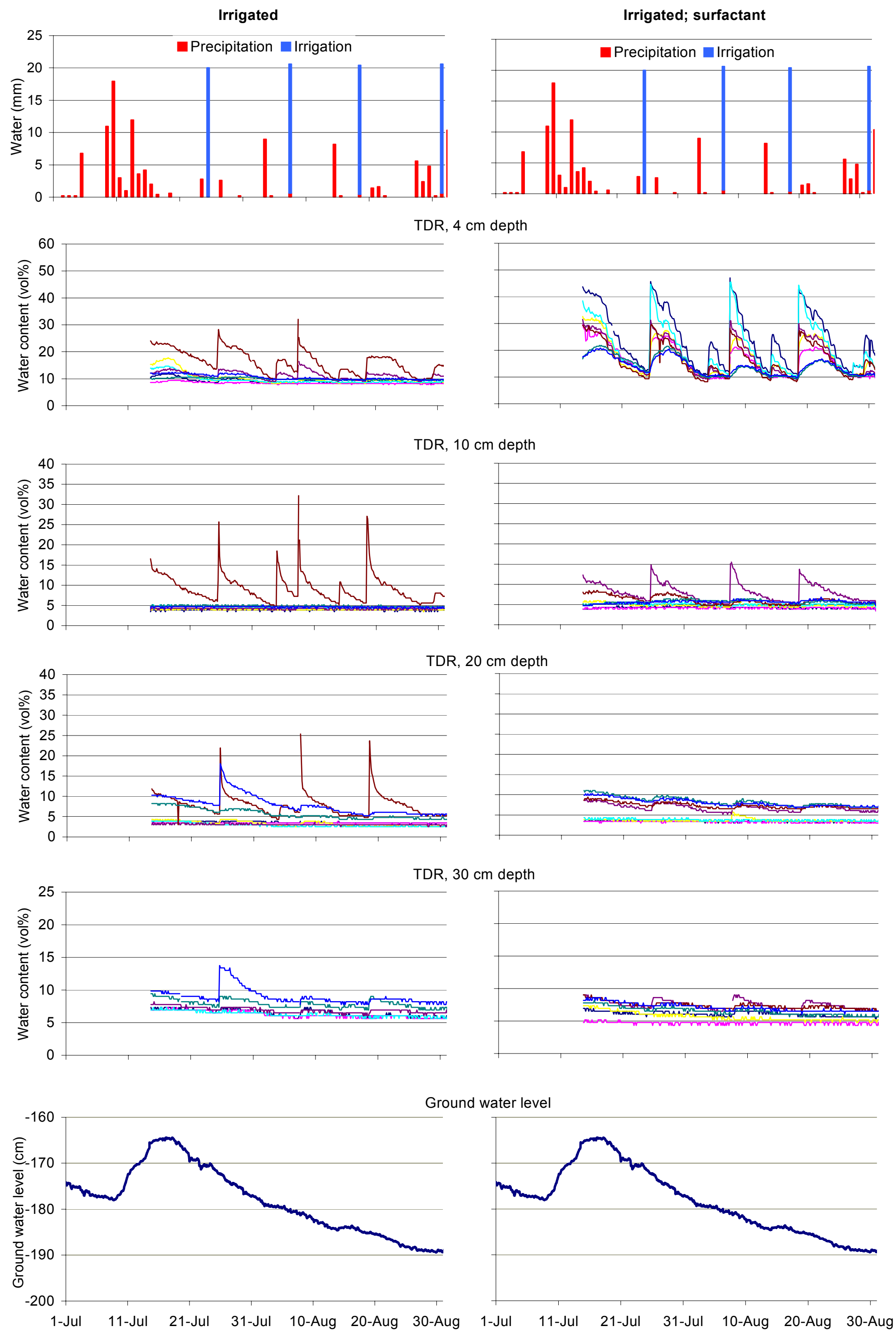

Figure 13 Soil water contents measured by the individual probes in the irrigated plot without and the irrigated plot with surfactant applications during the period 15 July to 31 August, 2000. Same colours have been used for probes above each other. Dates and amounts of precipitation and irrigation, and the course of the ground water level have been indicated too.

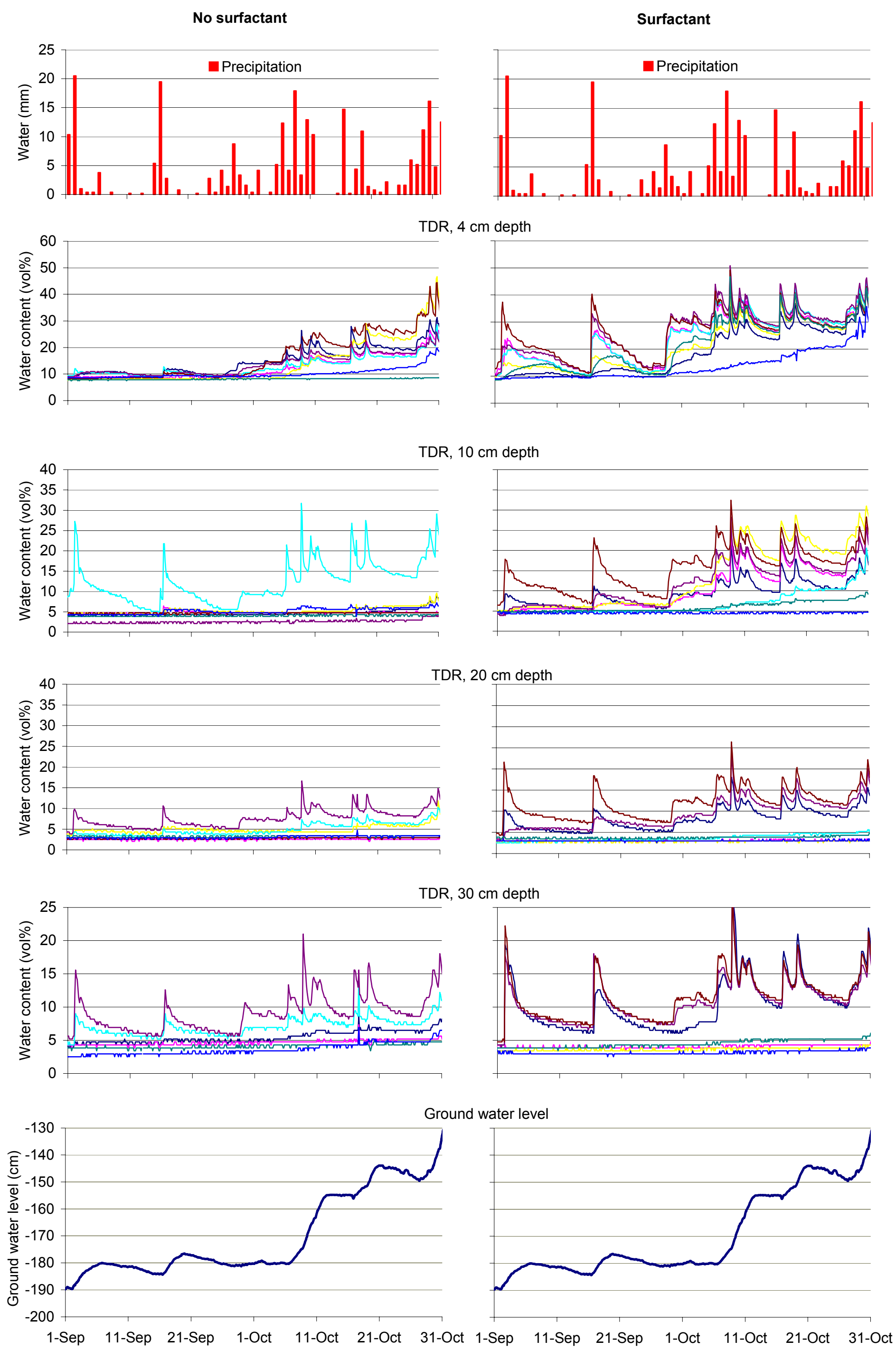

Figure 14 Soil water contents measured by the individual probes in the plot without and the plot with surfactant applications during the period 1 September to 31 October, 2000. Same colours at the four depths have been used for measurements with probes above each other. Also the amounts of precipitation, and the course of the ground water level have been indicated.

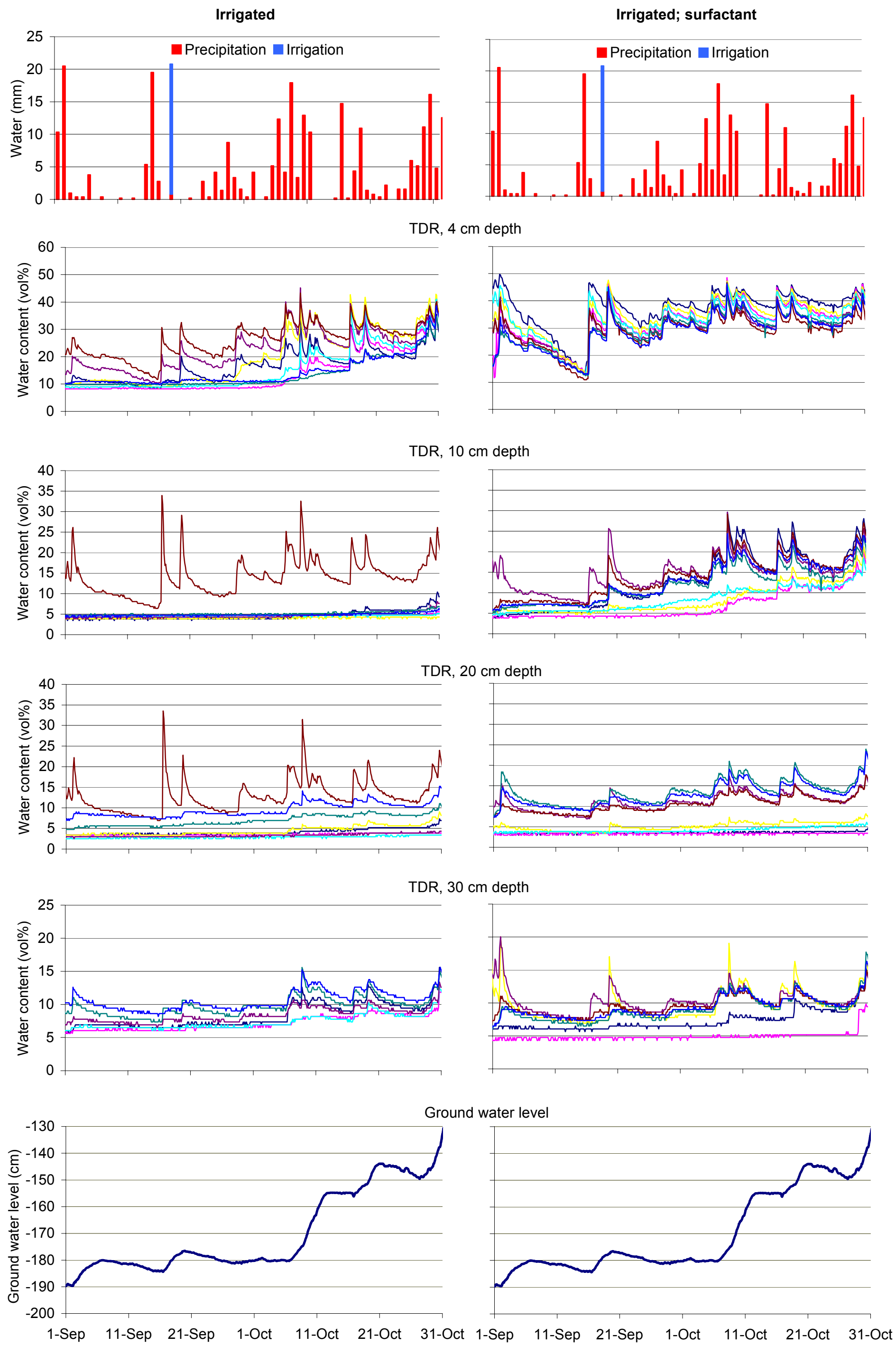

Figure 15 Soil water contents measured by the individual probes in the irrigated plot without and the irrigated plot with surfactant applications during the period 1 September to 31 October, 2000. Same colours have been used for probes above each other. Dates and amounts of precipitation and irrigation, and the course of the ground water level have been indicated too.

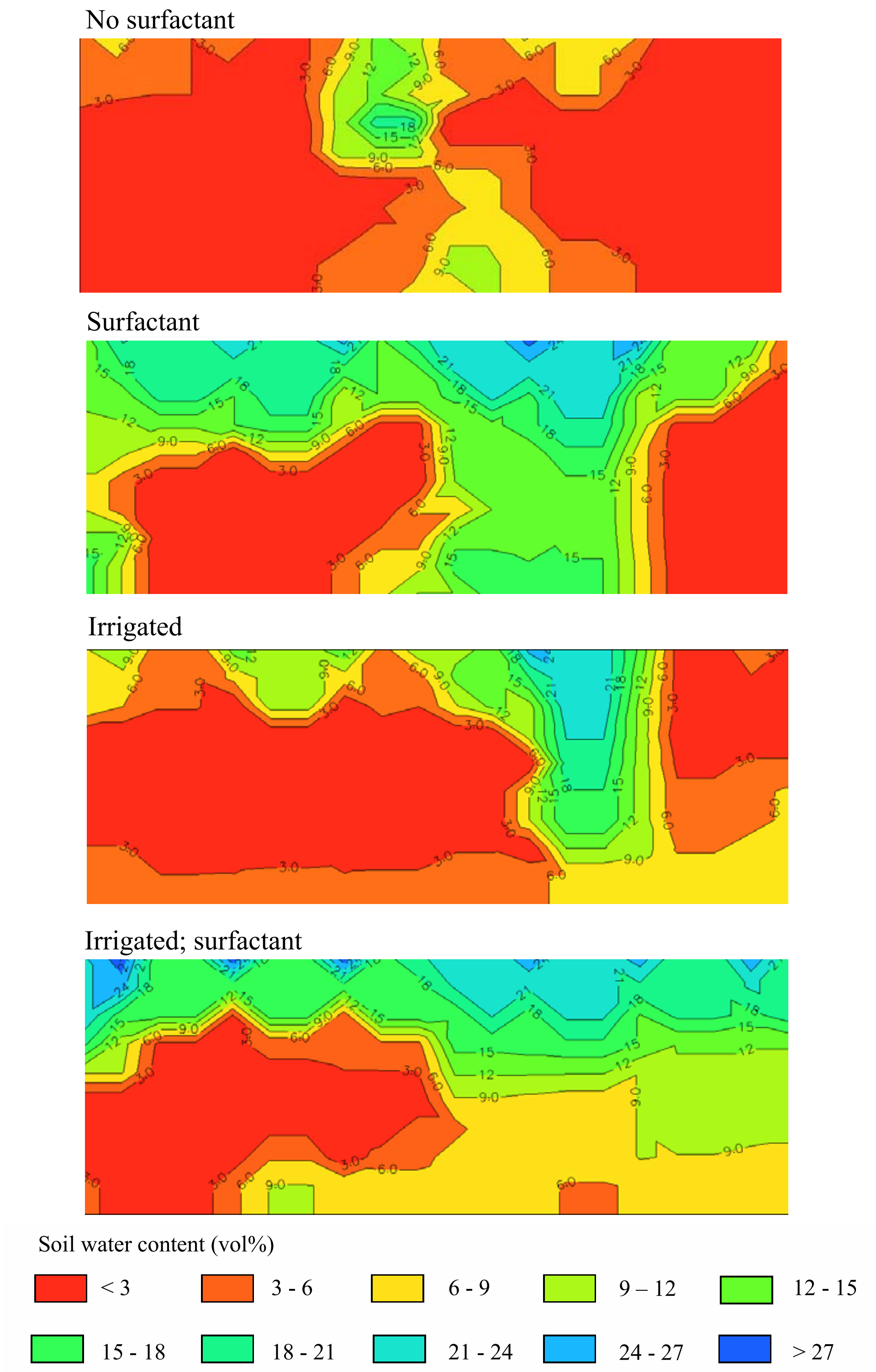

Figure 16 Contours of the soil water content in the four plots (width 80 cm; depth 30 cm) on 8 October, 2000.

3.2. Year 2001

3.2.1. Transect Sampling

3.2.1. Actual Soil Water Repellency on 28 September

All samples taken in the irrigated plots between 0 and 19 cm depth were wettable on 28 September, 2001 (Fig. 17). Also the surface layer of the non-irrigated plots was wettable at that time, however between 7 and 19 cm depth a part of the soil was extremely water repellent with WDPT values often exceeding six hours (Fig. 17).

3.2.1.2. Potential Water Repellency After Drying at 30^{0}C

The persistence of potential water repellency of the soil samples from the four plots, measured after drying at 30^{0}C, shows large differences between the four plots (Fig. 18). In the surface layer (0-5 cm depth) significantly lower WDPT values were measured in the surfactant treated plots, compared with the untreated plots. Between 7 and 19 cm depth significantly less repellency was measured in the irrigated plots, in comparison with the non-irrigated plots.

To conclude: surfactant applications lowered significantly the potential soil water repellency in the surface layer, and a combination with irrigation lowered the potential water repellency also significantly at depths of 7-19 cm.

The degree of potential water repellency measured with the alcohol percentage test was at all six depths the highest in the non-irrigated untreated plot and the lowest in the irrigated plot with surfactant applications (Fig. 19). Irrigation alone, lowered also significantly the degree of potential water repellency, as is shown for the untreated plots in Figure 19. However, also surfactant treatments alone, lowered the degree of repellency, as is shown for the non-irigated plots in Figure 19.

3.2.1.3. Soil Water Contens in the Four Transects

The mean water contents in the soil profiles of the four plots on 28 September, 2001 are depicted in the diagram of Figure 20. The mean contents in the two irrigated plots were at all six depths higher than in the non-irrigated plots. The mean soil water contents of the surfactant treated plot were at all depths higher in comparison with the untreated plot. Large differences in soil water content were found throughout the soil profiles of the non-irrigated plots (Fig. 21).

3.2.2. TDR Measurements

The mean soil water contents measured by the TDR probes at 4, 10, 20, and 30 cm depth in the four plots between 1 January and 30 June, 2001 are shown in Figure 22. The irrigations in May and June resulted in higher soil water contents at 4 and 10 cm depth, with the highest water contents in the surfactant treated plot. It is remarkable that the mean soil water contents in the non-irrigated plots at 20 and 30 cm depth were lower than in the irrigated plots during the whole period from 1 January to 30 June, thus also during January to April, the period without irrigations.

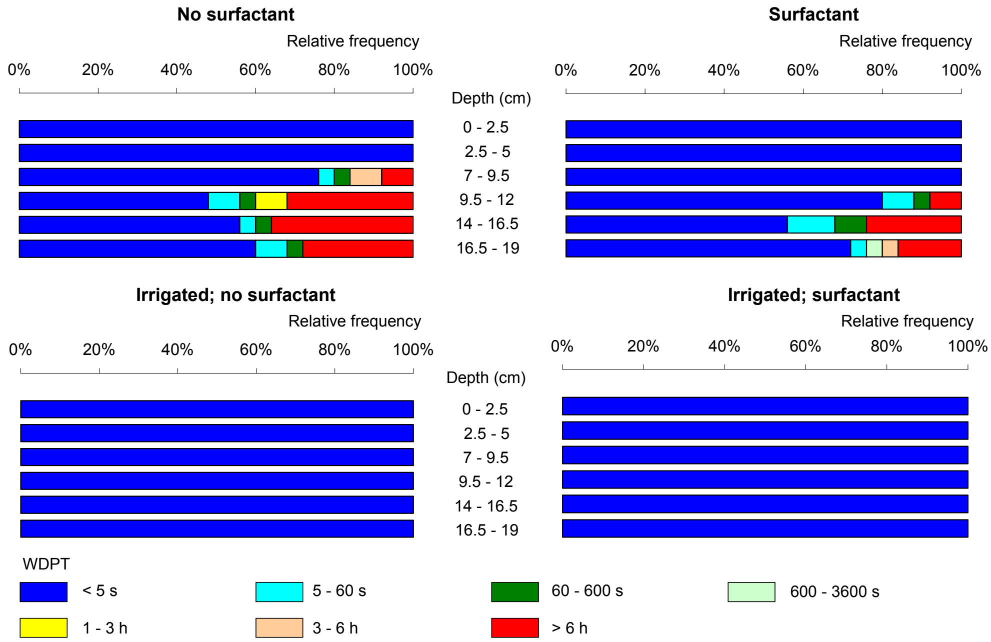

Figure 17 Relative frequency of the persistence of actual water repellency of field-moist samples taken at 6 depths in the non-irrigated and irrigated untreated and treated plots on 28 September 2001 (n = 25).

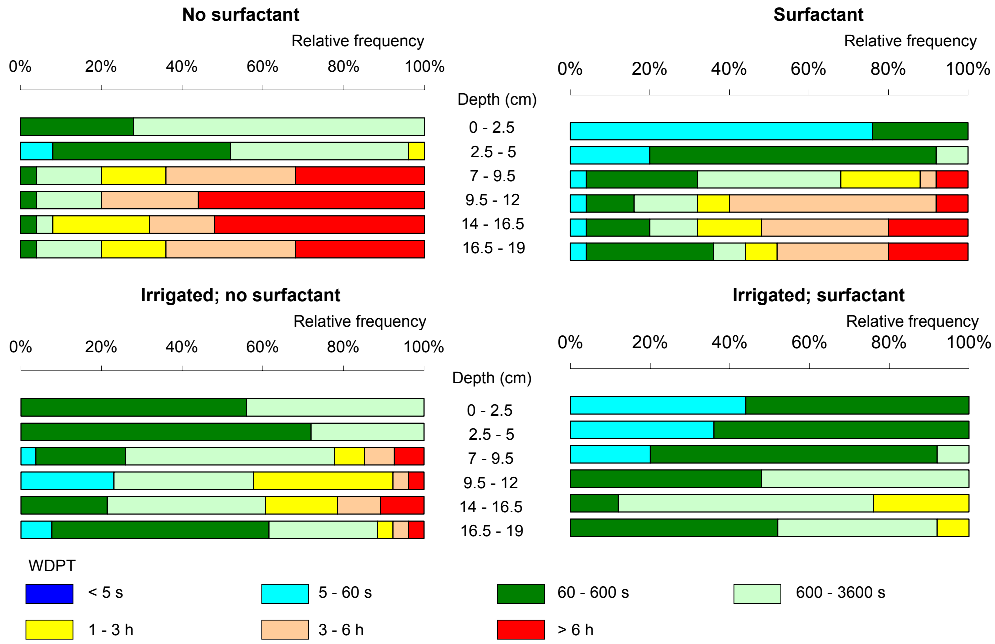

Figure 18 Relative frequency of the persistence of water repellency of soil samples taken at six depths in the non-irrigated and irrigated untreated and treated plots after drying at 30^{0}C.

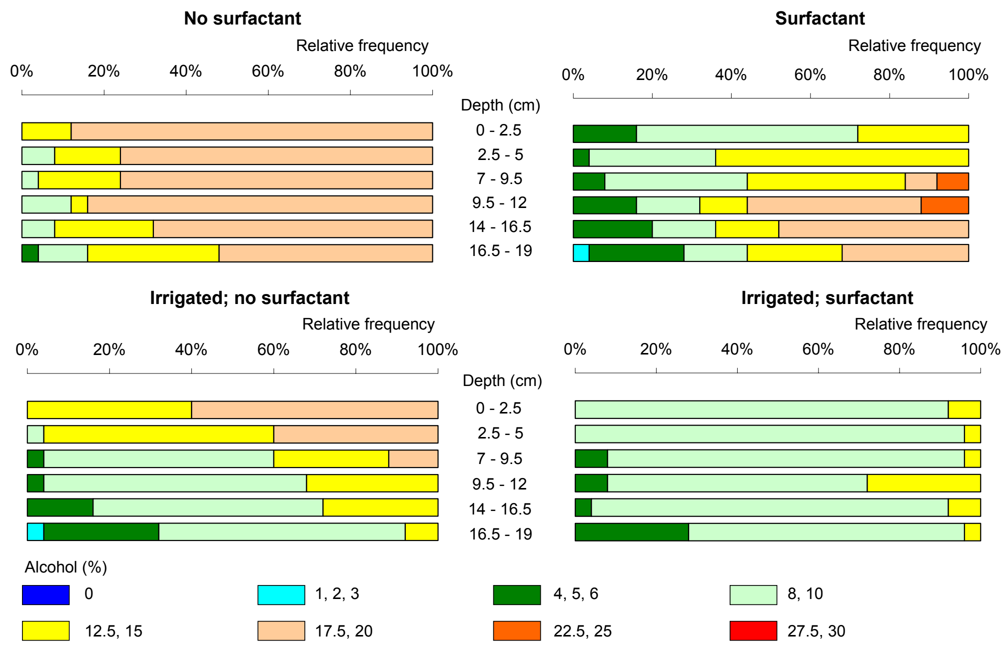

Figure 19 Relative frequency of the degree of water repellency of soil samples taken at six depths in the non-irrigated and irrigated untreated and treated plots after drying at 30^{0}C.

These differences have already been initiated as a result of irrigations in 2000 (see Fig. 11).

The mean soil water contents at 4, 10, 20, and 30 cm depth were also higher in the irrigated plots than in the non-irrigated plots between 1 July and 16 November, 2001 (Fig. 23). It is noteworthy that the mean soil water contents at 4 and 10 cm depth in the non-irrigated plot with surfactant applications were often significantly higher, in comparison with the untreated plot (Fig. 23).

The spatial and temporal variations in soil water content, due to the rain events at four depths in the four plots in March and April, 2001 are illustrated in Figures 24 and 25.

The soil water content measurements of the individual probes between 1 May and 30 June, 2001 in the non-irrigated and irrigated plots are depicted in Figure 26 and Figure 27, respectively. The rain events in May and June had more effect in wetting of the soil at 4 and 10 cm depth in the plot with surfactant applications, compared with the untreated plot (Fig. 26). On the other hand, only two probes gave a slight reaction on the rain events at 20 and 30 cm depth in the untreated plot, and there were no reactions in the treated plot at all.

Remarkable are the temporal variations in water content, due to irrigation and rain events at 4 cm depth in the irrigated plots between 1 May and 30 June, 2001 (Fig. 27). Spatial variations in soil water content were high at 4, 10, and 20 cm depth in both plots, as illustrated by the different probes (Fig. 27). This is an indication for preferential flowpaths.

Figure 28 shows soil water contents in the non-irrigated plots between 1 July and 31 August, 2001. The influence of rain events is evident by the reactions of some probes at several depths in the two plots. The rain events caused significantly higher soil water contents at depths of 4 and 10 cm in the Primer®604 treated plot, compared with the untreated plot (Fig. 28). It is noteworthy that in the untreated plot at 10 cm depth by all probes no changes in water content were detected during the months July and August, 2001 (Fig. 28).

Figure 29 shows the influence of rain events and irrigations on the spatial and temporal soil water contents at four depths in the two irrigated plots between 1 July and 31 August, 2001. Some probes at 10 and 20 cm depth in both plots indicate that some dry areas in the soil remain. In the irrigated plot without surfactant, these probes show a regular increase in water content after 16 August. The concerning probes in the irrigated plot with surfactant reacted earlier (half of July).

The spatial and temporal variations in soil water content in the non-irrigated two plots between 1 September and 31 October, 2001 are shown in Figure 30. It is evident from the diagrams that some probes detected no changes in soil water content, thus soil areas remained dry, although the several rain events. It is also noteworthy that soil moisture increased more at 4 and 10 cm depth in the Primer®604 treated plot, in comparison with the untreated plot.

Spatial and temporal variations in soil water content were high at 4 cm depth in the irrigated plots between 1 September and 31 October, 2001 (Fig. 31). However, spatial variations in soil water content were low at 10, 20, and 30 cm depth in both plots. This indicates that the profile at each depth was more or less uniformly wetted.

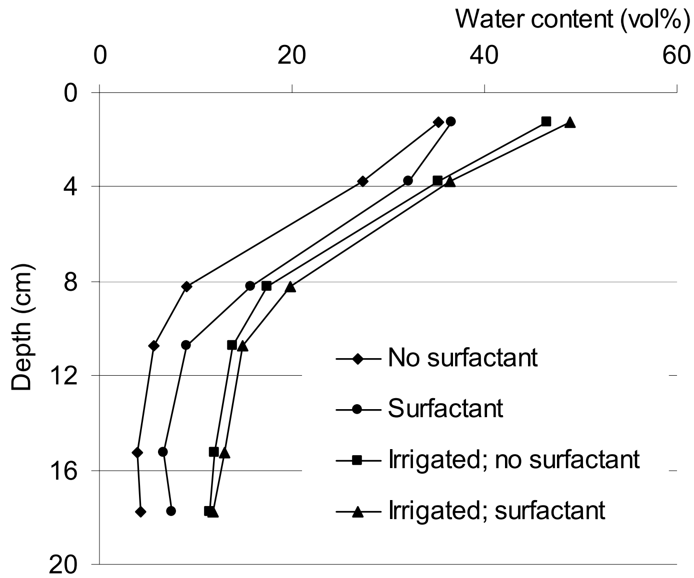

Figure 20 Mean water contents (n = 25) in the soil profiles of the four transects to a depth of 19 cm on 28 September.

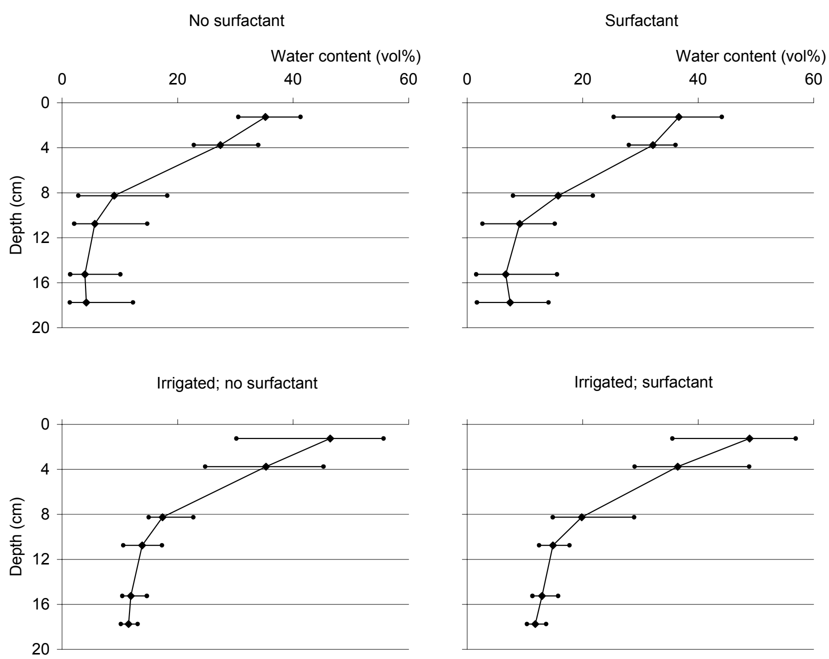

Figure 21 Minimum, mean, and maximum soil water contents (n = 25) to a depth of 19 cm in the four transects.

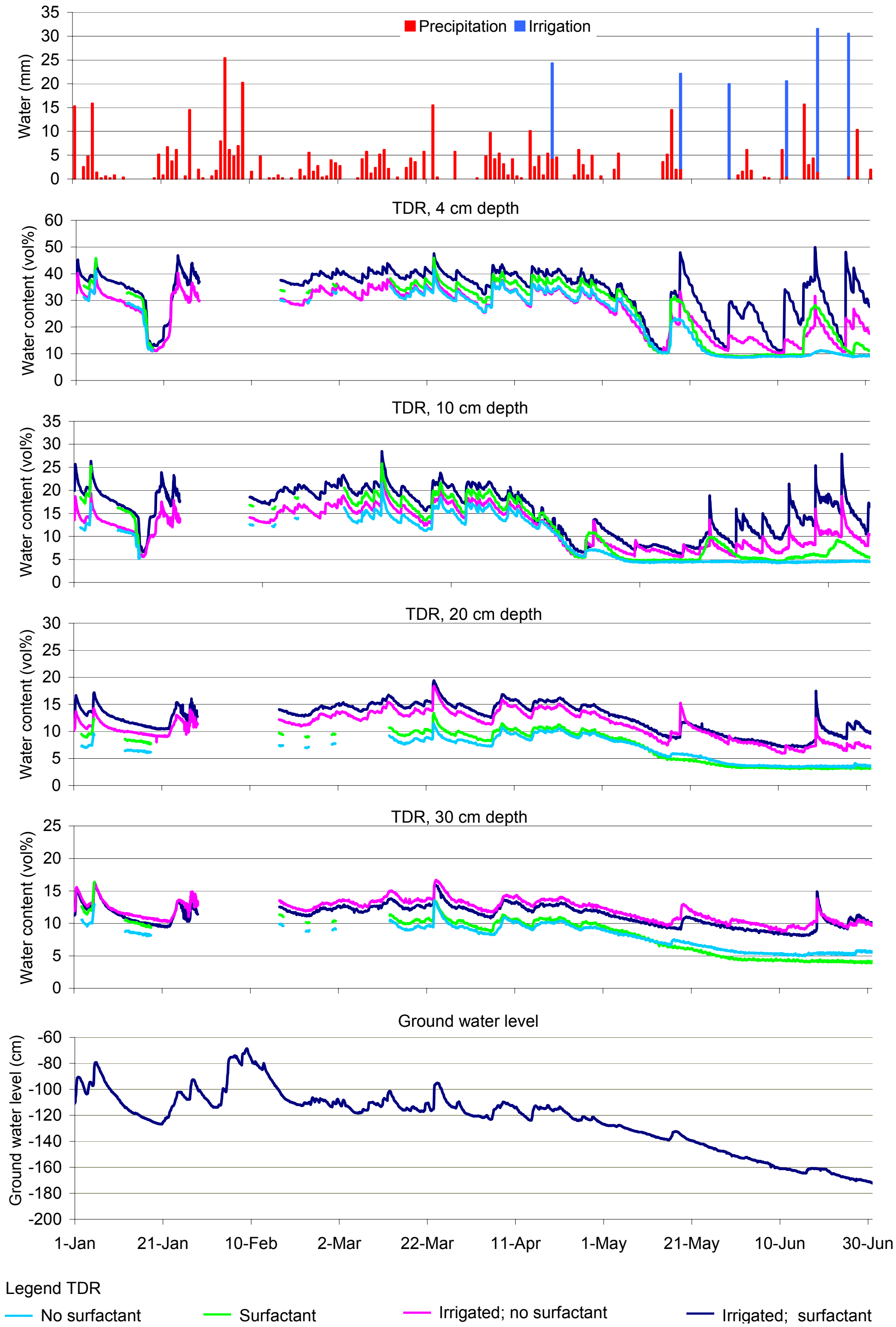

Figure 22 Mean soil water contents measured with the TDR probes at 4, 10, 20, and 30 cm depths in the four plots during the period 1 January to 30 June 2001. Also the amounts of precipitation and irrigation, and the course of the ground water level have been indicated.

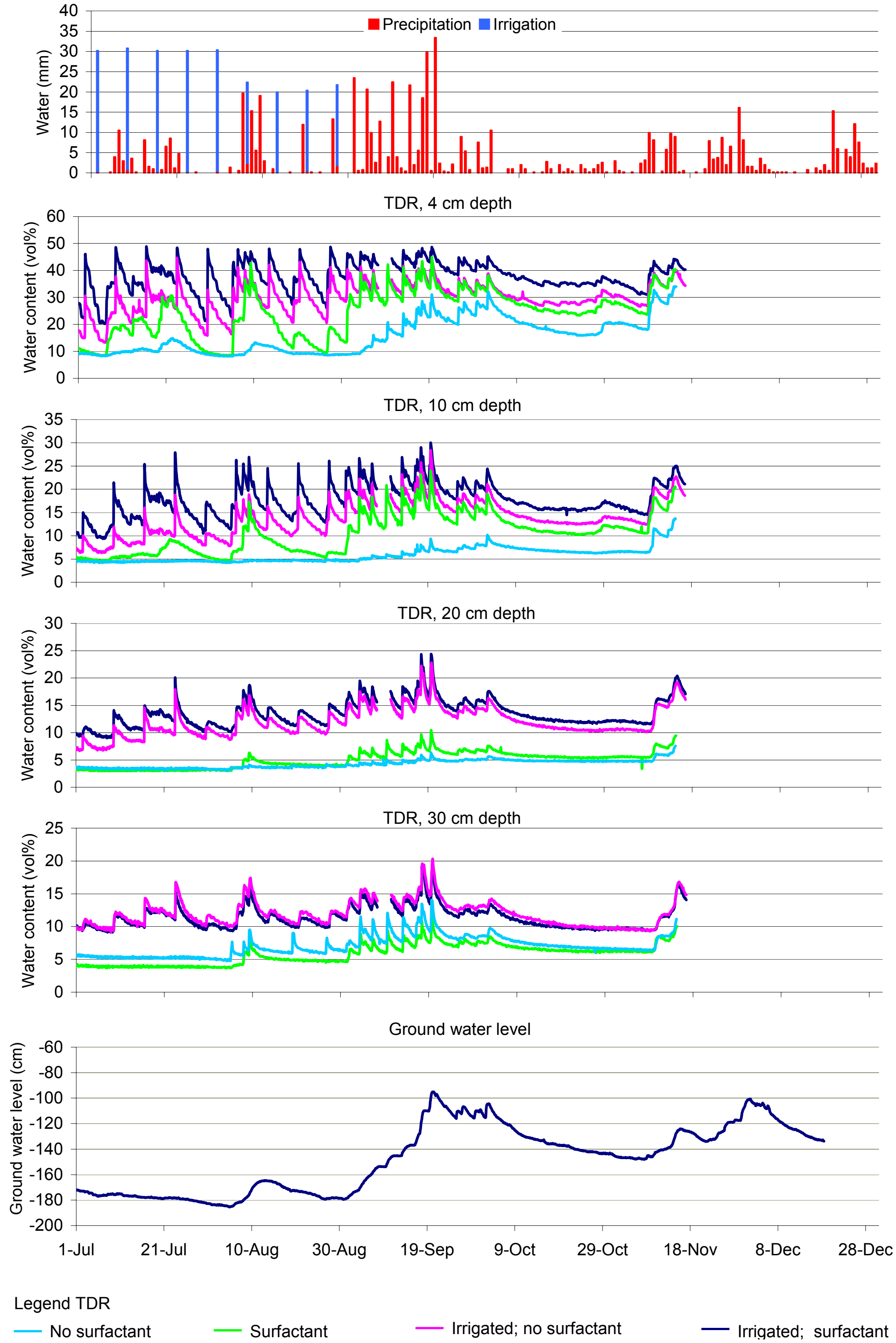

Figure 23 Mean soil water contents measured with the TDR probes at 4, 10, 20, and 30 cm depths in the four plots during the period July to December 2001. Also the amounts of precipitation and irrigation, and the course of the ground water level have been indicated.

Figure 32 shows the soil water contents in the non-irrigated plots at 4, 10, and 20 cm depth, in relation with the transition zone of the critical soil water content, above which the soil is wettable and below which the soil is water repellent. The grey zones, which are different for the untreated and surfactant treated plots, may consist of wettable as well as of water repellent soil. According to measurements described by Dekker et al. (2000b) ranges the transition zone in the untreated plots at 4 cm depth between 13.7 and 19.2vol%, at 10 cm depth between 3.1 and 6.3vol%, and at 20 cm between 2 and 4.8vol%. In the Primer®640 treated plots ranges the transition zone between 7.7 and 19.5vol% at 4 cm depth, between 2.9 and 7.5vol% at 10 cm depth, and between 2.4 and 5.9vol% at 20 cm depth (Dekker et al., 2000b).

Below the grey zone the soil is always water repellent, which was for instance the case at 4 cm depth in the untreated plot in the second half of May and in the first half of June, 2001, whereas during the same period soil water contents in the surfactant treated plot were found in the grey zone (Fig. 32).

Figure 33 shows that in the same period in the irrigated, untreated plot at 10 cm depth nearly all, and at 20 cm depth all probes detected soil water contents above the transition zone, thus indicating wettable soil. However, at 4 cm depth most probes measured regularly soil water contents, corresponding with values of the transition zone , or even below this zone. In the irrigated plot with surfactant treatments, soil water contents regularly decreased to values of the transition zone, but never came below it (Fig. 33).

Figure 34 shows that in the non-irrigated, untreated plot the soil water contents at 4 cm depth during the period 1 July to 31 August, 2001 were nearly always below the transition zone, thus indicating actual soil water repellency. At 10 and 20 cm depth nearly all water contents were detected in the transition zone. On the other hand, at 4 cm depth in the Primer®604 treated plot were soil water contents found above and corresponding with values of the transition zone during this period. Remarkable is that at 10 and 20 cm depth soil water contents were found above or corresponding with the soil water content of the transition zones.

Figure 35 shows that in the irrigated plot with surfactant applications at 4, 10, and 20 cm depth the soil water contents, measured by the TDR probes during the period 1 July to 31 August, 2001, were nearly always above the transition zone, thus indicating wettable soil. This was also the case at 20 cm depth during this period and after 10 August at 10 cm depth in the untreated, irrigated plot. However, some probes at 4 cm depth in this plot regularly detected soil water contents corresponding with values of the transition zone and occasionally below it (Fig. 35).

Figures 36 and Figure 37 show the temporal wetting of the irrigated plots, measured just before the weekly irrigations with 30 mm and later 20 mm water during the period 18 June to 3 September, 2001. It is noteworthy that a larger part of the soil profile became wetter and the dry pockets disappeared earlier in the surfactant treated plot, in comparison with the untreated plot (Figs. 36 and 37). The treated plot is more or less homogeneous wet after 23 July, whereas the untreated plot becomes homogeneous wet after 20 August.

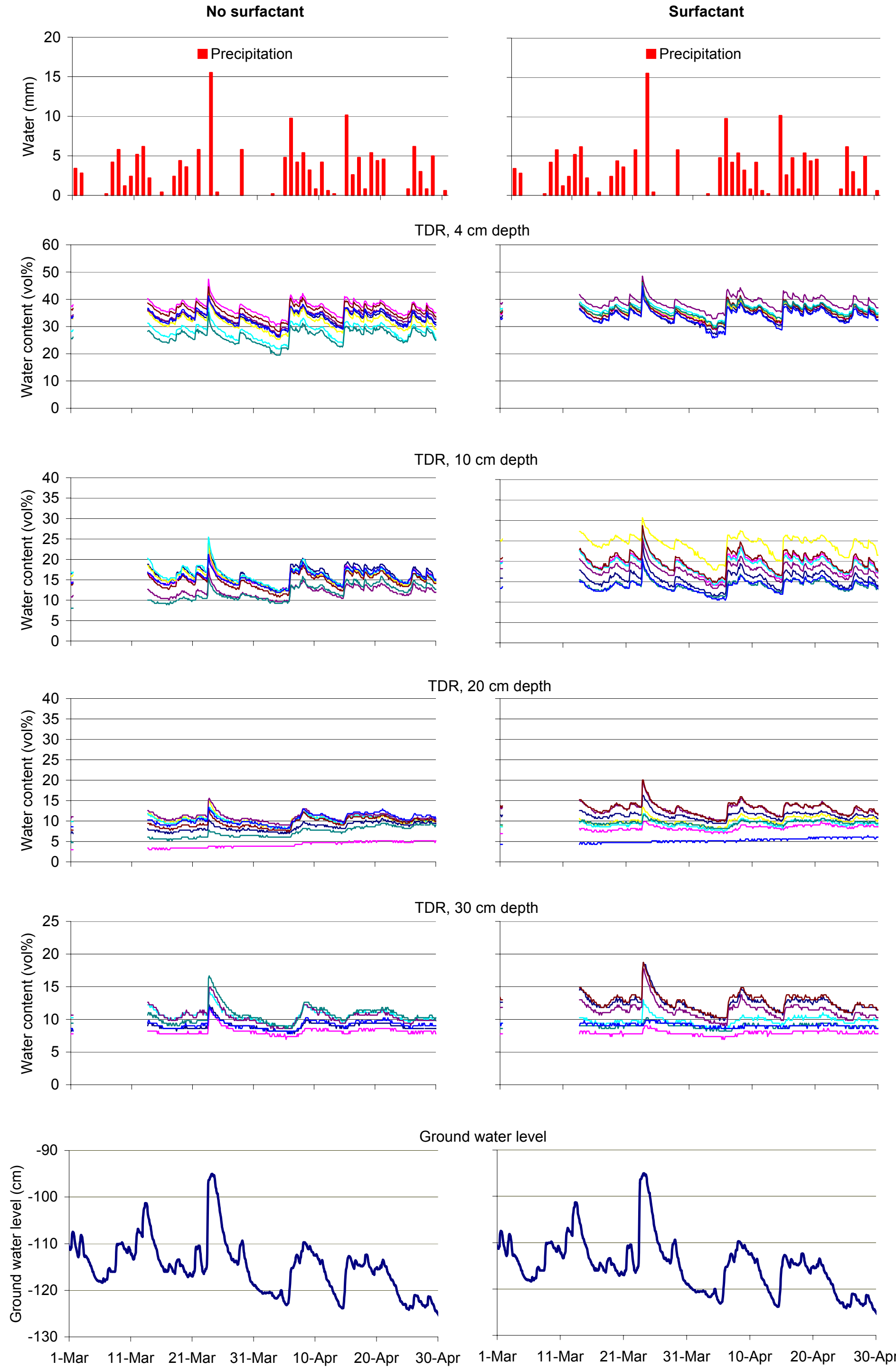

Figure 24 Soil water contents measured by the individual probes in the plot without and the plot with surfactant applications during the period 1 March to 30 April, 2001. Same colours at the four depths have been used for measurements with probes above each other. Dates and amounts of precipitation, and the course of the ground water level have been indicated too.

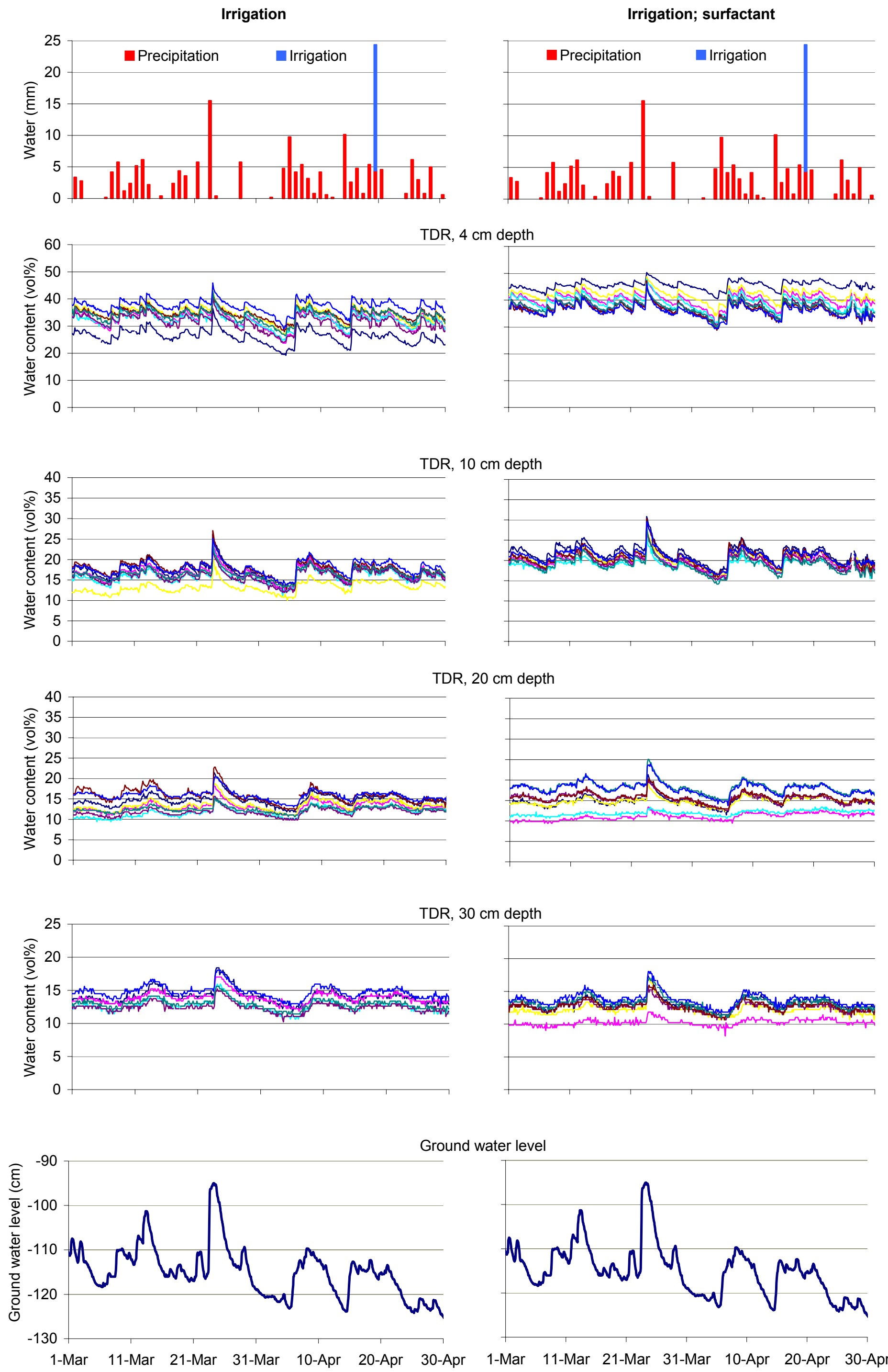

Figure 25 Soil water contents measured by the individual probes in the irrigated plot without and the irrigated plot with surfactant applications during the period 1 March to 30 April, 2001. Same colours have been used for probes above each other. Dates and amounts of precipitation and irrigation, and the course of the ground water level have been indicated too.

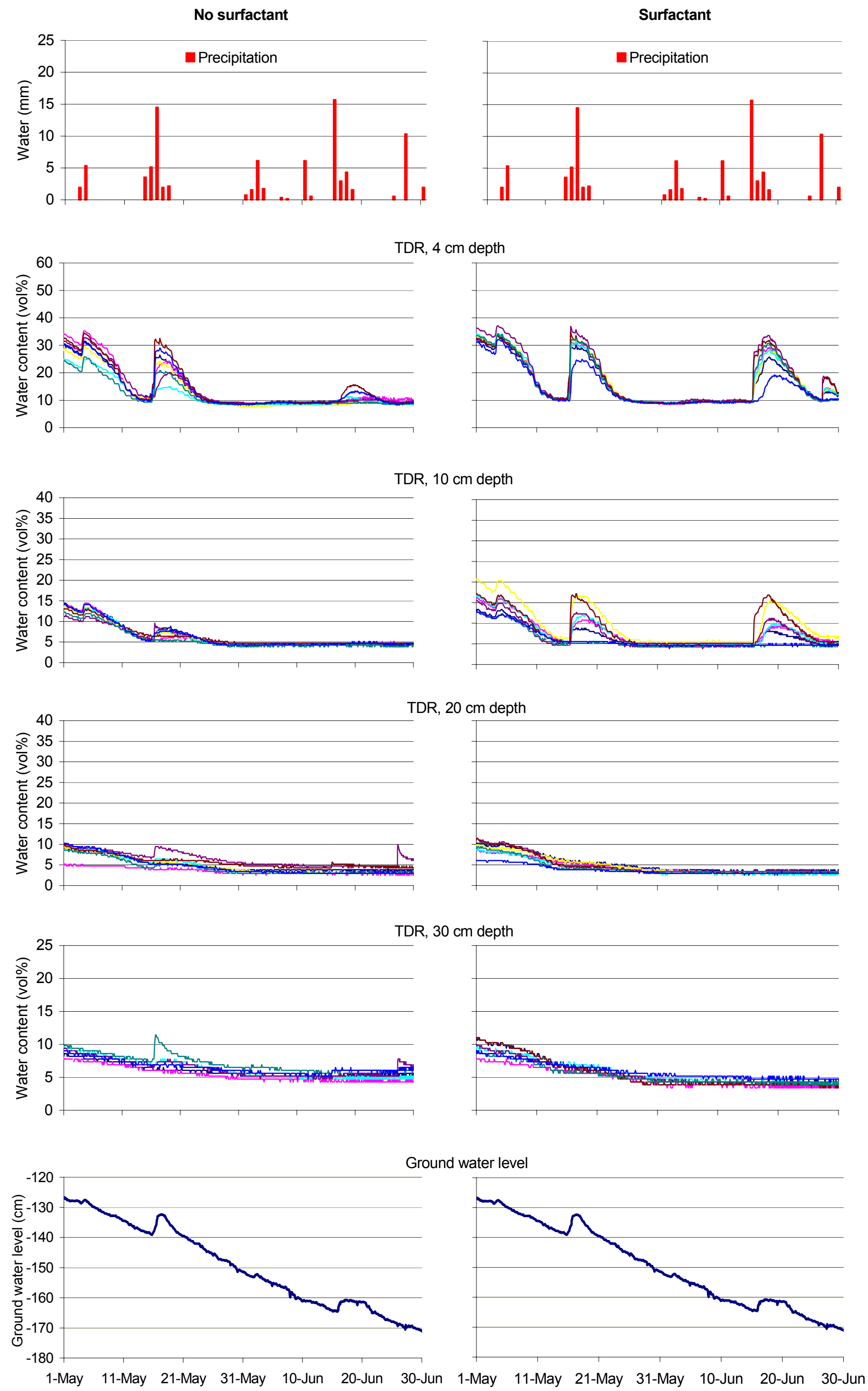

Figure 26 Soil water contents measured by the individual probes in the plot without and the plot with surfactant applications during the period 1 May to 30 June, 2001. Same colours at the four depths have been used for measurements with probes above each other. Dates and amounts of precipitation, and the course of the ground water level have been indicated too.

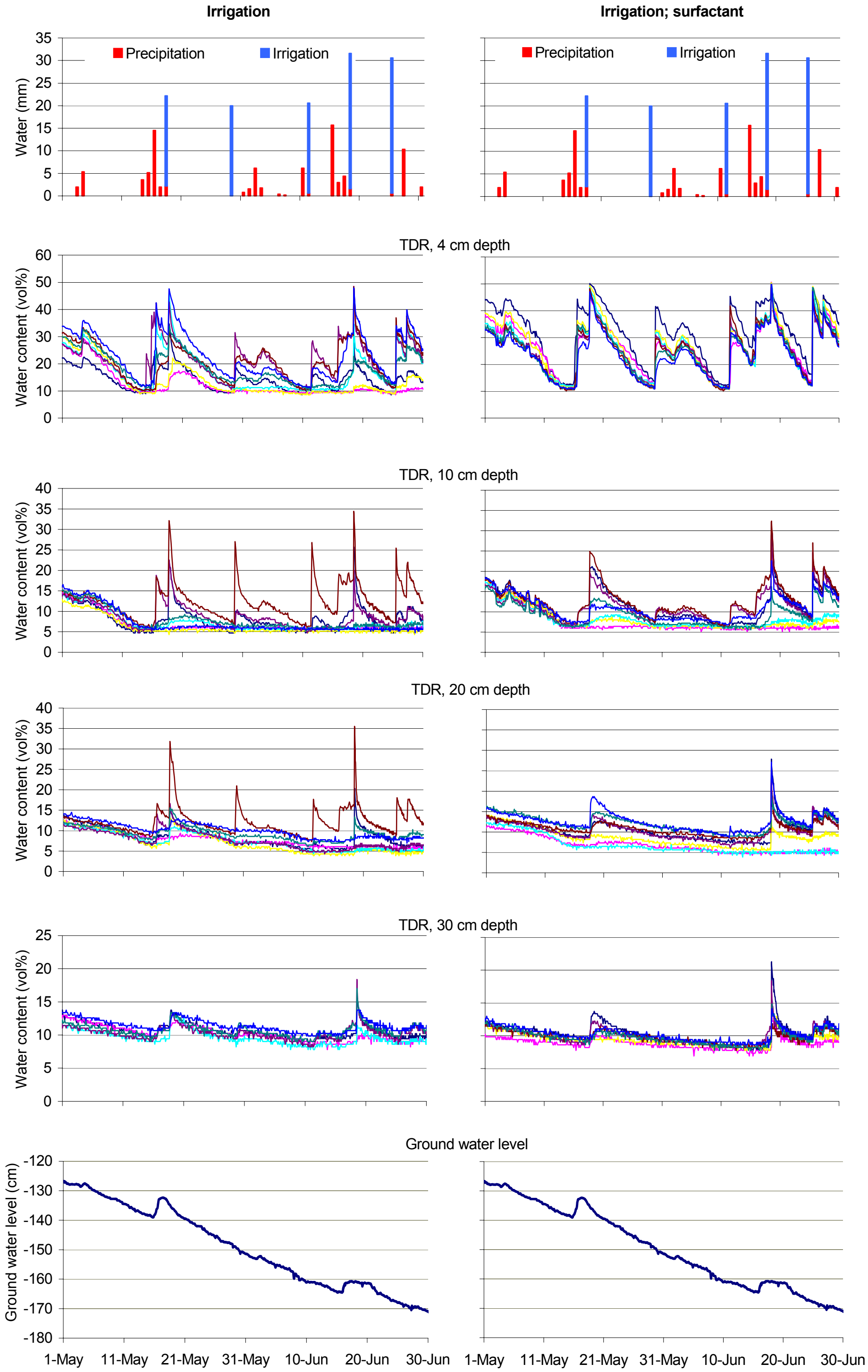

Figure 27 Soil water contents measured by the individual probes in the irrigated plot without and the irrigated plot with surfactant applications during the period 1 May to 30 June, 2001. Same colours have been used for probes above each other. Dates and amounts of precipitation and irrigation, and the course of the ground water level have been indicated too.

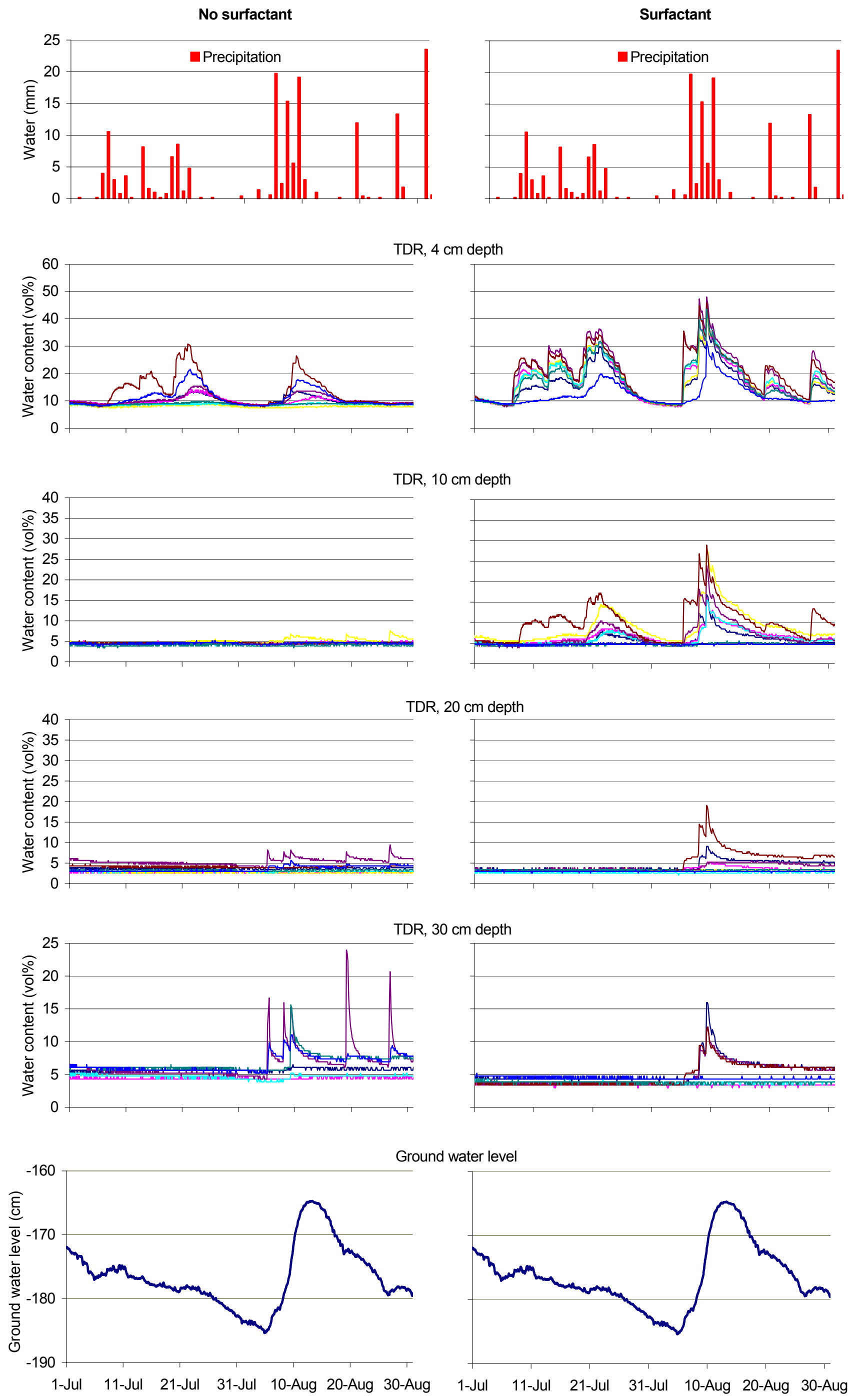

Figure 28 Soil water contents measured by the individual probes in the plot without and the plot with surfactant applications during the period 1 July to 31 August, 2001. Same colours at the four depths have been used for measurements with probes above each other. Dates and amounts of precipitation, and the course of the ground water level have been indicated too.

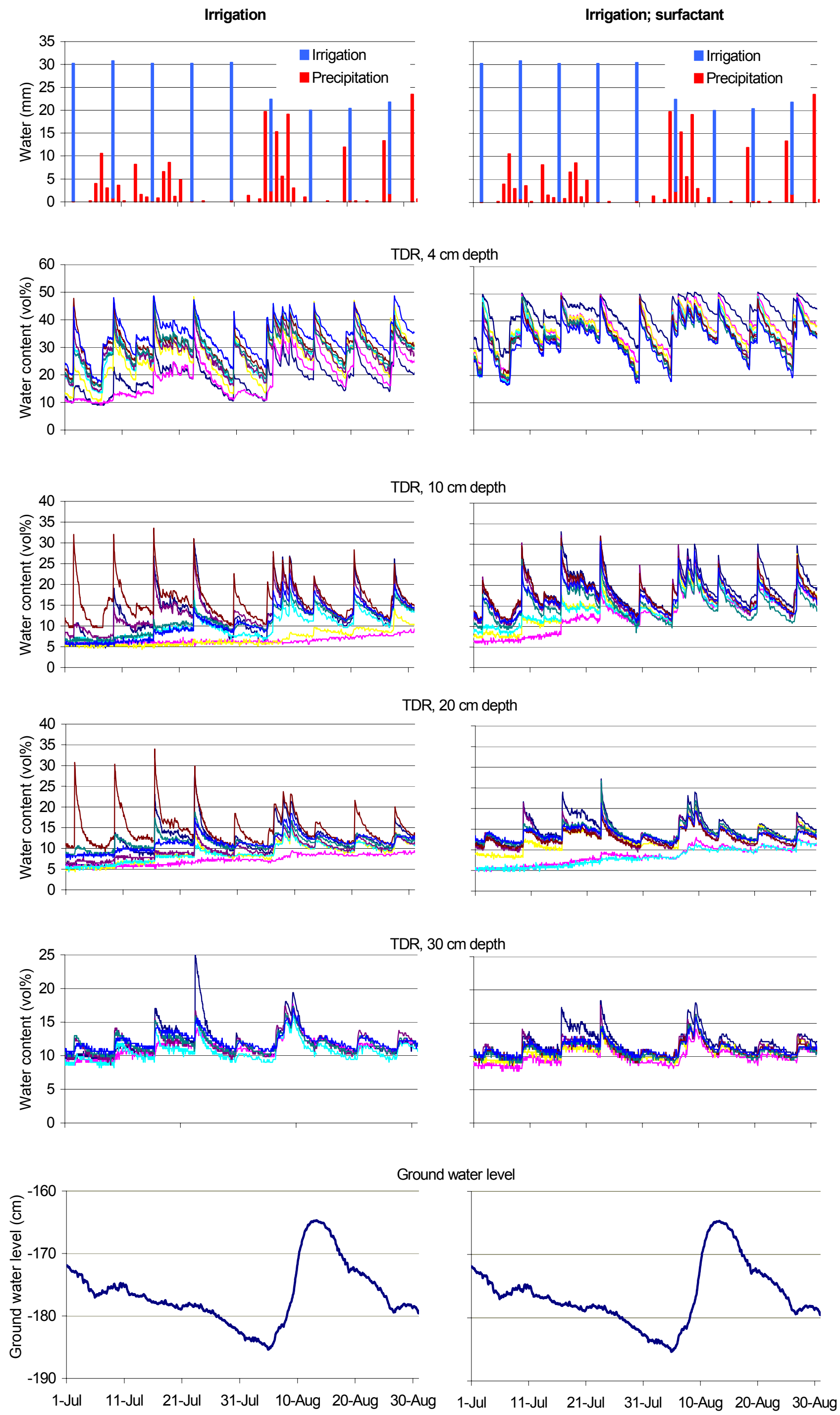

Figure 29 Soil water contents measured by the individual probes in the irrigated plot without and the irrigated plot with surfactant applications during the period 1 July to 31 August, 2001. Same colours have been used for probes above each other. Dates and amounts of precipitation and irrigation, and the course of the ground water level have been indicated too.

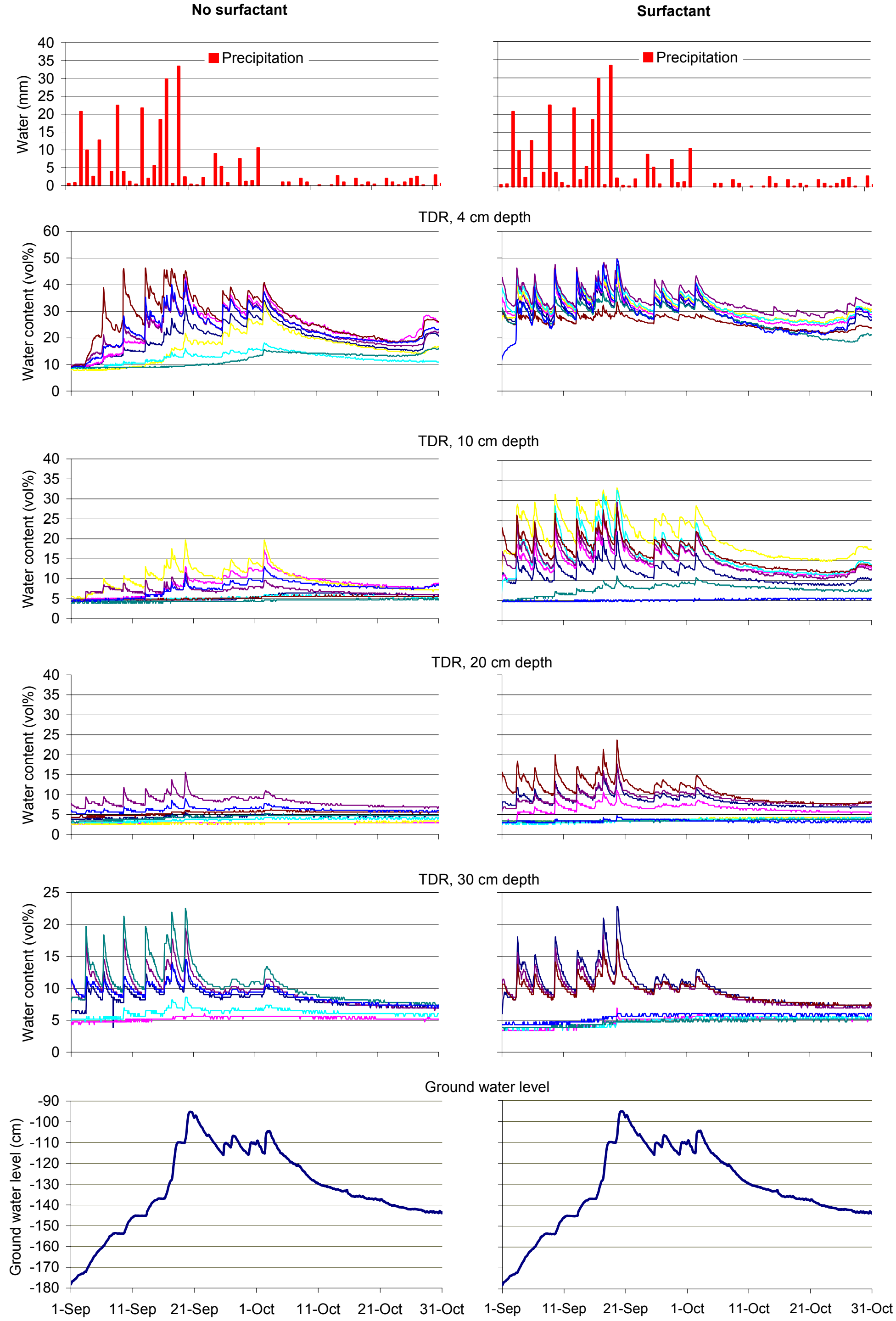

Figure 30 Soil water contents measured by the individual probes in the plot without and the plot with surfactant applications during the period 1 September to 31 October, 2001. Same colours at the four depths have been used for measurements with probes above each other. Dates and amounts of precipitation, and the course of the ground water level have been indicated too.

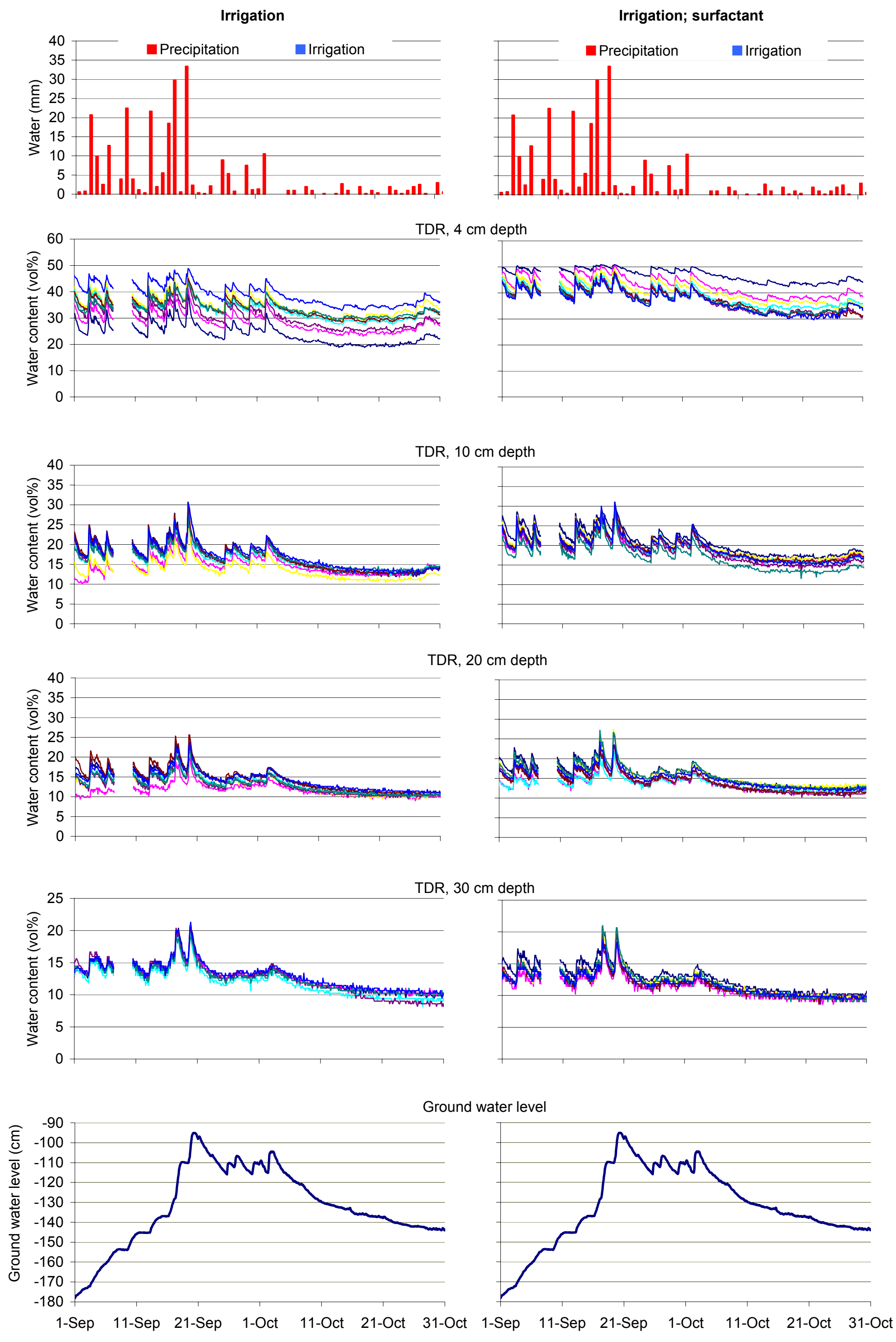

Figure 31 Soil water contents measured by the individual probes in the irrigated plot without and the irrigated plot with surfactant applications during the period 1 September to 31 October, 2001. Same colours have been used for probes above each other. Dates and amounts of precipitation and irrigation, and the course of the ground water level have been indicated too.

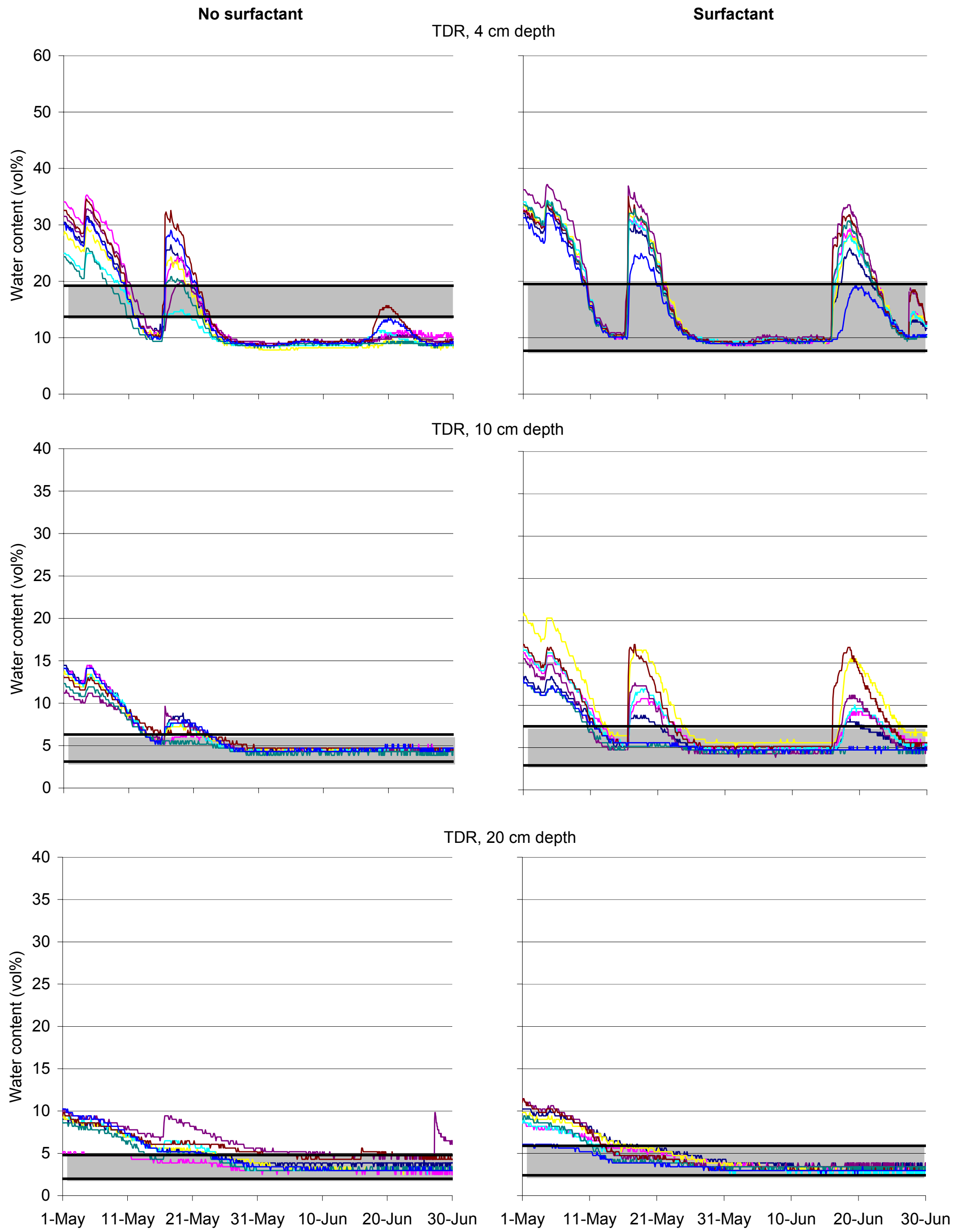

Figure 32 Soil water contents measured by the individual probes at 4, 10, and 20 cm depth in the plot without and the plot with surfactant applications during the period 1 May to 30 June, 2001. The grey zones in the diagrams indicate the transition zone of the critical soil water contents.

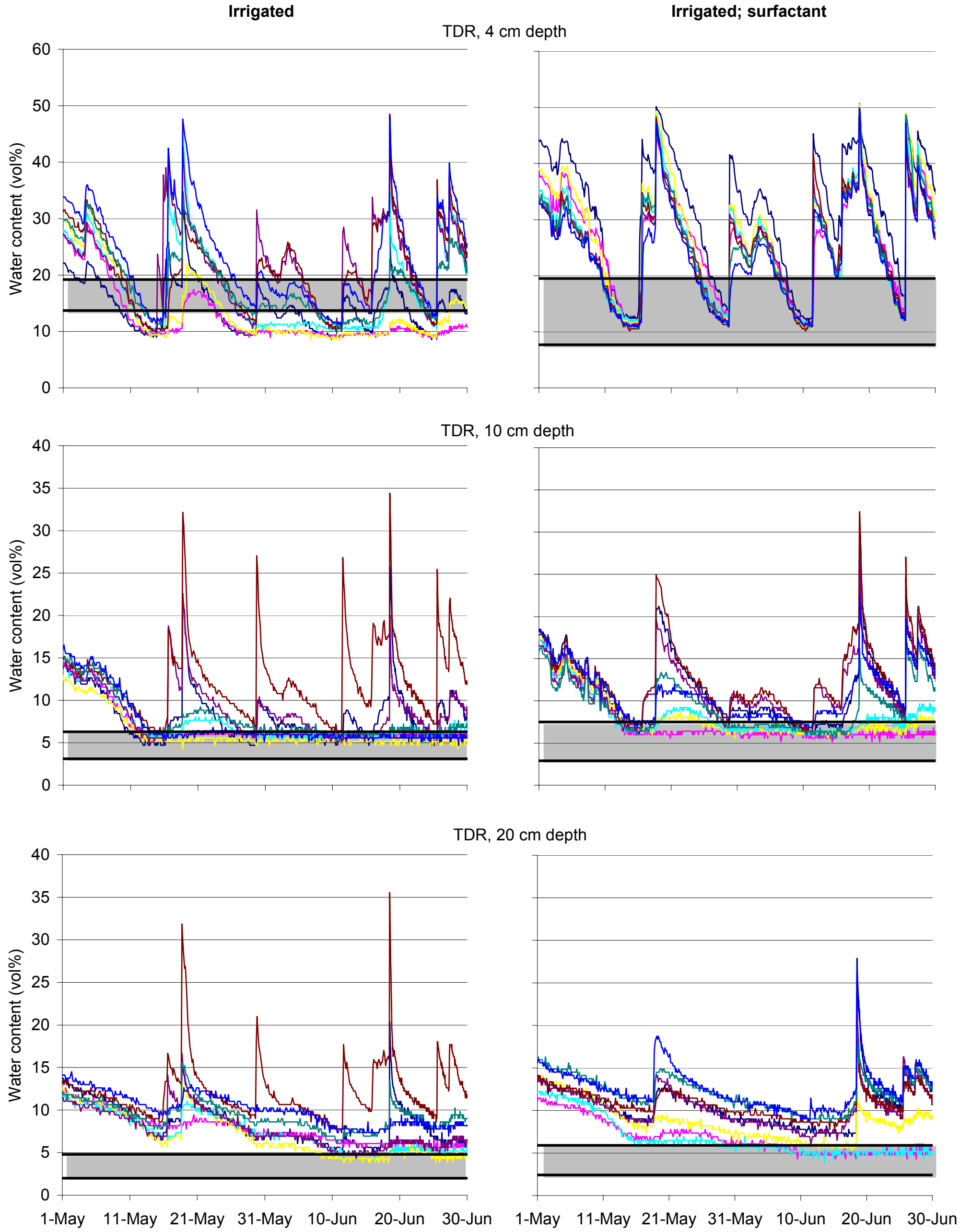

Figure 33 Soil water contents measured by the individual probes at 4, 10, and 20 cm depth in the irrigated plot without and the irrigated plot with surfactant applications during the period 1 May to 30 June, 2001. The grey zones in the diagrams indicate the transition zone of the critical soil water contents.

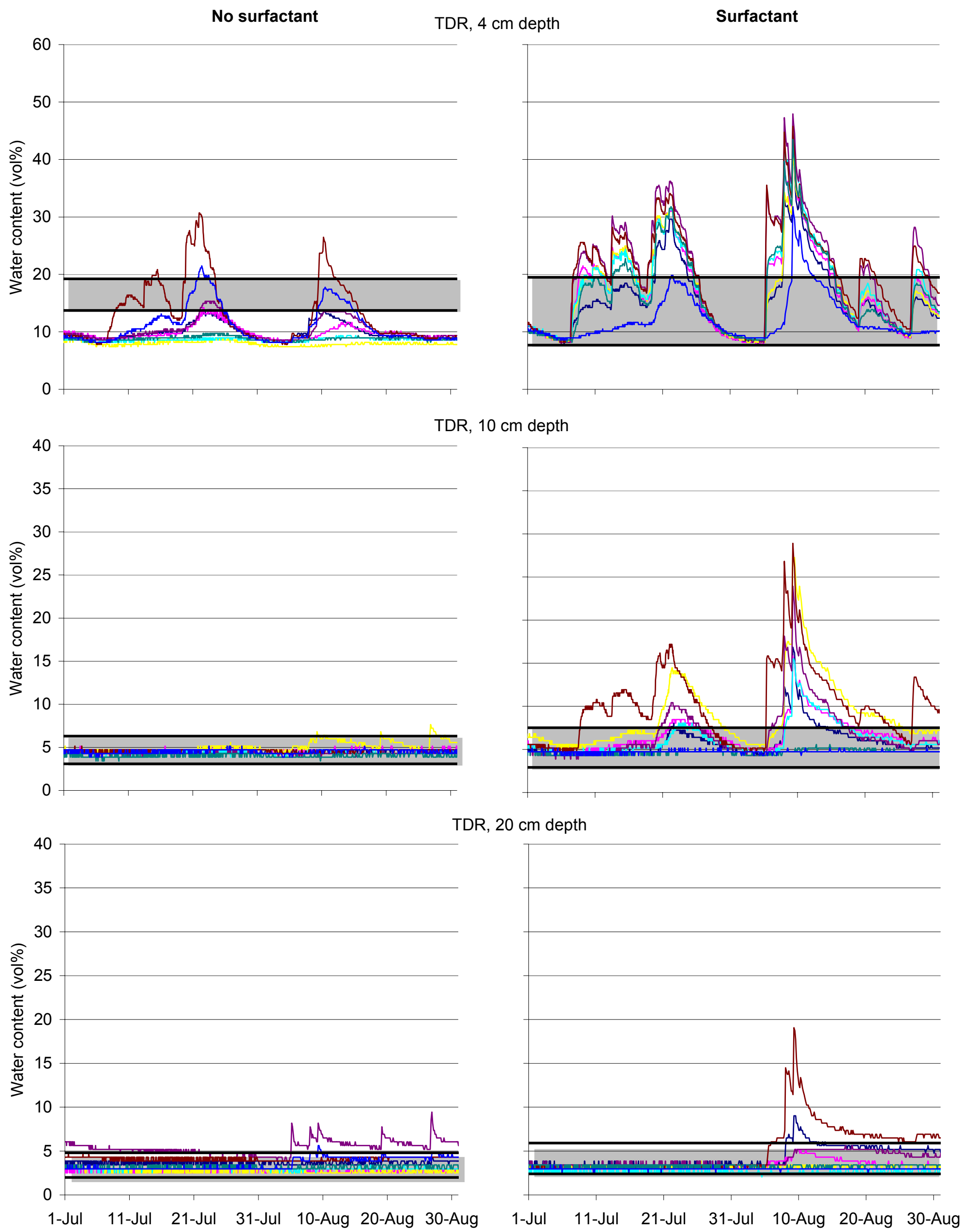

Figure 34 Soil water contents measured by the individual probes at 4, 10, and 20 cm depth in the plot without and the plot with surfactant applications during the period 1 July to 31 August, 2001. The grey zones in the diagrams indicate the transition zone of the critical soil water contents.

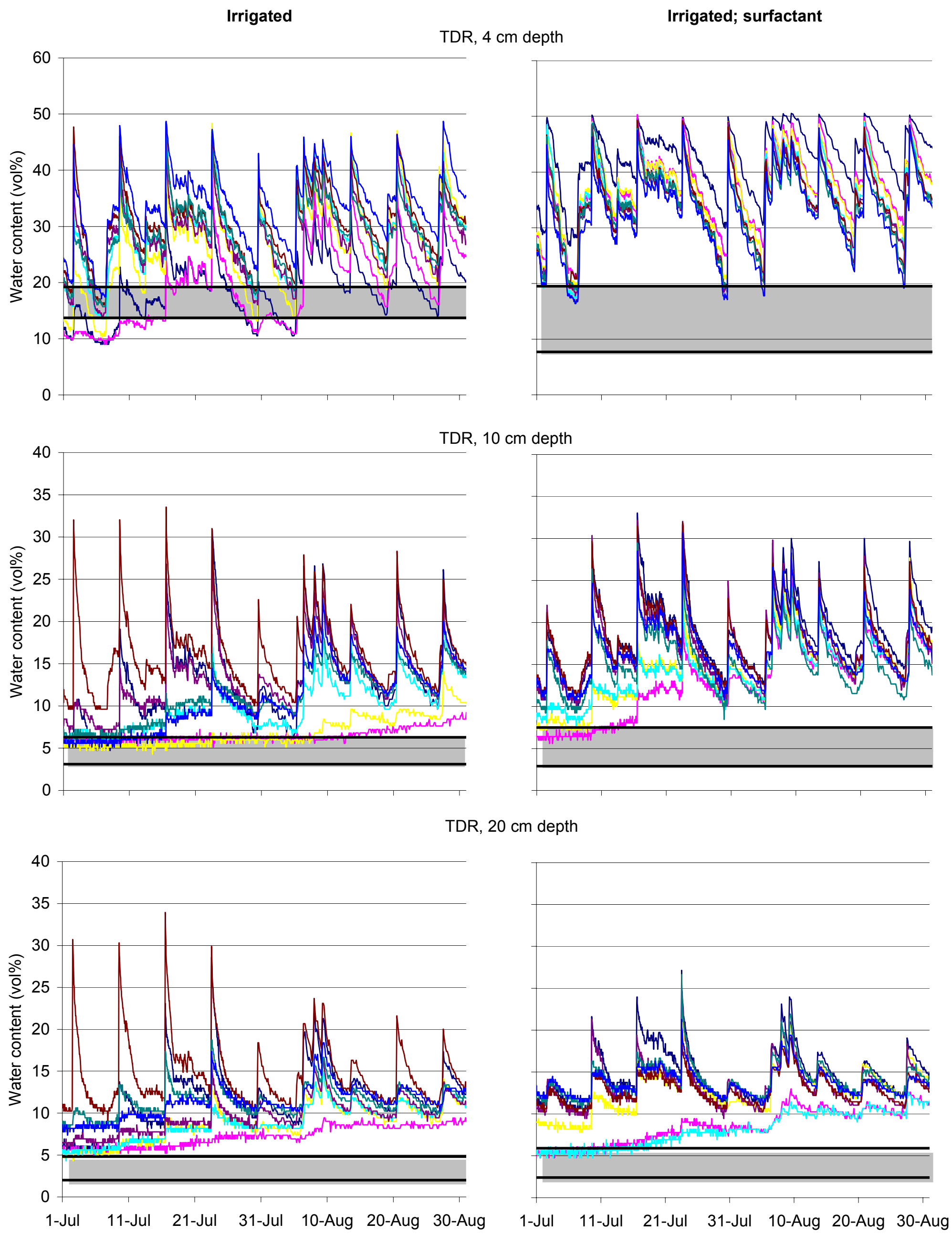

Figure 35 Soil water contents measured by the individual probes at 4, 10, and 20 cm depth in the irrigated plot without and the irrigated plot with surfactant applications during the period 1 July to 31 August, 2001. The grey zones in the diagrams indicate the transition zone of the critical soil water contents.

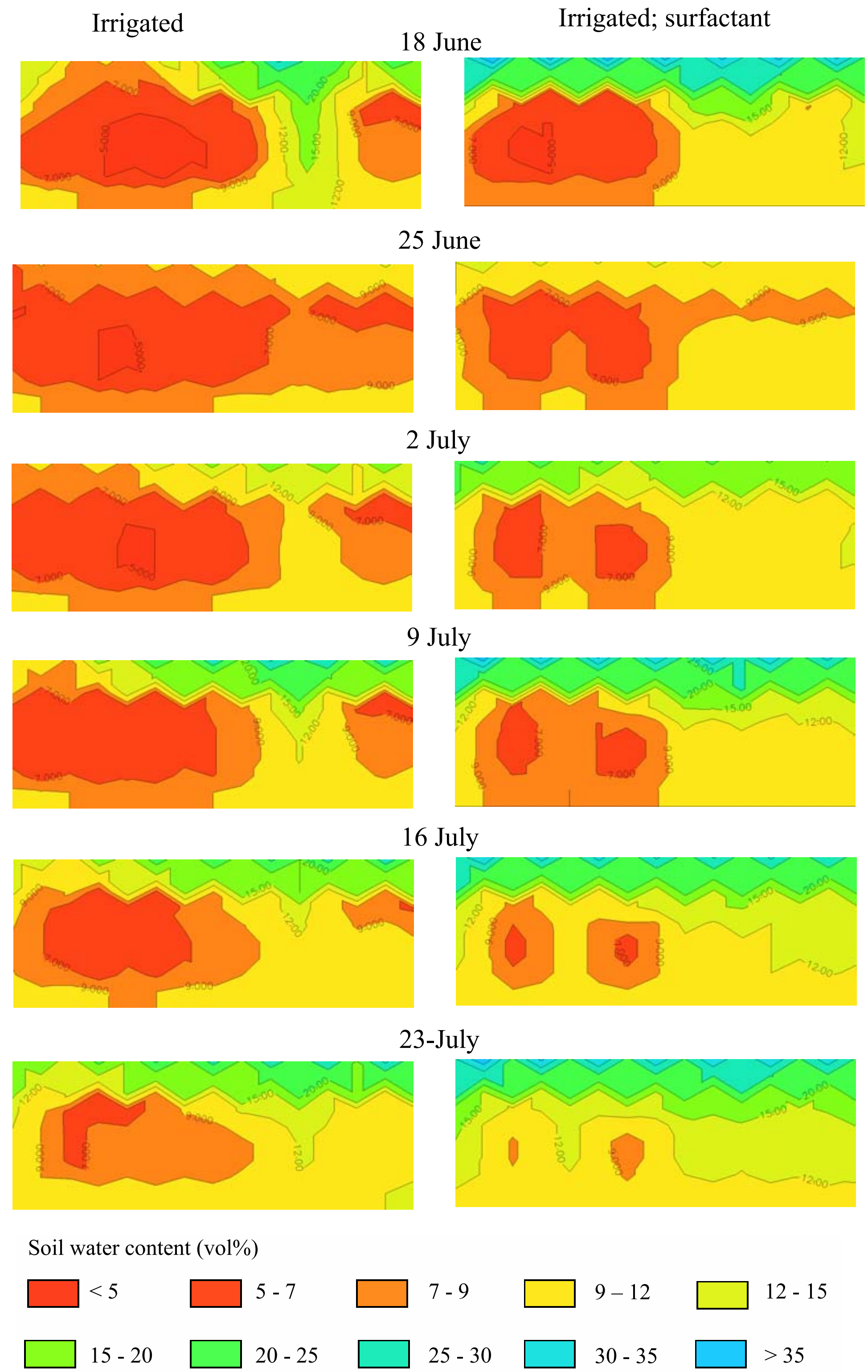

Figure 36 Contour plots of the soil water contents in the irrigated untreated and Primer®604 treated plot (width 80 cm; depth 30 cm) just before the weekly irrigations between 18 June and 23 July, 2001.

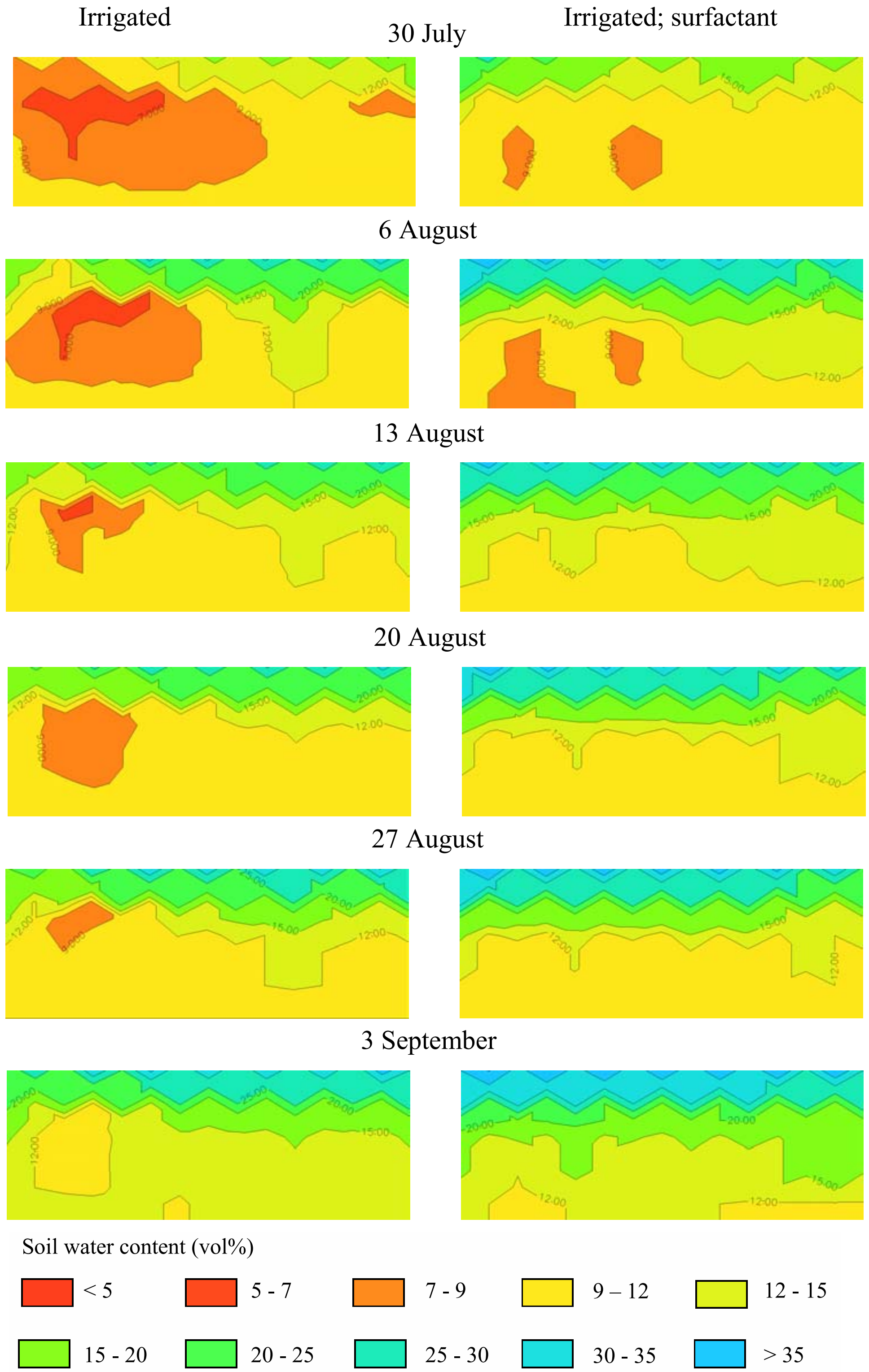

Figure 37 Contour plots of the soil water contents in the irrigated untreated and Primer®604 treated plot (width 80 cm; depth 30 cm) just before the weekly irrigations between 30 July and 3 September, 2001.

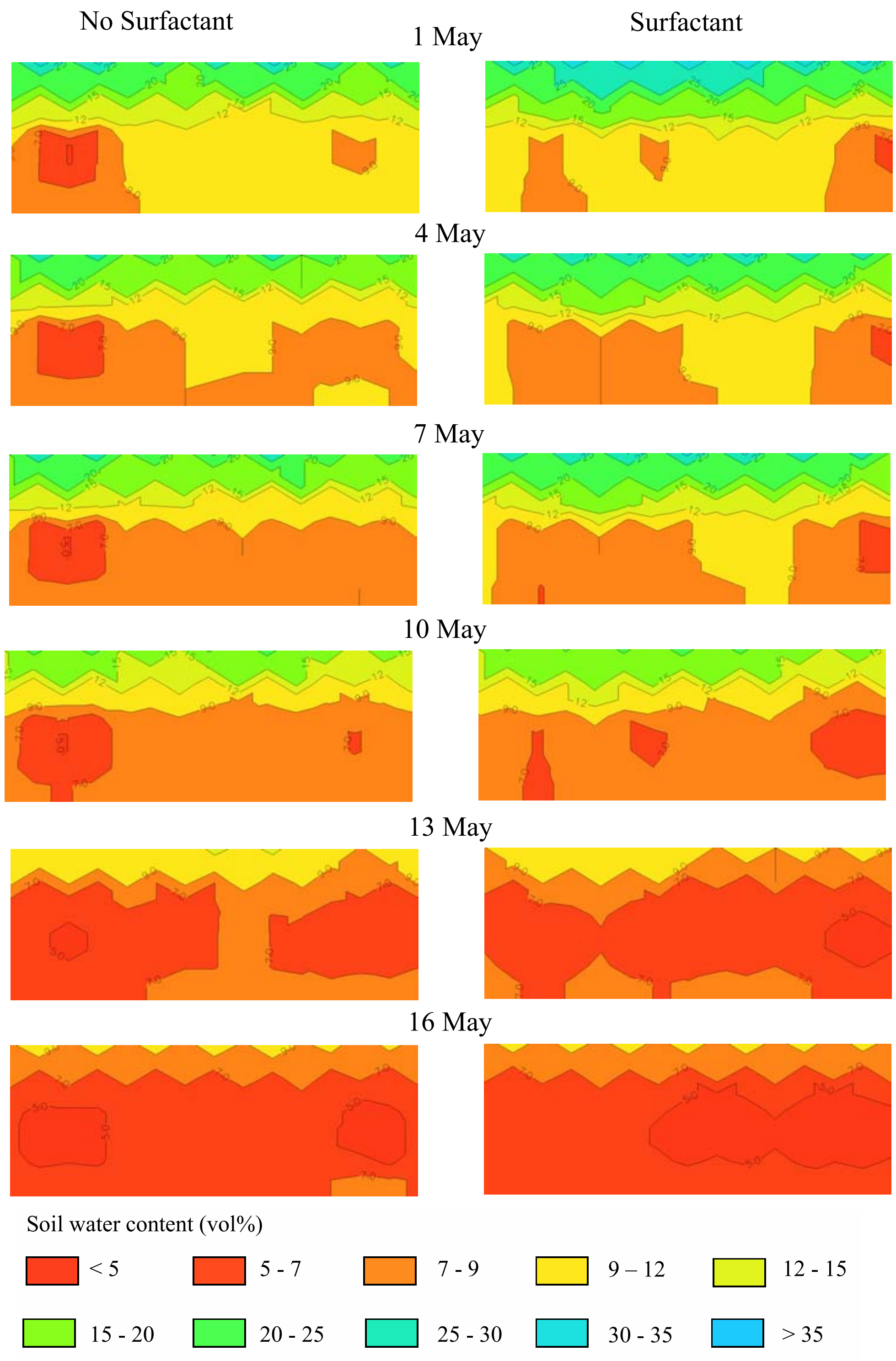

Figure 38 Contour plots (width 80 cm; depth 30 cm) of the decrease in soil water contents in the plot without and the plot with surfactant applications during a dry period between 1 and 16 May, 2001.

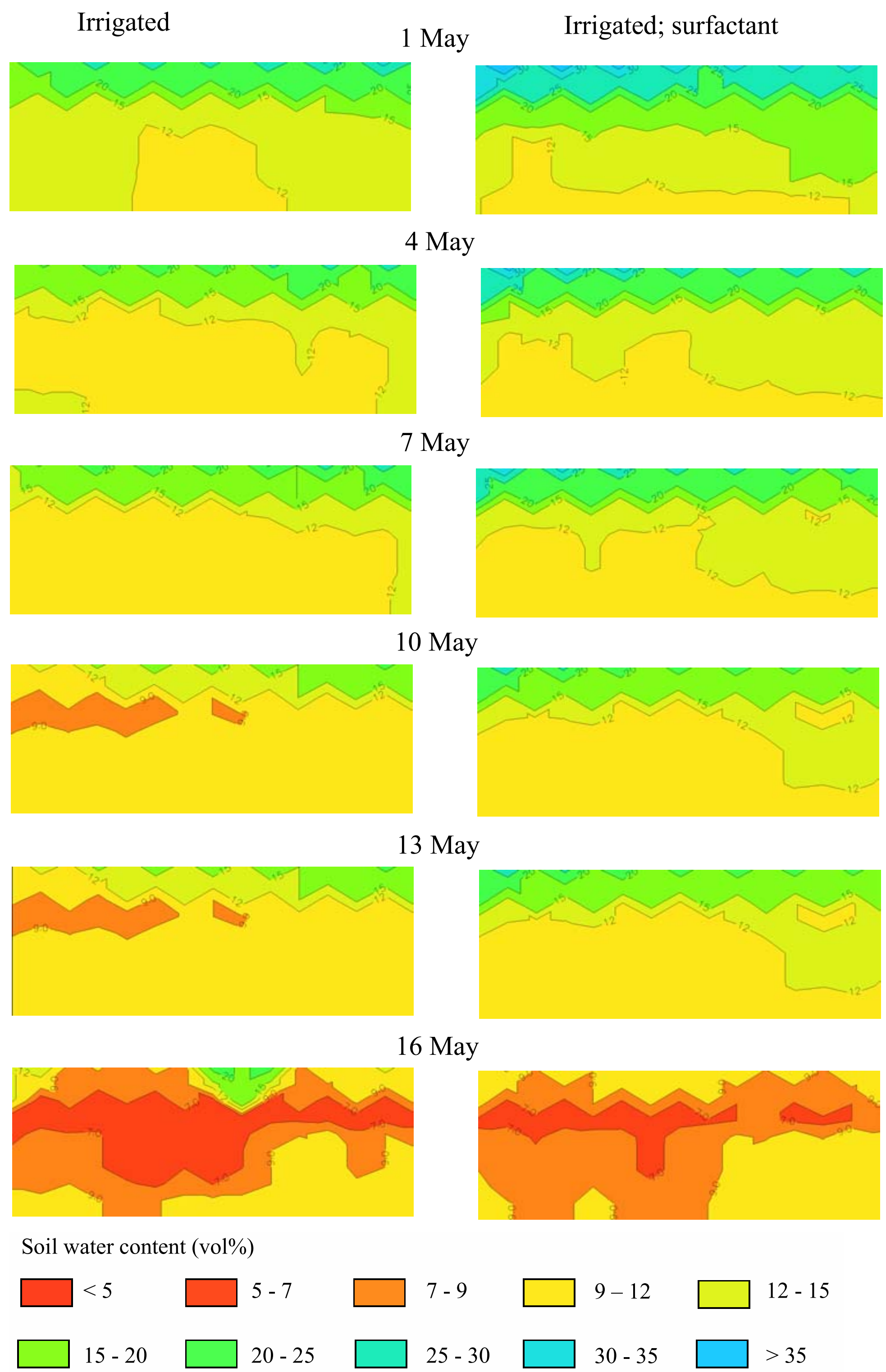

Figure 39 Contour plots (width 80 cm; depth 30 cm) of the decrease in soil water contents in the irrigated plot without and the irrigated plot with surfactant applications during a dry period between 1 and 16 May, 2001.

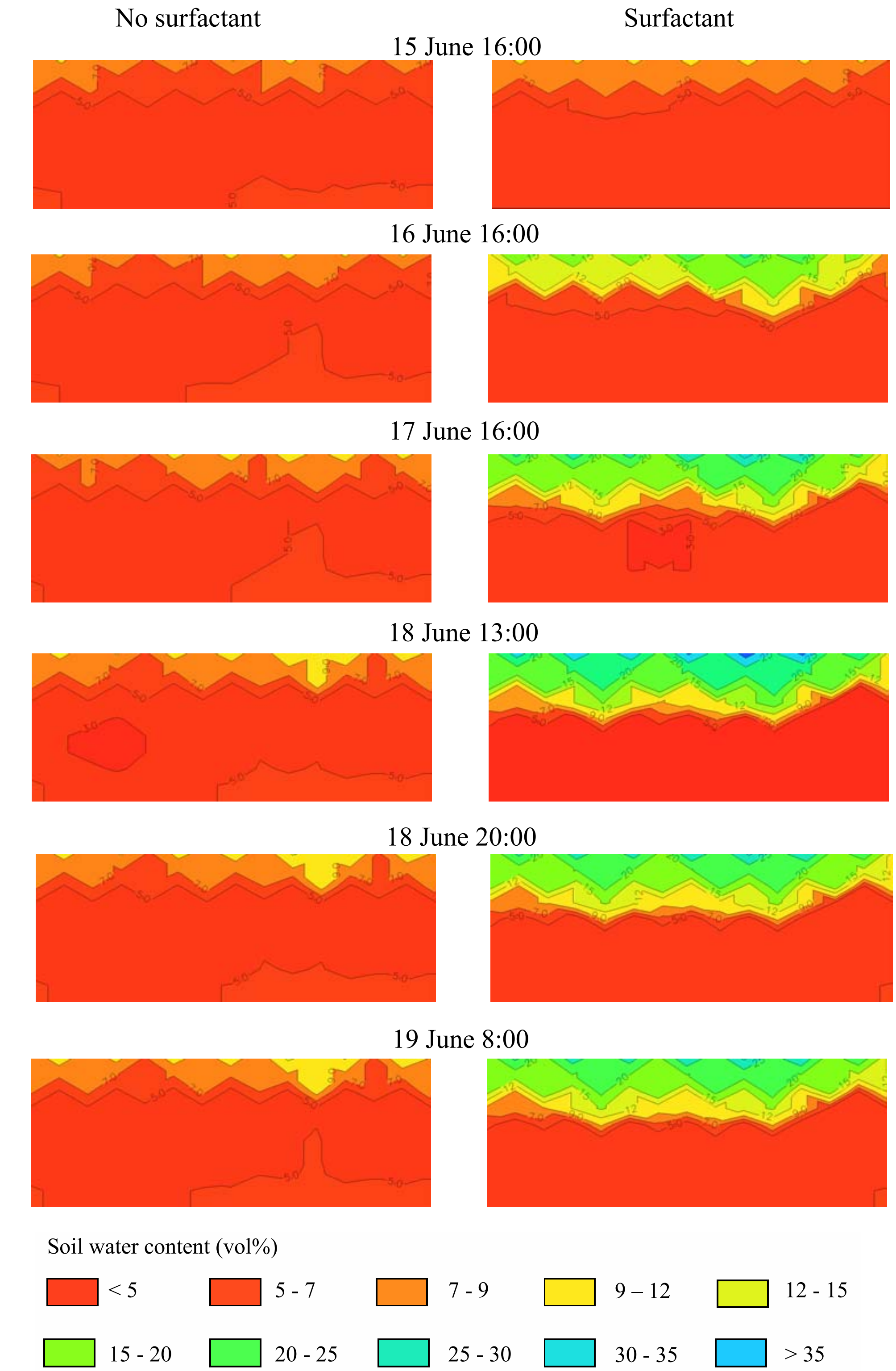

Figure 40 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the plot without and the plot with surfactant applications. Between 15 and 19 June several rain events occurred with a total amount of 25 mm precipitation.

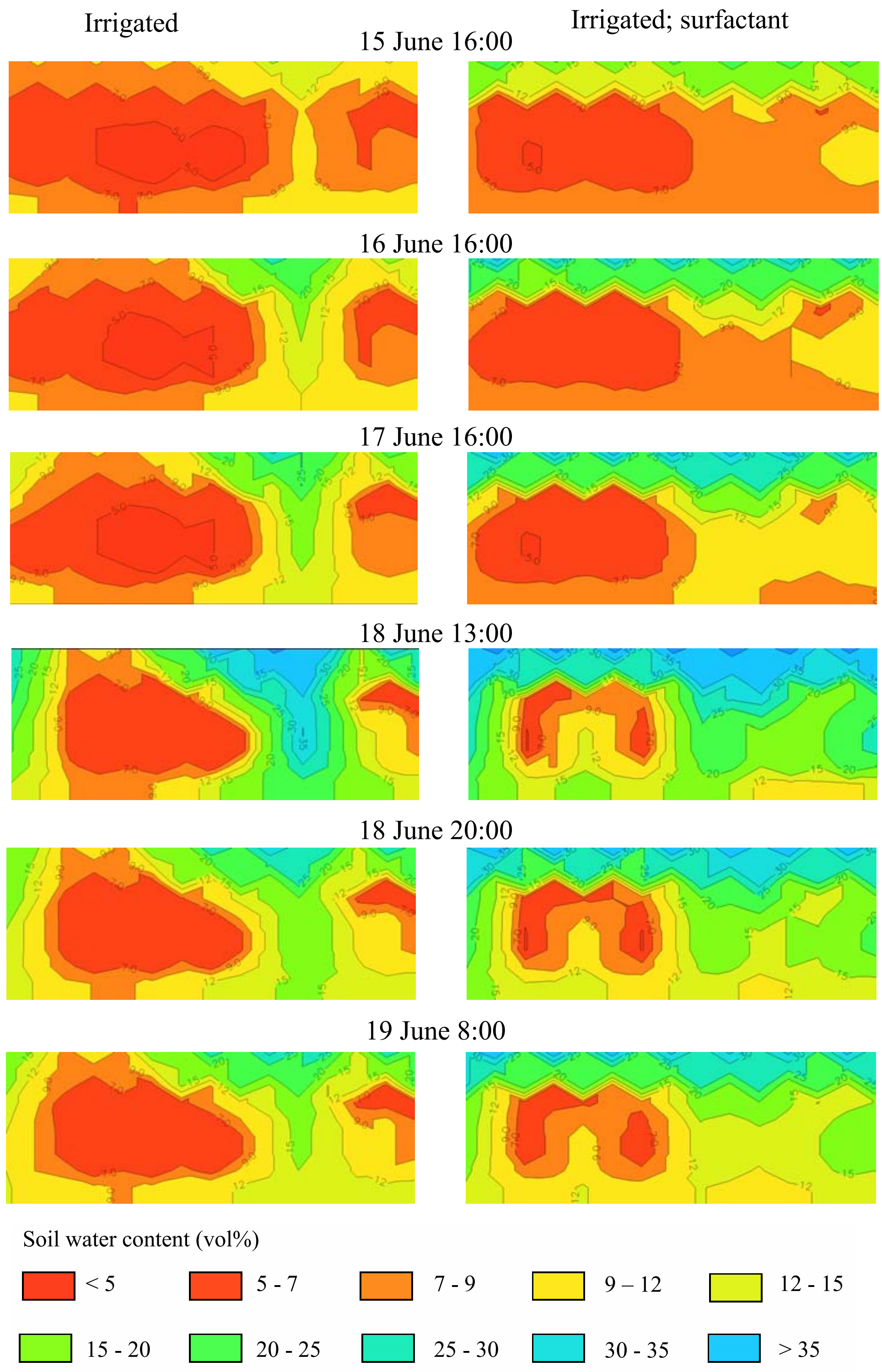

Figure 41 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the irrigated plot with surfactant applications. Between 15 and 19 June a total amount of 25 mm rain precipitated and 30 mm of water was irrigated on 18 June.

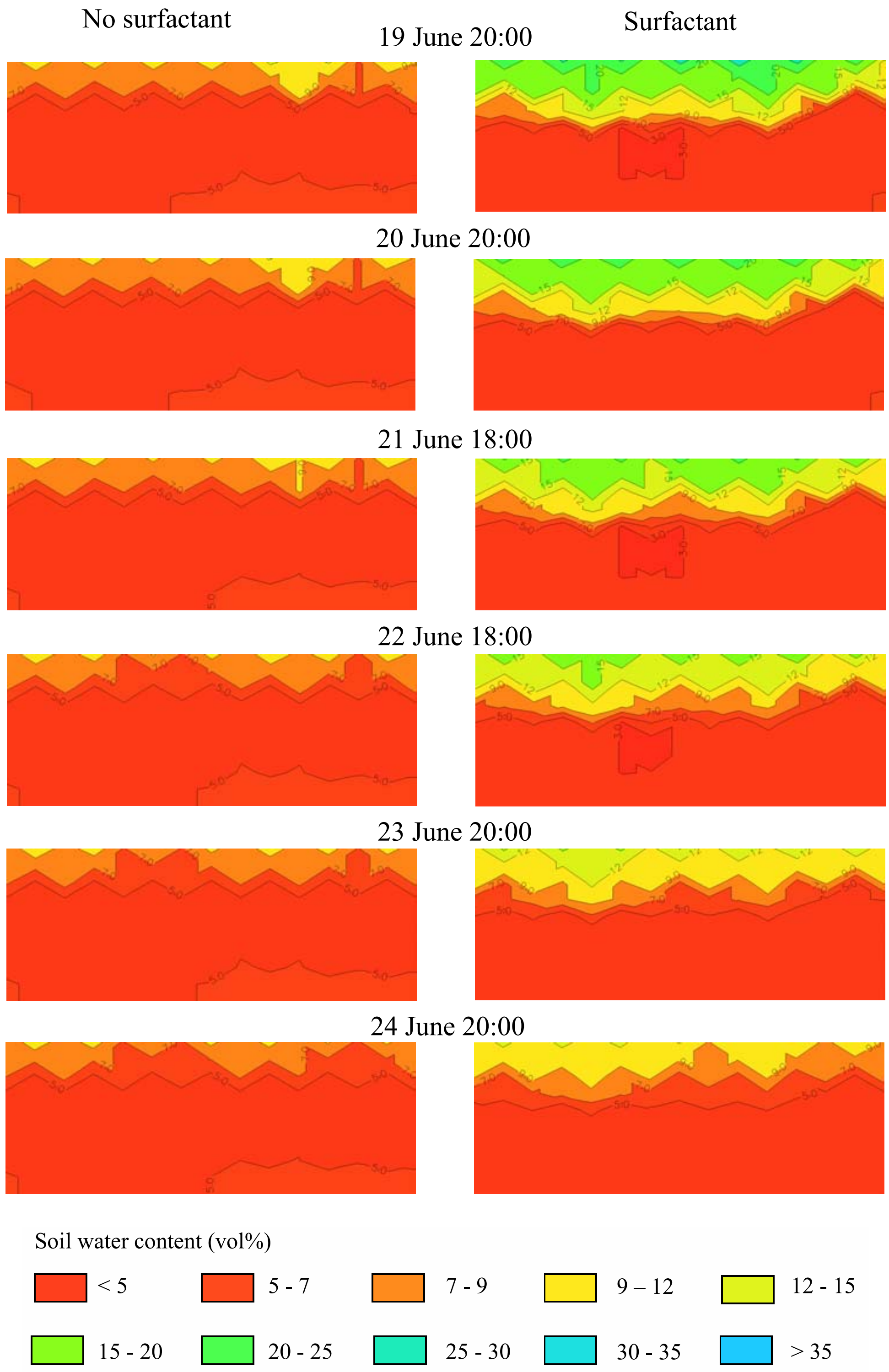

Figure 42 Contour plots (width 80 cm; depth 30 cm) of the decrease in soil water contents in the plot without and the plot with surfactant applications during a dry period between 19 and 24 June, 2001.

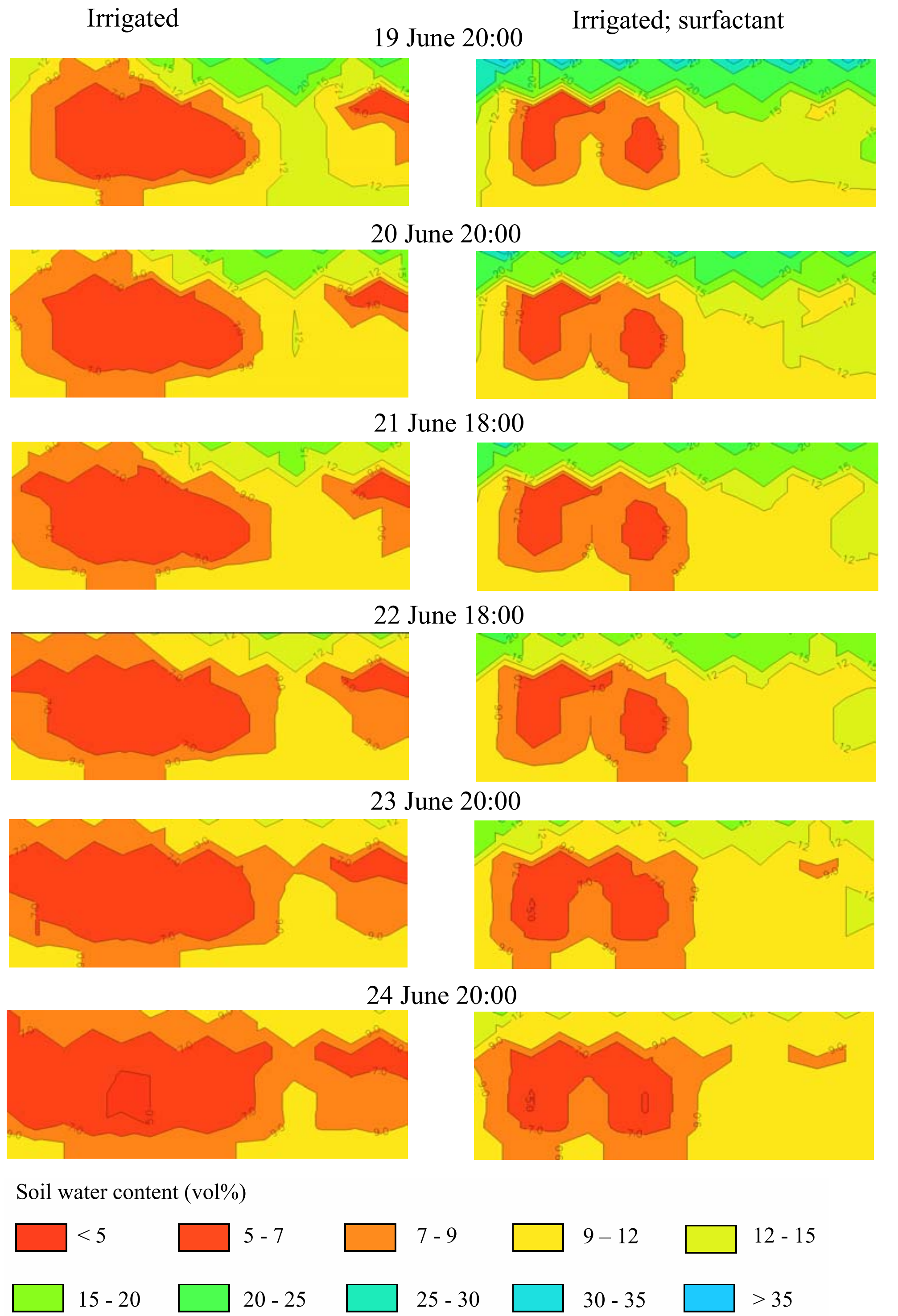

Figure 43 Contour plots (width 80 cm; depth 30 cm) of the decrease in soil water contents in the irrigated plot without and the irrigated plot with surfactant applications during a dry period between 19 and 24 June, 2001.

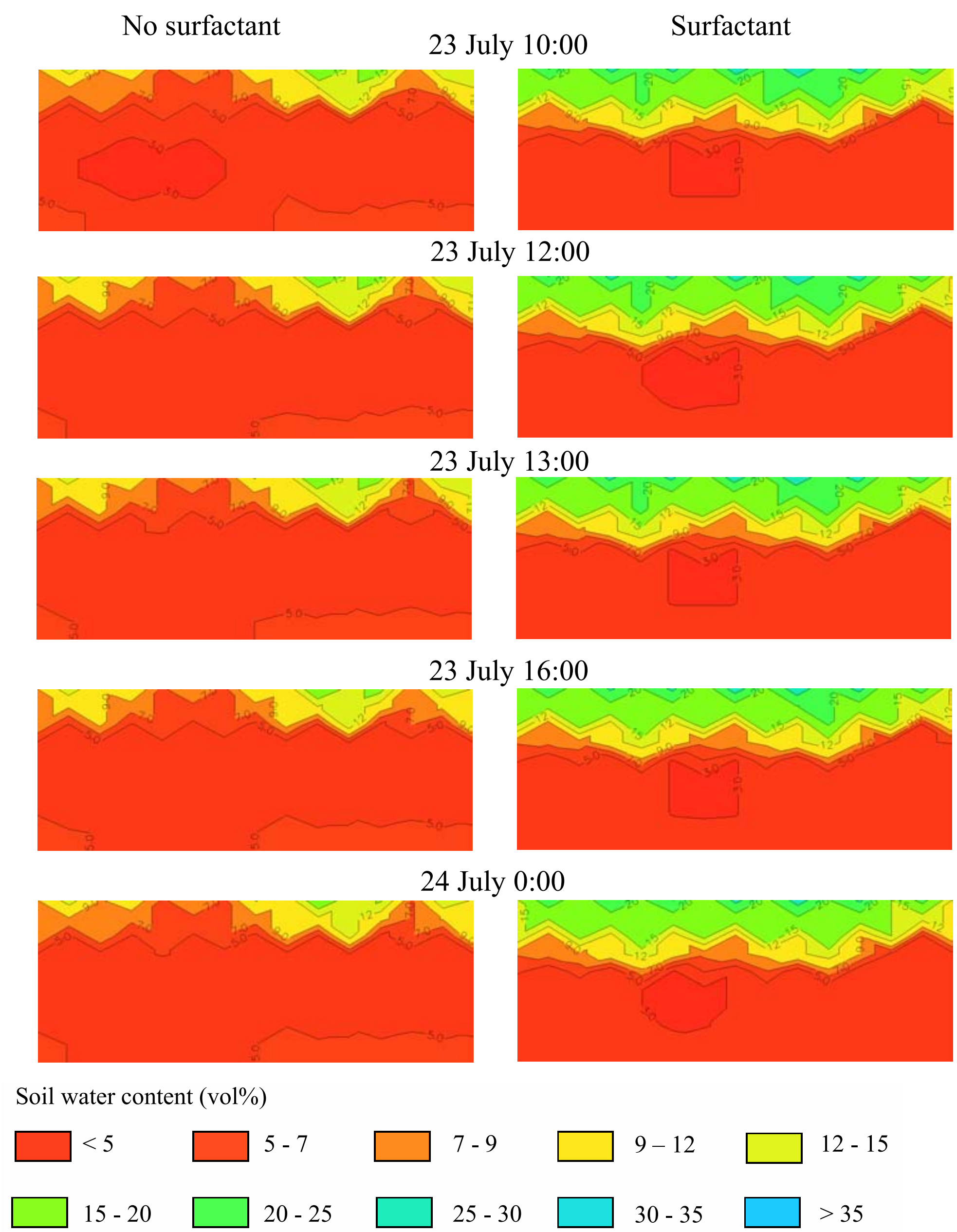

Figure 44 Contour plots (width 80 cm; depth 30 cm) of the soil water contents in the plot without and the plot with surfactant applications on 23 July, 2001.

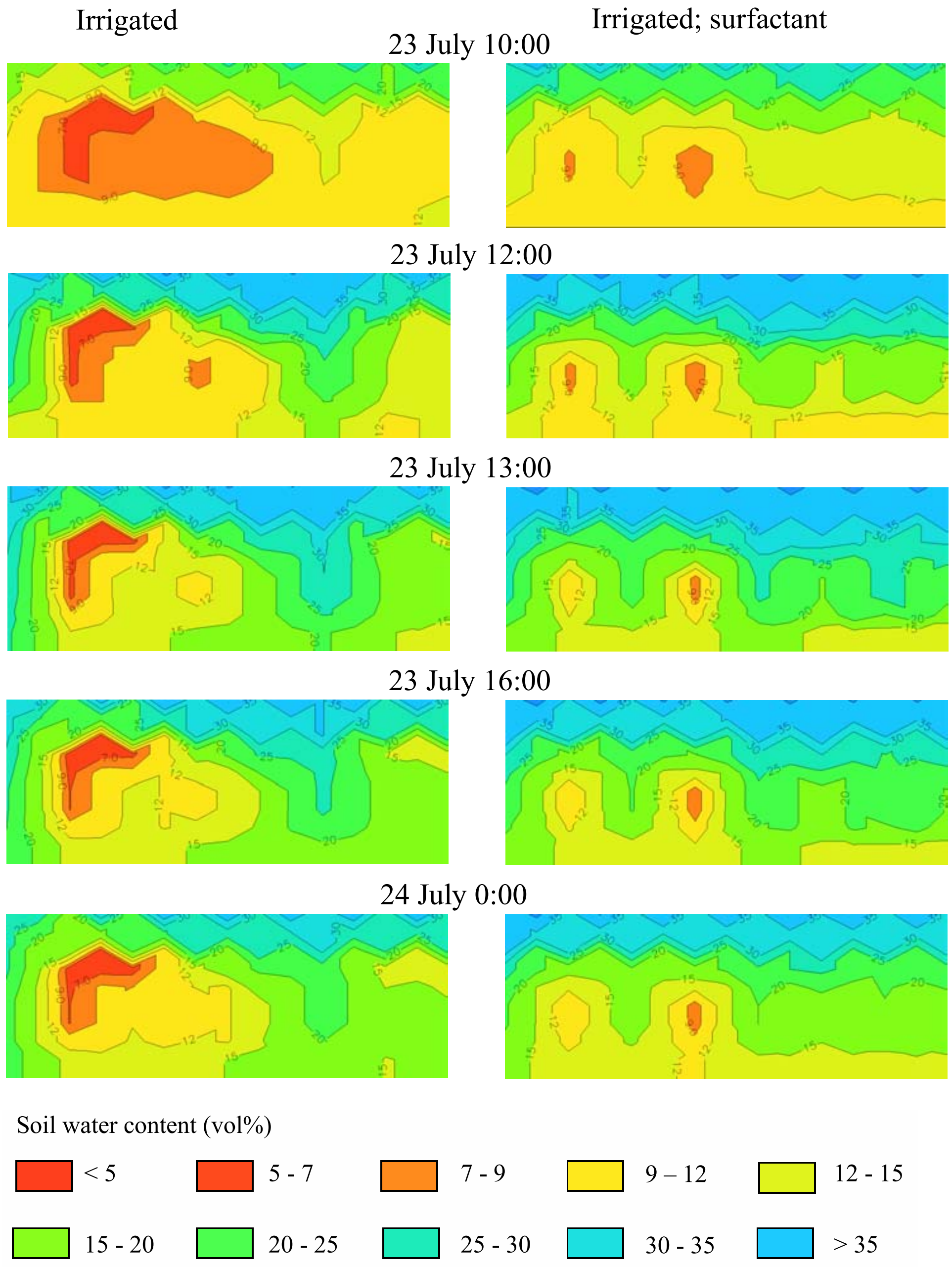

Figure 45 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the irrigated plot without and the irrigated plot with surfactant applications after an irrigation of 30 mm on 23 July, 2001.

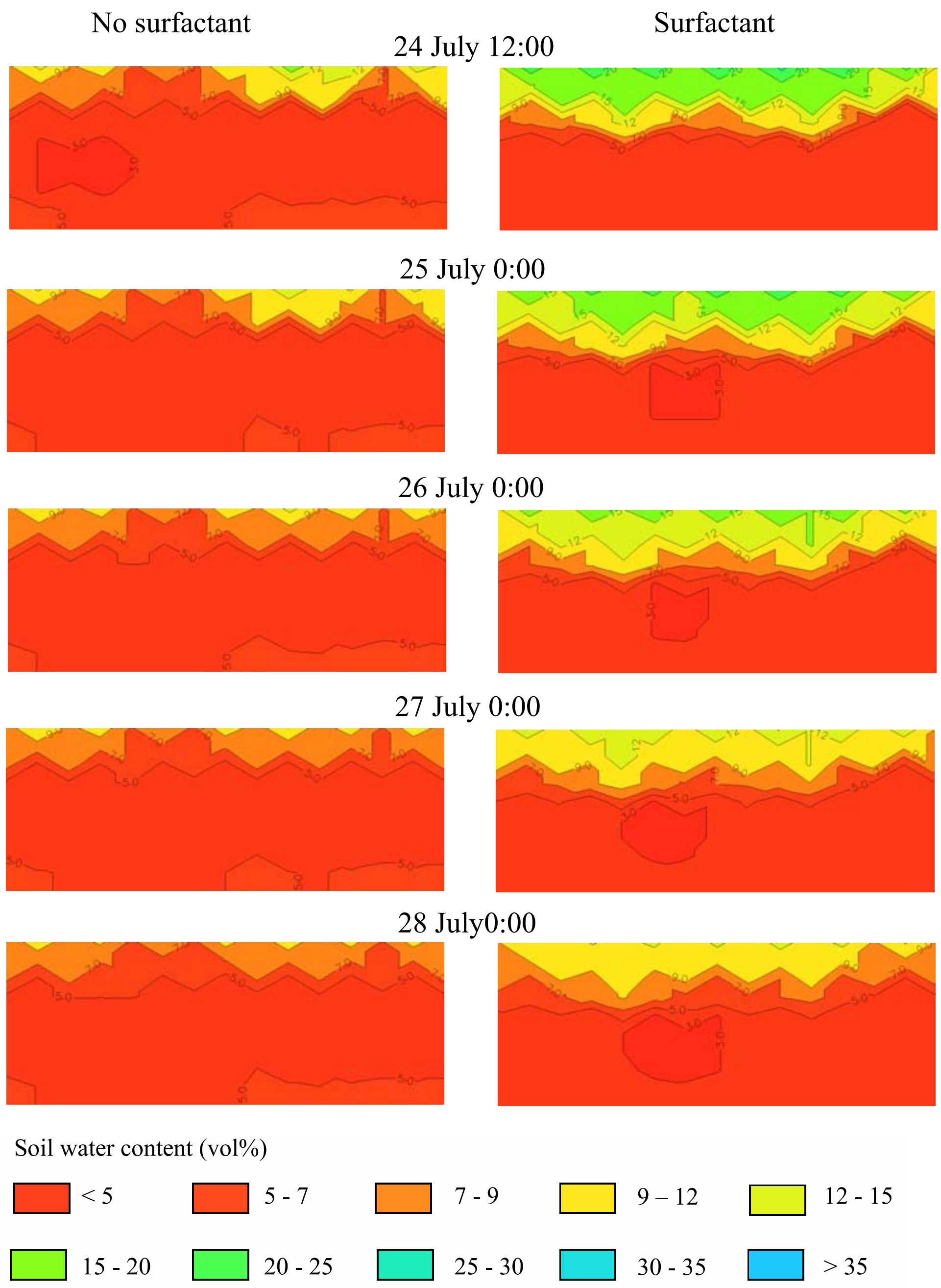

Figure 46 Contour plots (width 80 cm; depth 30 cm) of the decrease in soil water contents in the plot without and the plot with surfactant applications during a dry period between 24 and 28 July, 2001.

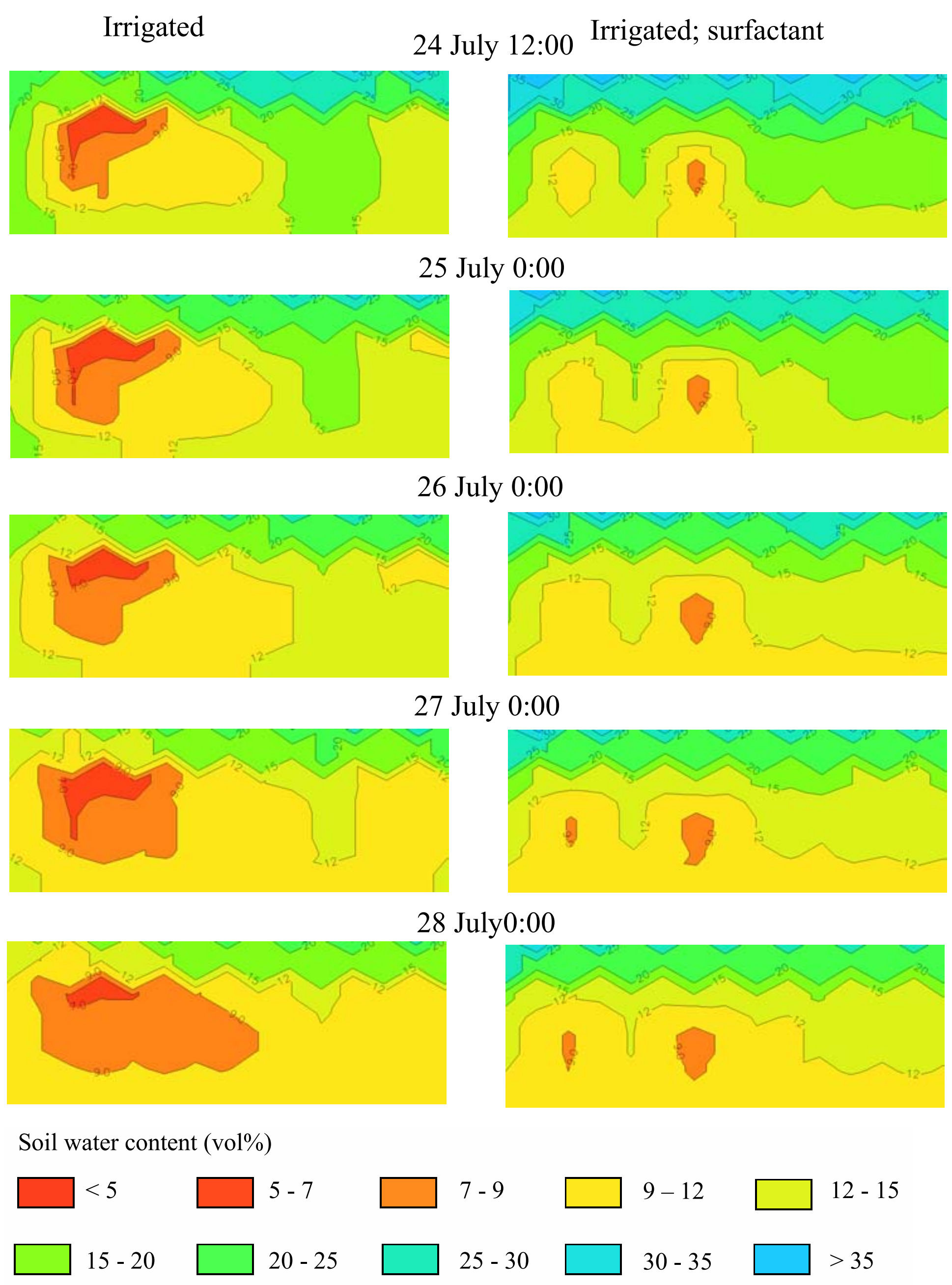

Figure 47 Contour plots (width 80 cm; depth 30 cm) of the decrease in soil water contents in the irrigated plot without and the irrigated plot with surfactant applications during a dry period between 24 and 28 July, 2001.

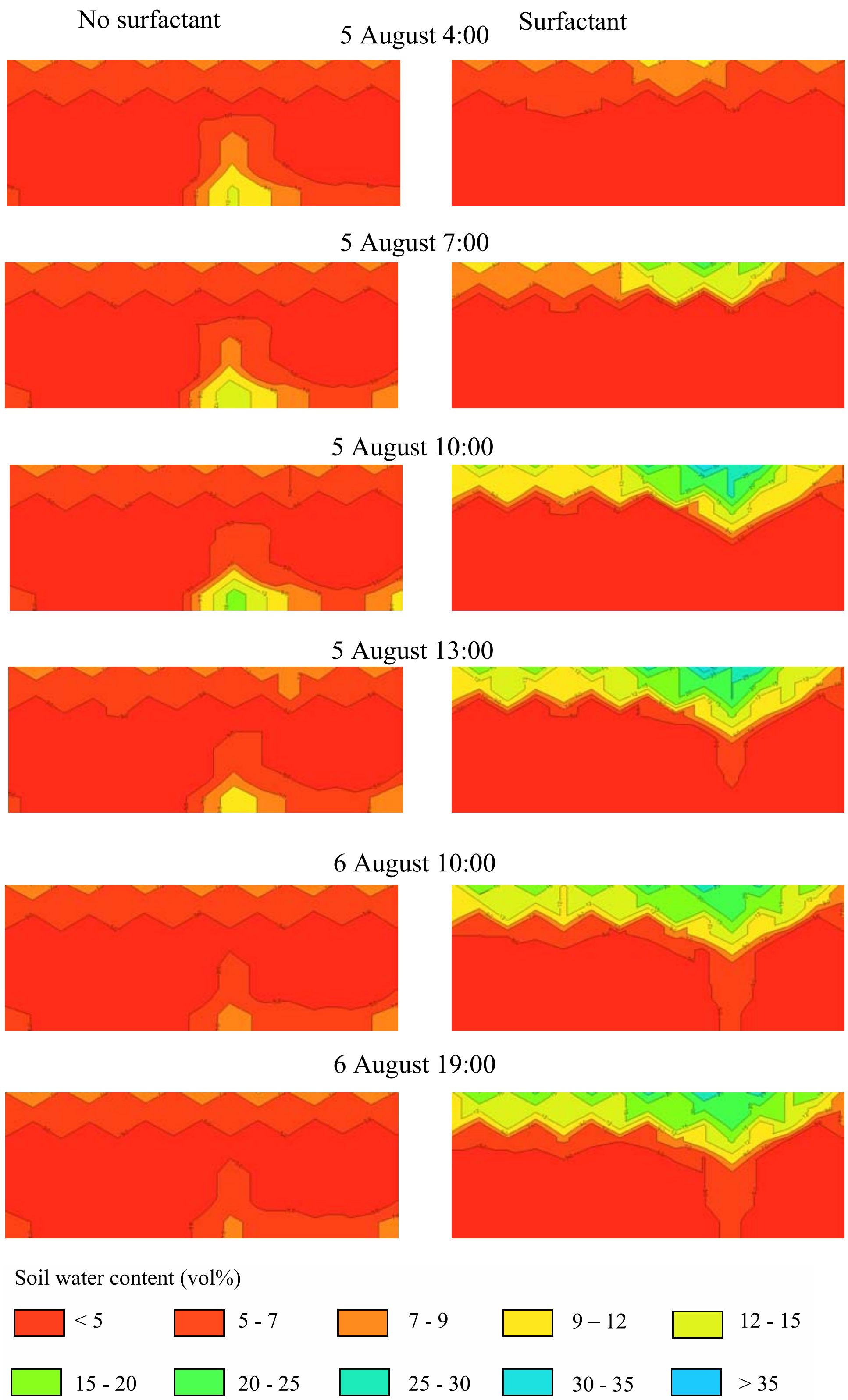

Figure 48 Contour plots (width 80 cm; depth 30 cm) of the increase in soil water contents in the plot without and the plot with surfactant applications, due to 15 mm precipitation on 5 August, 2001.

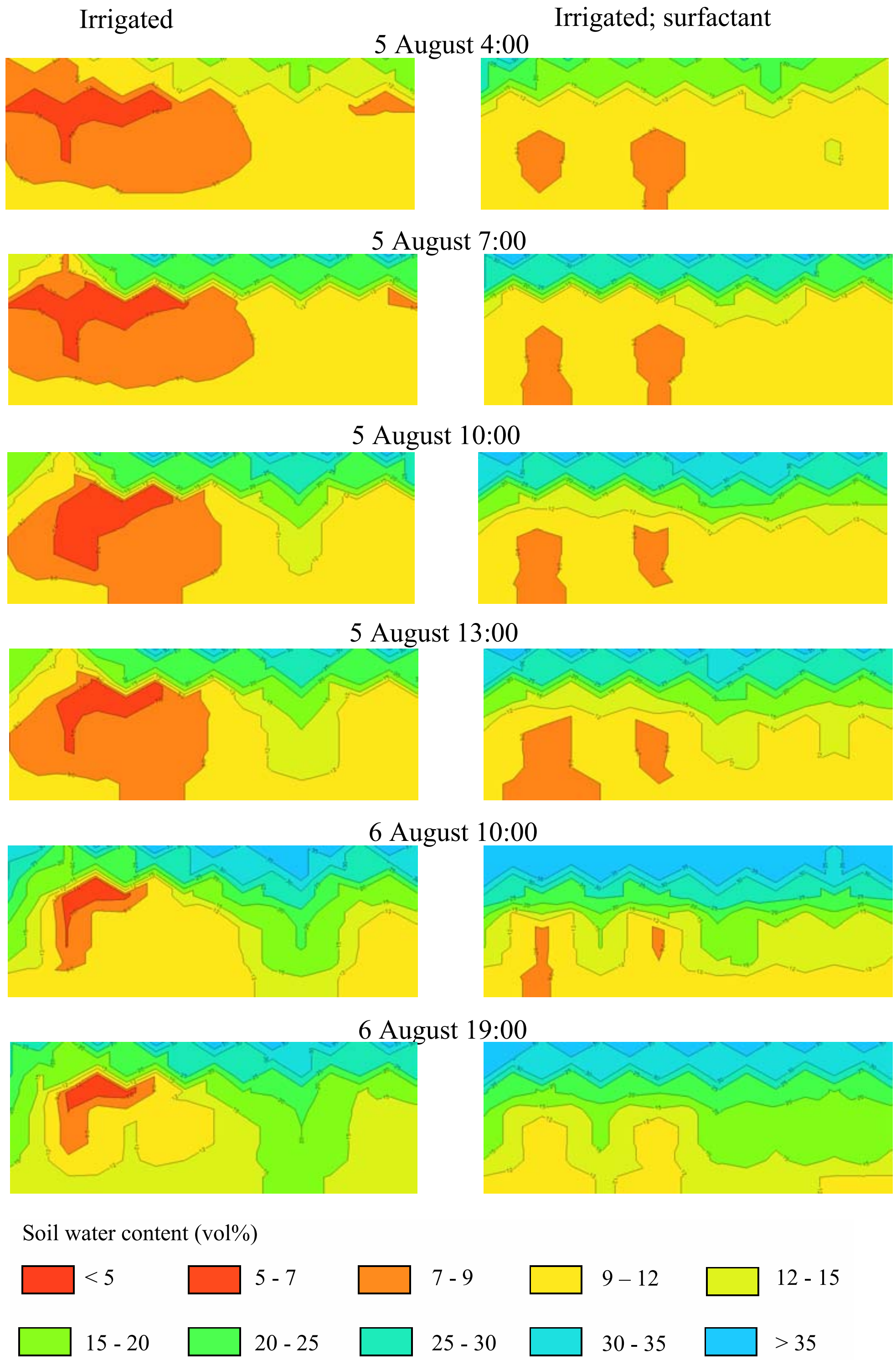

Figure 49 Contour plots (width 80 cm; depth 30 cm) of the increase in soil water contents in the irrigated plot without and the irrigated plot with surfactant applications, due to 15 mm precipitation on 5 August and 20 mm irrigation on 6 August, 2001.

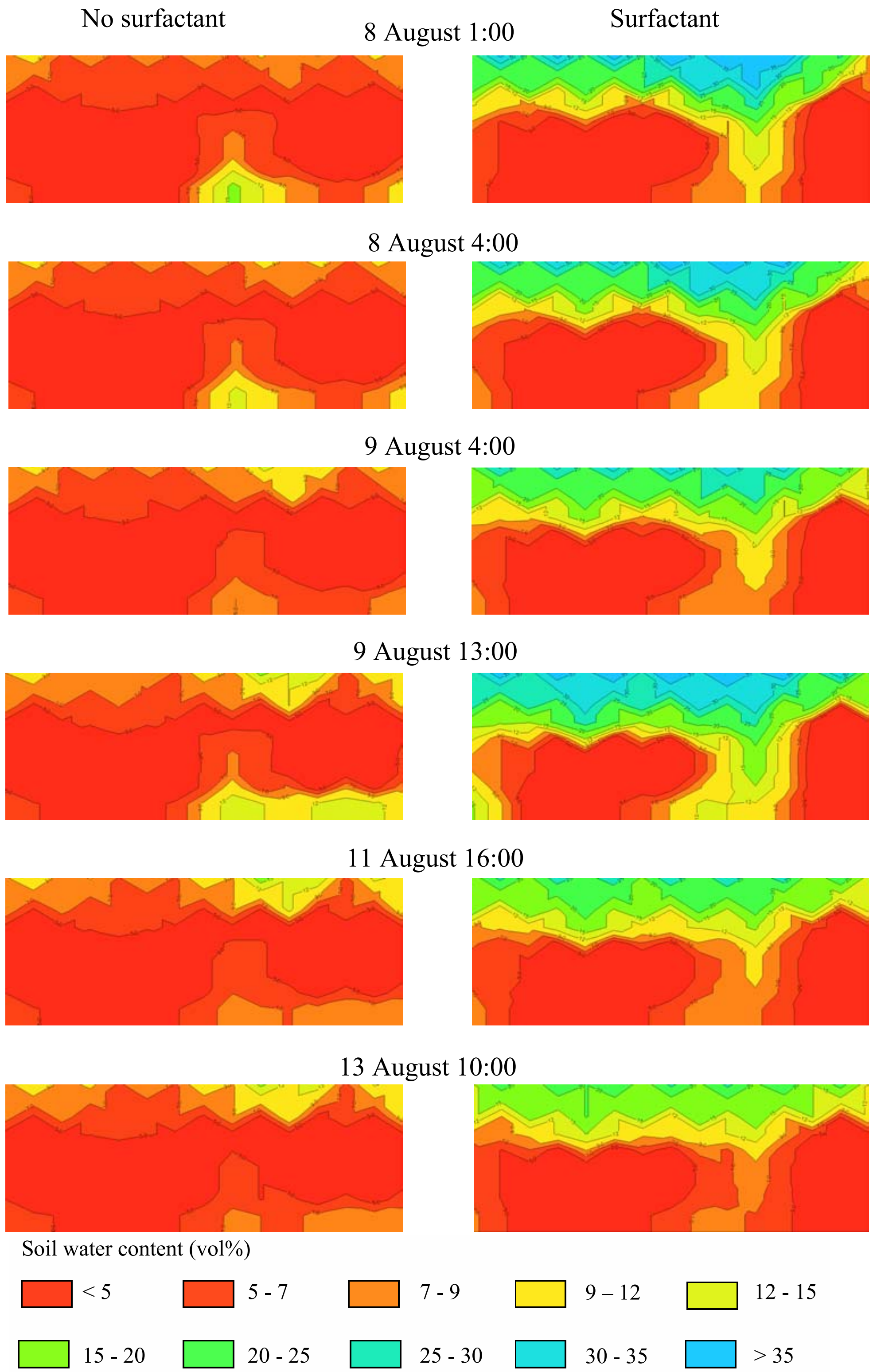

Figure 50 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the plot without and the plot with surfactant applications during a rainy period with 45 mm of precipitation between 7 and 13 August, 2001.

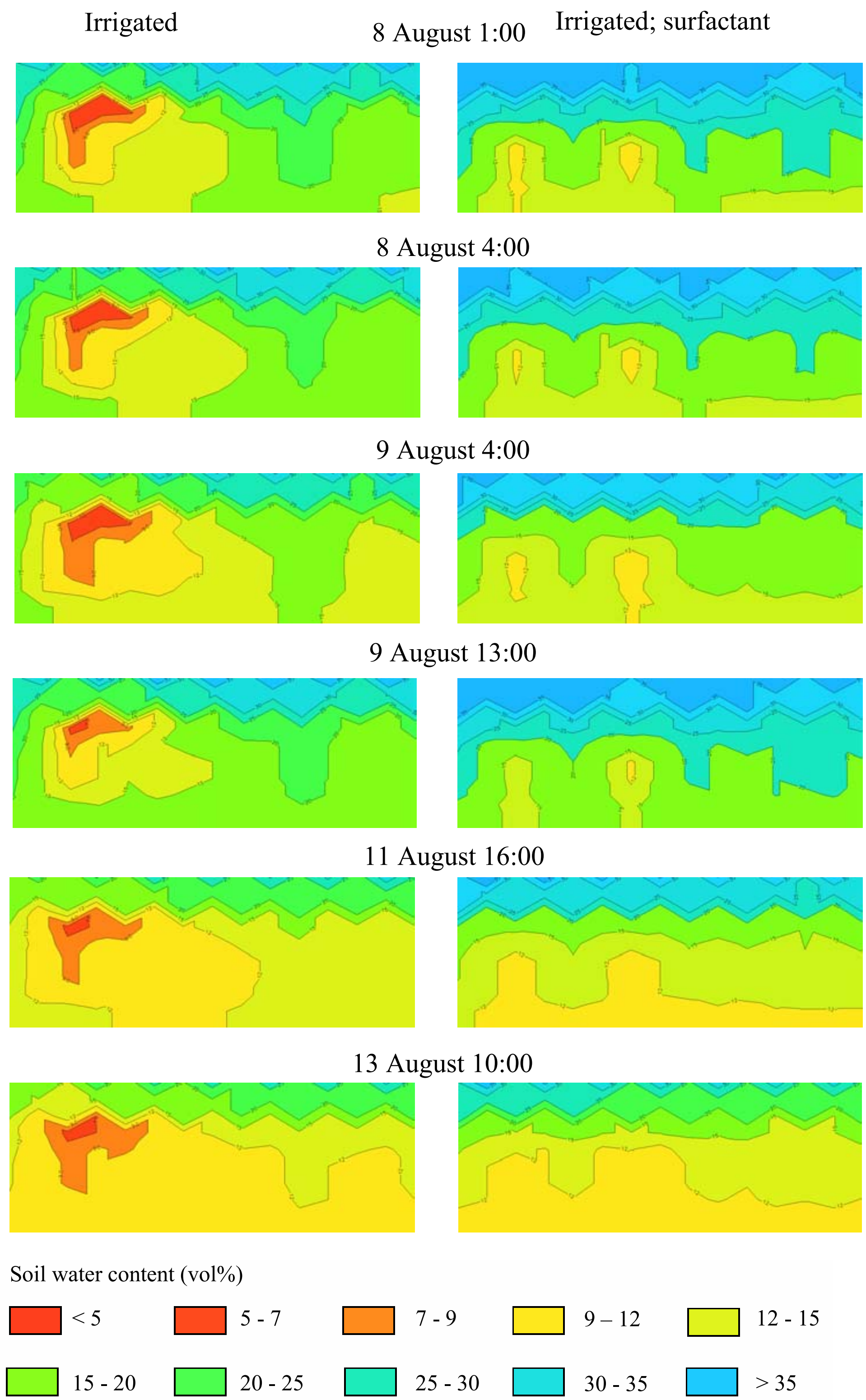

Figure 51 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the irrigated plot without and the irrigated plot with surfactant applications during a rainy period with 45 mm of precipitation between 7 and 13 August, 2001. The last irrigation (20 mm) took place on 6 August, see also Figure 49.

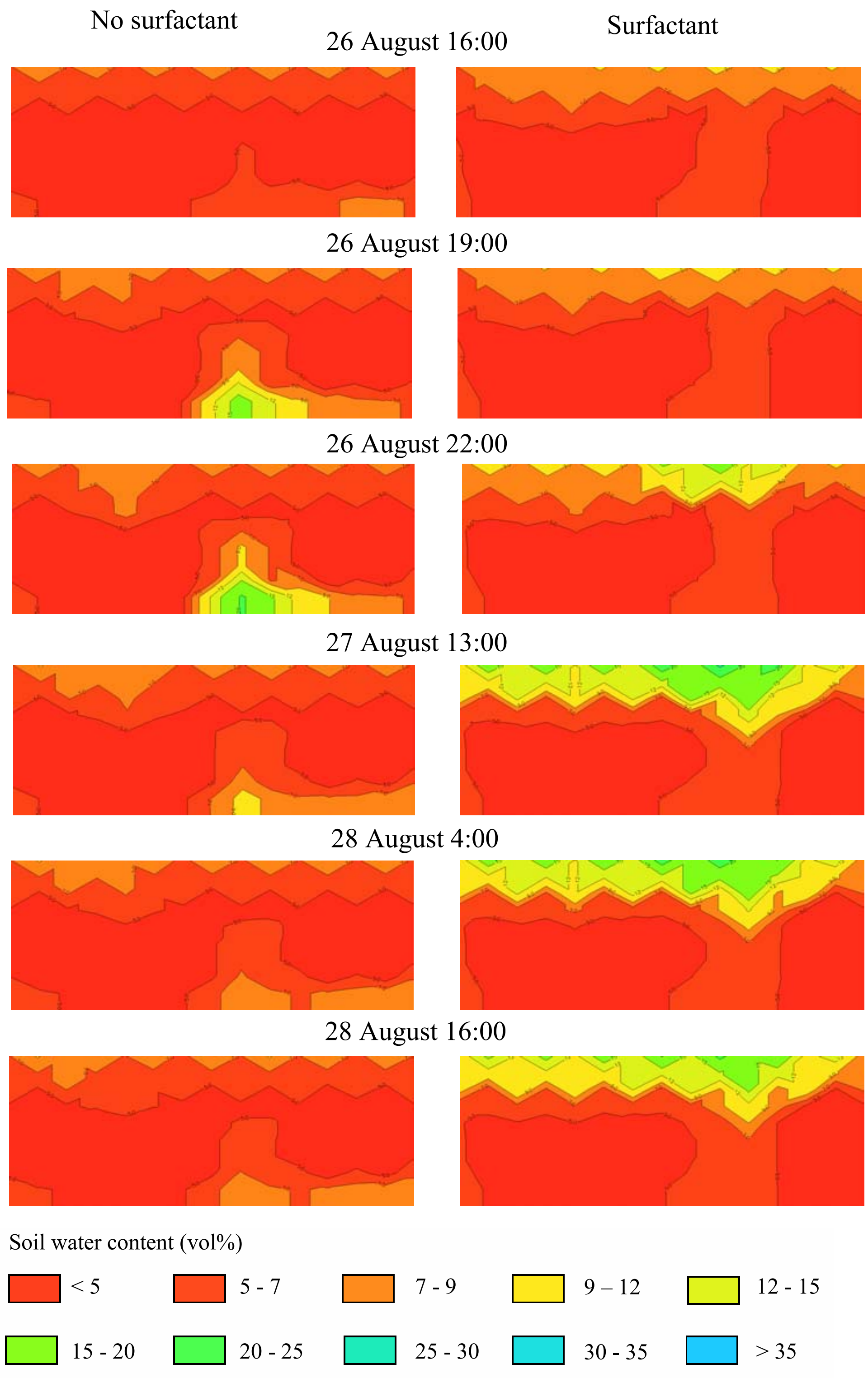

Figure 52 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the plot without and in the plot with surfactant applications, due to 16 mm precipitation on 26 and 27 August, 2001.

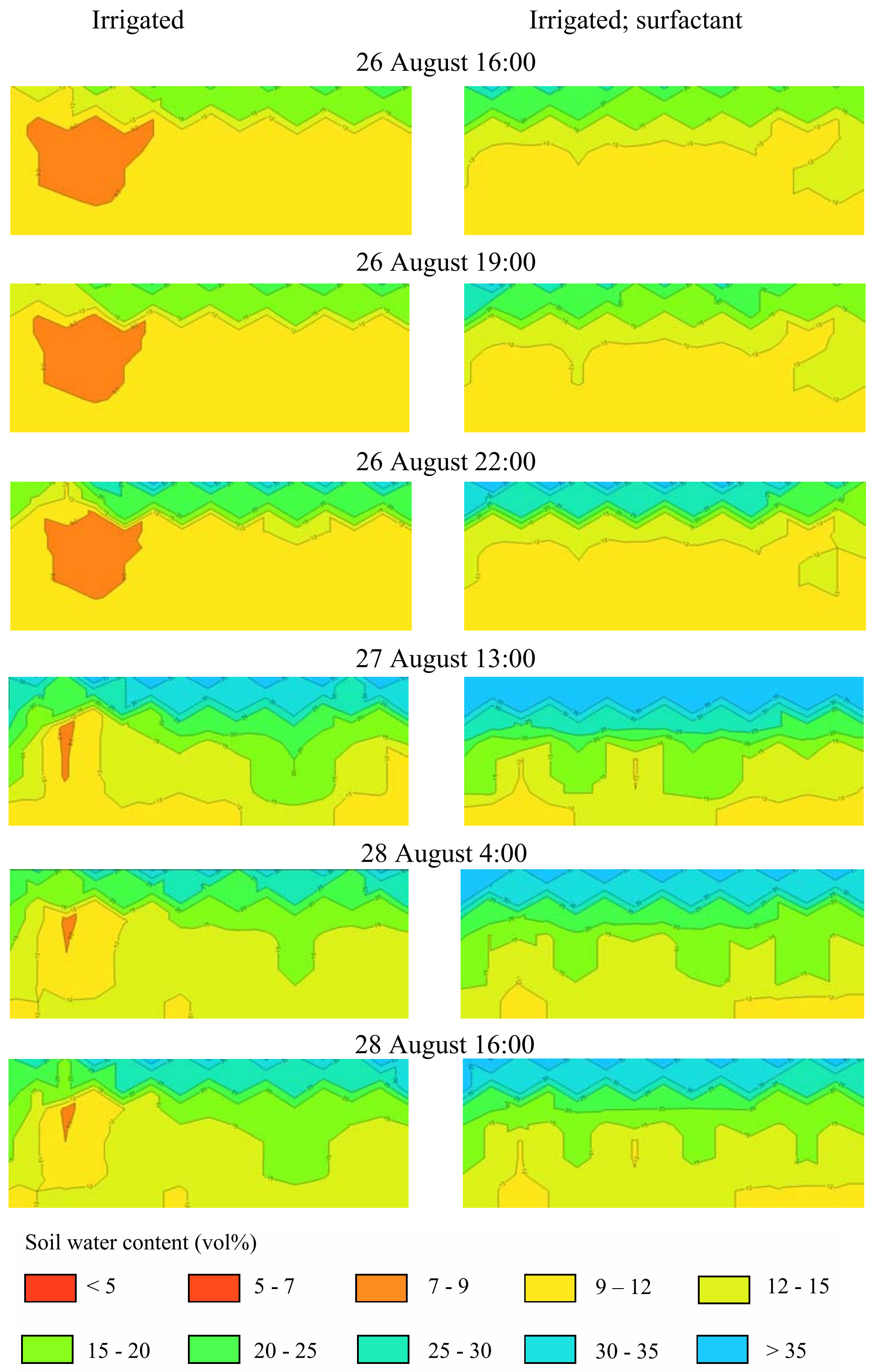

Figure 53 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the irrigated plot without and the irrigated plot with surfactant applications, due to 16 mm precipitation on 26 and 27 August and 20 mm irrigation on 27 August, 2001.

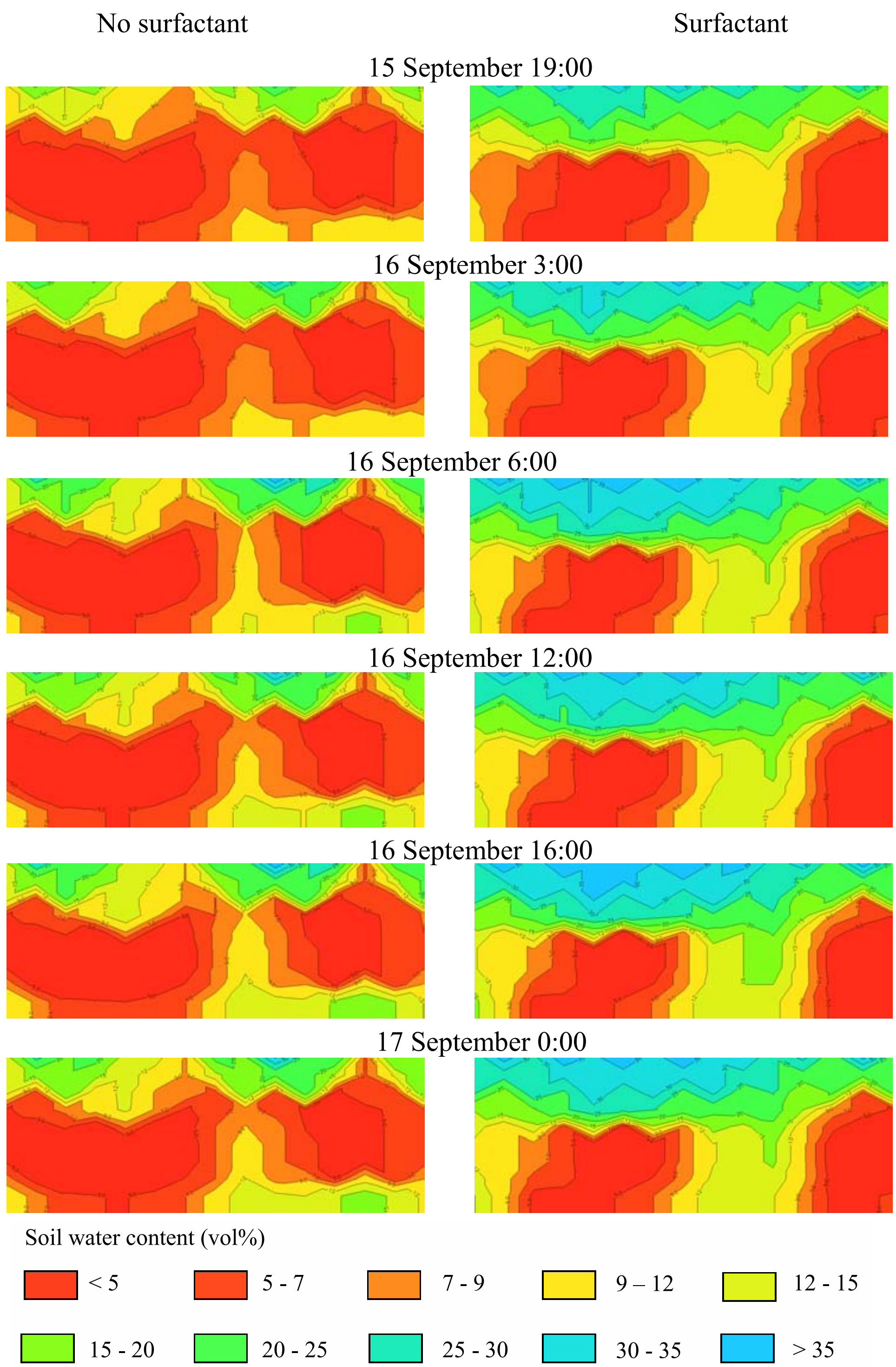

Figure 54 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the plot without and the plot with surfactant applications, during a period with a total of 48 mm precipitation.

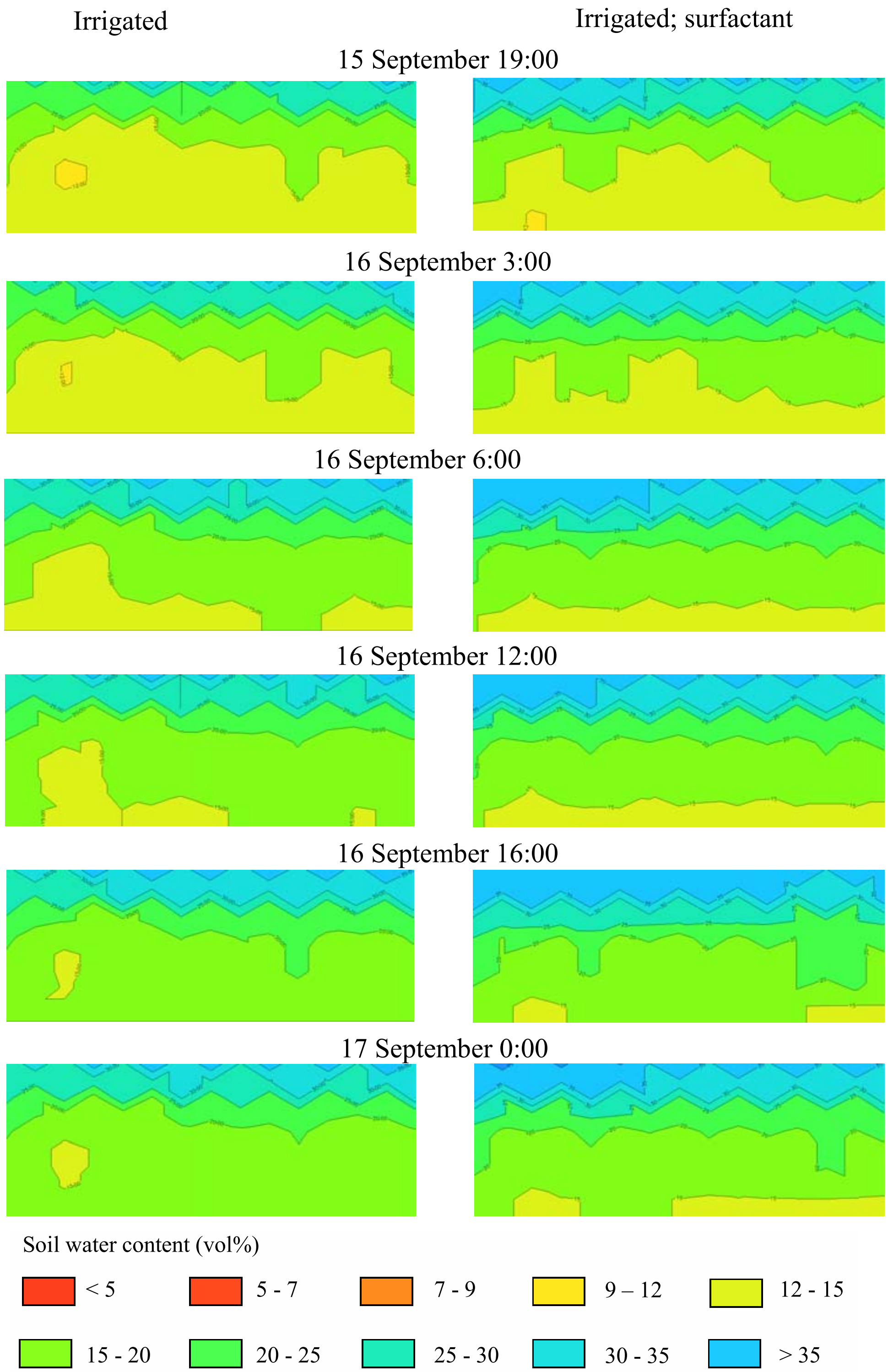

Figure 55 Contour plots (width 80 cm; depth 30 cm) of the changes in soil water contents in the irrigated plot without and the irrigated plot with surfactant applications, during a period with a total of 48 mm precipitation.

Figure 38 and Figure 39 show the temporal and spatial changes in soil water contents in the four plots during a dry period, and without irrigations between 1 and 16 May, 2001. The diagrams show clearly that the irrigated plots are significantly wetter and variations in soil water content much less than in the non-irrigated plots.

Figure 40 and Figure 41 illustrate the effects of 25 mm of precipitation between 15 and 19 June, and 30 mm of irrigation on 18 June, on the spatial and temporal changes of the soil water contents in the four plots. The diagrams in Figure 40 clearly show that the surface layer of the Primer®604 treated plot wetted much better due to rain events than the untreated plot.

The surface layer of the untreated plot became significantly dryer than the surface layer of the surfactant treated plot during the dry period between 19 and 24 June, 2001 (Fig. 42). During this dry period we detected also a significant wetter surface layer, and less dry areas deeper in the soil profile in the irrigated plot with surfactant applications, compared with the untreated, irrigated plot (Fig. 43).

Between ten and twelve o'clock in the morning of 23 July, 2001, 30 mm of water was irrigated on the two plots concerned. Figures 44 and 45 show the soil water contents in the four plots between ten o'clock in the morning and midnight. It is noteworthy, that the surface layer of the non-irrigated plot with Primer®604 applications, was significantly wetter than the surface layer of the untreated plot (Fig. 44). Although dry pockets remained in both plots, irrigation wetted the surface layer of the treated plot more homogeneous than the surface layer of the untreated plot (Fig. 45). Naturally, significantly higher soil water contents were found in the irrigated plots (Fig. 45), compared with the non-irrigated plots (Fig. 44).

The water contents during a further drying of the non-irrigated plots between 24 and 28 July, 2001 are shown in Figure 46. Remarkable is the always wetter surface layer in the surfactant treated plot. Figure 47 shows that during this dry period the surface layer of the irrigated plot with surfactant applications was significantly wetter than the untreated plot. Also less dry areas occurred in the treated plot, in comparison with the untreated plot.

Figure 48 shows that 15 mm of precipitation on 5 August, 2001 resulted in the wetting of the surface layer in the plot with surfactant applications, but only slightly influenced the soil water contents in the untreated plot. Figure 49 shows for the same times the changes in soil water content in the irrigated plots, due to the 15 mm of precipitation on 5 August, and the 20 mm of irrigation on 6 August, 2001. The diagrams show that less dry pockets occurred in the surfactant treated plot, compared with the untreated plot.

During the period 8 to 13 August, 2001 around 45 mm of rain precipitated, which only slightly influenced the soil water contents in the untreated plot, and evidently better wetted the surface layer of the Primer®604 treated plot (Fig. 50). At the same times the irrigated plot with surfactant applications was homogeneous wet in the surface layer and more or less homogeneous moist deeper in the soil profile (Fig. 51).

By contrast with the Primer®604 treated plot, the surface layer of the untreated plot scarcely wetted by the 16 mm of rain fallen on 26 and 27 August, 2001 (Fig. 52). The effects of the 16 mm of precipitation and 20 mm of irrigation on

27 August on the spatial and temporal variability in soil water contents of the irrigated plots have been depicted in Figure 53.

Figure 54 and Figure 55 show the effects of 48 mm of precipitation on 15 and 16 September, on the spatial and temporal changes of the soil water contents in the four plots. The diagrams clearly show that the surface layer of the surfactant treated plot wetted much better than the untreated plot (fig. 54). Only slight differences in soil water contents occurred between the two irrigated plots (Fig. 55).

3.3. Effects and Evaluation of Treatments

3.3.1. Mean Amounts of Water in the Soil Profiles

The mean amounts of water in four layers of the four plots during the period 15 July to 30 October, 2000 are shown in Figure 56. It is remarkable that the amount of water in the Primer®604 treated plot was significantly larger than in the untreated plot in the second half of the concerning period. It is noteworthy that the amount of water during that period in the treated plot was even larger than in the untreated, irrigated plot. Irrigation and surfactant applications resulted during the whole period in larger amounts of water in the profile, in comparison with the irrigated plot without surfactant.

Figure 57 shows slightly larger amounts of water in the surfactant treated plots, compared with the untreated plots during the period 13 March to 14 November, 2001.

The mean total amounts of water in the upper 35 cm of the four plots during the periods 15 July to 31 October 2000, and 13 March to 14 November 2001, have been depicted in Figure 58. This figure demonstrates again the larger amounts of water in the surfactant treated plots, when compared with the untreated plots.

The mean total amounts of water in the upper 35 cm of the four plots for some selected periods are shown in the diagrams of Figure 59. Large differences in amounts of water were found between the irrigated and the non-irrigated plots in 2001. In both years significantly larger amounts of water were often detected for the Primer®604 treated plots, when compared with the untreated plots.

3.3.2. Percentages of Areas Wettable Soil in the Profiles

The soil water contents measured with the TDR probes between 0 and 20 cm depth have been transformed into actually wettable and water repellent soil, making use of the critical soil water contents at different depths for the untreated and treated plots, as discussed in section 3.2.2.

Figure 60 shows that in comparison with the other plots, the irrigated plot with surfactant applications contained the most wettable areas in the upper 20 cm of the soil profile between July and October 2000, and that during that period actually water repellent soil was most evident in the plots without surfactant applications.

Table 3 shows that during the period July to October 2000 the mean area of wettable soil in the upper 20 cm of the profile was larger (29%) in the plot with surfactant applications, in comparison with the untreated plot (12%), and that the largest area of wettable soil (53%) was detected in the plot with irrigations and surfactant applications.

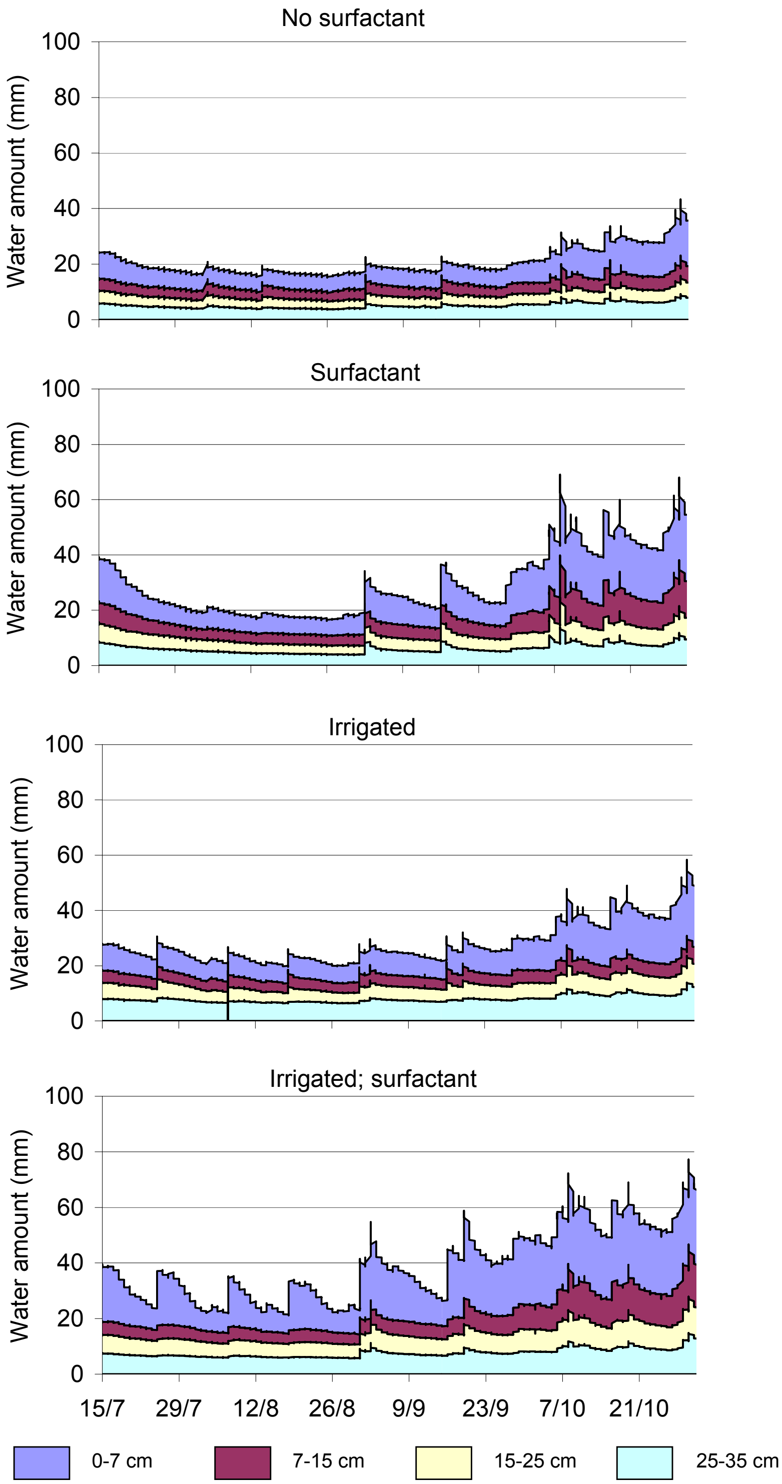

Figure 56 Mean amounts of water at depths between 0 and 35 cm in the four plots during the period 15 July to 30 October, 2000.

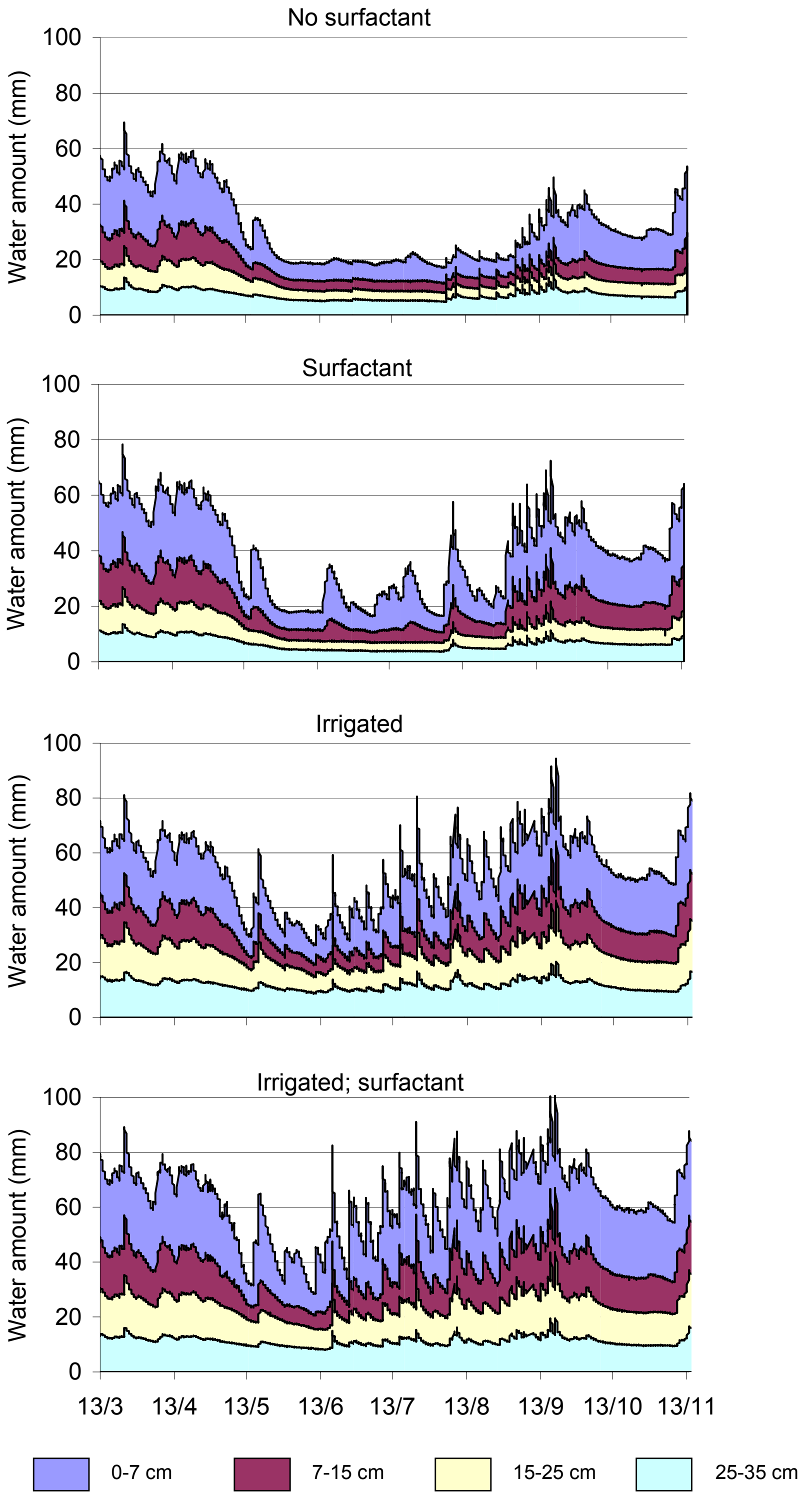

Figure 57 Mean amounts of water at depths between 0 and 35 cm in the four plots during the period 13 March to 14 November, 2001.

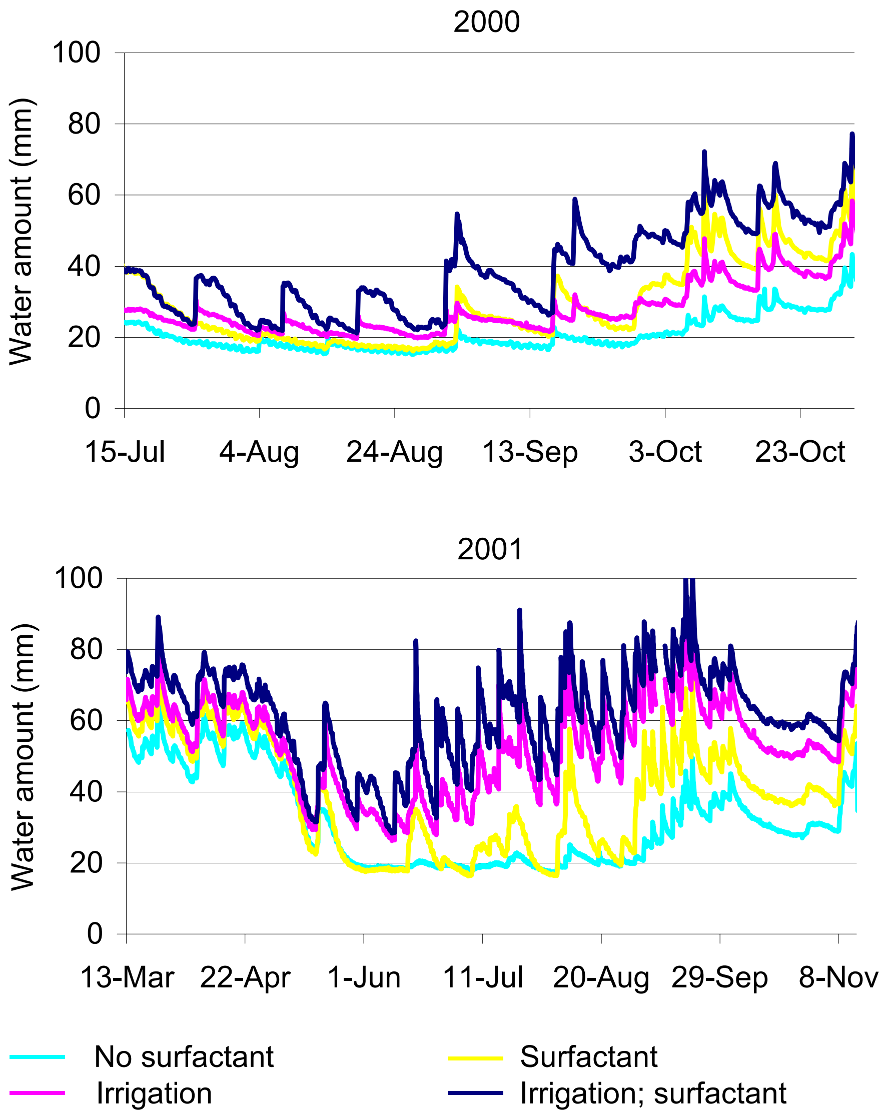

Figure 58 Mean amounts of water in the soil layer between 0 and 35 cm depth in the four plots during the periods 15 July to 30 October, 2000 and 13 March to 14 November, 2001.

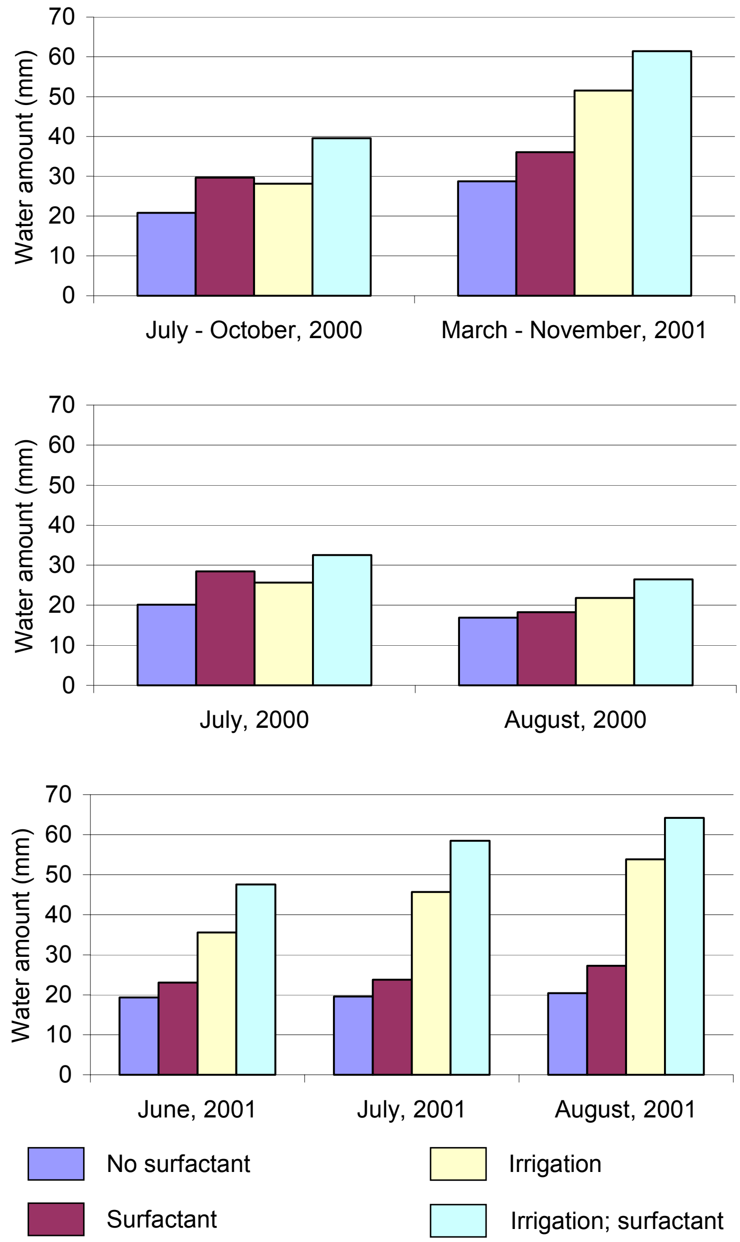

Figure 59 Mean amounts of water in the soil layer between 0 and 35 cm depth in the four plots during several periods.

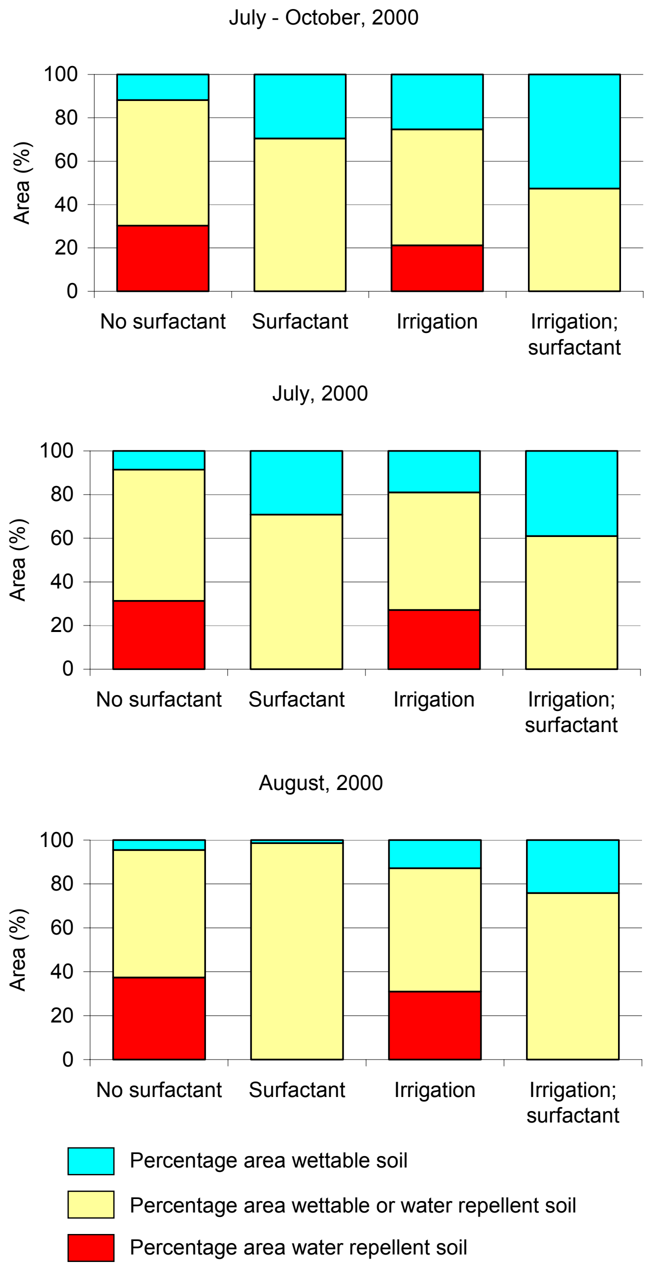

Figure 60 Mean percentages of areas wettable and water repellent soil in the profiles of the four plots between 0 and 20 cm depth, during the periods July to October, July, and August 2000.

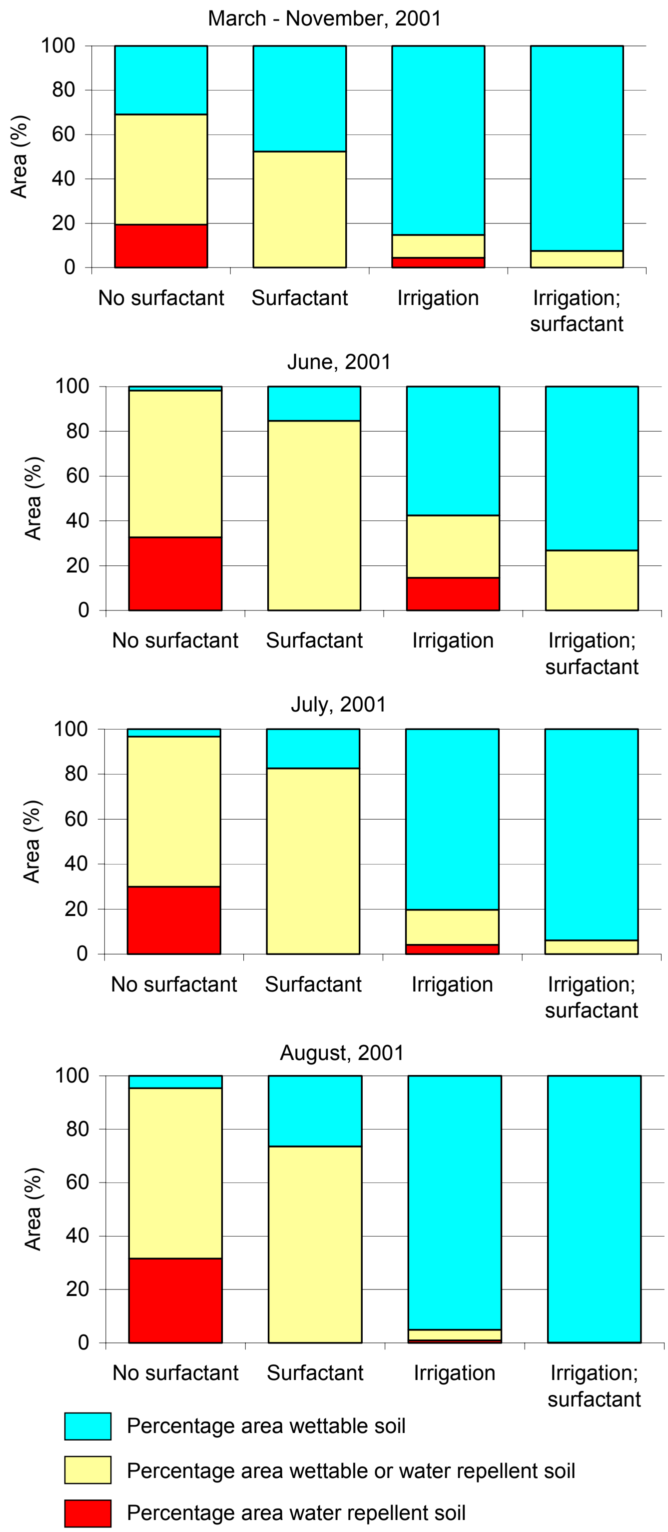

Figure 61 Mean percentages of areas wettable and water repellent soil in the profiles of the four plots between 0 and 20 cm depth, during the periods March to November, June, July, and August 2001.

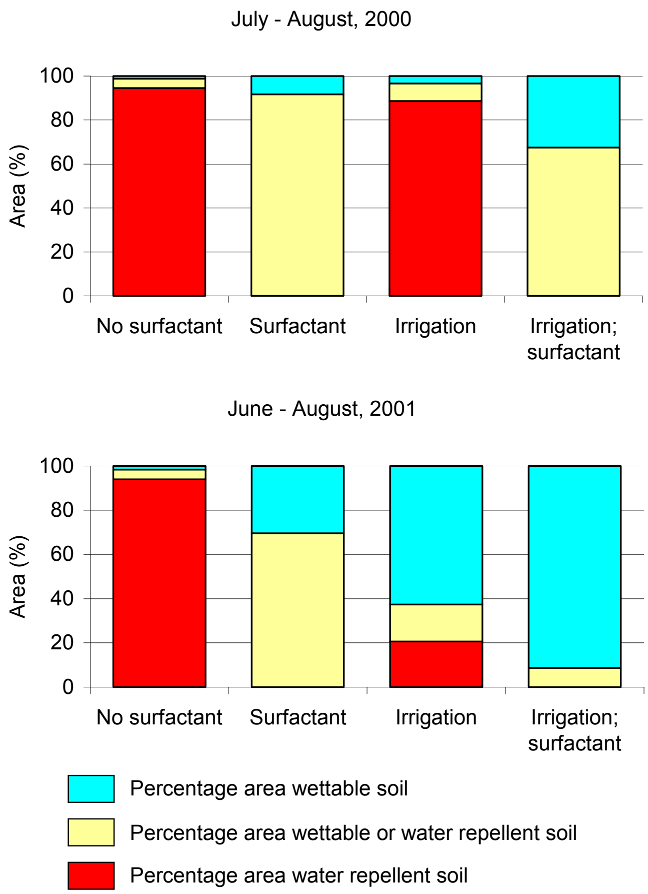

Figure 62 Mean percentages of areas wettable and water repellent soil in the profiles of the four plots between 0 and 7 cm depth, during the periods July to August 2000 and June to August 2001.

Table 3 Mean percentages of areas wettable and water repellent soil in the profiles of the four plots between 0 and 20 cm depth, during the period July to October, 2000.

Treatment	Wettable (%)	Wettable or repellent (%)	Water repellent (%)
No surfactant	12	58	30
Surfactant	29	71	0
Irrigation	25	54	21
Irrigation; surfactant	53	47	0

Figure 61 illustrates that surfactant applications improved the wettability of the soil, but that irrigations combined with surfactant applications, for instance in August, completely remained the profile wettable to a depth of 20 cm.

Table 4 shows that during the period March to November 2001 the mean area of wettable soil in the upper 20 cm of the profile was larger (48%) in the plot with surfactant applications, in comparison with the untreated plot (31%), and that the largest area of wettable soil (92%) was detected in the plot with the combination of surfactant applications and irrigations.

Table 4 Mean percentages of areas wettable and water repellent soil in the profiles of the four plots between 0 and 20 cm depth, during the period March to November, 2001.

Treatment	Wettable (%)	Wettable or repellent (%)	Water repellent (%)
No surfactant	31	50	19
Surfactant	48	52	0
Irrigation	86	10	4
Irrigation; surfactant	92	8	0

Figure 62 shows that during the periods July to August 2000 and 2001, the soil to a depth of 7 cm in the untreated plot was nearly completely water repellent, whereas irrigations in combination with surfactant applications resulted in a nearly 100% wettable soil in July-August 2001.

4. Conclusions

Applications of Primer®604 as well as irrigations lowered the persistence of actual water repellency in the surface layer (0-5 cm), as shown in Figure 5.

The combination of irrigations and surfactant applications was most effective in beating the water repellency phenomenon, however a part of the soil at depths between 7 and 19 cm still exhibited water repellency during the first year.

Surfactant applications resulted in significantly less persistence and degree of potential water repellency after drying the soil samples, taken at all 10 depths in the irrigated plots in the temperature range from 30 to 85^{0}C (Figs. 7 and 8).

Primer®604 applications resulted in higher mean soil water contents at 4 and 10 cm depth in the non-irrigated and irrigated plots during the periods 19 September to 31 December 2000, and July to November 2001.

Surfactant applications improved the wettability of the soil, but these applications were most effective in combination with irrigations.

It is recommended to start irrigations and surfactant applications before critical soil water contents are reached, to prevent the soil to become water repellent.

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