Chapter 14

Development and Application of Fuzzy Indicator for Assessment of Soil Water Flows

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Abstract

Despite abundant rainfall, southeastern sandy Coastal Plains of the USA can be droughty because of low water holding capacity soils. A Sentek frequency domain reflectometry sensor was used to measure volumetric soil water content at 30 min time steps and 10-cm depth intervals to 1 m. Sensor and rainfall data were collected starting on day of year 153 (June 1) to day of year 259 (September 15). We interpreted data using a semi-quantitative approach, which was based on fuzzy indicators of soil water flow. Results showed that fuzzy indicators of soil water flow could be useful in analysis of the soil water regime.

Keywords: fuzzy indicator, soil water flow, Coastal Plain soils

Introduction

In the southeastern Coastal Plains of the USA, rainfall is abundant, except for years when drought can be devastating (http://nc.water.usgs.gov/ and http://sc.water.usgs.gov/). Rainfall averages more than 1145 mm y^{-1} (http://www.dnr.state.sc.us/climate, http://www.nc-climate.ncsu.edu/). Yet water is the limiting growth factor because almost every year crops experience droughts of two weeks or more (Sheridan et al., 1979). Droughts can cause yield-reducing stress in these sandy soils that have low water holding capacities (0.08 g g^{-1}) (Sadler and Camp, 1986).

Effective rainfall (the amount of rainfall that is held in the profile for plant root uptake) can be estimated in a table lookup procedure (http://www.fao.org/documents/) or by calculation (http://aben.cals.cornell.edu/faculty/walter/GreenAmpt v4.doc). It can also be measured by determining differences in water content with time as rain adds water to the soil and roots take water from it. These measurements can be made with a number of devices that quantify soil matric potential or volumetric soil water content as it changes with time, such as tensiometers, time domain reflectrometry sensors, or neutron probes (Wiedenfeld, 2004; Burt et al., 2005). We used a Sentek EnviroSCAN sensor that uses capacitance probes to measure volumetric soil water content with frequency domain reflectometry.

Volumetric soil water content data interpretation is routinely carried out with a variety of models ranging from qualitative to quantitative. Qualitative and quantitative models differ in their technical development, i.e. use of expert knowledge versus process-orientated simulation models. Semi-quantitative models are based on combination of expert knowledge and process-orientated simulation. Fuzzy logic models are a special case of semi-quantitative models. One group of fuzzy models is labeled as fuzzy indicators. Fuzzy indicators are one way to interpret experimental data. For example, fuzzy indicators have been successfully applied to assess anthropogenic loading and ecosystem resistance (Bogardi et al.,1996), to design a strategy that limits pollution damage to agricultural fields (Kurtener et al., 1999), to rate the effectiveness of site-specific residue management in agricultural field management (Kurtener and Badenko, 2000), to interpret computer simulation of maize yields (Kurtener et al., 2001), to analyze drainage plots (Kurtener and Badenko, 2001), and to assess the quality of geo-referenced data (Kurtener et al., 2004a, 2004b).

The objective of this study was to use water content measured on half-hourly basis and rainfall measured at a nearby weather station to estimate infiltration and crop uptake throughout the growing season using a semi-quantitative approach.

Materials and Methods

Study site

In May 2005, two varieties of cotton (*Gossypium hirsutum* L. var. Coker 555 and 1218) were planted in plots at the Pee Dee Research Center of Clemson University about 8 km NE of Florence, SC USA (34.28744° N and 79.74370° W) using reduced tillage methods: no surface tillage, in-row deep (35 cm) disruption with a KMC subsoiler (Kelley Manufacturing Co., Tifton, GA, USA) on 0.97 m row widths in plots that were 7.6 m wide and 15 m long.

Plots were located on a Goldsboro loamy sand (fine-loamy, siliceous, subactive, thermic Aquic Paleudult in the USDA classification and Acrisol in the FAO classification). Goldsboro was a moderately permeable, deep, moderately well drained soil that formed in Coastal Plain marine sediments. Goldsboro typically had depths to seasonally high water tables that were at 50 to 75 cm depths. It had Ap and E horizons that were 30 to 35 cm deep with 2 to 8% clay content and 0.5 to 2% organic matter. These horizons typically had 1 to 3 meq per 100 g cation exchange capacity. A Bt horizon was below this. The Bt horizon was a sandy clay loam with 18 to 30% clay content and 0 to 0.5% organic matter. This horizon typically had 2 to 4 meq per 100 g cation exchange capacity with more structure than the Ap and E.

In late May, cotton was planted with Case-IH series 900 planters (Case-IH, Racine, WI, USA) at a rate of 12 plants m^{-1}. Nitrogen (90 kg ha^{-1} as ammonium nitrate) was applied in a split application (half at planting and half one month later). Nitrogen was banded approximately 5 cm deep and 15 cm from the rows. Lime, P, K, S, B, and Mn were applied as needed, based on soil test results and Clemson University Extension recommendations (Franklin, 2001). Weeds were controlled with glyphosate [N-(phosphonomethyl) glycine]. Insects were controlled by applying aldicarb (0.85 kg ai ha^{-1} of 2 methyl 2 (methylthio) propionaldehyde O methylcarbamoyloxime) in furrow for thrips [Frankliniella occidentalis (Pergande)]; other insecticides were applied as needed.

In mid October, cotton was chemically defoliated. In November, seed cotton yield was harvested using a two-row spindle picker and bagged. Each harvest bag was subsampled, and the subsample was saw-ginned to measure lint percent. Lint percentage was multiplied by seed cotton yield to estimate lint yield.

After planting, EnviroSCAN sensors (Syntek Pty Ltd, Stepney, South Australia) were installed in replicates 3 and 4 of each variety to scan water contents every half hour at 10 cm depth intervals to 1 m. Sensor data were stored in a CR21X (Campbell Scientific, Inc, Logan UT) and downloaded weekly. Rainfall data were collected from weather station Site Number 2037 of the National Water and Climate Center of the National Resources Conservation Service of USDA (http://www.wcc.nrcs. usda.gov/); the site was located about 135 m away from the sensors. Data from the weather station were collected on an hourly basis.

Semi-quantitative model for estimating infiltration and evapotranspiration

Soil water content data were analyzed using a semi-quantitative model based on mass balance. The model assumed that any change in water content for each time step (and each depth interval) was associated with upwelling, deep percolation, evapotranspiration, or infiltration. The model was the basis of a simple QBasic program developed to calculate infiltration, evapotranspiration from the profile, upwelling from below the zone of measurement, and deep percolation to soil below the zone of measurement. Data for model input were collected starting on day of year 153 (June 1) to day of year 259 (September 15). The model assumed that any subsurface lateral flow that might have added water into the zone of measurement was equal to lateral flow out of the zone.

Infiltration was calculated as an increase in soil water content during or near a rainfall event filling the soil at the surface and continuing down the profile. Deep percolation was calculated as loss of water out the bottom of the profile without changes in water content above. Upwelling was calculated as a gain of water in the bottom of the profile without losses in water content immediately above. Evapotranspiration was calculated as loss of water content from the profile that was not deep percolation or redistribution within the profile. Calculated data were fit to simple equations using Tablecurve 2D (Systat, Point Richmond, CA), EXCEL (Microsoft, Corp., Redmond, WA), and SAS (SAS, 2000).

Application of fuzzy indicator approach

A fuzzy indicator of water flow ($-1 \leq WFFI \leq 1$) was designed to show intensity and orientation of water movement. In particular, when depth of soil varied from 0 to 50 cm if $-1 \leq WFFI \leq 0$, water movement was interpreted as infiltration; and if $0 \leq WFFI \leq 1$, it was evapotranspiration. In a similar manner, when depth of soil varied from 80 cm to 1 m and $-1 \leq WFFI \leq 0$, water movement was interpreted as deep percolation; and if $0 \leq WFFI \leq 1$, it was upwelling.

WFFIj was defined as the fuzzy indicator of water movement at the boundary of two neighboring layers of soil. It was proportional to difference between soil water contents (volume water/volume total) in these two neighboring layers. Here j was an index between layers, which increases with depth of the soil, e.g. j=1 between layers 1 and 2, j=2 between layers 2 and 3... WFFI was modeled as a piecewise continuous function with time of data collection; it was calculated using a simple program based on EXCEL and MATLAB.

Results and Discussion

Observations of soil water content

Results of observations of soil water contents were presented in Figures 1 to 4. Figures 1 to 3 showed the soil water content plotted for each half-hour time step in the top 3 layers. Figure 4 illustrated in soil water content in bottom layer.

Calculation of rainfall, infiltration, and evapotranspiration

Using the Qbasic program, rainfall, infiltration, and evapotranspiration were calculated as cumulative amounts to smooth out any differences in time measurement between the weather station and the soil sensor data collection (sensor #1 in rep 3 cotton variety 1218 was shown as an example in Figure 5). Infiltration throughout days 153 to 210 generally ranged between 75 to 85% of rainfall (sensor #1 shown as an example in Figure 6) with spikes during storm peaks when water would have ponded on the soil surface. After day 210, the profile was usually full of water as a result of a hurricane, tropical storm, and tropical depression passing through the area. Since the profile was full, water was unable to infiltrate; it ran off the surface or evaporated. This lowered the cumulative (Figure 5) and average (Figure 6) amounts of infiltration from 75 to 85% down to 55 to 70% for all 4 sensors.

Evapotranspiration from the soil was mainly (41 to 48%) from depths 0 to 20 cm (Figure 7); next highest was 16 to 26% from depths 20-30 cm; below that it diminished exponentially with depth. Season long upwelling from the wetter, lower part of the profile into the upper dryer part of the profile was calculated at from 2.5 to 3 cm and movement of water upward in the profile as a result of root activity (upwelling that appeared to bypass sections of the profile) was calculated at less than 0.13 cm.

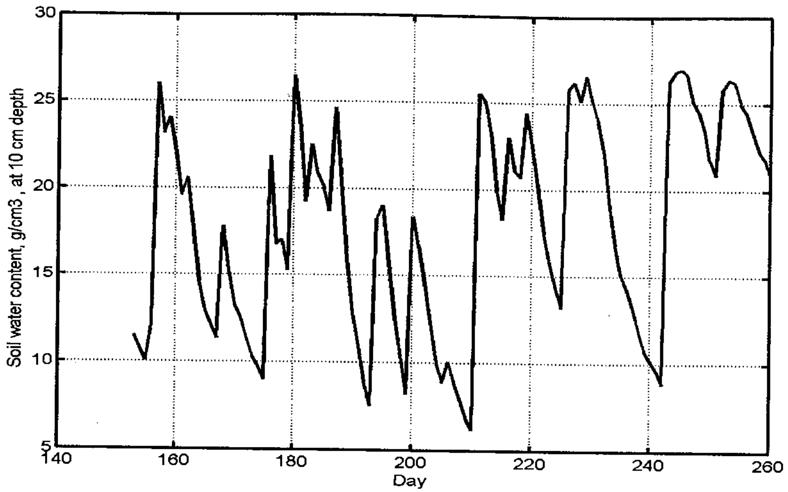

Fig. 1. The change in soil water content during vegetation season at 10 cm depth.

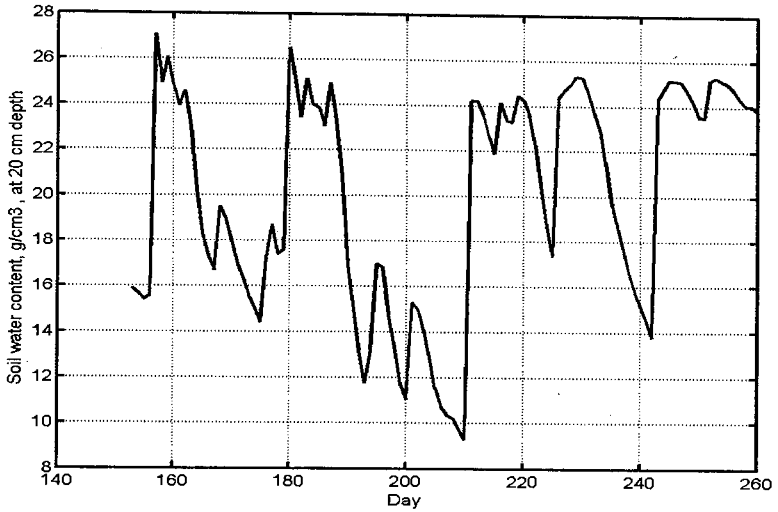

Fig. 2. The change in soil water content during vegetation season at 20 cm depth.

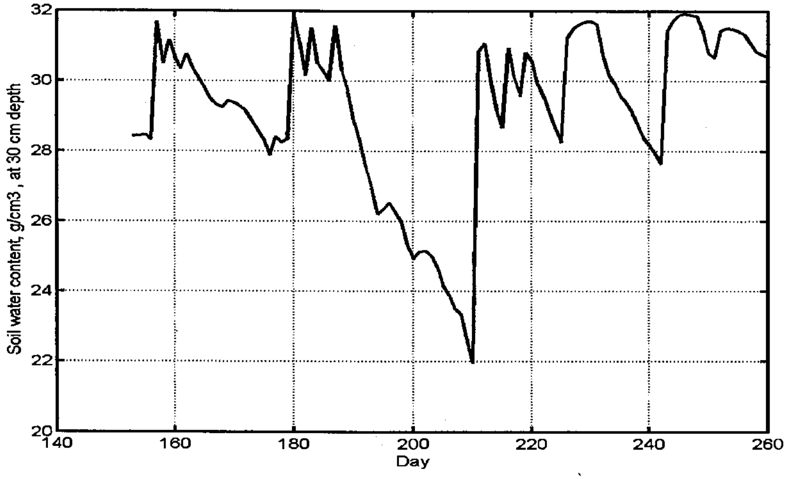

Fig. 3. The change in soil water content during vegetation season at 30 cm depth.

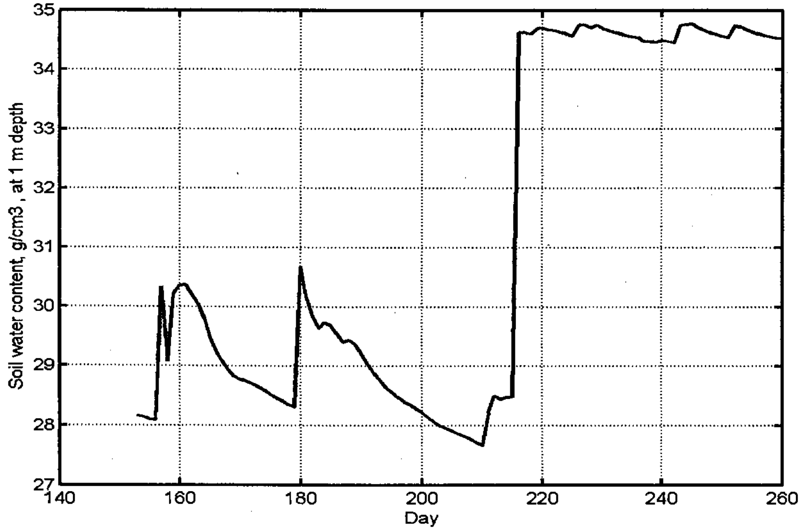

Fig. 4. The change in soil water content during vegetation season at 1 m depth.

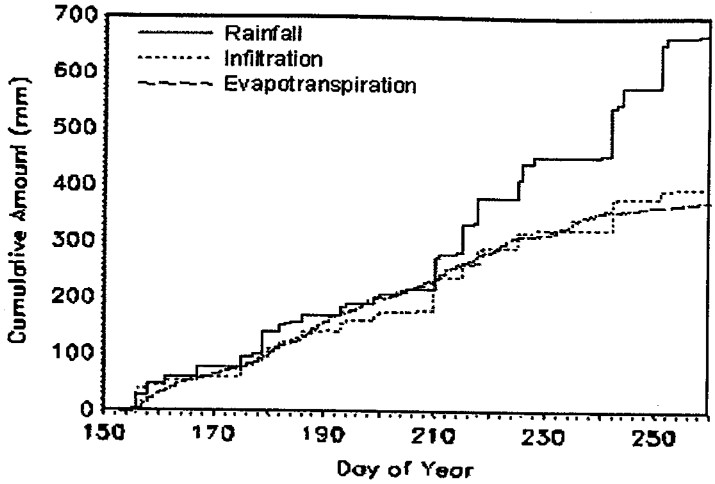

Fig. 5. Cumulative amounts of rainfall, infiltration, and evapotranspiration for cotton calculated at sensor #1.

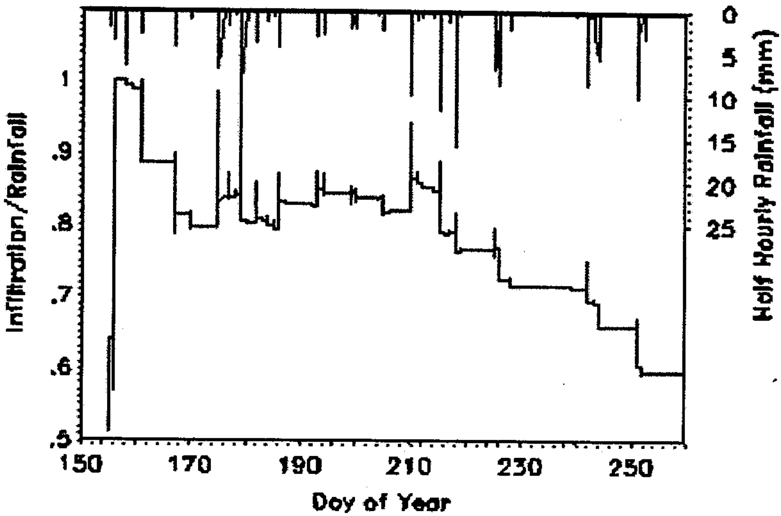

Fig. 6. Ratio of infiltration to rainfall and hourly rainfall totals as a function of day of year from May 31 to September 16, 2004.

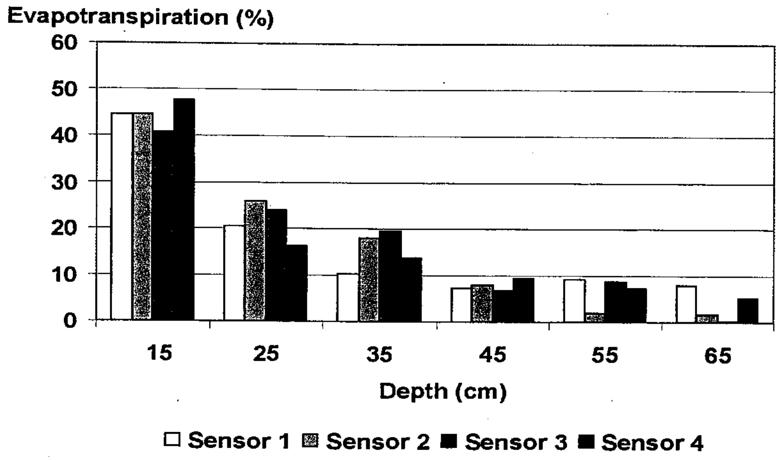

Fig. 7. Evapotranspiration decreases with depth. Sensor 1 was associated with rep 3 cotton variety 1218; sensor 2 with rep 3 cotton variety 555; sensor 3 with rep 4 cotton variety 1218; sensor 4 with rep 4 cotton variety 555.

Assessment of soil water flow using fuzzy indicators

Results of the fuzzy-indicator computer simulations were presented in Figures 8, 9, 10 and 11. In particular, Figure 8, 9 and 10 demonstrated the fuzzy indicators of water flow at the boundaries of the three top neighboring layers of soil, which were associated with infiltration (if WFFIj > 0), or with evapotranspiration (if WFFIj < 0). Figure 11 showed the fuzzy indicator of water flow at the boundary of two bottom layers of soil (depth = 90 cm), which was associated with deep percolation (if WFFIj > 0), or with upwelling (if WFFIj < 0).

Conclusions

Mid-season cumulative infiltration was 75 to 85% with rates topping 90% as a result of ponding during storms. Cumulative infiltration dropped to 60% after the profile filled with water as a result of several storms. Evapotranspiration was highest in the top foot, which contributed 64 to 70% of plant root uptake; it decreased exponentially below that. Since the soil had been deep tilled, we expected water to be taken from deep in the profile; however, two-thirds of the water for plant growth came from the top foot.

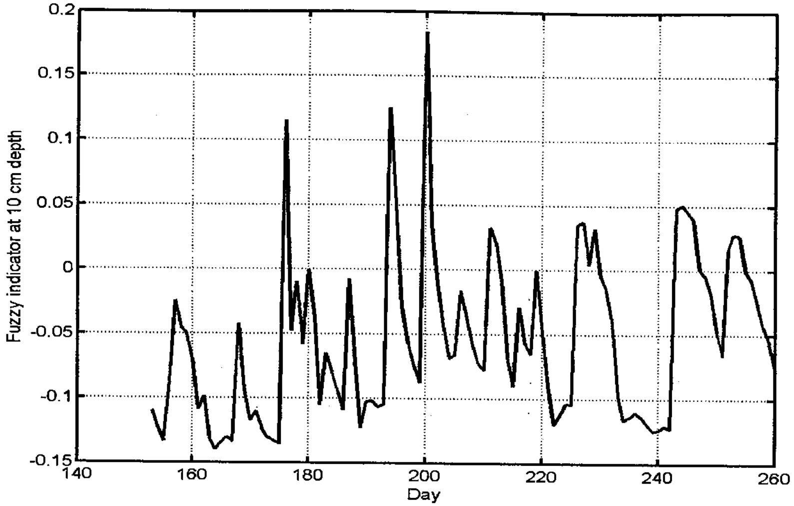

Fig. 8. Fuzzy indicator at 10 cm depth.

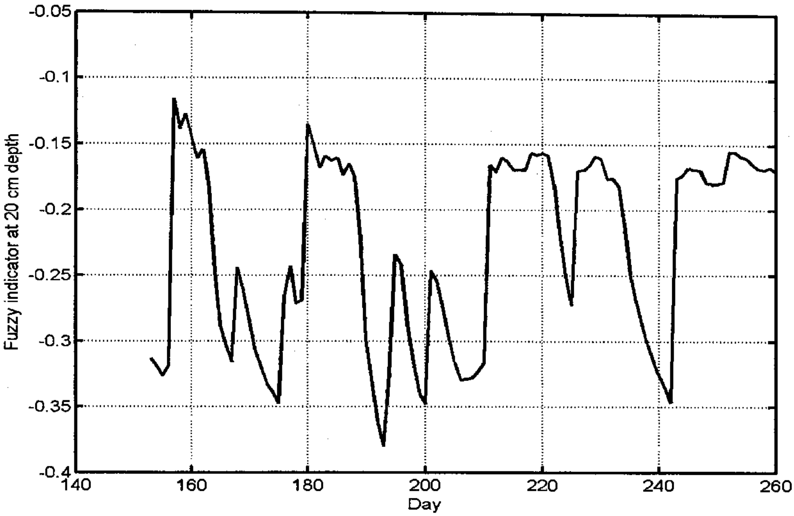

Fig. 9. Fuzzy indicator at 20 cm depth.

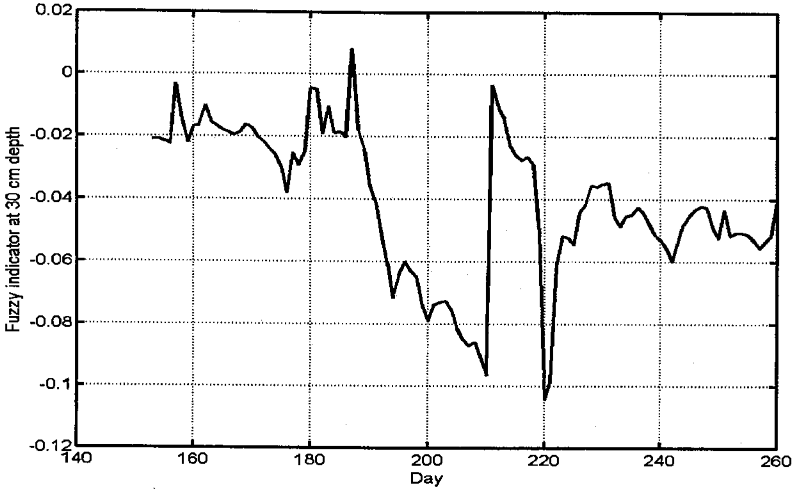

Fig.s 10. Fuzzy indicator at 30 cm depth.

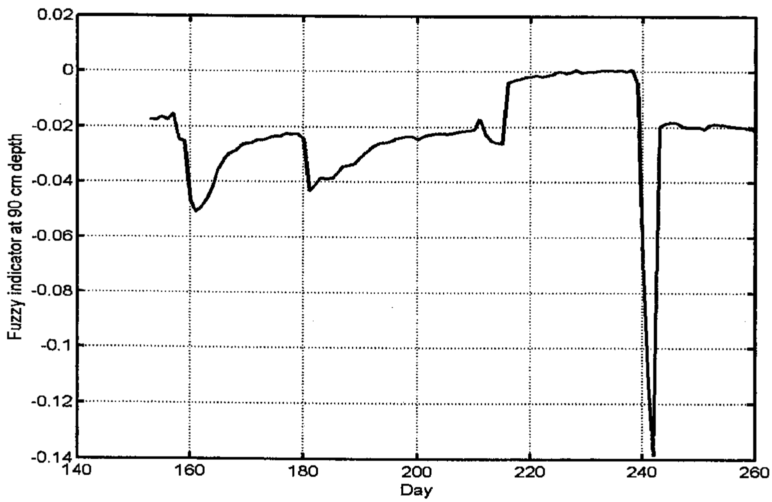

Fig. 11. Fuzzy indicator at 90 cm depth.

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Аннотация к главе 14

В главе 14 описывается математическая модель для оценки величины и направления потока почвенной влаги. Модель предназначена для анализа данных экспериментов, когда собранной информации оказывается недостаточно для определения величины и направления потока почвенной влаги традиционными методами.

Модель основана на применении нечеткого индикатора WFFI (-1 ≤ WFFI ≤ 1). Полагается, что, если -1 ≤ WFFI ≤ 0, то поток почвенной влаги направлен вглубь почвы, а, если 0 ≤ WFFI ≤ 1, то поток почвенной влаги направлен вверх (т. е. из почвы).

Для иллюстрации описываемой модели был проведен ряд расчетов. В качестве входных данных использовались данные эксперимента, проведенного на сельскохозяйственных полях, расположенных на землях Прибрежной равнины, США. Результаты расчетов показали, что разработанный нечеткий показатель может быть полезен при анализе водного режима почвы. В частности, когда исходной информации недостаточно для применения традиционных методов расчета, предложенный подход становится приемлемой альтернативой.