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RESEARCH ARTICLE

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Soil Hydrology of Irrigated Orchards and Agent-Based Simulation of a Soil Dependent Precision Irrigation System

Sven Grashey-Jansen* and Sabine Timpf

Institute of Geography, University of Augsburg, Augsburg 86135, Germany

In the context of the current discussions about climate change, the issue of protecting natural resources, especially water resources, is becoming more and more relevant. In many climate regions the availability of water in soils decides to a large extent their agricultural productiveness. Information about soil water dynamics provides valuable data to optimize irrigation practice with regard to volume and duration of irrigation. Irrigation must be based on objective and quantitative criteria, which focus primarily on soil properties and hydrological balances. Novel irrigation equipment requires detailed knowledge of the water distribution in the soil. Thus, a dense soil-hydrological measuring network must ideally be composed of special calibrated micro-sensors which are distributed in the soil for measuring soil moisture at high temporal and spatial resolutions. However, a proof of concept of the setup and operation of such a sensor network is needed before it may be realized. The management and control of sensor networks can best be modelled using an agent-based approach, where each sensor is represented by an agent in the model. The main result of this agent-based simulation is a detailed dynamic irrigation schedule based on water fluxes in the soil, adapting to real-time sensor information on soil moisture. This schedule results in a minimum amount of water used with maximum efficiency of irrigation.

1. INTRODUCTION

In many climatic regions the availability of water in soils determines to a large extent their agricultural productiveness. About 20% of the cultivated area of the earth must be irrigated because of limited precipitation. In many regions of the earth, irrigation represents an essential and indispensable factor of production whose necessity will become more and more imperative because of the climate change.

The water supply carries great weight in agriculture. Agriculture has a remarkable share of the global consumption of freshwater: about 70% of the freshwater total is used for irrigation. But freshwater is a sensitive resource that needs to be applied in agriculture in a more rational and effective way.[1] Therefore the theme of agricultural irrigation is of particular importance in the current discussion on the consequences of climate change.

The hydrological balance in soils is not only based on climatic factors, but a result of complex physical processes and numerous interactions between them. These processes and interactions are subject to enormous temporal and spatial variations, because they are controlled by external factors of the atmosphere or hydrosphere. But these factors are themselves subject to their own variations and interactions. On the other hand the pedosphere as a temporally static parameter shows enormous spatial variations. This pedological heterogeneity is not limited to the horizontal dimension, but it also is very multifaceted in the vertical dimension and–in a multidimensional view—leads to very complex soil-hydrological regimes. This represents a big challenge for orcharding, if a lucrative harvest can only be guaranteed by irrigating.

This contribution will show results of research on soil water dynamics under the influence of irrigation, which were carried out in the region of South Tyrol (Italy) for several years. We will also show how irrigation procedures and water consumption have the potential to be improved through a multi-agent simulation.

In the region of South Tyrol, with about 18.000 hectares and an annual production up to 900.000t the biggest coherent apple growing area in Europe, irrigation has always been a necessary factor of production. The transition from the Mediterranean to the Middle-European continental climate in principle provides good conditions for intensive crop cultivation. Therefore orcharding is possible up to a height of 800 metres above sea level maximum. In the sun-exposed slopes of the Vinschgau profitable orcharding is even possible up to 1.100 metres above sea level.

The average annual precipitation lies between 450 mm to 550 mm in the Vinschgau, an inner alpine arid valley, and about 650 mm in the region of the Mittleres Etschtal between Meran and Bozen. Because of these conditions irrigation has always been regarded as necessary, so that today more than 90% of the

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*Author to whom correspondence should be addressed.

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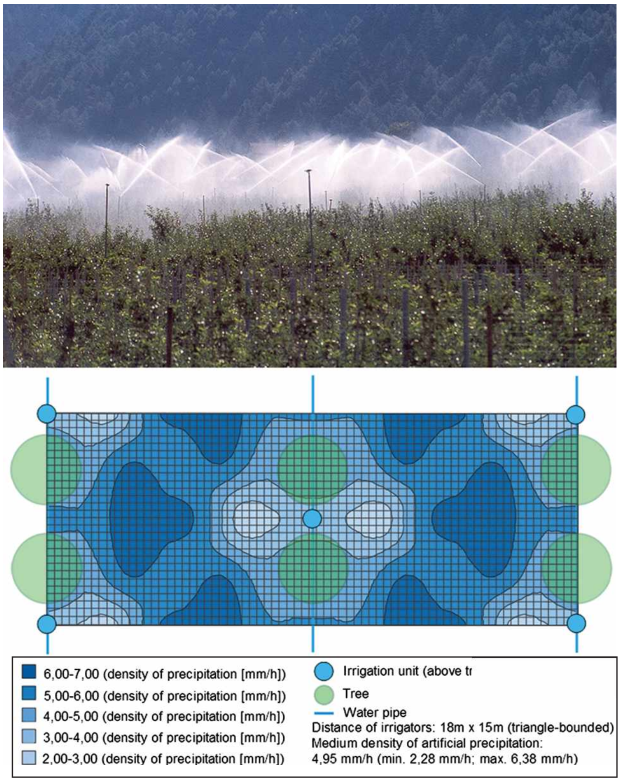

Fig. 1. Heterogeneous distribution of the irrigated water (modified according to Thalheimer and Paoli 2004).

South Tyrolese orchards are equipped with an irrigation system. The actual irrigation practice is based on primarily subjective criteria and–because irrigation over the treetops is also used–results in a very irregular distribution of the irrigation-water in the orchard-areas (Fig. 1), which is also due to the triangular or rectangular arrangement of the irrigation units (Fig. 2).

This arrangement causes an eminently unfavourable distribution of the density of the artificial precipitation, which may range between 2 mm/h and 6 mm/h under a constant operating pressure. The maximum of the density of the artificial precipitation is mostly attained at a distance of 1 m to 2 m from the irrigation unit (Fig. 3).

Because irrigation practice always directly affects the natural soil-water-balance and because over-irrigated areas have already been observed[2–5] in areas with a naturally high groundwater-table the current irrigation-strategies are being discussed with the emphasis on economic and ecological aspects. Over-irrigation wastes natural resources and power and may inflict damage on the environment through the leaching of nutrients that cause contamination in the ground water.[6] Furthermore, the existing irrigation-systems are used for frost-protection too, so that the agricultural consumption oft water in South Tyrol with 150 Mio m^3 per annum is twice as high as the industrial water consumption. Therefore irrigation is bound to become a cost-intensive factor of production in the near future.

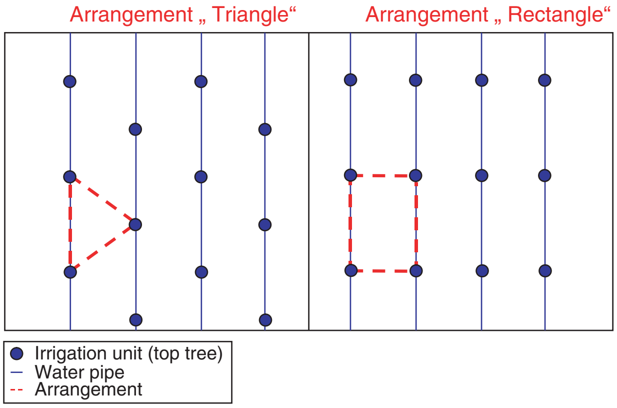

Fig. 2. Typical groupings of the irrigation units.

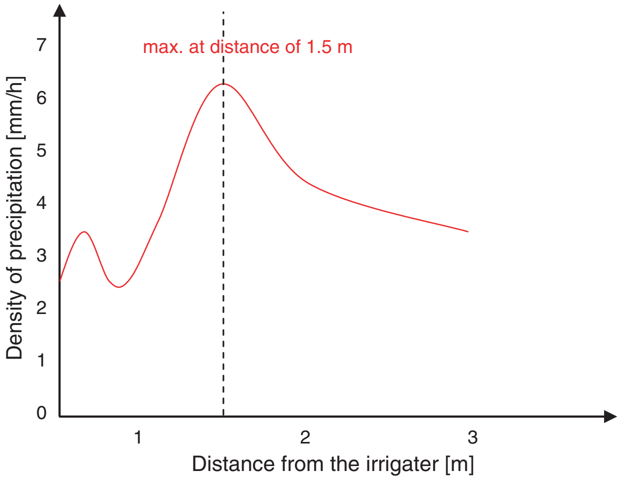

Fig. 3. Spatial differences in the density of precipitation.

Not only the growing public awareness in the region, but also the recommendations of the European Water Framework Directive cause legal constraints, so that the population increasingly discusses ways and means to optimize irrigation on the basis of objective criteria in the whole of Europe. To not endanger the irrigated cultures of different agricultural lines of production special irrigation strategies will be necessary in the future, which are oriented towards the actual water need of the plants and offer a higher efficiency. Different approaches have been discussed for several years under the term “precision irrigation.”

This paper will describe the problems that are connected with conventional irrigation from a soil-hydrological point of view using various examples. Furthermore it will present a simulation approach of a precision irrigation system regulated by specially calibrated wireless sensors. The simulation approach does not only detect the best point in time and the optimum water amount for irrigation, but it also delivers a differentiated irrigation plan, which is derived physically from the soil properties and described mathematically using an especially developed model. When the essential parameters are known this approach may also be applied at locations with other plant-specific limit values and criteria.

2. STATE OF RESEARCH

“Water” as a soil-forming and soil-affecting factor and its importance in the soil-plant-atmosphere-continuum (SPAC) was already assigned a key role decades ago.[7–13] It has also played an adequately important role in the summarising literature[14–17] as well as in special papers about this theme. In connection with that literature there are also studies about apple trees (*malus domestica*).[18–28] Regional studies about the influence of orchard-irrigation on the soil-water-dynamics have been published in the last couple of years.[3–5] In the science of agricultural and water economy the aspect of precision farming and precision irrigation is increasingly being discussed and researched.[29–32] Precision irrigation is defined as the timely and accurate water application in accordance with the spatial and temporal soil properties and in response to the plant demand under the different phenological development stages during the growing season.[1] The local pedological conditions, in addition to adapting the irrigation to the water demand of the plants in different phenological phases, plays an important role.[33–35]

Problems in a multidimensional capture of the relevant parameters still exist, because precision irrigation must be based on objective and quantitatively subsumable criteria, which are orientated towards the soil characteristics and the local hydrological balances even in very small-scale dimensions. This requires a measurement network with a high spatial resolution in the horizontal and vertical dimension. Sensor-based irrigation using wired sensors with pedohydrological calibration are considered to be a suitable method even if the sensor-technology is still in development. In addition to the usage of wired sensors[36] the application of wireless micro sensors, which are installed in the pedosphere for measuring the soil moisture at different depths, is a promising new approach. When a critical limit value is exceeded the sensor transmits a signal to the next irrigation unit.

New approaches in the soft- and hardware-technology have made it possible to build a wireless network with special sensor-nodes to cope with complex control systems. However, the traditional methods of permanent soil moisture measurement that rely on many measuring-points are impractical when used in large quantities in a horizontal and vertical measurement-network because of the size of these instruments and their high purchase price. In microelectronics different kinds of micro sensors have been developed, which are able to measure acoustical, thermal or solar parameters. In the geosciences wireless sensor networks are becoming more widely used.[37, 38] For soil moisture measurements wireless network-sensors have already been constructed.[39] But these sensors are currently in an early stage of development and so far only prototypes exist.

3. METHODS AND DATA BASES FOR SOIL-HYDROLOGICAL RESEARCH

In the context of perennial studies the systematic interdependencies of the water-balance of regional soils under the influence of irrigation have been researched by specially constructed measurement-networks.[5] The database obtained was used for soil physical and statistical analyses.

The intended purpose was to get further information about the actual need and the optimal extent of irrigation. To quantify the spatio-temporal fluctuations of the soil-water-dynamics some representative locations were chosen. The construction of specially developed data loggers allowed the recording of diverse relevant parameters at a high temporal resolution.

The capture of soil-water-tensions in different depths of 20 cm, 40 cm, 60 cm and 80 cm was the main consideration so that the main root system of the apple tress was included in these tensiometrical measurements. This parameter was the central target variable in the course of the field work because—(different from the soil-water-content)—the soil-water-tension delivers information about the actual water contingent which is de facto available for the plants. Furthermore, this parameter makes it possible to calculate the hydraulic potential-gradients which deliver important information about the vertical water-flow in the explored soils:

$$grad\ \psi_h = \frac{\Delta\psi_h}{\Delta z} = -\left[\frac{\psi_{h2} - \psi_{h1}}{z_2 - z_1}\right] \tag{1}$$

with: $grad\ \Psi_h =$ hydraulic gradient [cm/cm],
and:

$$\Psi_h = \Psi_m - \Psi_z \tag{2}$$

with: $\Psi_h =$ hydraulic potential [cm], $\Psi_m =$ matrix potential [cm], $\Psi_z =$ gravitation potential [cm]
and:
$grad\ \Psi_h = 0$: stagnation (no water movement);
$grad\ \Psi_h > 0$: ascending movement;
$grad\ \Psi_h < 0$: descending movement.

The simultaneous capture of other potentially relevant parameters, like natural precipitation, interval of irrigation, relative humidity, soil temperature, air temperature inside and outside of the plantations or water level of rivers and groundwater-tables, made it possible to create a large data base.

These time series have been supplemented by studies about the infiltration-characteristics and detailed physical soil-analysis in open terrain and the laboratory. Here especially studies about the particle sizes were done because the particle size distribution contains very important soil information.[40, 41]

In addition to initial analyses of the measured data, the data base was used to detect quantitative and mutual dependencies between the captured factors. Here different mathematical-statistical methods of data analysis were used. Longer termed variations and marked phases of anomalies in the history of captured tensiometrical time series were described by applying numerical low-pass-filters. The use of numerical high-pass-filters allowed the optimized analysis of high-frequency-variabilities. Bivariate and partial correlation analyses were used for initial checks and for the quantification of connections assumed to exist between the soil water tension and the data for possible sources of influence. Calculations of (partial) auto correlation functions (ACF) served to identify location and depth specific inertia-influenced reaction speed and repetition patterns. In order to be able to quantify in the soil-hydrological processes the natural temporal delays as well as the dependencies and reaction speeds connected with them, the relevant time-lags were calculated by cross-correlations (CCF) for all correlation pairs. By condensing information and through pattern recognition, Principal Component Analysis (PCA) helped to extract the basic types of varieties of soil water tension. In the course of gradual regression processes it was possible to select from the total sum of parameters those parameters of influence which—being predictors—contribute significantly to explain the variations of the target parameters: soil water tension.

4. RESULTS OF THE SOIL-HYDROLOGICAL RESEARCH

Soil water tension proves to be a parameter very much dependent on the respective depths. In upper soil areas until about 40 cm atmospheric influences clearly have an impact on soil

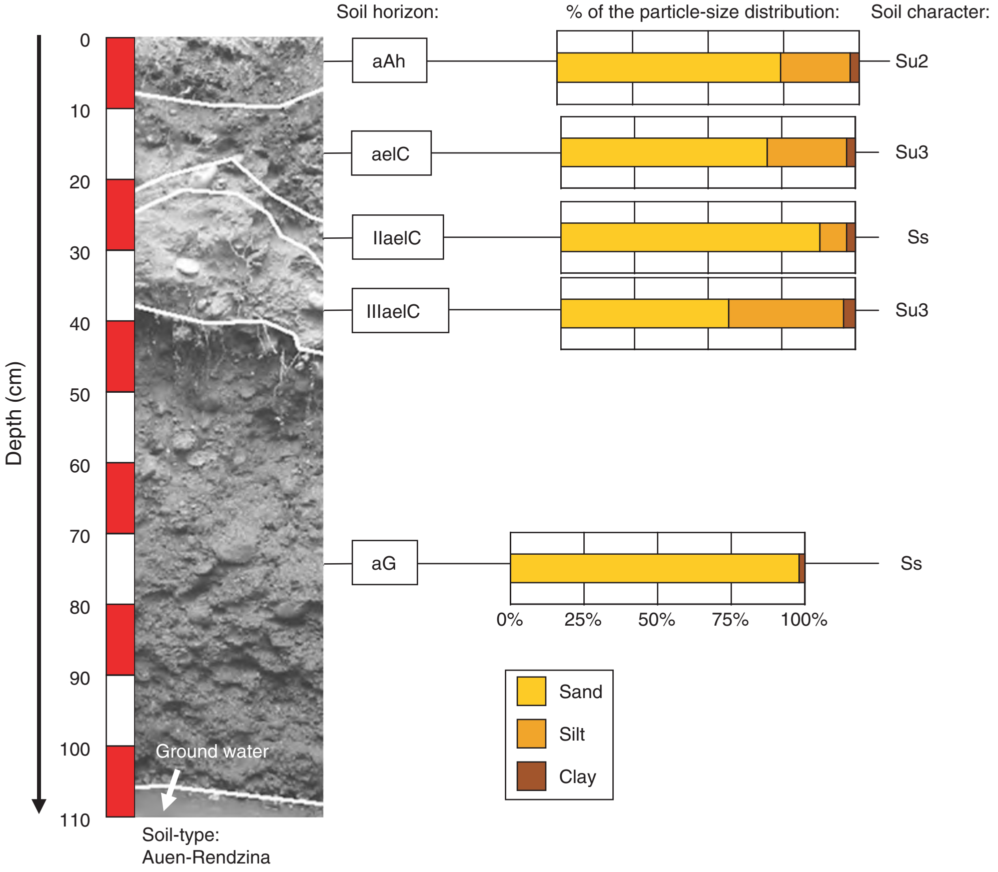

Fig. 4. Soil profile with demarcation of different layers and their particle-size distribution.

water tension. At locations with a proximity to ground water the ground water level turns out to be a significant parameter that strongly influences the soil water tension at the depths of 60 cm and 80 cm. The majority of the orchards is located at the bottom of the Etsch Valley. Therefore, most locations are marked by the floodplain dynamics and an accordingly high position of the level of ground water.

Figure 4 shows the structure of soil at a location with a high subsoil water level. Apart from the heterogeneous composition of the substrates the rising groundwater level can be observed.

The whole profile of this soil is marked by very sandy substrates. From about 40 cm under the ground surface level the soil-horizon aG is built by pure sand. This mineral substrate communicates with the groundwater level. In Figure 5 one can see that the tensiometric area in 80 cm soil depth is nearly permanently influenced by the groundwater.

Under the influence of capillary rising processes a temporary influence of the soil water balance up to the main root system of the apple trees between 40 cm and 60 cm depth must be expected.

A look at the range of soil water tension which is relevant for orcharding between 100 hPa and 600 hPa reveals that the soil profile contains only small amounts of water in those in the tensiometric depths that are of major importance in orcharding. But this could be explained by the composition of substrates in the soil. This fact is documented in Figure 6. There the soil water tensions *wt* are opposed to the soil water contents *wc*.

The time series of the hydraulic gradients (1)—using the soil hydrological potential-concept with the soil surface as the plane of Reference (2)—were calculated on the basis of tensiometric time series with a high temporal resolution at different depths. These gradients provide valuable information about the vertical

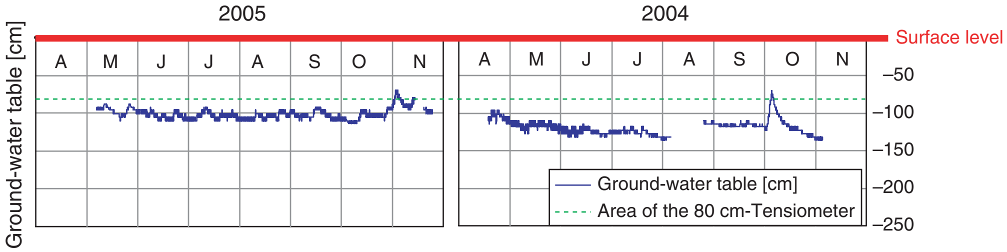

Fig. 5. Progress of groundwater fluctuations at the observed location (observation period from april to november 2004 and 2005).

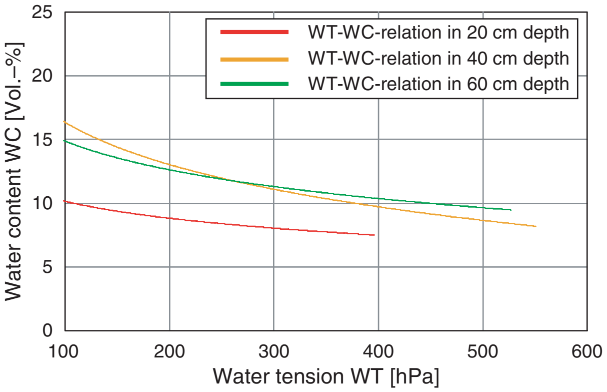

Fig. 6. Measured relations between soil water tension and soil water content.

soil water dynamics. Hydraulic gradients >0 describe an ascending movement and gradients <0 describe a downward movement of water in the soil. By observing the time series of these hydrological potential gradients in Figure 7 a predominance of a descendent water movement between 20 cm and 40 cm under surface could be observed. Between 40 cm and 60 cm these relations are much less distinct, because here sometimes ascending water movements occur. However, with regard to the depth zone between 60 cm and 80 cm, one can observe the dominance of ascending soil water movement, which is presumably connected with a high ground-water table.

The results of the statistical data analyses corroborate these assumptions. The calculation of *ACFs* for different depths is mapped in Figure 8 and shows a progressive inertia of the soil water tensions with increasing depth. The interval of persistence is extended up to 10 hours in 80 cm under the soil surface level. This implies that the reactions of the soil water tensions loose their dynamics with increasing depth because the soil moisture there is becoming more and more uncoupled from the atmospheric influences.

A look at the calculated *CCFs* in Figure 6(a) shows an increase of the time lags and therefore, lower dynamics in the soil water tensions down to 60 cm depth (26 hours from 20 cm to 40 cm and 45 hours from 20 cm to 60 cm). However, for the signal distance between 20 cm and 80 cm the shortest time lags (14 hours) are calculated. This can be explained by the high ground-water level. This situation becomes even more obvious, if one looks at the CCF for the time series of the soil water tensions between 60 cm and 80 cm under surface in Figure 9(b). For that a negative time lag of 10 hours is calculated, which can be explained soil-physically by the temporal advance of the reactions of the soil-water tensions in 80 cm in contrast to those in 60 cm depth. When the measured time series of the groundwater levels is included into the CCF-calculations, Figure 9(c) shows that a signal-change in the groundwater level is registered only after 22 h by the soil water tensions in the depth of 60 cm. However, a time lag of 0 h in 80 cm depth is calculated for the same relationship.

This could imply that the signal time lag is beyond the 48 h time slot or—which is soil physically more plausible—it takes less than 1 h, so that it was not measurable with the temporal resolution used.

The fact that a hydrological communication happens despite a vertical distance (on average 30–40 cm) between the groundwater level and the point of measurement in a soil depth of 80 cm must be attributed to the existence of capillary rising processes. But in the sandy and therefore very porous soil here (pure sand) these processes quickly reach their maximum rising rates of about 5 mm per day. This explains why the effect of capillary rising in a depth of 60 cm is largely absent because the sandy soil substrate does not allow higher rates of capillary rising or a higher rise of the groundwater level so that the level of tensiometric measurement in 60 cm depth may not profit from the groundwater influence within shorter spaces of time. For the soil textural class of pure sand this means (with regard to the bulk density and the position of the effective root zone[42]) a maximum capillary rising rate of 3, 5 mm per day for this location.

Both the calculations of the PCA not shown here as well as the results of the MRC verify the depth-specific influence of groundwater in the main root area of apple trees.

These results indicate that the water supply of apple trees at locations with a high subsoil water level may be mainly achieved

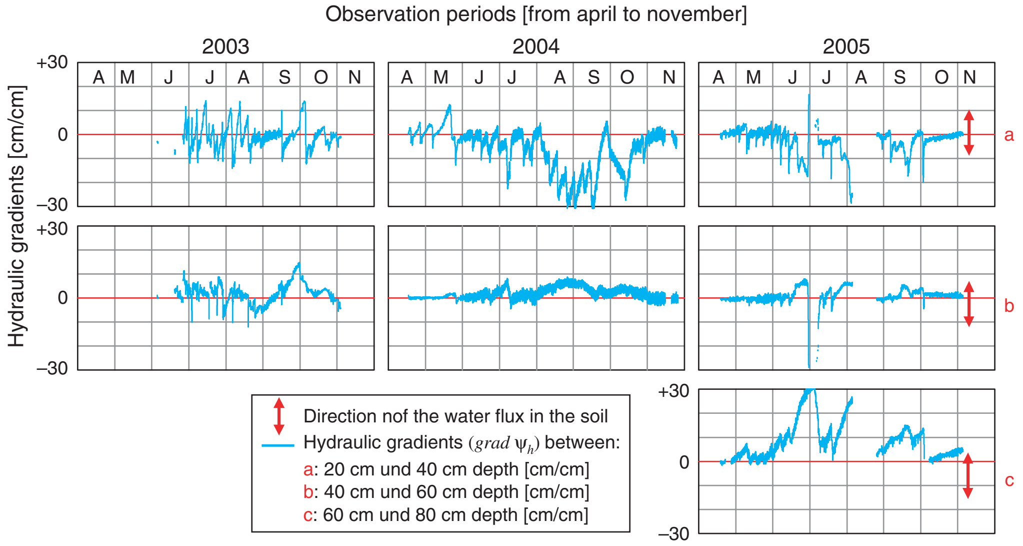

Fig. 7. Progress of hydraulic gradients *grad* ψh between different depths at the observed location (observation period from april to november 2003, 2004 and 2005).

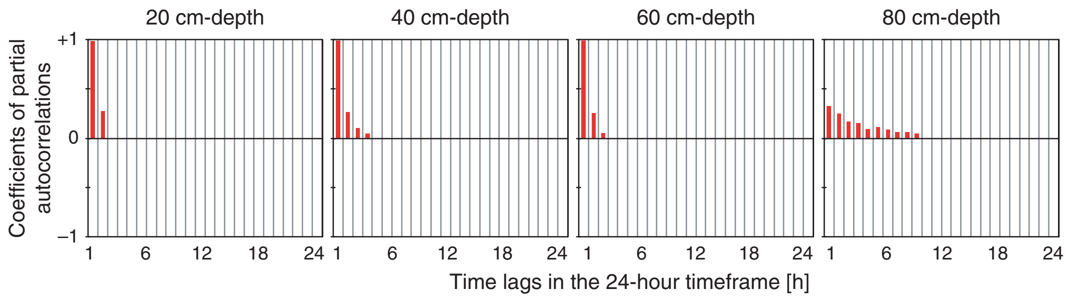

Fig. 8. Positive significant coefficients of partial autocorrelation of the tensiometric data sets in different depths in the 24-hour timeframe (significance level between $\alpha \leq 0,001$ und $\alpha \leq 0,05$).

by processes of capillary rising. Consequently, intensive irrigation seems to be unnecessary.

That a reduction of the irrigation intensity may be advantageous with regard to the fruit growing has been proved[2] and has also been observed in the context of recent studies at a groundwater influenced location.[43,44] In addition, the calculations have shown that the effectiveness of the irrigation also depends on the pedological composition, which is very variable, depending on location and soil depth. In particular, the important influence of pedological characteristics has become obvious: not only do they contribute through various horizon-specific differentiations to influence the infiltration characteristics and the relation between the soil water content and the soil water tension of a given location, but they also determine the effectiveness of capillary rising processes from the groundwater.

Therefore, pedological characteristics should be regarded as an essential factor for the spatial and temporal fluctuation of soil water dynamics—a fact which has been mostly disregarded so far. Results indicate that the main root system of locations with proximity to ground water can be sufficiently supplied with water through capillary rising processes. The fact that this can provide sufficient water supply for orchards under certain conditions was proved at one location with proximity to ground water that was not irrigated at all in the years while the research took place and yet the amount of fruit harvested was no less than that of a neighbouring location where irrigation was used.

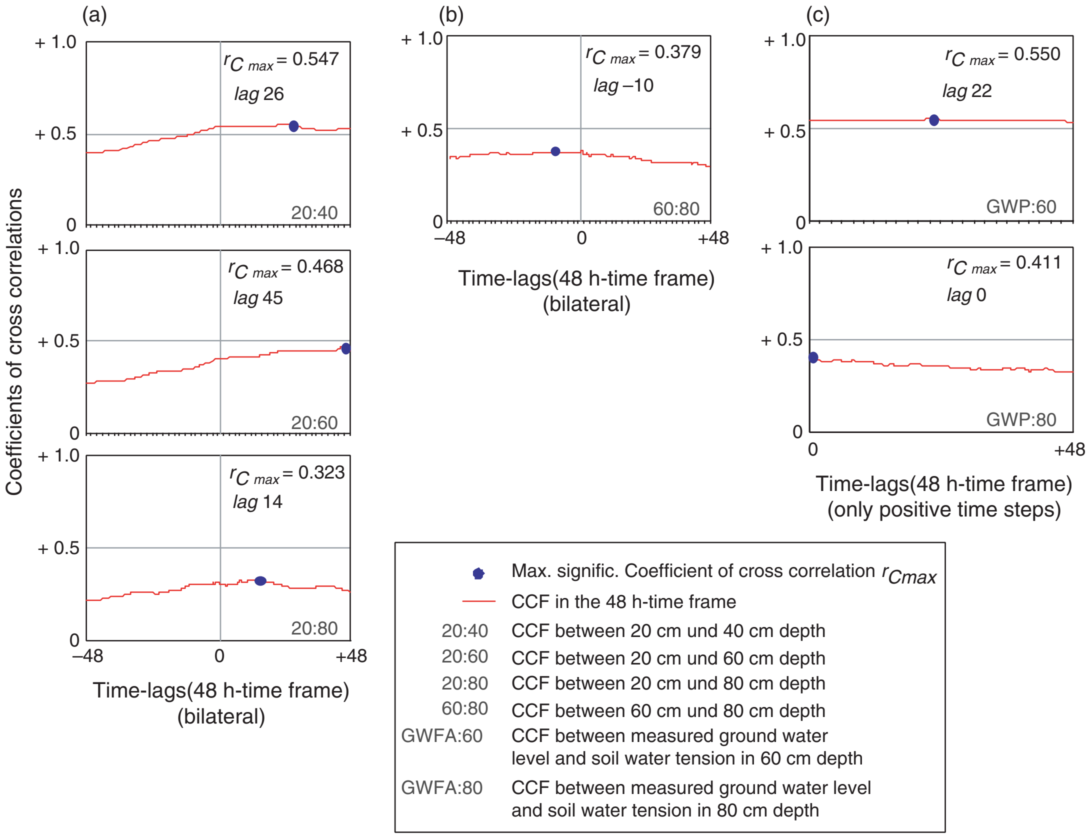

Fig. 9. Significant coefficients of cross-correlations in the 48 hour timeframe (significance level $\alpha = 0.01$). (a) Time lags of tensiometric data sets (between 20 cm, 40 cm, 60 cm and 80 cm). (b) Time lags of tensiometric data sets (between 60 cm and 80 cm). (c) Time lags of tensiometric data sets (60 cm and 80 cm) and data sets of groundwater level.

5. MULTI-AGENT BASED SIMULATION

The results of water shortage have been apparent in the past years of 2003 and 2005. The irrigation water, especially in the Middle Etsch Valley, is taken from wells. Meanwhile, because of the enormous water consumption, a depression in the ground water table has become noticeable. For the years to come it will be of pivotal importance to reduce water consumption to the absolutely necessary minimum. To cut costs it will also be necessary in the future to determine the demand of irrigation and the amount of water consumption according to objective and measurable criteria.

This emphasizes very strongly that drop-irrigation, as an effective and water-saving alternative, must be encouraged despite the high installation-costs. This kind of irrigation practice can be optimized, if the dripper units do not give the water up to a rigid and uniform schedule, but the need for irrigation is matched with the real amount of soil water, which is available for the plant. A wireless sensor network could provide information on existing soil moisture, transmit this information to the dripper units that in turn react by dripping exactly the amount of water that is needed by the plant. This approach makes precision irrigation possible.

On observing irrigation in practice one will realize time and again that the heterogeneity of the soil structures and textural classes in the main root zone are more or less completely neglected. But the availability of soil water for plants is primarily determined by the composition and the structure of the soil. The different soil-physical parameters are of vital importance here. Especially the mineral particle-size distribution is decisive for the relation between water content and water tension in the soil.

Currently a working group at the Institute of Geography (University of Augsburg) is developing a simulation of the envisaged wireless soil-moisture sensor-network (see Section 5.2).[45] This simulation approach is based on the above mentioned soil-physical interdependencies and it is realized by a multi-agent toolkit.

5.1. Simulation Approach

Multi-Agent Simulation (MAS) is a relatively new paradigm in the geosciences. The current state of the art of modelling in the geosciences corresponds to dynamic statistical and stochastic modelling of complex phenomena as well as systems dynamics. In contrast, Multi-Agent Simulations model the simultaneous interaction of multiple agents such as moisture sensors and dripping units. Multi-Agent Simulation models follow the paradigm of agent-based modelling. Agent-based modelling has the advantage to be able to model an explicit connection between the micro- and the macro level of the phenomenon. If the goal is to understand how the macro-behaviour of a system (such as irrigation) is composed of the states of single agents (sensors, soil stratum) and how changes at the system level (amount of water) influence the behaviour of the individual agent (soil moisture), then an agent-based model is a good choice. In addition, system behaviour can be modelled that is independent of the behaviour of individuals (seasons, rain, temperature, lowering of water table) but influences the environment in which individual decision are made, thus adding complexity to the model. Being able to relate individual behaviour (of sensors) to system behaviour (irrigation control) is one of the main reasons to choose multi-agent modelling and simulation as a research method. Multi-agent systems can manifest self-organization and complex behaviours even when the individual strategies of all their agents are simple.

Similar to the process of deriving a statistical model, researchers using MAS develop models based on presumed or observed geo-processes such as water percolating in the soil. This target process is abstracted to a process model and represented in the form of a computer program. The program is run and the simulation produces data based on initial conditions that are for example observed in reality or derived from other sources. The simulated data can then be compared to data gathered in the field to verify and validate the simulation.[46]

Statistical models and simulation models can both be used for explanation and prediction. However one advantage of a multi-agent simulation in comparison to a statistical model is that the initial conditions and any other variables may change at any time during the simulation because of interaction between the agents.

Depending on the research question the simulation may be used to predict the values of specific variables over time or it may be used to determine if the simulation process itself is feasible, producing a correct statistical distribution compared to observed data. A simulation is advisable if a real-world experiment cannot be carried out. In our case, we want to determine the intensity and length of irrigation for the soil to have optimal moisture for the plants at all times.

A multi-agent simulation is the process of running several times a computational model comprised of many agents operating within an environment. In a spatially explicit multi-agent simulation the environment and its parts are also represented as agents with parameters and processes of their own in addition to the target agents. This allows the programmer to explicitly model environment–environment, environment-agent and agent–agent interaction.

Agents possess an internal state and set of behaviours or rules which determine how the agent's state is updated from one time-step to the next during the simulation. The agents in a multi-agent system have several important characteristics:[47]

- the agents are at least partially autonomous, i.e., they can sense the environment and other agents, plan which rules to carry out and act on this plan without consulting a “controller,”
- agents have local views, i.e., no agent has a full global view of the system,
- agents are decentralized, i.e., there is no designated controlling agent.

Spatially explicit agents, i.e., geo-agents, have a geometric extent and other morphological attributes that will be considered, the proximity to other agents can be computed using a quantitative or qualitative measure, the locality of the agents is expected to have a bearing on the problem and spatial nearness and neighbourhood can be defined.

5.2. Irrigation Simulation Aquasim

In the German Guidelines for Soil Mapping[42] the textural classes are differentiated into 34 groups. The following descriptions are limited to simple structured soils. But the model presented is also able to do simulations with other compositions of soils. For the demonstration of the simulation we compare two soils with a depth of 45 cm. Example (a) is a heterogeneous soil profile with four layers (mS: 0–17 cm; Ls4: 18–25 cm; Su2: 26–30 cm; mS: 31–45 cm; Table I). Example (b) is also a heterogeneous

Table I. Soil textural classes (according the German classification) of the used examples.

		Particle size distribution (mass%)			Particle size distribution (mass%)		
Tectural class	Acronym	Clay	Silt	Sand	Fine sand	Medium sand	Coarse sand
Medium sand	mS				0 to ≤10	70 to ≤80	20 to ≤30
Faintly silty sand	Su2	0 to <5	10 < 25	70 to <90			
Strong sandy loam	Ls4	17 to <25	15 to <30	45 to <68			
Sandy-loamy silt	Uls	8 to <17	50 to <65	18 to <42			

soil profile with four layers (mS: 0–17 cm; Su2: 18–30 cm; Uls: 31–45 cm; Table I).

The most important part for the model is the simulation of the soil water dynamics which determines the water volume available to the plant. Based on a few soil moisture sensors which were implanted at the layer borders the moisture values in the space between the sensors are simulated. This setup makes it possible to estimate the actual soil water dynamics by a minimal number of sensors. The sensor nodes are connected with a control unit at the soil surface.

The control unit is the principal item of the simulation because it is placed between the sensors and the irrigation unit (Fig. 10).

The soil water tensions provide important information about the volume of water that is really available for plants. The pedotransfer functions which are used by the model describe the relationship between the water content θ as a dependent variable and the pF-value as an independent variable by nonlinear regressions of third degrees. Figure 11 shows the four pedotransfer functions of the relevant soils with the corresponding curves of desorption.

Based on the measurement of soil moisture the implementation of these transfer functions in the irrigation-model could therefore give temporal and spatial information about the progress of the soil water tension. The soil moisture values between the real sensor nodes are interpolated so that there are moisture values for each centimetre in the soil which were used for the calculation of the soil water tensions. In this way one gets direct information about the actual status of the water supply for the plants and the calculation of the water tension also allows estimating the actual need of irrigation in the progression of time. This important aspect is often neglected by observations that only take the soil water content into account.

Regarding the irrigation demand (= achieving the plant specific critical soil water tension) the sensibility is variable. In the example shown the irrigation will start by achieving water tension values of 500 hPa. This conforms for example to a water content of about 10, 2% in pure sand soil, 28, 7% in a pure silt soil and 36, 8% in pure clay soil. The irrigation demand is detected in the model by those sensors which are positioned in the root area (i.e., in Fig. 10 the whole soil profile). The detecting sensors could be real sensors at the layer border or virtual sensors between the real sensor nodes.

When the irrigation starts, the infiltration follows the descending water flow in the soil which is normally dominated by gravity. In addition to the gravity the water flow in the soil is driven by the hydraulic gradient $grad\psi_h$ as the result of different hydraulic potentials in different depths. The hydraulic gradients contribute in a decisive way to the water movement and they also determine the velocity and the direction of the movement. If the hydraulic potentials in the upper soil have continuously higher values than the potentials in the lower soil the water movement will be ascending. These ratios can be described by (1). The consideration of these (part-) potentials is elemental for the control of the water fluxes in the soil. As the model uses the soil surface as the level of reference the physical laws of (2) are valid for the hydraulic gradients of (1).

To calculate the average hydraulic conductivity as a function of the soil water tension the hydraulic conductivity $k_{(\Psi)}$ for the average value between saturation and the actual water content is calculated:

$$k(\psi) = k_f \cdot \frac{[1-(\alpha|\psi|)^{n-1}\cdot(1+(\alpha|\psi|)^n)^{-m}]^2}{[1+(\alpha|\psi|)^n]^{ml}} \tag{3}$$

with:

$k(\Psi)$ = unsaturated water conductivity as a function of the matrix potential [cm/d],
kf = saturated water conductivity [cm/d]
Ψ = matrix potential [hPa]
α, n, m, l = van Genuchten-parameters

The conversion of the measured water contents into the corresponding Ψ_m-values is done by the described pedo-transfer functions. For the parameter l it can be accepted with a sufficient accuracy that $l = 0,5$. The parameter m is described with the restriction $m = 1 - 1/l$. With just the knowledge of the soil textural class the residual parameters of van-Genuchten can be taken from the literature.[48–52]

The calculation of the spatially and temporally variable water fluxes can alternatively be described by the Richards-Equation (4).

$$\frac{d\theta}{dt} = \frac{d}{dz}\left(k(\psi)\frac{d\phi}{dz}\right) \tag{4}$$

The use of this nonlinear and partial differential equation is very difficult to solve and consequently needs a lot of computing time.[53]

$K_{(\Psi)}$ allows with the calculation of q a quantitative description of the length of time that the water needs on its way through the observed depth point dx in the vertical soil profile during the saturation process.

The subsequently needed hydraulic gradient is calculated with (1) for the average water content of the respective centimetre in question and the medium water content of the next deeper centimetre.

$$q = k(\psi) \cdot grad\psi_h \tag{5}$$

The calculation of q corresponds in effect to the maximal possible irrigation intensity where the water is not dammed up yet in any way. The model, in its present state of development, assumes—for the sake of simplification—that the water tensions will stagnate after activating the irrigation. In the area of the layer borders the calculation of the hydraulic gradients must be done by the pedotransfer function of the following textural class of soil.

However, it is important to bear in mind that the real velocity of the water flow is still higher because the water has to move

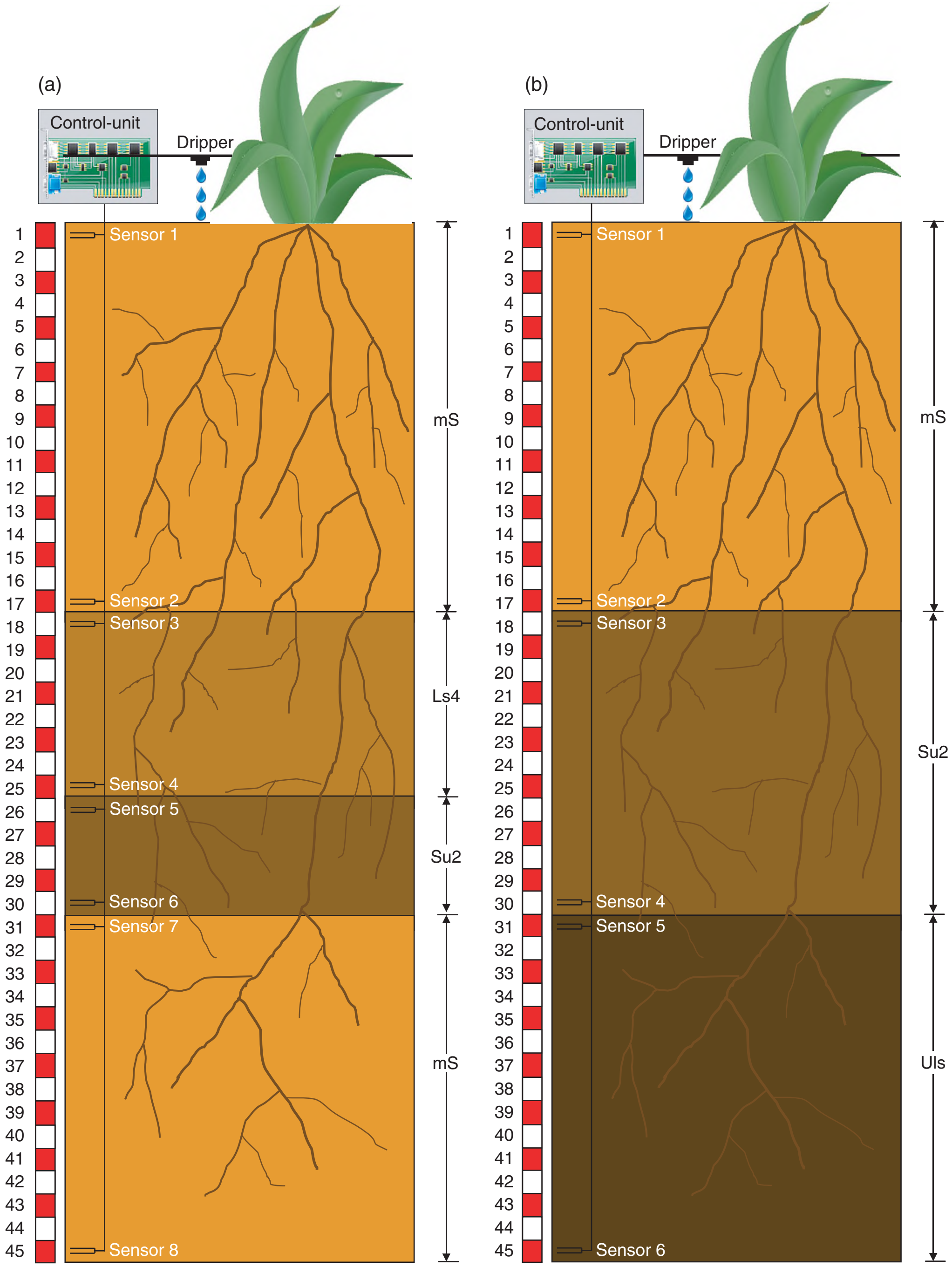

Fig. 10. Setup of the sensor based simulation in two soil-examples (a and b). Soil-depth in centimeter is denoted on the left side, the soil textural classes are denoted on the right side.

around the soil matrix. That means that the real distance of the water flow which is covered during the calculated time is longer than the distance of one centimeter.[53] But so far it has not been possible to simulate this effect.

The simulated descending water movement in the soil from one centimetre in the depth d_{x1} to the next following centimetre in the depth d_{x2} follows with a cascading model (see below), which is integrated into the whole model as a kind of sub-model. In a first step the actual fillable water storage volume wc_{fill} per centimetre depth is calculated:

$$wc_{\text{fill}} = (wc_{\text{sat}} - wc_{\text{act}}) \cdot 0,1 \tag{6}$$

with:

wc_{fill} = fillable water amount [mm]
wc_{sat} = water amount at field capacity pF 1, 8 [mm]
wc_{act} = actual water amount [mm]

In the context of this simulation approach pF 1, 8 was taken for all soil textural classes as the minimum level of the field capacity without any pedospecific differentiation. Each soil compartment

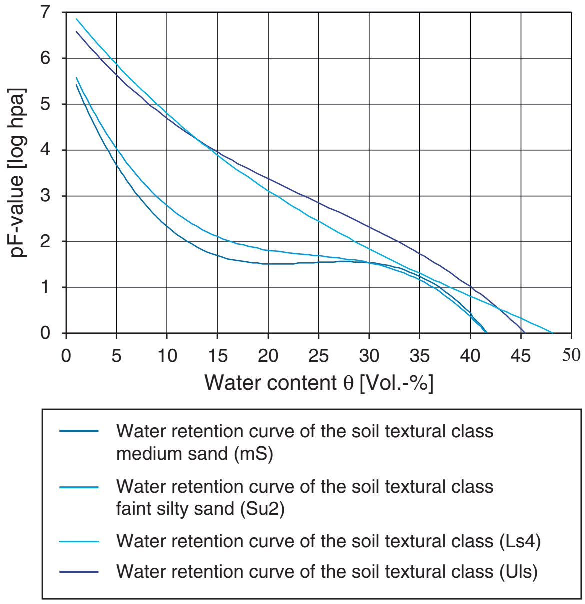

Fig. 11. Water retention curves of the different soil texturals (referring to the soil examples of Fig. 10).

fills up from the actual water content until field capacity is reached. Below pF 1, 8 the water cannot be held back at the soil matrix anymore because of missing bonding forces. The maximal adhering water amount at pF 1, 8 varies depending on the soil textural class.

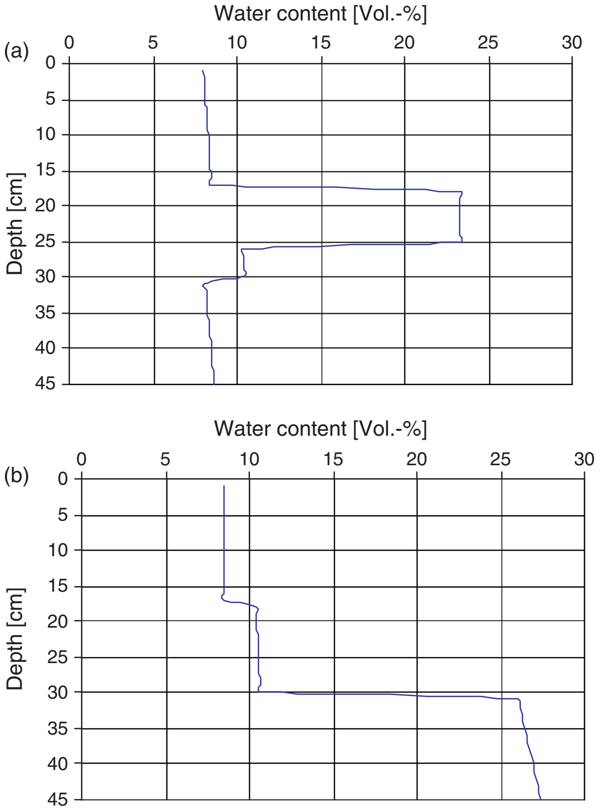

Fig. 12. Vertical distribution of the simulated water content (referring to the soil examples (a) and (b) of Fig. 10).

With q and wc_{fill} the model calculates the duration it which is needed with the intensity q to fill up the actual centimetre with water:

$$it = \frac{wc_{\text{fill}}}{q} \tag{7}$$

The calculation of the time, which is needed for the percolation through the meanwhile saturated centimetre d_x until reaching its basis d_{x+1} is described by the percolation time tp. The parameter tp can be derived from the saturated hydraulic conductivity of the corresponding soil textural class because the value of the hydraulic gradient in dx always amounts to 1 after its saturation. The overall duration tt for the infiltration of the irrigated water can easily be calculated by adding up the partial results.

$$tt_{dx_2} = tt_{d_{x_1}} + it_{d_{x_2}} + tp_{d_{x_2}} \quad tt_{dx_3} = tt_{d_{x2}} + it_{d_{x_3}} + tp_{d_{x3}}$$

$$tt_{dx_4} = tt_{d_{x3}} + it_{d_{x_4}} + tp_{d_{x4}} \quad tt_{dx_5} = tt_{d_{x4}} + it_{d_{x5}} + tp_{d_{x5}} \quad \ldots$$

6. RESULTS OF THE SIMULATION: IRRIGATION PLAN

The simulation calculates all necessary parameters based on the measured soil moisture values and the soil specific physical values. Figure 12 shows the measured und calculated water contents at date x in the whole vertical soil profile.

Both soils show anomalies in their vertical moisture graphs which range between 8 and 23, 2 Vol-% at soil (a). Soil (b) shows a water content between 8, 5 and 27, 5 Vol-%. The

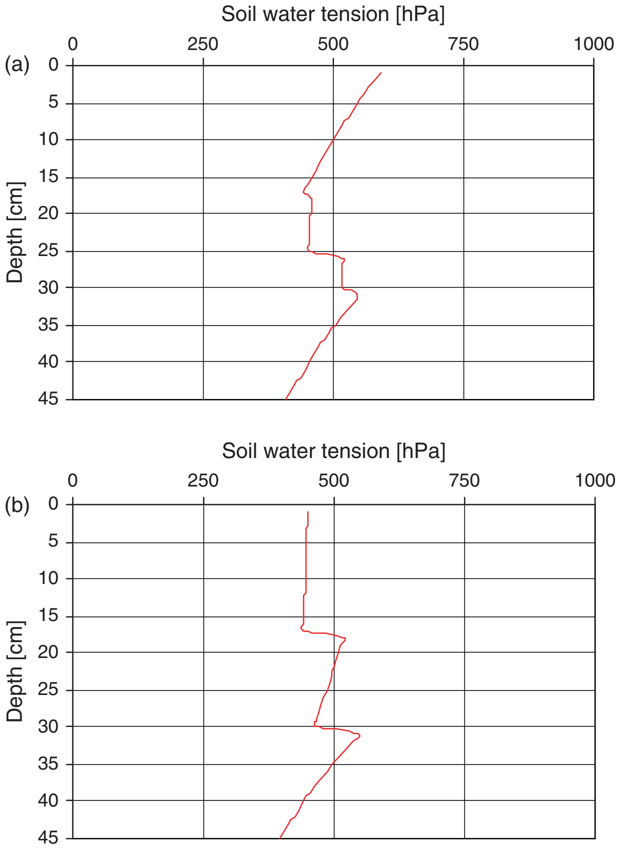

Fig. 13. Vertical distribution of the simulated water tensions in the soil profiles (referring to the soil examples (a) and (b) of Fig. 10).

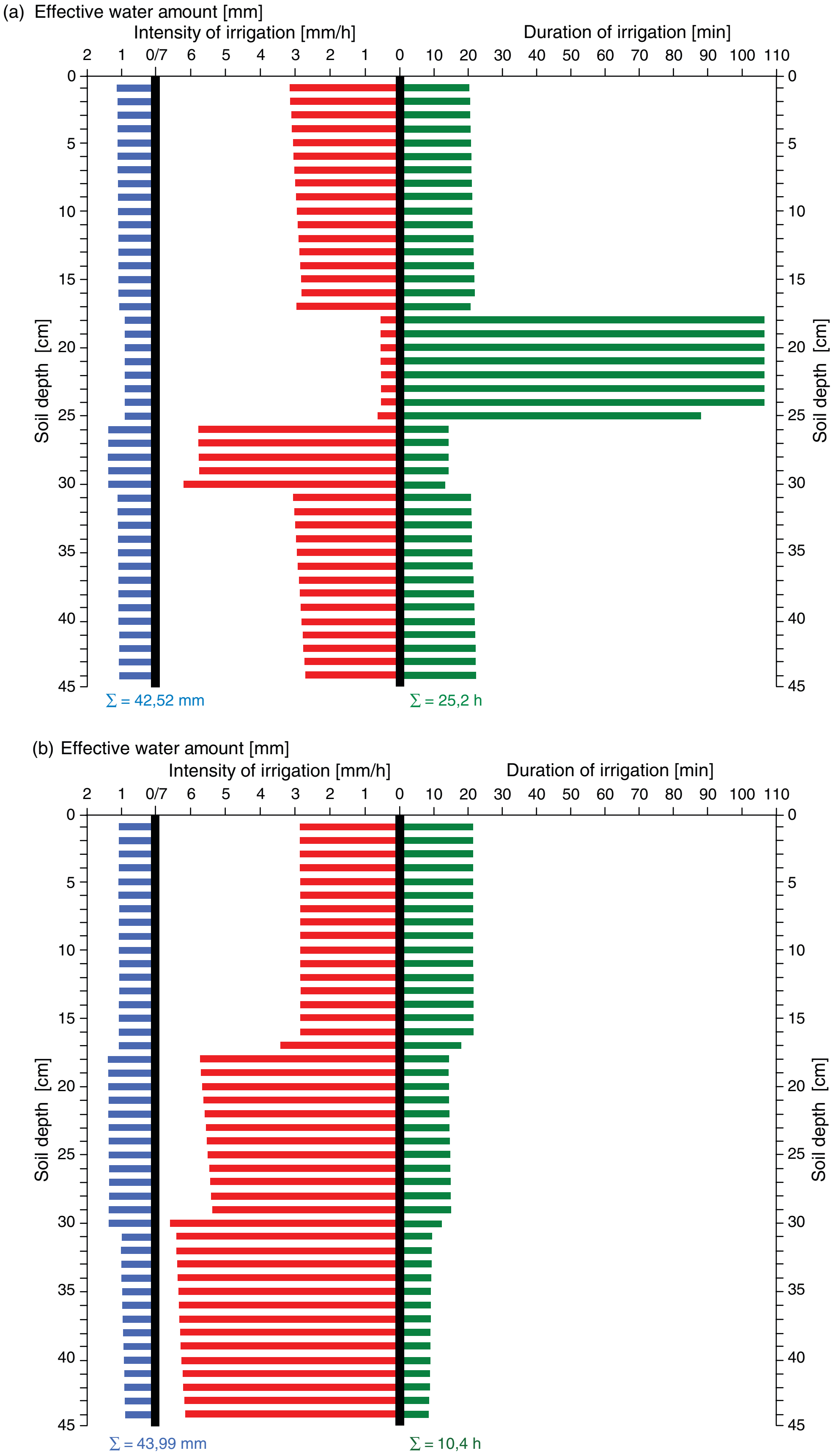

Fig. 14. Output of the simulated irrigation schedule (referring to the soil examples (a) and (b) of Fig. 10).

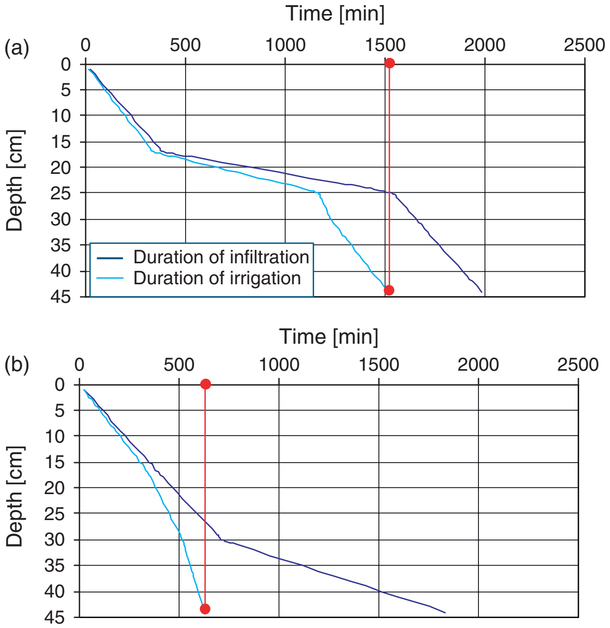

Fig. 15. Comparison of the simulated infiltration time and irrigation time (referring to the soil examples (a) and (b) of Fig. 10).

corresponding hPa-values of the water tension calculated by the PTFs are depicted in Figure 13. They show in both cases (a + b) an obviously more regular progress of the water tensions. This is caused by the potential equalisation of the soil water tensions, plausible from the soil physical point of view. Here again the soil specific variable and nonlinear relation of the two soil hydrological parameters becomes obvious.

In both cases the critical value of 500 hPa is exceeded so that necessity of irrigation is signalled.

The model calculates an irrigation plan to ensure a water application which is efficient and meets the demands. Thereby, the irrigation does not happen intermittently but in a continuous and dynamic way. This means that the amount of the water applied during the irrigation process is subject to controlled dynamic fluctuations. The irrigation plan (Fig. 14) shows these dynamics. The intensity of irrigation is variable during the whole period of irrigation because each soil depth (= area of real and virtual sensor nodes) contains the amount of water which corresponds to its maximal volume of water content at field capacity. This explains the varying values of the effective water amount. In addition to the intensity of irrigation the duration of irrigation is also controlled. Because of this dynamic way of irrigating the soil is given the needed water gradually, following the soil hydrological characteristics. As a consequence of the inert hydraulic conductivity of the Ls4-layer in soil (a) the complete irrigation time of 25, 2 h is much longer than in soil (b). The water quantities spent are in the

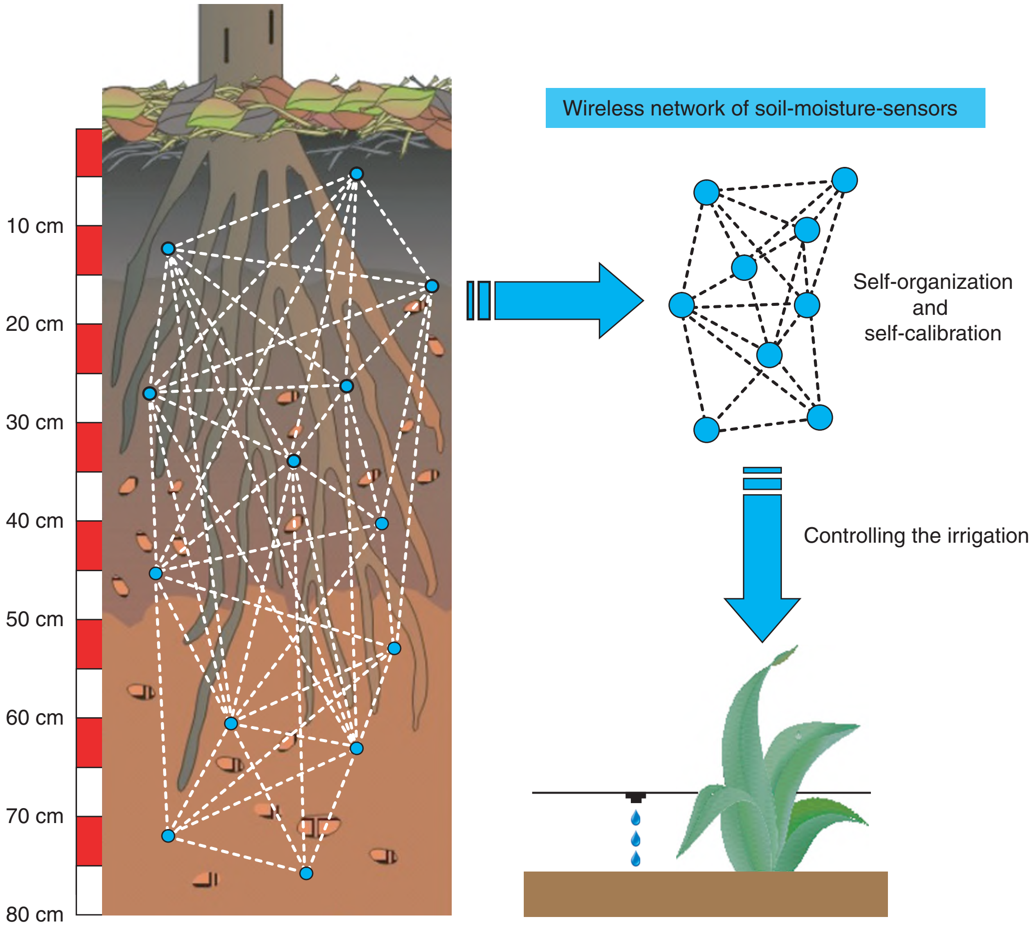

Fig. 16. Self-organization and self-calibration of the sensor network.

order of 40 mm and thus differ only marginally from one another. This can be explained by the fact that both soils show a fillable volume of pores with similar dimensions in their total build-up.

Figure 15 illustrates that the infiltration of the irrigated water down to the base of soil (b) takes more than 30 h, so that the process of infiltration continues for more than 20 h. At this point of time (red line) the water has reached a soil depth of about 30 cm. In soil (a) the time lag between the end of the irrigation and the infiltration to the base takes just 8 h even though the whole process of infiltration covers a longer period of time.

7. CONCLUSIONS

In this contribution a solution for the problem of precision irrigation based on objective criteria such as water distribution in the soil and pedological conditions has been presented. To optimize irrigation practice economically and ecologically it is essential to provide an objective basis for the irrigation process. However, atmospheric parameters as well as groundwater proximity must not be overrated: close attention to the pedological conditions should be a primary consideration. Once these pedological conditions are known it is much easier to evaluate the effectiveness of atmospheric and hydrological sources of influence. Only on this basis of large-scale and detailed information on the soil conditions a promising and serious attempt at tackling this task for the whole region can be undertaken and thus provide valuable information for an irrigation method strictly orientated along the specific requirements.

The idea is to control the irrigation by means of pedospecific calibrated moisture sensors and their integration in a sensor network producing a dynamic real-time irrigation plan. Such an irrigation plan adapts to measured soil water dynamics, differentiating between different soil strata and soil depths. The model allows for a heterogeneous substrate demonstrating that knowledge of the different soil types and their "behavior" with different moisture values is one of the main factors for successful control of the irrigation network.

This contribution documents the first results of the evaluation of such a network on a simulative basis and thus shows that the pedospecific calibration of the sensors is crucial to an irrigation control, which is tailored to the demands of the plants. The simulation also shows that a dynamic irrigation plan can be produced solely depending on real-time information from the moisture sensors.

8. OUTLOOK

The intended additional incorporation of different bulk densities, different contents of organic matter and the integration of more differentiated limits in the field capacities will optimize this simulation approach.

In a further step of simulation exogenous (especially atmospheric) parameters of influence will be included in the model in order to observe the effects of precipitation and evapotranspiration because they influence the soil water balance in a decisive way. Air and soil temperature as well as the relative humidity or the subsoil water level will also be integrated in the simulated interactions.

But the focus of these studies is not only the soil water balance itself but also the smart simulation of the interaction and communication between the sensors in the sense of 'Organic Computing'—a new field of science in applied informatics. In the ideal case this simulative approach provides information on the functionality (consumption of energy, positioning of the sensors, capabilities and limits of self-organization…) and the hydrological balance in soils (actual demand of irrigation, precision irrigation, recommendations of applications…) (Fig. 16).

However, intelligent precision irrigation does not have to rely on the development and usage of high tech methods. The predefinition of objective criteria for irrigation-improvement may also constitute of local pedological knowledge in combination with the longstanding experience of the regional agriculture and thereby achieve promising results. But simulations may help to better understand the sub processes and their interdependences.

Currently a validation of the model is planned using laboratory experiments setting up the microsensors in known soil substrates. Once this calibration process has been carried out, the sensors will be taken into the field for reliability testing and finally irrigation control.

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